



**Analysing Renewable Energy Finance as an Evolving Complex System:
Lessons from Offshore Wind**

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I, Asker Voldsgaard, confirm that the work presented in this dissertation is my own. Where information has been derived from other sources, I confirm that this has been indicated in the dissertation in accordance with academic standards.

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Abstract

The development of cost-competitive renewable energy technologies has transformed the viability of deep decarbonisation pathways. Nevertheless, the current pace of USD 0.3tn annual investments in renewable energy needs to be nearly quadrupled on average between 2021-2050 to comply with a 1.5-degree Celsius scenario (IRENA, 2021, 46, 100). Scholars have examined the central role of technological learning curves, but the crucial role of investment decisions to deploy low-carbon technologies remains under-examined.

This dissertation applies complexity theory to understand renewable energy finance, which makes it possible to analyse the heterogeneity, interactions, and learning processes in the investor community that constrain and enable the deployment of new low-carbon technologies at a low cost of capital. This dissertation adds empirical grounding to the complexity theory of energy finance and makes up for the neglected role of the state as an entrepreneurial investor in energy technology.

The dissertation uses offshore wind as a case by studying all investment deals from the first park commissioned in 1991 to the end of 2021 with an investment database compiled for the dissertation. Complexity theory and the fine-grained data material enable a longitudinal study of how investment patterns have evolved over the entire lifetime of a low-carbon technology. It, thereby, contributes towards an empirically grounded theory of how finance and investment influence sustainability transitions.

The social network analysis and qualitative accounts of the interactions among investors reveal how offshore wind financing evolved as a complex system through five phases. It also shows how entrepreneurial state investors, including utility companies and investment banks, have been decisive in shaping the evolution towards a mature private investor community. These insights are used to propose a conceptual framework for integrating the role of finance into sustainability transitions research and a policy framework for how public investments can be used in financial system governance.



Impact statement

This dissertation advances our understanding of the role of finance in enabling and constraining the development of new sustainable technologies. Low-carbon technologies are generally capital-intensive and the global mitigation of climate change requires vast amounts of investment in such technologies. Improved financial conditions are therefore essential for reducing the cost of the transition, since the cost of capital regularly makes up 30-50% of their total cost.

The comprehensive investment data material for offshore wind offers a unique opportunity for longitudinally examining how finance and investment have influenced the development of a low-carbon technology that has become a cost-competitive energy technology over the recent decade. This study thereby contributes to the development of a theory of finance in sustainability transitions that can inform analysis of other cases and aid the design of policy initiatives appropriate to the causal mechanisms in the nexus between finance and low-carbon technologies.

The dissertation proposes that renewable energy finance should be considered as an evolving complex system, which cannot be adequately analysed as a single representative investor. One main implication is that finance is not neutral and that financiers cannot be expected to price the risk of new technologies in a way that is conducive to deployment and learning – and hence lower future risk. The maturation of investor ecosystems, or networks, should therefore be a stronger consideration in the design of industrial policy programmes, such as the IRA legislation in the US or the EU's response to IRA under development at the time of writing.

The analysis shows that state-owned enterprises and state investment banks can have system-shaping roles in overcoming the technological and financial 'valleys of death' on the way to becoming a mature technology. Governments with state-owned enterprises in sectors important for reaching net-zero emissions should therefore consider the potential for driving early learning curves of burgeoning sustainable technologies by using the existing sectoral and organisational capabilities to pioneer large-scale demonstration and early commercial deployment. As the technologies require expanded market adoption to develop economies of scale, state investment banks should be used strategically to finance this demand, while at the same time focusing on accumulating investment know-how and spreading it to new financial and non-financial entrants.



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Table of contents

List of figures:.....	16
List of tables:.....	19
List of abbreviations.....	20
 1. Introduction.....	 21
<u>PART 1: FOUNDATION</u>	
2. Renewable energy finance literature review	39
3. Theoretical framework: Renewable energy finance as an evolving complex system ..	61
4. Methodology	78
<u>PART 2: ANALYSIS</u>	
5. The sectoral trends in offshore wind investment	111
6. From cradle to a mainstream asset class: A network analysis of how offshore wind technology matured and became financialised	130
7. Raising green animal spirits: Know-how diffusion in the investor network.....	175
<u>PART 3: DISCUSSION AND SYNTHESIS</u>	
8. Methodological evaluation	222
9. Analytical synthesis: Renewable energy finance as an evolving complex system.....	235
10. Theoretical synthesis: Lessons for sustainability transitions research	281
11. Policy synthesis: Governing green finance as an evolving complex system	300
12. Conclusion	316
References	333
Appendices	377

Detailed table of contents

List of figures:.....16

List of tables:.....19

List of abbreviations.....20

1. Introduction.....21

1.1. The sustainability transition context.....22

1.2. Understanding investment in renewable energy technology.....28

1.3. The theoretical framework.....30

1.4. Research design 31

1.5. Research contributions 32

1.5.1. Contribution 1: Renewable energy finance as an evolving complex system.....32

1.5.2. Contribution 2: The system-shaping role of entrepreneurial state investors 34

1.5.3. Contribution 3: The role of finance and investment in sustainability transitions research.....35

1.5.4. Contribution 4: Governance by investing 36

1.6. Thesis structure.....37

PART 1: FOUNDATION

2. Renewable energy finance literature review 39

2.1. Renewable energy support policies 40

2.2. Accounting for investor heterogeneity 41

2.2.1. Private investors.....42

2.2.2. State-owned investors	44
2.2.3. Civic sector investors	45
2.3. Barriers to private investment.....	45
2.3.1. Organisational barriers.....	46
2.3.2. Market barriers	48
2.3.3. Policy barriers	49
2.4. Risk and the cost of capital.....	50
2.4.1. The impact of the cost of capital on RE production	50
2.4.2. Heterogeneous cost of capital	52
2.4.3. Financial learning effects	53
2.5. Calls for a systems perspective on renewable energy finance.....	54
2.5.1. Reasoning based on efficient markets and rational investment behaviour	55
2.5.2. Reasoning based on adaptive markets	57
2.6. Summary of theoretical caveats to consider	60
3. Theoretical framework: Renewable energy finance as an evolving complex system ..	61
3.1. Complexity science and economics.....	61
3.1.1. Heterogeneous actors with bounded rationality.....	63
3.1.2. Explicit interaction in networks	64
3.1.3. Emergent properties	65
3.1.4. Evolutionary processes	66
3.1.5. Non-equilibrium dynamics	67
3.2. Complexity, finance, and investment	69
3.3. Sustainability transitions research, complexity, and finance.....	71

3.4.	Institutional mechanisms shaping the renewable energy finance system.....	74
3.4.1.	Mechanism 1: Bounded rationality	75
3.4.2.	Mechanism 2: Evolutionary processes.....	75
3.4.3.	Mechanism 3: Actor heterogeneity	75
3.5.	Towards a theory of renewable energy finance as an evolving complex system.....	76
4.	Methodology	78
4.1.	Research questions	78
4.2.	Operationalisation: Scope and terminology	81
4.2.1.	Renewable energy finance	81
4.2.2.	Investment know-how.....	83
4.2.3.	The ontology and epistemology of evolving complex systems	86
4.3.	Research design and analytical approach	88
4.3.1.	Research approach	88
4.3.2.	Research design	90
4.3.3.	Case selection and the structure of the analysis.....	91
4.3.4.	Periodisation of five investment phases.....	94
4.4.	Methods	97
4.4.1.	Method 1: Network visualisation.....	97
4.4.2.	Method 2: Network statistics	99
4.4.3.	Method 3: Qualitative sources	105
4.5.	Data.....	106
4.5.1.	Data sources	106
4.5.1.1.	Investment data	106

4.5.1.1. Qualitative data sources	108
4.5.2. Data collection and handling	109
4.6. Summary.....	110

PART 2: ANALYSIS

5. The sectoral trends in offshore wind investment	111
5.1. Deployment of generation capacity	111
5.1.1. UK's protective space for large-scale OSW	113
5.1.2. Diversified deployment.....	116
5.2. Investment trends.....	118
5.3. Cost trends	120
5.3.1. Technological cost trends	121
5.3.2. Financial cost trends	123
5.4. Finance and offshore wind's two valleys of death	127
5.5. Summary.....	129
6. From cradle to a mainstream asset class: A network analysis of how offshore wind technology matured and became financialised	130
6.1. Introduction to the historical network analysis.....	130
6.1.1. The asset foundation of the political economy of climate change.....	131
6.1.2. Structure and methodology	134
6.2. The phase-by-phase evolution of the investor network.....	134
6.2.1. Phase 1: SOE exploration (1989-2001)	134



6.2.2. Phase 2: Utility company-led upscaling (2002-2009)	139
6.2.3. Phase 3: State-led maturation (2010-2015).....	144
6.2.4. Phase 4: Post-Paris learning and know-how diffusion (2016-2018)	151
6.2.5. Phase 5: Offshore wind as a mainstream asset class (2019-2021).....	155
6.3. Looking across the phases: Maturation from cradle to a mainstream asset class.....	159
6.3.1. Assessing the full-period network	159
6.3.2. Network growth dynamics	161
6.3.3. Network effects and path dependency in the investor composition	164
6.3.4. Offshore wind investment as a prism for the political economy of climate change 170	
6.4. Summary.....	172
7. Raising green animal spirits: Know-how diffusion in the investor network.....	175
7.1. The capability foundation of green animal spirits	175
7.2. The micro-level dynamics of offshore wind investment	176
7.3. Methodological approach	179
7.4. The diffusion of offshore wind investment know-how via networks.....	180
7.4.1. Path analysis across phase 1 and 2: Few solid bridges	180
7.4.1.1. Few early carriers of know-how	180
7.4.1.2. The introduction of project financing	183
7.4.1.3. The path dependency of positive precedents	186
7.4.1.4. State investment banks enter as counter-cyclical and entrepreneurial investors ..	189
7.4.2. Path analysis across phase 2 and 3: More network paths emerge.....	190
7.4.2.1. A more diversified flow of know-how	191
7.4.2.2. Responding to adversity.....	194
7.4.2.3. State investment banks as trustworthy partners.....	195



7.4.2.4. Integrating institutional investors through financial innovation.....	199
7.4.3. Path analysis across phase 3 and 4: Financial learning and engineering.....	202
7.4.3.1. Polarisation of the know-how flows	202
7.4.3.2. The know-how core	204
7.4.3.3. Comparative state investment banking	206
7.4.3.4. Financial engineering to increase debt leverage	207
7.4.4. Path analysis across phase 4 and 5: Private financials dominate the know-how flows	210
7.4.4.1. A mature private investor network with diminishing roles for SIBs.....	210
7.4.4.2. Major oil companies: Transferable know-how or a systemic disruption?.....	213
7.5. A systemic view on flows and accumulation of know-how	214
7.5.1. The fragility of early know-how formation	214
7.5.2. Self-organisation and robustness	216
7.5.3. Towards a capability-based theory of green animal spirits	218
7.6. Summary: How a renewable energy investor community matured	220

PART 3: DISCUSSION AND SYNTHESIS

8. Methodological evaluation	222
8.1. Construct validity	222
8.2. Internal validity.....	225
8.3. External validity	228
8.4. Reliability	232
8.5. Summary.....	234
9. Analytical synthesis: Renewable energy finance as an evolving complex system.....	235
9.1. Offshore wind financing analysed through a complexity lens	235



9.1.1. Heterogeneous actors	236
9.1.2. Network interaction	237
9.1.3. Evolution.....	238
9.1.4. Emergent properties	240
9.1.5. Non-linear dynamics	243
9.1.6. Towards a complexity theory of renewable energy finance	246
9.2. The complexity-institutional nexus and the raising of green animal spirits.....	250
9.2.1. State-owned enterprises – learning curve initiators?	253
9.2.1.1. Rethinking the governance of state-owned enterprises	255
9.2.2. State investment banks – public value ephors?.....	258
9.2.2.1. The four roles of state investment banks in OSW	259
9.2.2.2. Governing the state investment banks	261
9.2.3. The systemic impacts of entrepreneurial state investors.....	264
9.2.3.1. Integrating entrepreneurial state investors in a sustainability policy mix	265
9.2.3.2. A long-term ownership role?	272
9.3. The future of offshore wind investment – a brewing storm?	273
9.3.1. Four disequilibrating processes.....	274
9.4. Summary.....	279
10. Theoretical synthesis: Lessons for sustainability transitions research	281
10.1. Finance and investment as a co-evolutionary element	284
10.2. Co-evolution of finance and investment at multiple levels	286
10.2.1. The three levels of finance and investment.....	286
10.2.2. The influences upon financing and investment	289
10.2.3. Influences by finance and investment.....	290

10.3.	A generalised complexity approach to finance in sustainability transitions research?	292
10.4.	Summary and further perspectives	296
11.	Policy synthesis: Governing green finance as an evolving complex system	300
11.1.	A green finance governance typology	300
11.2.	Governance by market efficiency to mitigate climate-related financial risk.....	304
11.3.	Governance by credit guidance to accelerate the reallocation of capital.....	307
11.4.	Governance by investing to advance the maturation of low-carbon technologies and spread the requisite investment know-how	310
11.4.1.	Considerations for implementing governance by investing.....	312
11.5.	Summary.....	314
12.	Conclusion	316
12.1.	The general conclusion.....	316
12.2.	Research methodology and dissertation overview	320
12.3.	Analytical outcomes	322
12.3.1.	The history of offshore wind investment.....	322
12.3.2.	The creation and diffusion of investment know-how	325
12.4.	Research contributions	326
12.4.1.	Contribution 1: Renewable energy finance as an evolving complex system.....	326
12.4.2.	Contribution 2: The system-shaping role of entrepreneurial state investors	327
12.4.3.	Contribution 3: The role of finance and investment in sustainability transitions research.....	328

12.4.4. Contribution 4: Governance by investing	329
12.5. Implications for further research	330
12.5.1. The complexities of renewable energy finance	330
12.5.2. Theorising the role of finance and investment in sustainability transitions.....	331
12.5.3. Towards a public investment approach to green finance governance	331
References	333
Appendices	377
Appendix A: The cost of electricity and the role of finance	377
Appendix B: Theoretical impacts of public sector investment in renewable energy	386
Appendix C: Semi-structured interview guide	388
Appendix D: Offshore wind finance statistics.....	389
Appendix E: Offshore wind finance networks	391
Appendix F: Offshore wind network statistics	394
Appendix G: Lead investor analysis of Ørsted's forward network reach	398
Appendix H: UK offshore wind industrial funding schemes	401
Appendix I: Risks in offshore wind investment	403
Appendix J: China's place in the investor network.....	406
Appendix K: Database descriptions	409
Appendix L: Comparison of neoclassical and complexity economics.....	410



List of figures:

Figure 1.1: Accelerating expansion of renewable energy capacity.....	24
Figure 1.2: Steep learning curves for renewable energy technologies.....	26
Figure 1.3: Dissertation structure, chapters, and research questions	38
Figure 3.1: Co-evolution among transition elements	72
Figure 4.1: The importance of deployment finance for the offshore wind industry	82
Figure 4.3: Investors obtain know-how from previous projects and diffuse the know-how	102
Figure 5.1: Annual additions of offshore wind capacity and cumulative growth (2001-2021)	112
Figure 5.2: The changing geography of the cumulative stock of offshore wind capacity	115
Figure 5.3: Annual finance for offshore wind by type of finance, sector, and ownership type	119
Figure 5.4: Cost profile of offshore wind.....	121
Figure 5.5: The two offshore wind learning cycles.....	122
Figure 5.6: Easing financial conditions for using debt in project finance.....	124
Figure 5.7: Large impact on the cost of electricity from offshore wind by different cost of capital assumptions	126
Figure 5.8: Primary finance and the two valleys of death.....	128
Figure 6.1: SOE exploration (phase 1: 1989-2001)	136
Figure 6.2: Energy and utility company upscaling (phase 2: 2002-2009)	140
Figure 6.3: State-led maturation (phase 3: 2010-2015).....	146
Figure 6.4: Post-Paris learning and know-how diffusion (phase 4: 2016-2018)	152
Figure 6.5: Offshore wind as a mainstream asset class (phase 5: 2019-2021).....	156
Figure 6.6: The full-period offshore wind finance network (1989-2021).....	160
Figure 6.7: Three stages of complex system evolution for offshore wind	163

Figure 6.8: Distributions of network ties and investments in the five phases.....	165
Figure 6.9: Degree centrality of offshore wind investors in the five phases (1989-2021).....	168
Figure 7.1: Know-how exposure from phase 1 (1989-2001) and diffusion in phase 2 (2002-2009)	181
Figure 7.2: Know-how exposure from phase 2 (2002-2009) and diffusion in phase 3 (2010-2015)	191
Figure 7.3: Know-how exposure from phase 3 (2010-2015) and diffusion in phase 4 (2016-2018)	203
Figure 7.4: Know-how exposure from phase 4 (2016-2018) and diffusion in phase 5 (2019-2021)	211
Figure 9.1: The roles of SOEs and SIBs in the adoption of new sustainable technologies	268
Figure 9.2: Design complexity and customisation determining cost-reduction potential.....	271
Figure 10.1: A co-evolutionary framework with offshore wind finance	285
Figure 10.2: The co-evolution of offshore wind financing, technologies, institutions, and business strategies in a three-level perspective.....	288
Figure 12.1: Research questions, chapters, and contributions	322
Figure 0.1: Cost of electricity production at different interest rates (2020-EUR/MWh).....	383
Figure 0.2: Change in LCOE (%) from changing interest rates.....	384
Figure 0.3: The composition of the types of financing	389
Figure 0.4: The distribution by sources of annual primary financing.....	389
Figure 0.5: The sources of finance for refinancing offshore wind projects	390
Figure 0.6: Acquisition finance by source	390
Figure 0.7: The full-period network of acquisition finance	391
Figure 0.8: The full-period network of refinancing	392



Figure 0.9: The full-period network of primary financing 393

Figure 0.10: Eigenvector centrality of offshore wind investors 1989-2021 395

Figure 0.11: Betweenness centrality of offshore wind investors 1989-2021 396

Figure 0.12: Distributions and forward and backward reach 397

Figure 0.13: Ørsted’s forward reachable set via paths of earliest arrival.....398

Figure 0.14: China’s know-how bridges to the investor network 406

List of tables:

Table 2.1: Sectoral and ownership diversity among RE investors.....	42
Table 4.1: The five phases of offshore wind investment	95
Table 6.1: The growth of the offshore wind investor network.....	162
Table 8.1: Comparing capital intensity and centralisation of sustainable energy technologies	229
Table 9.1: The complexity characteristics of offshore wind investment	246
Table 11.1: A green finance governance typology	304
Table 11.2: Policy instruments of green finance governance	315
Table 0.1: LCOE differentials for offshore wind under different WACC assumptions	385
Table 0.2: The theoretical impacts of public sector investment in renewable energy	386
Table 0.3: Semi-structured interview guide	388
Table 0.4: UK Offshore wind industrial funding schemes.....	401
Table 0.5: Ties between investors and projects from the three data sources	409
Table 0.6: Investors and projects in the database	409
Table 0.7: Comparison of neoclassical and complexity economics.....	410

List of abbreviations

Abbreviation	Concept
CAPEX-OPEX ratio	Capital expenditure to operational expenditure ratio
EIB	The European Investment Bank
EKF	The Danish export credit agency, Eksport Kredit Fonden
GFC	The Great Financial Crisis of 2008
GIB	The UK's SIB Green Investment Bank
KfW	The German SIB Kreditanstalt für Wiederaufbau
LCOE	Levelised cost of electricity
MW	Megawatt
NIB	The Nordic Investment Bank
OSW	Offshore wind
PPA	Power purchase agreement
RE	Renewable energy
SIB	State investment bank (including multilateral and supranational banks)
SOE	State-owned enterprises
USD	US dollars
WACC	Weighted average cost of capital



Chapter 1

Introduction

A sustainability transition to stay within the Paris Agreement's climate target of “well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C” requires sizeable investments in the deployment and development of new sustainable technologies that either produce or use electricity (IEA, 2021a; IRENA, 2021a). This scale of investment has raised concerns about whether the financial sector and business communities will provide enough cheap capital to support a rapid green transition at a low cost to society (Hafner et al., 2020; Jacobsson and Jacobsson, 2012). The number and size of investments, the offered cost of finance, and the propensity to deploy novel technologies are all factors that can enable or hinder a socially inclusive, cost-effective, and rapid transition. The IPCC has warned that “progress on the alignment of financial flows with low greenhouse gas emissions remains slow”. This means there is a “climate financing gap”, which “reflects a persistent misallocation of capital” (Kreibiehl, S., et al., 2022, p. 1549). The transition of financial flows therefore requires more enabling environments both in terms of economic and financial policies to overcome high risk perceptions and bring down the financial cost of the transition (ibid., p. 1586-1588).

Some scholars are optimistic regarding the volume of finance available (Polzin et al., 2021a; Polzin and Sanders, 2020), while others highlight the barriers to investment (Ameli et al., 2019; Hafner et al., 2020; Hall et al., 2017a; OECD, 2020a), the neglected role of state-owned investors (Elie et al., 2021; Mazzucato and Semieniuk, 2018), and the need for investor learning in bringing down the cost of capital (Egli et al., 2019a, 2018a).

This dissertation aims to contribute to our understanding of the role of finance and investment in sustainability transitions by using complex systems theory to examine how offshore wind has been financed throughout its entire deployment from 1991-2021. The main research question (RQ1) is:



What can be learned about how finance and investment influence sustainability transitions by analysing renewable energy finance as an evolving complex system?

Sustainability transitions research is a rapidly growing research programme that uses interdisciplinary approaches to examine how “unsustainable consumption and production patterns in socio-technical systems such as electricity, heat, buildings, mobility and agro-food (...) require radical shifts to new kinds of socio-technical systems, shifts which are called ‘sustainability transitions’” (Köhler et al., 2019, 2). However, the role of finance “is largely marginalised by the transitions literature” (Geddes and Schmidt, 2020, 1).

Complexity theory helps analyse how heterogeneous actors make investment decisions and how their interactions contribute to the maturation of the investor community, which has been identified as a structural barrier to renewable energy investment (Hall et al., 2017a). The analysis shows an evolving pattern of interactions and an integral role of the state as investor, which provides new insights for theorising the role of finance in sustainability transitions research (Kölbel et al., 2020) and how to govern the financial sector to promote sustainable investments (Kedward et al., 2022).

1.1. The sustainability transition context

The rapid reductions in the cost of renewable energy technologies over the past decade have made deep decarbonisation scenarios politically viable and technically feasible in the hard-to-abate sectors, like industry and transport, through direct or indirect electrification (Grubb et al., 2021a; Way et al., 2022). From a historical perspective, energy and finance have been inextricably linked to each other since Benjamin Franklin used the financial logic of credits and debits to comprehend electricity as the movement of negative charges separated from positive counterparts. Franklin named the flow of electrons ‘current’ as an analogy to the flow of monetary ‘currency’ in the economy (Freedman, 2006, p. 208). Since then, new energy technologies, such as waterpower, steam, electricity, and oil, have formed the core of new techno-economic paradigms whose initial implementations have been enabled by optimistic financiers



and financial innovations (Pathania and Bose, 2014; Perez, 2002). Innovation has advanced both financial practices (Minsky, [1986] 2008) and the generation and storage of electricity, which has created a potential for powering economies only with the use of renewable energy sources (Jacobson, 2020). The finance and energy sectors have also co-evolved due to the capital-intensive nature of energy resource extraction, generation, and distribution (Pathania and Bose, 2014).

The importance of the finance-energy interlinkage only increases as the global challenge to decarbonise energy systems unfolds, given the extraordinary capital-intensity of renewable energy technologies, most notably solar and wind energy, that entail significant up-front investments in the generation equipment (Schmidt, 2014). The 1.5-degree Celsius target of the Paris Agreement entails a total of USD 34tn in RE investments from 2021-2050, while the current national plans¹ would lead to USD 9.8tn. These totals correspond to USD 1.1tn and USD 0.3tn in average annual investments, respectively, while USD 0.3tn were invested in RE in 2020 (IRENA, 2021, 46, 100).² For the transition to have a favourable outcome, it requires investors willing to provide capital at a faster pace than hitherto at a low cost of capital since financing can often be the largest cost component over the lifetime of a renewable energy installation (IEA, 2019, 24).

Because of the sizable investments needed, renewable energy developers will have to obtain external financing in addition to their retained earnings. Consequently, a widespread focus has emerged on green finance governance to align capital flows with the Paris Agreement (UNEP, 2014). Finance has to be an enabler rather than a constraint on the deep economic restructuring implied by the Paris Agreement (UNEP, 2018, 2014).

Schumpeter was an astute observer of the animating, rather than passive, role of finance in the capitalist system (Mazzucato and Wray, 2019). He memorably described the banker as the “ephor of the exchange economy” with reference to the overseers of the kings of Sparta. For this role,

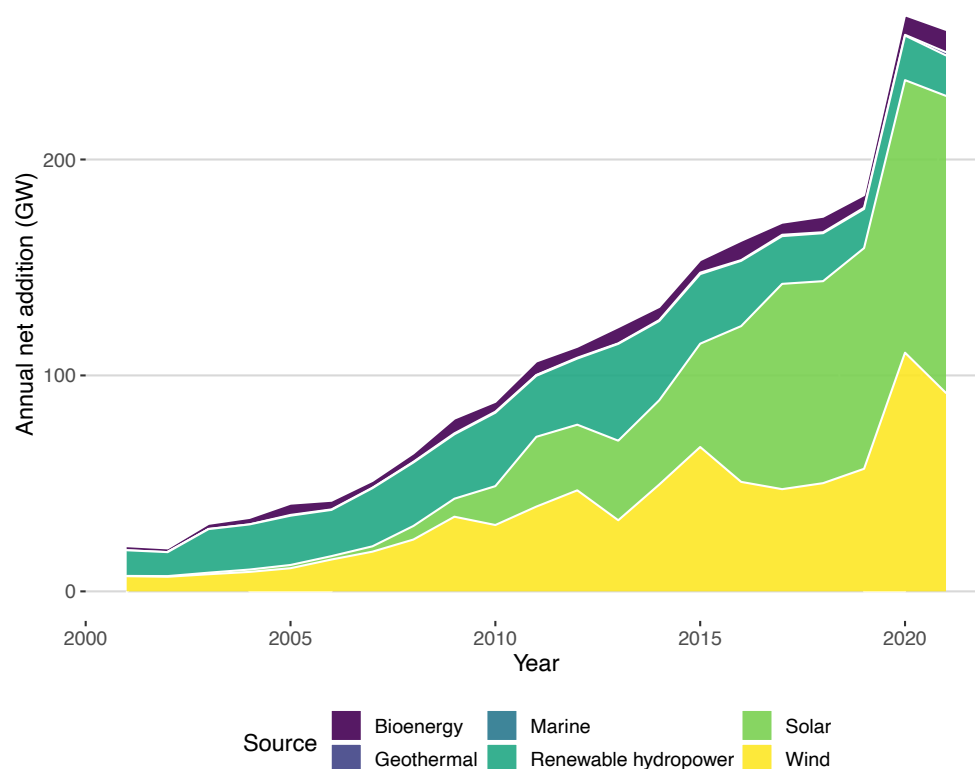
¹ Including Nationally Determined Contributions under the Paris Agreement.

² IEA (2021a, 155) similarly finds that the world invested \$0.5tn in electricity capacity from all energy sources between 2016-2020, and a transition to net-zero emissions will require annual investments in renewables alone to be above \$1.3tn on average from 2021-2040 and continue at \$0.8tn towards 2050.

he heralded the banker as “a phenomenon of development [who] makes possible the carrying out of new combinations, authorises people, in the name of society as it were, to form them” (Schumpeter, [1934] 1983, 41). For Schumpeter, innovation and economic restructuring were the sources of economic development. The bankers were the crucial enablers of this dynamism because of their ability to create new purchasing power for entrepreneurs seeking to disrupt incumbent modes of production through the commercial deployment of new technologies.

Figure 1.1 displays how the deployment of wind and solar energy technologies has accelerated since 2000 to more than 200GW of annual additions in recent years. We are, therefore, in the midst of a phase of ‘creative destruction’ (Schumpeter, 2013) that will displace the use of fossil fuels (Mathews, 2013).

Figure 1.1: Accelerating expansion of renewable energy capacity



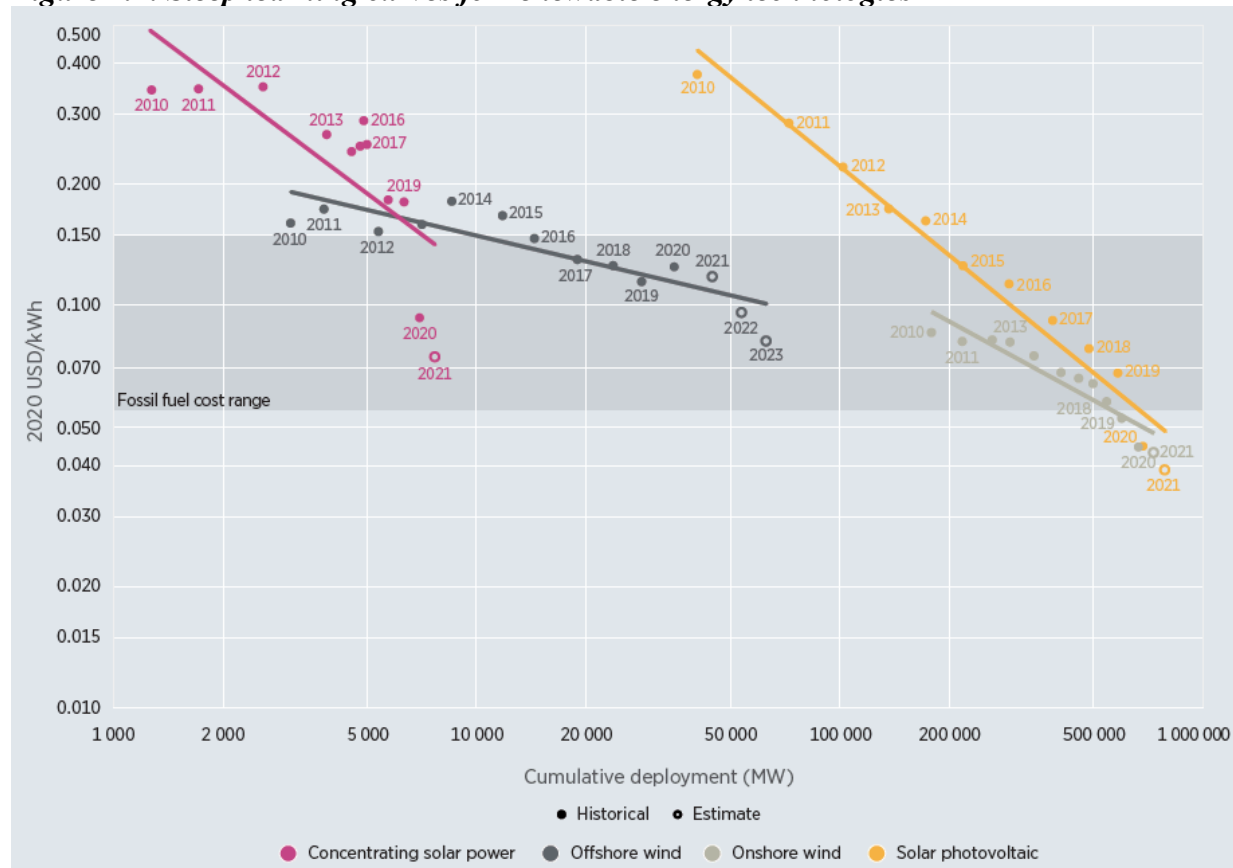
Source: IRENA (2021c)



However, Schumpeter's vision of bankers financing disruptive innovation is not straightforwardly applicable to long-term changes in energy systems. Decades of path-dependent innovation and infrastructure development in favour of fossil fuel technology had left a large competitiveness gap for renewable energy technologies, which could not simply be solved by banks deciding to finance a group of disruptive entrepreneurs (Seto et al., 2016; Unruh, 2000). On the contrary, one could expect the financial ephors to eschew sustainable technologies, despite their long-term potential for revolutionising energy systems. Nonetheless, renewable deployment has been a success, not so much because of the fossil fuel use it has displaced up to this point but because of the associated consequences for innovation (Grubb et al., 2017).

One of the most significant technological developments over the past decade has been the rapid reduction in the cost of renewable energy generation. From 2010 to 2021, the cost of electricity production has fallen by 60% for offshore wind, 68% for onshore wind and 88% for solar photovoltaics (IRENA, 2022a). Evolutionary economics scholars anticipated this downward trajectory, as they recognised the comparative advantage of renewables in mass manufacturing, learning by doing, and economies of scale compared to the extraction of fossil fuels (Mathews and Reinert, 2014). And, indeed, the technologies have followed steep learning curves with large percentages in cost reductions per doubling of the cumulative deployment (Figure 1.2).

Figure 1.2: Steep learning curves for renewable energy technologies



Source: IRENA (2021b, 39). **Note:** The fossil fuel cost range has been elevated by the cost increases in 2022.

Note: The y-axis shows the estimated levelised cost of electricity. Learning rates per doubling for: CSP (36%), offshore wind (15%, notably lowered by stagnant costs between 2010-2015), onshore wind (32%), and solar PV (39%).

These rapid technological changes and recent increases in gas and oil prices have turned renewable energy into a cheaper energy source than fossil fuels (IRENA, 2022a) and thereby created the potential for a technological revolution based on an abundance of cheap energy (Mathews, 2013). One study enhancing the consideration of continued learning in renewables and adjacent technologies, incl. batteries and hydrogen-based fuels, estimates a fast transition will globally save \$5–\$15 trillion compared to not transitioning away from fossil fuels (Way et al., 2022). This opportunity for economic gains stands in contrast to estimates included in the latest IPCC (2022, 41) report that do not comprehensively consider these factors, which finds that keeping the temperature below 2 degrees Celsius will cost a GDP loss of 1.3%–2.7%. Consequently, the mechanisms responsible for inducing innovation and enabling learning curves

are among the most important phenomena to analyse for mitigating climate change (Grubb et al., 2021a).

In one sense, learning curves are endogenous since deployment leads to lower costs, which in turn incentivises more deployment. Still, one comprehensive review of learning curve dynamics finds that deployment is the “dominant causality” in learning curve relationships (Grubb et al., 2021, 35). Deployment creates cost reductions through induced innovation and opportunities for economies of scale, specialisation, and competition in supply chains for a larger market (Ibid.; Way et al., 2022). Some of the learning curves in Figure 1.2 have been analysed to decompose the cost reductions by components and underlying drivers (e.g. Junginger et al., 2020). Economic analyses of the mechanisms have mainly used patent data since it is readily available. However, patent data only includes codified knowledge, not tacit know-how embedded in organisations and persons. In their literature review of learning curve dynamics, Grubb et al. (2021, 37) observe that:

The tacit knowledge and capabilities associated with deployment contribute to the other main observable metric — final costs or prices, but these aspects are little charted. Studies of the contribution from the declining cost of finance as a technology-industry matures has only just begun to receive appropriate academic attention.

This is the research gap that this dissertation contributes towards. Immature investor communities can be a constraint on the deployment of new energy technologies (Hall et al., 2017a) and learning among investors has been therefore identified as a neglected aspect in the deployment of new technologies (Christensen and Hain, 2017; Egli et al., 2019a, 2018a), which adds to the technological cost reductions delivered by the industry by lowering the cost of capital. An academic literature on renewable energy finance and investment has been growing since the 2000s, which can help us understand how developers and financial investors become confident enough to invest in large renewable energy projects at a low cost of capital (Elie et al., 2021).



1.2. Understanding investment in renewable energy technology

The renewable energy finance literature has moved through different focal themes since the early 2000s when most attention was paid to market designs and demand-side policies. Then came a growing focus on investor heterogeneity and their different characteristics. Later, barriers to investment and a particular focus on the cost of capital came to the centre of attention. There has also been a minor focus on the roles of civic and state-owned investors, which, however, remains under-explored (Elie et al., 2021).

Policy studies have for decades considered which market design policies are most effective and efficient at promoting investment in renewable energy (ibid.; Polzin et al., 2019). A key concern is how to adjust risks and rewards for investors, e.g. through feed-in tariffs, certificate schemes, or auctions (Egli, 2020; Polzin et al., 2019). Feed-in tariffs and auctions for fixed price contracts turned out to be more effective as they removed market price risk in the notoriously hard-to-predict electricity markets (Mercure et al., 2021b; Schmidt, 2014), while the cost reductions have later allowed renewables to be deployed with more price risk (Markard, 2018).

However, the role of investors and finance has often been reduced to a representative rational decisionmaker weighing objective risks and rewards (Pollitt and Mercure, 2018). While an abstract and simplified representation can be useful for some analytical purposes, the neglect of uncertainty, bounded rationality, and social influences, such as narratives, (Kay and King, 2020) limits our understanding of how new sustainable technologies get deployed and how their costs develop over time. This led to an inductive tendency in the literature to consider the heterogeneity among investors and their cognitive limitations and dispositions when considering renewable energy investment (Bergek et al., 2013; Chassot et al., 2014; Helms et al., 2020; Wüstenhagen and Menichetti, 2012). These studies used interviews and surveys to provide a more nuanced and behavioural perspective on the investors making the decisions that translate market incentives into deployment – or inaction.

More recently, literature has focused on additional barriers to private investment (Ameli et al., 2019; Granoff et al., 2016; Hafner et al., 2019; Hall et al., 2017a; Hu et al., 2018), such as financial regulation, organisational short-termism, and a lack of suitable investment vehicles. There has also been a more explicit focus on the cost of capital across different technologies,

countries, and investors (Angelopoulos et al., 2016; Donovan and Corbishley, 2016; Egli et al., 2019b; Helms et al., 2020; Hirth and Steckel, 2016; IEA, 2021b; Polzin et al., 2021b). Recently, there have been calls for a more systems-based understanding of how finance and investment shape sustainability transitions (Gabor, 2021; Geddes and Schmidt, 2020; Hafner et al., 2020; Hall et al., 2017; Köhler et al., 2019; Naidoo, 2020)

While the removal of price risk through market regulation has been accommodative for the deployment of renewables, we still have a limited understanding of the maturation occurring in the investor communities that translate incentives and perceptions of risk into investment decisions. Egli et al. (2018) have shown how learning-by-doing among investors has been an underappreciated factor in the decreasing cost of electricity since the cost of capital has until recently been assumed to be fixed rather than empirically estimated in cost statistics (IRENA, 2022a). This result points to the need for a more evolutionary perspective on how financial systems co-evolve with the technologies they invest in (Bale et al., 2015; Geddes and Schmidt, 2020; Köhler et al., 2019).

Together, these findings raise the question of how investors can become more supportive of the deployment of emerging sustainable technologies. If investors are more familiar with the risks facing a specific new technology, it will be cheaper to provide sufficient demand-pull to overcome the applied hurdle rates. In Keynes's (1964 [1936], 161-163) macroeconomic explanation for the persistence of the great depression, he presented a socio-psychological theory of how private business is guided by "animal spirits" referring to "a spontaneous urge to action rather than inaction" which is not "the outcome of a weighted average of quantitative benefits multiplied by quantitative probabilities". Keynes's emphasis on fundamental uncertainty regarding investments in long-lived capital assets meant that "the basis for making such calculations does not exist". In innovative, decentralised economic systems, all economic actors "have to make decisions about situations that are to a large degree unprecedented (...) based on a holistic consideration of the detailed circumstances at hand" (Bhide, 2010, 102).

This perspective is especially applicable to the case of renewable energy investment since the installations last 20-30 years, use technologies with, until recently, thin track records, and sell their output in the unpredictable electricity market (Christophers, 2022a). It is therefore important



to explore how *green animal spirits* can arise in both financial and non-financial businesses, which urges them to feel confident about investing in sustainable technologies at a low cost of capital. Surely, electricity market design is an essential factor as it can socialise the risks. Nevertheless, the process through which mature investor communities based on technology-specific investment know-how, rather than financial exuberance, emerge around new sustainable technologies has not yet been comprehensively researched. This dissertation, therefore, aims to contribute towards *a capability-based theory of green animal spirits* that can inform the continued expansion of renewable energy and the development of decarbonisation technologies that rely on the use of clean electricity.

1.3. The theoretical framework

To examine the role of finance in sustainability transitions, scholars must have valid theories of finance to guide our inquiry. Hall et al. (2017) make the cogent argument that energy investment is often analysed based on the neoclassical theory of efficient financial markets that dependably allocate capital to the most worthwhile investments. This approach encourages reasoning based on a representative investor with robust foresight. A less common perspective in use is the behavioural theory of finance, which focuses on individuals' limited cognitive ability to gather and process information, also known as 'bounded rationality' (Simon, 1955), which predisposes actors to make sub-optimal but satisfactory ('satisficing') decisions.

Hall et al. (2017) argue that behavioural finance applies to micro-level, individual decision-making, while the theory of efficient finance applies to an idealised, meso-level benchmark of optimising behaviour at the margin. However, both theories are insufficient for explaining investment behaviour at the strategic level, where investments in infrastructure and innovation change economic structures and move the technological frontier. Such financial decisions change the conditions under which satisficing and optimising behaviours occur. Grubb et al. (2014), who conceptualised the distinction between these 'three domains' of different social scales, find that evolutionary and institutional economic theories are better suited for explaining transformative investment decisions.

Hall et al. (2017) consequently apply an ‘adaptive market hypothesis’ (Lo, 2012) with inspiration from evolutionary economics (Nelson and Winter, 1982), which emphasises the constant need for investors to experiment and adapt to uncertain changes in the technological, financial, and political environments, and actor compositions that together render the market for energy finance “turbulent” and hence inappropriate to study as an efficient market (Hall et al., 2017, 294). Although their approach has been widely cited as it provided a novel lens for understanding the co-evolutionary role of finance, including how financial conditions shaped the UK's electricity market reform, little has been done to advance this evolutionary perspective on the role of finance in sustainability transitions (Geddes and Schmidt, 2020).

This dissertation seeks to remedy this lacuna by drawing upon the literature on complexity economics and institutional economics to provide a more system-based understanding of how finance and investment impact decarbonisation. Complexity economics studies the explicit interaction in networks of heterogeneous actors. The interconnected actors continuously evolve in their knowledge and behavioural patterns as adaptive responses to feedback and changes in their environment. This evolutionary and interactive process generates aggregate outcomes that can change abruptly in non-linear ways and cannot be explained with reference to a representative actor (Arthur, 2014, 2021; Beinhocker, 2007).

1.4. Research design

To answer to the main research question (RQ1), this dissertation analyses the entire history of offshore wind financing from 1989 to 2021. I have selected offshore wind as a case because of its rapid cost decline³ and its quality of being deployed in fewer and larger projects than other technologies with similar cost trends. This characteristic offers a methodologically rare opportunity for conducting an in-depth, longitudinal case study of all investment deals in a renewable energy technology from its very first deployment until it reaches a state of maturity. Since complexity theory stresses the importance of early conditions and events for shaping the

³ Which is also shared by onshore wind and solar PV.

system's trajectory, early data coverage is a methodologically attractive property of offshore wind.

The study uses various forms of visual and statistical network analysis to get a multifaceted understanding of how financial patterns have evolved. Moreover, since networks are better at showing social structures that constrain or enable certain behaviours than discovering what occurs at the micro level within the interactions, the study uses mixed methods by drawing on expert interviews and written accounts of notable events and trends in the industry.

To study offshore wind as an evolving complex system, the main research question (RQ1) is operationalised into four sub-research questions that together yield four scientific contributions. The first two sub-research questions motivate the analyses:

RQ2: *How has offshore wind investment co-evolved with the technology over time, and how have these changes shaped the political economy of climate change?*

RQ3: *Which investors and interactions have been important for investment know-how creation and diffusion in the offshore wind sector?*

The analytical synthesis in chapter 9, based on the results in chapters 5-7, produces the first two research contributions. These conclusions, in turn, raise two research questions regarding, first, the theoretical implications for sustainability transitions research and, secondly, the implications for financial governance, which each generate a research contribution.

1.5. Research contributions

1.5.1. Contribution 1: Renewable energy finance as an evolving complex system

Sustainability transition scholars have called for use of complexity economics to better understand the economics of co-evolutionary transition processes (Bale et al., 2015; Foxon et al., 2013; Hafner et al., 2020; Naidoo, 2020). The adopted complexity framework builds upon the insights by Hall et al. (2017) about the financial system's adaptive, and hence evolutionary,

behaviour. This dissertation advances the adaptive market hypothesis by broadening the focus beyond capital markets to more relational forms of financing. Hall et al. (2017) convincingly argue that capital markets, i.e. primarily bonds and equity traded on public exchanges, are unlikely to be a reliable source of funding for renewable energy. For a more general theory of renewable energy finance, the complexity perspective offers a framework that more explicitly encompasses the investor heterogeneity and interactions within the investor community besides capital market intermediation.

Considering renewable energy finance as an evolving complex system provides a coherent approach for examining how investor communities learn over time through learning-by-doing and co-investments. Graphical and statistical network analysis is combined with qualitative accounts of micro-level events and practices to explain the emergent properties of the investor system, incl. the investment pattern and the cost of capital analysed in chapter 5. The evolutionary and interactive processes that generate investment know-how over time are focal points for the inquiry (Loasby, 2002; Lundvall and Johnson, 1994).

Chapter 6 uses visual networks and network statistics to describe the evolution of offshore wind investments through five distinct phases *from cradle to a mainstream asset class* (RQ2). There is a shift in investment patterns that mainly come from state-owned enterprises (SOEs) and civic utilities in the first experimental phase to two distinct growth phases of the network with more involvement from private utilities, private banks, and state investment banks (SIBs)⁴. Finally, in the last two phases after the Paris Agreement, the investor network becomes more orderly in the sense of having a larger group of private investors, now including institutional investors, capital funds, and major oil companies, with sufficient know-how to finance offshore wind at scale, at a low cost of capital, and despite the increasing market risk. The network analysis thereby shows *green animal spirits* arising in different types of investors as the system evolves.

Chapter 7 complements these results by focusing on how the know-how foundation for this optimism got created and diffused across the five phases of the network (RQ3). It analyses each investor's exposure to experience from new parks financed in the previous phase and each

⁴ Including supranational and multilateral development and investment banks.

investor's potential for influencing the investor network in the following phase. This analysis displays the fragility of know-how formation in the investor community's early phases. Over time, self-organisation, learning-by-doing, and the central role of the SIBs in the growth phases led to a larger and more robust core of investors with extensive investment know-how.

1.5.2. Contribution 2: The system-shaping role of entrepreneurial state investors

One comprehensive review of the renewable energy finance literature finds an 'over-representation' of research on RE support policies, which reveals "a conception of the state as a regulator to the detriment of an entrepreneur or direct investor" (Elie et al., 2021, 10). This is an unfortunate oversight since state-owned investors have been more prone to invest in riskier renewable energy technology (Mazzucato and Semieniuk, 2018; Steffen et al., 2020b), public sources currently provide 51% of global climate finance, of which development banks and state-owned financial institutions provided 42%-points (CPI, 2021), and public investments in renewable energy mobilise private investments (Deleidi et al., 2020). Consequently, there has been an increasing interest in how SIBs can promote sustainable transition pathways (D'Orazio and Löwenstein, 2020; Geddes et al., 2018; Geddes and Schmidt, 2020; Mazzucato and Penna, 2016) and the potential for state-owned enterprises to contribute to innovation systems (Benassi and Landoni, 2019; Tönurist and Karo, 2016). The thesis considers *entrepreneurial state investors* as financial and non-financial organisations whose investments target the promotion of structural and/or technological economic change.

The analyses reveal how a small group of *entrepreneurial state investors* were integral to the development of foundational innovations in the offshore wind industry and for generating the initial investment know-how base that private financiers could later utilise to finance offshore wind. These insights provide new empirical evidence for how the evolution of complex systems is shaped by institutional factors (Gräbner, 2017) by perceiving policy-oriented state-owned organisations as contingent mechanisms that can alter the behaviour of private actors over time if governed for that purpose (D'Orazio and Valente, 2019).

It also adds methodologically to the growing literature on public investments that has relied on regression analysis or organisational case analyses. This dissertation contributes to the literature

with the first longitudinal technology case study, which systematically examines the role of investments by state-owned organisations. The analyses prompt renewed consideration of how to govern SOEs and SIBs to increase the probability of catalytic impacts on the maturation of sustainable technologies and investor ecosystems.

For SOEs, this dissertation proposes that broad *Technology Frontier Investment Mandates* can realise the potential of using decentralised decision-making in SOEs to advance innovation by deploying technologies at the earliest part of their learning curves. The current governance of SIBs appears more encouraging than SOE governance, but more focus could be placed upon the role of SIBs in improving investment know-how among private investors rather than a quantitative focus on mobilising ‘scarce funds’ from private financiers.

1.5.3. Contribution 3: The role of finance and investment in sustainability transitions research

Sustainability transitions scholars have advanced the study of how vast socio-technical systems become prone to lock-in and how to strategically alter such systems through the promotion of new niche technologies despite the ubiquitous negative feedback effects (Geels, 2019, 2002; Köhler et al., 2019; Seto et al., 2016; Unruh, 2000). However, the approach has been criticised for including too few economic considerations beyond niche innovations, such as investment and prices (Foxon, 2011; Foxon et al., 2013). Recently, the role of finance has been highlighted as an economic factor that should be integrated into co-evolutionary perspectives on how deep decarbonisation can be achieved (Geddes and Schmidt, 2020; Hall et al., 2017; Köhler et al., 2019; Naidoo, 2020). Moreover, a better understanding of the role of finance can also contribute to understanding the political economy that enables and constrains transitions (Geels, 2014; Roberts and Geels, 2019). The third sub-research question therefore asks:

RQ4: *What is the role of finance and investment in sustainability transitions?*

The theoretical synthesis (chapter 10) proposes how the complexity view of finance can be integrated into Foxon's (2011) co-evolutionary framework to show how finance co-evolved with technologies, institutions, and business strategies in the case of offshore wind. These elements



have influenced offshore wind at the micro, meso, and macro levels and contributed to shaping the evolution of finance. The emergent properties from the financial network, including technology deployment, the cost of capital, and a tendency towards financialisation, have in turn also influenced how technologies, institutions, and business strategies have changed over time.

The framework also contributes to the political economy literature on how changes in asset holdings change climate politics (Colgan et al., 2021). The case of offshore wind shows how a niche innovation became a mainstream and financialised asset class in the portfolios of major capital funds and with debt financed by large international banks. The changing patterns of asset creation and asset holding reshape the political economy of climate change by opening vast new asset classes to extract financial profits from the \$0.8-1.3tn in annual electricity capacity investments between 2021-2050 (IEA, 2021a, 155).

In other words, the case shows how new energy infrastructure installed to generate profits and interest income for private financials creates the material foundation for initiatives such as the Glasgow Financial Alliance for Net Zero (GFANZ, 2022), which has united \$130tn assets under management, to commit to net zero-alignment by 2050 and “drive ambitious and credible public policies that enable the net-zero transition”. While other asset-based accounts focus on risks to climate-vulnerable assets as a driver of changes in the political economy (Colgan et al., 2021), the evolutionary process towards financialisation of technology deployment of offshore wind, suggests that the emerging plausible future of large-scale de-risked profit opportunities could be a stronger force behind the increasing political support from financial interests (Gabor, 2021).

1.5.4. Contribution 4: Governance by investing

Lastly, this dissertation considers how the case study of how offshore wind has been financed provides inspiration for the ongoing efforts to align the financial sector with the Paris Agreement:

RQ5: *How can insights from the complexity analysis motivate new ways of governing financial systems to support sustainable innovation and transition of economic provisioning systems?*



Green finance governance has emerged as an instance of polycentric governance (Jordan et al., 2018; Ostrom, 2014). Numerous private sector (Liebreich, 2021), technocratic (NGFS, 2019; TCFD, 2017), and political measures (Steffen, 2021; UNEP, 2020) have been undertaken to align the financial sector's investments with the Paris Agreement. This dissertation develops a green finance governance typology with three main modes of governance:

- 1) *Governance by market efficiency*: The currently dominant mode of governance that aims to avoid climate-related financial risk by improving carbon information disclosure (Ameli et al., 2019; Christophers, 2017).
- 2) *Governance by credit guidance*: A contender mode of governance with more emphasis on coercive regulations, as it is sceptical about the potential for more information to be enough to reallocate capital at the required scale and speed (Kedward et al., 2022).
- 3) *Governance by investing*: A novel mode of governance developed based on the offshore wind case analysis and literature on complex system governance (Colander and Kupers, 2014; Keating and Katina, 2019; Loorbach, 2010). It aims to accelerate sustainable innovation and technology adoption by using SOEs to advance learning curves by investing in frontier technologies and by using SIBs to accumulate and diffuse investment know-how through co-investments, so new technologies face a financial system more capable of assessing the risks and returns.

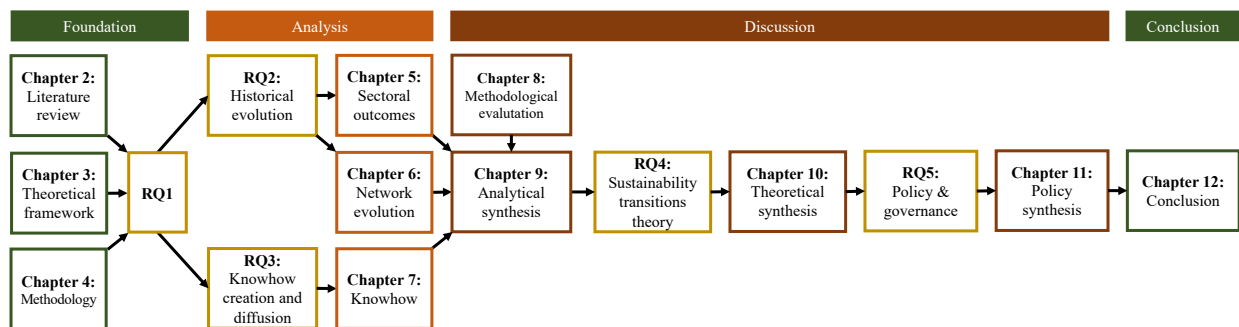
The governance by investing approach can potentially contribute with financial policy elements to policy mixes proposed in the sustainability transitions literature (Grubb et al., 2017; Kivimaa and Kern, 2016; Loorbach, 2010; Rogge and Reichardt, 2016).

1.6. Thesis structure

This dissertation contains three chapters developing the theoretical and methodological foundations, three analytical chapters, four discussion chapters, and a conclusion (Figure 1.3).

Chapter 2 contains a review of the renewable energy finance literature. It takes notice of Hall et al.'s (2017) call for an adaptive perspective and the general neglect of the state's role as an investor, which motivates the development of a theoretical framework in chapter 3. Chapter 4 presents the methodological framework and operationalisation of key terms, including investment know-how.

Figure 1.3: Dissertation structure, chapters, and research questions



Note: Own illustration.

Chapter 5 is a descriptive analysis of the aggregate developments in the offshore wind sector, which are interpreted in this dissertation as emergent properties of the investor network. Chapter 6 uses graphical and statistical network analysis to examine the history of offshore wind financing, including the dominant actors and implications for the political economy of climate change. Chapter 7 focuses on the creation and diffusion of investment know-how through longitudinal networks of co-investment partnerships.

Chapter 8 evaluates the methodological strengths and weaknesses of the analyses. Chapter 9 is an analytical synthesis, which combines the analytical results and discusses the insights obtained from adopting a complexity perspective. Chapter 10 is a theoretical synthesis of how the lessons from the complexity analysis of offshore wind can advance the understanding of the role of finance in sustainability transitions research. Chapter 11 considers how the analytical and theoretical conclusions can be used in policymaking to govern green finance. Finally, chapter 12 concludes by summarising the results and contributions of the dissertation.



PART 1: FOUNDATION

Chapter 2

Renewable energy finance literature review

The importance of investments in renewable energy (RE) for mitigating climate change motivates this review of the renewable energy finance literature. The global commitment in the Paris Agreement to keeping global heating “well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C” requires vast investments in sustainable technologies and enabling infrastructures. This has led to an increasing focus on the ‘green financing gap’, i.e. the discrepancy between the current investments in climate mitigation and the investments required in Paris Agreement-compliant scenarios (Hafner et al., 2020; Jacobsson and Jacobsson, 2012). The 1.5-degree Celsius target of the Paris Agreement entails a total of USD 34tn in RE investments from 2021-2050, while the current national plans⁵ would lead to USD 9.8tn. These totals correspond to average annual investments of USD 1.1tn and USD 0.3tn, while USD 0.3tn were invested in RE in 2020 (IRENA, 2021, 46, 100). Hence, investments are on track to living up to political plans, but they fall short by almost $\frac{3}{4}$ of what is needed to avoid the uncertainties of climate tipping points in the biosphere beyond 1.5 degrees heating (Anderson et al., 2020; Lenton et al., 2019).

Elie et al. (2021) recently surveyed the RE finance literature and detected eight clusters of research that can be further categorised into three general research strands concerning:

- 1) support policies to create a market for RE,
- 2) the behaviour and characteristics of private financial actors, and
- 3) non-financial investors, incl. households and individuals and corporations’ investments in carbon offsets.

⁵ Including Nationally Determined Contributions under the Paris Agreement.



On a timeline, they portray the development of the literature as starting with an emphasis on policy instruments to promote RE development. From the mid-2000s, heterogeneity of investor characteristics came into focus (e.g. Bergek et al., 2013), progressing to a focus on barriers to private investment (e.g. Ameli et al., 2019; Polzin et al., 2019). Increasing attention has been given to the assessment of risk and the implications for the cost of capital (Angelopoulos et al., 2016; Egli et al., 2018) and the role of public investments (Geddes et al., 2018; Mazzucato and Semieniuk, 2018). More recently, scholars have called for a systems-based view on the role of finance in sustainability transitions since investors are commonly reduced to a representative rational agent or considered in isolation. Moreover, the role of public investments has been under-examined. The review below is structured in accordance with this timeline and emphasises recent developments in the field.

2.1. Renewable energy support policies

The first strand of RE finance literature focuses on what energy support measures are most efficient and effective for promoting renewable energy investment (Elie et al., 2021). One central issue is whether price- or quantity-based support schemes are more effective (Menanteau et al., 2003). Price-based schemes, such as feed-in tariffs (FiT), obligate utilities to purchase RE production at a subsidized price for a specified period (Batlle et al., 2012). The costs are then allocated to consumers or the national treasury. Renewable portfolio standards are quantity-based schemes that place obligations on power retailers to ensure a specific amount of their sales is covered by green power certificates (Mitchell et al., 2006). RE power generators receive certificates in accordance with their production, which they can sell in the certificate market, ultimately to utilities, to support their revenues. Competitive bidding among developers for a fixed-price contract (price per kWh) for a pre-announced amount of RE is another option (Batlle et al., 2012).

Early debates in Europe concerned how to best stimulate RE investment. Grubb et al. (2002, p. 300) found that "more targeted policies might be expected to stimulate innovation more efficiently and effectively" than solely relying on carbon taxes. The Renewables Obligation (RO) certificate scheme in the UK (adopted in 2002) and the FiT scheme in Germany (adopted in 2000,



replacing its feed-in-premium scheme) are frequently compared in the literature (Mitchell et al., 2006). FiT schemes reduce risks to developers more than quantity-based schemes because they provide price certainty and do not rely on winning a competitive bid for support. However, they can be expensive for customers or public authorities that finance the subsidies since the quantity is not under control (Menanteau et al., 2003). Despite this, the German FiT scheme delivered lower costs to consumers and more deployment than the UK's RO scheme (Butler and Neuhoff, 2008), and tended to lead to higher venture capital investments in the wind sector (Criscuolo and Menon, 2015).

Since the early 2010s, there has been a shift away from FiT schemes towards various auction formats to increase price competition while maintaining revenue stability for generators and cost control for the public treasury (del Río and Linares, 2014; Toke, 2015). In the UK, this has led to a rapid reduction in the cost of offshore wind (Mercure et al., 2021b). Recent studies suggest that RE technologies have matured enough to increasingly compete without support policies (Markard, 2018; Pahle and Schweizerhof, 2016). Therefore, there is an increasing focus on exposing RE to day-ahead price signals in the 'spot market' to prevent possibly inefficient deployment in response to fixed price contracts (Energy Systems Catapult, 2021).

In a panel data study, Polzin et al. (2015) found FiT schemes to be more effective for deploying less mature technologies, while renewable portfolio standards are better for diffusing the uptake of mature RE technology. Greenhouse gas emission quota schemes become effective only if alternatives are sufficiently mature to enable substitution. Polzin et al. (2019) conducted a literature review and found that support schemes are most effective if they both reduce risks and increase returns to reach the level of risk-adjusted returns required by investors.

2.2. Accounting for investor heterogeneity

While the early literature was dominated by a focus on electricity market policies, a growing body of literature has analysed the heterogeneity among renewable energy investors (Bergek et al., 2013; Dinica, 2006; Helms et al., 2020; Mazzucato and Semieniuk, 2018; Polzin and Sanders, 2020; Wüstenhagen and Menichetti, 2012). A common thread is that finance is not neutral to economic activity. Investors have different propensities to invest in different technologies based

on their business models, experience norms, conventions, and cognitive biases. The heterogeneity among financiers generates different risk-return requirements and a variety of time horizons with implications for maturity and patience when investing in the real economy (Spratt, 2015). Institutional factors thereby affect which investments are undertaken and shape the direction of technical change.

The literature can be categorised by studies of private, public (i.e. state-owned), and civic investors (local community associations). Heterogeneity within and across the three groups is examined in the literature. Table 2.1 categorises the different types of investors (Spratt, 2015) by these forms of ownership and by economic sectors.

Table 2.1: Sectoral and ownership diversity among RE investors

		Ownership form		
		Public	Private	Civic
Economic sector	Financial	State investment banks Public commercial banks Sovereign wealth funds Multilateral development banks	Commercial banks Investment banks Asset owners (pension and insurance funds) Asset managers (private equity, managed funds)	Cooperative banks Member-owned funds (e.g. pension funds) Non-profit investors
	Non-financial	Energy companies Utilities	Energy companies Utilities Independent power producers Manufacturers	Utilities Citizen RE projects

Note: Own categorisation with inspiration from (Spratt 2015). Public ownership means state or municipal ownership, not ‘listed on a public exchange’.

2.2.1. Private investors

Dinica (2006) provided an early effort to shift the focus from energy support policies to the investor perspective to better understand the deployment of renewable energy technology. The author concluded that it is not the type of policy instrument per se that is crucial but rather the

policy design due to its impact on perceptions of risk and return. Wüstenhagen and Menichetti (2012) were among the first to highlight investor heterogeneity both along the innovation chain (from research and development towards commercialisation) and at particular stages along the chain. They found that the available types of investors mattered because they responded differently to policies. Bergek et al.'s (2013) empirical study found that there is a heterogeneous group of investors in RE and that the composition varies among different types of RE technologies. Helms et al. (2020) considered how different investor types used different hurdle rates to determine if the return on investment is worthwhile. Institutionalised hurdle rates have likely caused a late adoption of RE among utilities due to institutionalised preference for high risk-high return projects, since policy de-risked renewables are usually low risk-return projects. Likewise, due to the high risk-return preferences of oil companies, Christophers (2022) raises concern about the endurance of oil companies as RE investors.

Blyth et al. (2015) highlighted the importance of heterogeneity in balance sheet strength by examining the limited space for RE investments on the balance sheets of private utilities and commercial banks in the UK after the Great Financial Crisis. This weakness led to increasing attention to attracting investments from institutional investors. However, Salm (2018) found that institutional investors increased their required risk premium to twice the level of utilities if the project was fully exposed to electricity price risk. This reluctance among institutional investors has been considered a challenge since they were identified as a crucial source of finance for renewable energy (Nelson and Pierpont, 2013; Polzin et al., 2021a). Institutional investors denote large pools of assets, such as pension and insurance funds, that provide financial services to members and customers. With long-term maturities on the liability side of the balance sheet, institutional investors have the potential to provide cheap, patient finance compatible with the longer repayment schedule of renewable energy (Nelson, 2020). These investors are sometimes described as 'recyclers of capital' that can either refinance finished projects at lower rates or acquire existing assets to free up the previous owner's balance sheet for investments in new constructions. The low interest rate policies in the 2010s have increased their interest in green infrastructure, although their USD 314bn of investments in this category is only 2.8% of what they could invest under current financial regulations (Röttgers et al., 2020).



Considerable attention in academic and policy communities has therefore been dedicated to ‘unlocking’ financing from institutional investors (Ameli et al., 2019; Nelson and Pierpont, 2013). This includes international initiatives such as the IMF and multilateral development banks’ *Billions to Trillions* agenda, the World Bank’s *Maximizing Finance for Development* or the G20’s *Infrastructure as an Asset Class* (Gabor, 2021). However, there is a paradox to attracting institutional investors to RE since they prefer portfolio-based risk management strategies. Decentralised smaller installations are better suited from a portfolio risk perspective, but on the other hand, they are too small to warrant specialised investment teams (Clark, 2019). One solution could be specialised funds that acquire and pool smaller projects (Ameli et al., 2019; Fink, 2014).

2.2.2. *State-owned investors*

Although much focus in the literature is on private investors (Elie et al., 2021), Mazzucato and Semieniuk (2018) have found that public sector investors have provided large amounts of RE finance and, importantly, a greater propensity to invest in the more risky early stages of deployment of RE technologies. Among private sector actors, industrial companies and commercial banks have tended to invest in riskier technologies. These findings encourage a shift in focus from merely the total amount of financing, as suggested by the green finance gap concept, to include the composition and qualities of various forms of finance. State-owned utilities have also tended to invest in renewables before privately owned utilities (Steffen et al., 2020b). State investment banks (SIBs) have been identified as important organisations for promoting innovation and learning both through the quantity of capital invested and by spreading know-how to co-investors, and more indirectly by signalling trust in projects and emerging technologies (D’Orazio and Löwenstein, 2020; Geddes et al., 2018; Geddes and Schmidt, 2020; Mazzucato and Penna, 2016). However, Elie et al. (2021) found that the state’s role in the RE finance literature has largely been reduced to a market regulator rather than to an entrepreneurial actor.



2.2.3. *Civic sector investors*

While recent years have seen more policy efforts to attract institutional investors, earlier periods of RE investment have been characterised by large shares of investments from the civic sector (Curtin et al., 2017). In 2012, citizens owned around 50% of onshore wind and solar energy installations in Germany (Yildiz, 2014). Civic groups are generally not sophisticated investors; therefore, they have benefited from de-risked cash flows from FiT support systems to smaller projects. Civil actors struggle more when support procedures are more complicated and when the risk of not obtaining support is higher, such as in auction schemes. The increasing size of modern projects increases the money at risk for developers who cannot benefit from diversifying risk with a portfolio of projects (Curtin et al., 2017).

There has been a social acceptance advantage to civic-led investments in renewable energy, since the claims on public lands and eyesight by RE installations become more acceptable with local ownership (Toke et al., 2008). By ensuring local value retention, civic investments also strengthen the spatial justice of the green transition (Hall et al., 2018). Lastly, Hall et al. (2016) argued that the decentralised banking sector in Germany was dominated by cooperative and public banks with public purpose mandates and that this was an important reason behind the success of civic energy investment, in comparison to the UK's more centralised financial system.

2.3. *Barriers to private investment*

The many sources of investor heterogeneity and the falling level of RE investments from 2011-2013 (IRENA, 2021, 46) led to a growing literature aiming to identify *investment barriers* to 'unlock' more private investment, especially from institutional investors (Hafner et al., 2019). The various barriers that keep investors reluctant to invest in sustainable technologies mean that price signals alone will not be efficient policymaking (Rosenbloom et al., 2020). Instead, it requires a policy mix (Kivimaa and Kern, 2016) that includes financial policies (Campiglio, 2016).

Following Ameli et al. (2019), we can distinguish three types of investment barriers: *Organisational barriers*, *market structures*, and *political barriers*. Organisational barriers relate



to the internal capabilities to conduct sound due diligence and cognitive determinants of investment decisions, such as socialized logics. Market structures refer to the available investment instruments, channels, and partners, incl. their interaction and coordination. Finally, political barriers refer to energy and financial policies that can work against deployment of renewables.

2.3.1. Organisational barriers

Organisational barriers to investments in renewable energy include short-termism, policy uncertainty, cognitive rules, liquidity preference, and lack of knowledge/technical advice. Mignon and Bergek (2016) argued that institutional factors are often neglected, and that the heterogeneity of actors implies a corresponding variety of demands to the formal and informal institutional context. Wüstenhagen and Menichetti (2012) found that bounded rationality, status quo bias, and loss aversion subdue renewable energy investment, and Masini and Menichetti (2012) showed that energy investors were considerably risk-averse and prefer proven technologies. Clark (2019) found that private investors prefer investing in existing rather than new infrastructural installations to avoid construction risks. Nelson (2020) noted that institutional investors' liquidity preference is constrained by their business model, and that they seek to diversify their risk, which further limits how much finance can be allocated to single, large RE projects.

Liquidity preference is also promoted by financial regulation, such as Solvency II in the EU, and internal incentives for decision-makers are often structured to reward short-term financial results (Ameli et al., 2019). The development of dedicated and knowledgeable investment teams who are familiar with the business characteristics of sustainable assets and technologies is crucial (Ameli et al., 2019; Nelson, 2020), but Hafner et al. (2020) found that lack of knowledge/technical advice is one of the main barriers identified in both academic literature and policy reports. Christensen and Hain (2017) also highlighted the deficiency of relevant information for RE investors, which leads to sub-optimal investment behaviour.

Assessing the risks and rewards of sustainable investments is difficult and contributes to short-termism in the financial sector (Haldane, 2015). This, along with policy uncertainty, is a major barrier to green investment (Hafner et al., 2020; Chassot et al., 2014). Louche et al. (2019) identified four logics of contemporary finance that constrain sustainable investment behaviour: short-termism, predictability based on ex-post data, price efficiency, and risk-adjusted returns. Lack of knowledge and know-how in investment teams can lead to biased and inefficient investment behaviour. Additionally, path dependency in the financial community arises from adherence to current expertise, herd behaviour, status quo-biased data availability, and risk perceptions. In addition, vested interests shape policies and agendas to suit existing portfolios (Hafner et al., 2020).

Due to the inability of financiers to value distant risks and returns, the climate crisis has been described as a ‘crisis of temporalities’ (Christophers, 2019; Hope, 2011) and a ‘tragedy of the horizon’ (Carney, 2015). This has led to a growing literature on climate-related financial risk (Battiston et al., 2017; Christophers, 2019; D’Orazio and Popoyan, 2019; Krogstrup and Oman, 2019; Mercure et al., 2018; Semieniuk et al., 2021; TCFD, 2017). Avoidance of climate-related risk has predominantly been the framing used in green financial policymaking rather than the need to accelerate the green transition or prevent an expansion of the fossil fuel supply (Christophers, 2017; Kedward et al., 2022).

Lastly, the world’s existing portfolios of carbon-intensive assets are distributed across balance sheets in the financial sector. These carbon assets may risk becoming stranded in case of rapid transformation and thus temper investors’ desire to see a rapid transformation (Ameli et al., 2019; see also Curtin et al., 2019; Mercure et al., 2018). This is one of the mechanisms that position the economy in a ‘carbon lock-in’ (Seto et al., 2016; Unruh, 2000).

Despite all these organisational barriers, Hafner et al. (2020) pointed to the dynamic character of the financial system where actors can change, learning can occur, and the composition of investors can evolve. As mentioned above, investors are investing in RE in accordance with political plans (IRENA, 2021a), which suggests these evolutionary processes have had a positive impact.



2.3.2. *Market barriers*

Infrastructure investments lack liquidity by default (Granoff et al., 2016). As mentioned, this is at odds with the short-termism of financial investors (Haldane, 2015; Louche et al., 2019), which raises demands for asset liquidity and a rapid return on investment. So far, financial markets have insufficiently provided appropriate investment channels that combine RE investments with institutionalised liquidity preferences (Ameli et al., 2019; McInerney and Bunn, 2019; Nelson, 2020; Nelson and Pierpont, 2013). It has been suggested to promote wider use of market-based financial investment structures that pool assets in funds to diversify the risk and optionally issue transferable ‘tranching’ liabilities, where there is a repayment hierarchy among creditors⁶, to accommodate different desires for risk and provide liquidity to the holder (Fink, 2014; Nelson, 2020; Röttgers et al., 2020). In addition to these forms of financial securitisation, McInerney and Bunn (2019) suggested green bonds, green investment banks, and crowdfunding could offer attractive benefits, although fiscal support still appeared to be required.

Developing countries face more considerable difficulties in channelling finance to infrastructure based on lacking expertise, weak and unstable political governance, poor credit rating and exchange rate risks (Granoff et al., 2016). A higher cost of finance contributes to weak economic growth in developing countries, which makes financial provisioning a global governance issue (Ameli et al., 2021).

Ameli et al. (2019) identified an endogenous barrier arising from the reflexivity of markets. It is individually rational to maintain fossil-based investments on the expectation that other actors will do the same and thus maintain high asset valuations compared to sustainable investments, whereby investors remain exposed to significant carbon-based risk to avoid short-term losses by moving against the market. Mignon and Bergek (2016, 310) encouraged further consideration of how “investors’ networks” operate and to regard investor network formation as a policy lever, where “network effects can be utilized to trigger emerging investors’ decisions”, so the reflexivity of finance becomes a driver rather than a hindrance of the transition. Ameli et al. (2019)

⁶ The debt that gets paid first is the senior debt holders. The last are the junior debt holders. Mezzanine debt is positioned in between senior and junior debt.



suggested a more prominent role for long-term public investment, more supportive monetary policies and macroprudential regulation, reformed anti-monopoly regulation, and new, less expensive investment channels.

2.3.3. *Policy barriers*

Nelson (2020) identified three main policy barriers to more private investment in RE: energy policy design, unrelated financial and energy regulations such as financial liquidity and capital requirements, and policy uncertainty (see also Leisen et al., 2019). Policy uncertainty has been a recurrent barrier, especially because of retroactive changes to support policies, as seen in Spain in 2015). In relation to energy policy, the OECD (Röttgers et al., 2020) suggests promoting institutional investment by scaling up project pipelines. Insufficient expansion plans for renewables limit the anticipated market size and hence the economies of scale for investors who consider investing in organisational capabilities. More projects would allow institutions to build up internal expertise and consequently execute deals with more certainty and less transaction cost.

Ameli et al. (2019, 9) found that EU market liberalisations that restrict investors from owning both transmission and generation assets limit institutional investment since monopoly regulation of transmission asset income provides predictable cash flows with less price or technology risk.

As mentioned above, financial regulations designed to reduce risks in banks (Basel III) and insurance funds (Solvency II in the EU) have steered financial institutions away from illiquid investments such as RE assets (Ameli et al., 2019; BNEF, 2013). A recent review process initiated by the EU Commission on the Solvency II framework aims to improve climate risk analysis by institutional investors and increase equity investments by expanding the scope of investments that qualify for the more favourable 22% risk factor ascribed to “long-term” investments (instead of 39%). This would reduce capital requirements to free up investment capacity (EU COM, 2021). The Bank for International Settlement is likewise in consultation regarding climate-related adjustments to the framework for financial risks in banking (BIS, 2021).

2.4. Risk and the cost of capital

The literature on the impacts of RE support policies and investor heterogeneity led to an increasing focus on the cost of capital. One of the benefits of FiTs and auctioned fixed-price contracts was to lower the cost of capital, which again translated into cheaper clean electricity, more deployment and more learning (Mercure et al., 2021b). Therefore, scholars and policy organisations have increasingly paid attention to the role of finance in the cost of electricity, technology-specific cost of capital, and financial learning effects.

2.4.1. The impact of the cost of capital on RE production

The cost of capital carries significant implications for the trajectory of the green transition and the desired policy mix. Hirth and Steckel (2016) showed that the typical higher share of capital expenditure (CAPEX) relative to operational expenditure (OPEX) in renewable energy projects compared to fossil fuel-based projects made the cost of capital a decisive concern for policymakers. If the cost of capital is high in the economy, fossil fuel projects will be favoured, all else equal. Policymakers would then need to impose a higher carbon tax or strengthen other supportive measures to achieve substitution into renewable energy technology.

Schmidt (2014) likewise argued that perceptions of investment risk are more impactful for low-carbon projects as they are reflected in the cost of capital, which again was more significant for capital-intensive technologies with higher CAPEX-OPEX ratios. Schmidt even found that the mitigation cost for competitive low-carbon technologies could increase by up to 330% due to higher risk perception if revenues are not de-risked by policies (see also Steckel and Jakob, 2018). Schmidt argued that policymakers should consequently be more inclined to de-risk renewable projects due to the sizeable cost effect of uncertainty and risk perceptions. The author lists possible policy levers incl. insurance, guarantees, co-financing, improving local institutions, such as permitting processes, and generating better financing cost data. In addition, the impact of risk perceptions underscores the importance of developing and diffusing experience and capabilities



among investors (Egli et al., 2018), which can be seen as a network challenge (Mignon and Bergek, 2016).

Each technology's levelised cost of electricity (LCOE) is commonly calculated to compare the cost of producing electricity from different energy technologies. The LCOE measures the earnings “that would recoup all costs, including return on investment but excluding transmission, distribution, and grid services” (Krupa and Harvey, 2017, 917). It is measured as the sum of costs, incl. required financial returns, over the lifetime of a project divided by the sum of electricity produced over the same period (see Appendix A). It hence shows what the expected average electricity price should be for inducing investments under the assumed required cost of capital. However, for variable energy technologies, what counts is the ‘capture price’ at the time of production and the synchronous production of RE tends to depress (or ‘cannibalise’) the price at the time of production (Halttunen et al., 2020; Jones and Rothenberg, 2019; López Prol et al., 2020). Offshore wind has been pointed out as offering more ‘system value’ since its production is less volatile and hence less synchronous with onshore and solar wind (IEA, 2019).

The cost of capital enters the calculation of LCOE as the factor used to discount future costs and revenues. Because earlier investments must be financed while operational expenditures can be paid out of future revenues, the cost of capital raises the cost of electricity more for technologies with high CAPEX-OPEX-ratios like RE. Calculations based on the Danish Energy Agency's LCOE tool (2022, see Appendix A), show that moving from 5% to 10% in the cost of capital would increase the cost of electricity from offshore wind by 47%, onshore wind and utility-scale solar PV LCOEs would rise 52-54%, solar PV on industrial and commercial roofs would rise 60% – while only becoming 8% more expensive for new gas-fired power plants.

The cost of capital commonly used as a discount factor is the estimated *weighted average cost of capital* (WACC) (see Appendix A). It is calculated as the costs of financing from equity and debt sources, weighted by the debt-to-equity ratio. Debt is usually a cheaper source of capital, so higher debt ratios and lower risk premiums by lenders can increase the return on investment by the project sponsors. Yet, this raises the question of how investors determine the cost of capital for a particular project.

One common approach to assessing the value of an asset is the *capital asset pricing model* (CAPM) which combines the expected future cash flow with the asset's inherent risks and volatility of returns compared to the wider market (Krupa and Harvey, 2017, see Appendix A). Investors seek to be compensated with the risk-free rate (strongly influenced by monetary policy) and a risk premium depending on the characteristics of the asset. In theory, the resulting cost of capital should be project-specific. Yet, it has been shown that the cost of capital for the same type of project is often investor-specific (Helms et al., 2020), which points to the importance of organisational characteristics and barriers reviewed above. The CAPM model can be criticised for abstracting from this organisational reality and the uncertainty of the future (Kay and King, 2020, more below).

2.4.2. *Heterogeneous cost of capital*

The CAPM approach to asset valuation results in various costs of capital for particular technologies and locations due to variations in the assessment of technology risk, political risk, energy market risk and variations in broader financial conditions. Steffen (2020) surveyed the cost of capital across technologies and jurisdictions between 2009-2017 and detects a robust rank order between the cost of capital for different technologies with the lowest cost for solar PV, a medium level cost for onshore wind, and the highest cost of capital for offshore wind. He also finds that developing countries display a higher cost of capital, although there is heterogeneity among industrialised and developing countries. For instance, the WACC for offshore wind in 2017 was 7,8% in Denmark and 12,6% in the UK. Such cost differentials can imply that fewer projects will be initiated or that consumers will pay more for their renewable electricity, which again weakens the economic case for decarbonising other sectors through electrification.

Offshore wind energy has faced elevated cost of capital due to a multiplicity of risk factors (Karlton, 2016; more in chapter 5). IRENA (2020) stated that “the relative lack of experience of financing institutions with offshore wind projects and their relative lack of understanding of the technology-specific risks in operating wind farms offshore would likely have resulted in higher risk premiums to cover this uncertainty”. They find that their usual 7.5% WACC assumption for



all technologies in developed countries did not reflect financial circumstances for offshore wind between 2010-2016.

Angelopoulos et al. (2016) surveyed risk factors and estimated WACC for onshore wind in Europe and found Germany to have the lowest cost, around 3.5–4.5%. Other mature markets had a WACC below 6% (DK, FR, BE), a sub-mature group faced between 6%-7% WACC (UK, FI, AU, NL), while less mature markets had a WACC between 7%-12%. They found that Germany benefited from lower risk levels and fierce competition in banking: “Many banks consider wind energy projects as secure investments and underbid each other”, which has been decisive for Germany’s lead over Southern European countries in solar PV deployment despite worse geographical conditions. They also found that participation by SIBs, such as EIB and KfW, “can significantly lower the WACC”, which suggests we should consider how the financial system interacts and not only perceives risks in isolation.

2.4.3. Financial learning effects

The importance of the cost of capital means that the processes through which the cost of capital can be lowered are a crucial, although neglected, topic for green transition studies (Egli et al., 2019a, 2018b). The RE support literature showed that de-risking revenues is one important demand-side tool. However, there are other risks than price risks, and it is increasingly challenged whether it is prudent to shield renewables from price signals (Energy Systems Catapult, 2021; Pahle and Schweizerhof, 2016). Learning among investors is, therefore, likely to become more important as de-risking policies are removed.

Egli (2020) found that the main risk drivers for solar PV and onshore wind investment over time in the UK, Germany, and Italy have been curtailment, policy, price, resource, and technology risks. Between 2009 and 2017, policy and technology risks have decreased, while curtailment and price risks have been on the rise. The declining risks were affected by “increasing technology reliability at a lower cost, data availability, better assessment tools and credible and stable policies” (ibid., 1). The study also finds that investor networks have contributed: “the maturing investment ecosystem – together with more experienced investors– has created trusted



relationships to facilitate [RE] investments. Investors like to do business with known partners” (ibid., 8).

Egli et al. (2018) found that financing conditions for renewables have strongly improved since 2000. They identify the macroeconomic conditions (the interest rate policy) and experience effects within the renewable energy finance industry as the two main drivers of the cost decline. From 2000-2005 to 2017, the cost of capital declined by 69% for solar PV and 58% for onshore wind projects. Consequently, approx. 40% of the LCOE reductions for solar PV and onshore wind projects can be attributed to the falling cost of capital. The authors estimate investor learning curves, showing that for each doubling of cumulative RE investment between 2000-2005 and 2017, debt margins above the risk-free interest rate decreased by 11% for both solar PV and onshore wind.

Egli et al. (2018, 1088) found that cost of capital for solar PV has been reduced the most by needing less investment per MW because of the rapid technological improvements, while the general interest rate and experience effects have mattered more for onshore wind. One investor responded to Egli (2020, 8) in an interview: “The developers learn a lot. The financial investors learn over time, and the regulators, too, learn over time. That total learning effect leads to decreasing levelised costs of electricity”. However, Egli (2020, 9) identified “an important time lag between technical readiness and access to low-cost financing for a technology”, which may be accelerated “using smart policies to increase knowledge spillovers between investors and create a resilient RET investment ecosystem (e.g., trusted partners with a common understanding of risks)”. The cost of capital literature, therefore, points to investor learning as one of the mechanisms that reduce the cost of new technologies.

2.5. Calls for a systems perspective on renewable energy finance

Although the RE finance literature has examined how investors are boundedly rational and, by varying degrees, limited by insufficient experience to assess risks and returns accurately, policies are often developed based on the assumption of efficient financial markets (Hall et al., 2017; Wüstenhagen and Menichetti, 2012). Several scholars have therefore called for a systems perspective of how finance affects sustainability transitions (Ameli et al., 2019; Geddes and

Schmidt, 2020; Hafner et al., 2020; Hall et al., 2017; Naidoo, 2020). Hall et al. (2017) argue that better policymaking requires a more accurate theory of how the financial system functions and how the system influences investments in sustainable energy technologies. They find that there are appropriate theories of finance at the micro level and in idealised markets at the meso level, but not regarding strategic investments at the macro level (following Grubb et al.'s (2015, 2014) three-domain model).

At the micro-level of individual decision-making, the insights from behavioural finance theory (Shiller, 2019, 2003) examined in the investor heterogeneity and investment barrier literature provides a valid theory. At the meso level of idealised optimising behaviour, the neoclassical efficient markets hypothesis (Fama, 1970) provides a benchmark framework for comparing the behavioural limitations to a state of efficient capital markets that use all available information to allocate capital to the most productive opportunities. However, Hall et al. (2017) find the strategic investments that move the technology frontier and change the economic structures, which condition the micro and meso level behaviour, are not satisfactorily explained by behavioural and neoclassical financial theory. They argue that, in addition to behavioural and cognitive constraints, energy finance is constrained by the changing conditions for energy investments, the impact of continual changes in wider financial markets, and the immaturity of investor communities that cannot learn and adapt quickly enough. Therefore, they theorise “energy finance as an adaptive market”. The following two sections elaborate on the distinctions between perceiving financial markets as efficient and adaptive.

2.5.1. Reasoning based on efficient markets and rational investment behaviour

The role of finance is generally left out of neoclassical climate change economics since finance is assumed to be a passive sector that distributes saved-up funds to the most productive and/or profitable uses (Pollitt and Mercure, 2018). This approach to finance compounds the neglect of the role of innovation, uncertainty and path dependency in sustainability transitioning (Farmer et al., 2015; Grubb et al., 2021b; Mercure et al., 2019). Two mainstream theories for understanding finance from an efficiency perspective are the *efficient markets hypothesis* and the *capital asset pricing model* (CAPM), which was introduced above (for more detail, see Appendix A). The core



proposition of the efficient markets hypothesis is that market prices reflect all relevant, publicly available information about the future value of investments (Fama, 1970). In one sense, this appears intuitively true. If markets have not responded to available information, someone could profit by arbitraging this value, thereby delivering on the theoretical promise.

From this perspective, it is efficient to rely on private capital markets to allocate funds for investment and thus avoid inefficiencies incurred from not investing based on financial ‘fundamentals’. The government has no reliable way to aggregate this information, so it is deemed more likely to make wasteful investments. This is the theory underlying the belief that finance can be aligned with sustainability if firms disclose their climate impacts and exposures to climate change to correct the information deficit in financial markets (Ameli et al., 2019; Hall et al., 2017).

According to the CAPM model, investors should apply project-specific risks, which should affect hurdle rates accordingly (the hurdle rate for a low-risk project should be lower). However, as mentioned above, it is a regular corporate practice to apply investor-specific hurdle rates in order to simplify internal processes and lower the cost of business operations (Helms et al., 2020, 91). In practice, firms apply hurdle rates substantially above their WACC to provide an “NPV cushion”⁷. As a result, hurdle rate premiums of 5 per cent or more above the WACC are “not unusual” (Ibid. 92). Hurdle rate premiums can offset optimistic cash flow projections and pressure management to improve their investment bargains, though they also reflect a lack of capable personnel and relevant experience with the asset class in question (ibid.).

Importantly, for the CAPM model to work as a tool for understanding market behaviour, one must assume that everyone interprets future risks and returns *in the same way*, i.e. as if risks were objective facts:

Behind the efficient portfolio frontier and capital asset pricing model lies the idea that individuals make similar assessments of the underlying probability distribution. Since the model assumes that

⁷ NPV: Net Present Value is the discounted stream of present and future costs and benefits.



everyone in this small world interprets risk in the same way, differing only in their ‘risk appetite’, the proposition that higher risk implies higher reward and vice versa follows inexorably
(Kay and King, 2020, 346).

A view informed by the CAPM model would focus on matching different investments with financiers who have a commensurate risk appetite (e.g. Polzin et al., 2021; Polzin and Sanders, 2020) or on de-risking investments with policies to match the risk-return characteristics of e.g. institutional investors (Polzin et al., 2019; Schmidt, 2014; Steckel and Jakob, 2018). There would be little focus on *how the risk and return perceptions are formed over time in specific organisations* through learning-by-doing and adaptation to changes and narratives in their environment (Kay and King, 2020). Especially concerning emerging technologies with narrow track records, uncertain risks and use markets under structural change, we should be concerned about the investor system’s ability to respond efficiently to technological opportunities (Angelopoulos et al., 2016; Louche et al., 2019).

2.5.2. Reasoning based on adaptive markets

Hall et al. (2017) argued that in the realm of transformative investments, such as capital-heavy renewable energy investments, the efficient markets hypothesis (Fama, 1970) was an invalid description of how financial markets operate. Instead, energy finance studies should replace it with an “adaptive market hypothesis” (AMH) (Lo, 2004). According to the AMH, the financial sector can not be expected to provide optimal finance for the investments needed to undertake structural economic transformations. The AMH view suggests that investors are constrained by both internal cognitive and organisational factors and external structural factors. The internal factors relate to the insights of behavioural finance, while the external factors can be crises, innovation, regulations, or social sentiments.

Because of the uncertainty about sustainability transitions, behaviour deemed irrational by behavioural finance, such as loss-aversion and overconfidence, should instead be regarded as a rational way of dealing with irreducible uncertainty (Bolton et al., 2016; Kay and King, 2020;



Lo, 2012, 2004; Soufian et al., 2014). As Clark (2019) observes, "While it is widely assumed that wind and solar facilities have an operating life of somewhere between 20 and 30 years, technological innovation could simply make existing facilities uncompetitive and, perhaps, obsolete". The long technological lifetime of sustainable technologies, thus, induces hesitance to invest.

Hall et al. (2017) found the AMH especially relevant for energy finance based on four characteristics: First, investors are boundedly rational given the significant uncertainties during project lifespans (Bolton et al., 2016). Energy investment "is characterised by large, lumpy investments amortised over several political and even economic cycles", which leaves investors unable to do accurate risk assessments (Hall et al., 2017, 286). Second, the changing investment environment constantly forces investors to learn and adapt. Investors are making investment decisions under the basic condition that "During the time it takes to draw profit from generation assets, there may be significant changes in governments, policy, societal preferences, technology alternatives, financial vehicles, and market regulation" (Ibid. 286). Third, the wider financial markets affect the submarket of energy finance – specifically, they consider how the Great Financial Crisis led to tighter financial conditions for renewables. Fourth, the field of energy finance constantly changes as individuals, firms and institutions co-evolve, enter and exit over time, which render the general business conditions "turbulent" (Ibid. 286).

Because of these four characteristics, Hall et al. (2017, 293) found RE investment to be constrained by three structural barriers: "lack of a mature community of investors, mismatches between investment and fund manager timescales, and lack of suitable investment vehicles". These structural barriers are forcing investors to "adapt and experiment" to find new ways of sourcing and providing finance. Nonetheless, the investor system will be prone to get stuck on sub-optimal paths with too little investment undertaken on too expensive terms (Hafner et al., 2020). Hall et al. (2017, 294) articulate the risk to policymaking created by adopting an inaccurate theory of finance:

if energy policy assumes the existence of efficient markets, then policy may not provide the conditions for finance capital to adapt quickly enough to capitalise energy investment in time for a meaningful transition to a decarbonised

electricity system (...) current energy policy operates paradoxically, in that it tries to solve third-domain issues (under-investment in innovation and decarbonisation) with policy based on second-domain assumptions (market efficiency).

More specifically, reliance on market efficiency theory may lead policymakers to only adopt price-based demand-stimulating policies, such as subsidies and carbon taxes, while assuming that finance will flow in optimal ways to invest in sustainable technologies. In that case, the supply side attention would confine policy to tackling the market failure in relation to technology research and development (R&D) (Jaffe et al., 2005), while leaving the financial sector unaddressed.

Based on a comprehensive review of the ‘barrier literature’, Hafner et al. (2020, 32-33) concur with Hall et al. (2017) that there is a need for systems thinking. They find that the barrier literature insufficiently perceives the interconnectedness of the barriers, which together form “system barriers”. Therefore, they recommend perceiving the barriers as a “complex system” characterised by: two-way interconnections and interrelationships (on multiple levels) among the system’s components, path dependency and lock-in caused by reinforcing and balancing feedback loops, emergent system behaviour not reducible to the system’s components, non-linear dynamics, e.g. due to risk-return thresholds or reinforcing feedback effects, and overlapping sub-systems. While a neoclassical approach to finance suggests policymaking should rely on the efficacy of price incentives and risk disclosures, a systems approach leads to a wider scope of policies, including market-shaping policies (Hafner et al., 2020, 28; Mazzucato, 2016).

Adaptive and interactive behaviour is difficult to analyse empirically. Agent-based models and network analytical methods have been recommended to capture the complex patterns arising from adaptive behaviour (Bale et al., 2015, 2013; Foxon et al., 2013). D’Orazio and Valente (2019) explore the role of investor heterogeneity from a complexity perspective in an agent-based model. They find that diffusion of environmental innovation “is more pronounced when the presence of the public investment bank is combined with strong consumers’ preferences oriented towards environmental quality”. The public investment bank is implemented in the model by making financing cheaper for green purposes, so studies of how public investment banks interact

with and influence the wider investment ecosystem could illuminate the potential for dynamic impacts over time by having active public investment banks. Barazza and Strachan (2020) use an agent-based model to examine electricity investment and find that the presence of heterogeneous market actors with limited foresight leads to path dependency and investment cycles because of self-reinforcing feedback effects from learning-by-doing and imitation of successful peers. These characteristics back-load the investments compared to scenarios based on efficient, homogenous investors.

2.6. Summary of theoretical caveats to consider

The review of the RE finance literature suggests that the proposition by Hall et al. (2017) to apply an adaptive view on energy finance remains underdeveloped and in need of empirical studies for further theory development. There has been increasing attention to complexity perspectives and evolutionary processes in both finance (Farmer et al., 2012; Kirman, 2011) and sustainability studies (Aghion et al., 2019; Balint et al., 2017; Foxon et al., 2013; Grubb et al., 2014). And the complex systems concept, introduced to the RE finance literature by Hafner et al. (2020), shows a way forward for developing the theory of energy finance as an adaptive market. However, complex systems and adaptive behaviour are inherently difficult to analyse empirically.

Moreover, in accordance with Elie et al. (2021, 10), the review supports that the “over-representation” of research on RE support policies “reveal[s] a conception of the state as a regulator to the detriment of an entrepreneur or direct investor”. Finally, there was a lack of interest in the financing of riskier RE technologies (Elie et al., 2021). The next chapter, therefore, develops a framework for analysing RE finance by combining complexity theory, the theory of entrepreneurial states, and the RE finance research examined in this chapter.



Chapter 3

Theoretical framework: Renewable energy finance as an evolving complex system

This chapter reviews complex systems theory with an emphasis on applications to finance and sustainability transitions. A combination of complexity theory and the insights from the RE finance literature review is used to develop a theoretical framework for analysing RE finance as an evolving complex system.

3.1. Complexity science and economics

Complexity science has been defined as “the study of the phenomena which emerge from a collection of interacting objects” (Johnson, 2011, 3-4), which has been applied as an analytical approach across scientific disciplines from physics and biology to social sciences. The core tenet of complexity science is that there are no general rules imposing order on the behaviour of the system’s actors. Rather, complex systems feature an ongoing reflexivity whereby the interactions of the actors at the micro level form a structure or state at the meso level, which continuously also shapes behaviour at the micro level (Arthur, 2014, 2021). When enough persons act in the same space, the resulting crowd effects rarely produce an optimal order despite the best individual intentions. Instead, undesirable events such as traffic jams, financial market crashes, or social reproduction of unsustainable lifestyles can emerge (Dosi, 2013; Johnson, 2011). Such emergent properties cannot be explained by the properties of the isolated elements (Foster and Metcalfe, 2012). The features of a car or its driver cannot explain why a car jam occurs, nor where and when it does.

From a complexity perspective, “coordination rather than efficiency” is the central problem in economics (Kirman, 2011, i). Neoclassical economics is predominantly concerned about how market interaction via the price mechanism coordinates an efficient use of scarce resources in the absence of ‘market failures’ (Tirole, 2017, p. 24). When the conditions for perfect markets are not satisfied, sub-optimal equilibria may result and may warrant policy interventions. Complexity



economists find that that neoclassical economics is too constrained by the focus on optimising, rational actors and the resulting equilibrium states of rest in the system (Arthur, 2014). From this perspective, it is unsatisfactory to focus on how the system recovers from an external shock, while neglecting endogenous causes of instability and evolutionary persistence of change (Beinhocker, 2007, see Appendix L: Comparison of neoclassical and complexity economics for a structured comparison of neoclassical and complexity economics).

Complexity economics therefore attempts to understand how an economy ‘self-organises’, including via other types of interaction than prices, and how this process can result in *prolonged periods of stability and sudden major upheavals*. It takes inspiration from physics in perceiving such shifts as ‘phase transitions’ that emerge as collective patterns at the meso-level ‘above’ the individual actors, which they continually adapt to (Kirman, 2011, i). Recently, neoclassical macroeconomists have also called for fundamental improvements to the foundational models to place the possibilities of multiple equilibria at the center (Vines and Wills, 2020).

Complexity economists have criticized the dominant neoclassical school of thought for abstracting from the complexity of economic phenomena by using representative actors with rational expectations based on assumed knowledge of the correct underlying model (discussed in Kirman (2021) and Woodford (2011)), thus abstracting from interaction, and imposing equilibrium end-states, thereby constraining co-evolutionary patterns and emergent phenomena (Arthur, 2014). Some actor heterogeneity has been incorporated into neoclassical game theory and increasingly in macroeconomic models. However, “Greater precision, though, comes at the price of increased complexity” (Tirole, 2017, p. 109). Complexity economics embraces this complexity through its non-equilibrium approach and by using computational methods to simulate outcomes.

Complexity economics asks how actors react to the patterns they co-create, while neoclassical economics predominantly considers what actions are consistent with stable outcomes (Arthur, 2022). General equilibrium theory examines what prices and quantities of goods and services pose no incentives for change. Classical game theory examines what strategies, moves, or allocations that are rational for an actor given the likely strategies and allocations of her rivals. In contrast, complexity economics considers how actions, strategies and expectations can



endogenously change over time based on the aggregate patterns resulting from their choices (ibid.). It thereby examines a system that is not conceived as coming to rest.

Eric Beinhocker (2007, 97) has characterised complexity economics as a research program, rather than a single theory, with five “big ideas” shared in the community. These five ideas contain ontological propositions about what the economy *is*, which carry epistemological implications for *how* to study it. The five big ideas are:

1. Heterogeneous actors with bounded rationality
2. Explicit interaction in networks
3. Emergent phenomena
4. Evolutionary processes
5. Non-equilibrium dynamics

3.1.1. Heterogeneous actors with bounded rationality

Beinhocker’s first property of complex economic systems is actor heterogeneity. Imperfect knowledge and bounded rationality are core assumptions about each actor since knowledge is dispersed in the network (Kirman, 2011, 11; Simon, 1955). Instead, actors are believed to follow strategies as ‘rules of thumb’ that are continuously updated based on their success in the surrounding environment. In this way, feedback from the environment causes agents to learn over time. This perspective corresponds well with the RE finance literature on investor heterogeneity and decreasing cost of capital due to learning among financiers (Egli et al., 2018).

The complexity approach is, therefore, more applicable to economic activity under a state of uncertainty rather than calculable risks. Knight (1921, 20) famously drew this distinction between risk, which refers to known or knowable frequency distributions such as games of roulette, and uncertainty designates the vast range of future outcomes for which we are unable to estimate valid numerical probabilities (Kay and King, 2020, 84). To Knight, the presence of uncertainty was one of the advantages of capitalism and its “capacity for innovation arising from the search for profit in an uncertain and constantly changing environment” (ibid., 270).



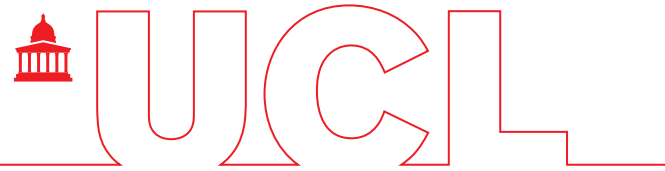
Keynes shared Knight's emphasis on fundamental uncertainty but contrarily saw it as the source of capitalism's cyclicalities because investments had to be undertaken with a view to an unknowable future. Keynes (1937) explained some of the sources of uncertainty that render neoclassical models like the efficient market hypothesis and CAPM invalid descriptions of investment behaviour:

I do not mean merely to distinguish what is known for certain from what is only probable ... The sense in which I am using the term [uncertainty] is that in which the prospect of a European war is uncertain, or the price of copper and the rate of interest twenty years hence, or the obsolescence of a new invention, or the position of private wealth owners in the social system in 1970. About these matters **there is no scientific basis on which to form any calculable probability whatever.** We simply do not know. Nevertheless, the necessity for action and for decision compels us as practical men to do our best to overlook this awkward fact and to behave exactly as we should if we had behind us a good Benthamite calculation of a series of prospective advantages and disadvantages, each multiplied by its appropriate probability waiting to be summed (my emphasis, Keynes, 1937, 213-14).

A person in 2019 would find it hard to believe that a Financial Times headline in 2022 would read: "War and stagflation threaten global economy as pandemic recovery slows" (Giles, 2022). War, stagflation, and pandemic would unlikely have been in most people's mental model of how the economy would evolve. Yet, every economic actor is forced to form a model to guide our decision-making, well aware that the expectations might be wrong (Minsky, [1986] 2008). Complexity economics emphasises that the uncertainty of the future causes adaptive and interactive behaviour (Beinhocker, 2007).

3.1.2. *Explicit interaction in networks*

Secondly, complexity economists explicitly analyse the interaction of heterogeneous actors in networks and how the networks change over time. This contrasts with indirect forms of



interaction, such as stylised market mechanisms like auctions. Indeed, networks are “an essential ingredient in any complex adaptive system” since there can be no complexity without interactions (Beinhocker, 2007, 141). Kirman (2011, p. 8) likewise emphasises that “economic agents choose those with whom they trade, and to treat a market, for example, as an anonymous game ignores the specific, intricate trading and relational networks that develop and influence market outcomes”. This relation-based ontology of the economy is shared by economic sociologists that have studied how economic behaviour and financial conditions are conditional on the actor’s social embeddedness in network relations (Granovetter, 1985; Uzzi, 1999; Uzzi and Gillespie, 2002; Uzzi and Lancaster, 2003). Consequently, Ormerod (2012) concludes that “the assumption that people make choices in isolation, that they do not adopt different tastes or opinions simply because other people have them, is no longer sustainable”. Network effects cause actors to change their preferences and behaviours in response to what others do and learn.

Networks are important because they propagate change: “When a transmissible event happens somewhere in a sparsely connected network, the change will fairly soon die out for lack of onward transmission; if it happens in a densely connected network, the event will spread and continue to spread for long periods” (Arthur, 2021, 140). Higher connectivity thus generally leads to more consequences of events. The distribution of connections also shapes processes and outcomes. Power law distributions are a common network phenomenon where few actors have a disproportional share of the connections and hence a form of network capital that can create ‘rich-get-richer’ dynamics because of preferential attachment behaviour (Barabási and Albert, 1999).

3.1.3. *Emergent properties*

The networked interaction of heterogeneous actors leads to emergent properties at the meso and macro levels of the system that are typically the economic outcomes of public concern, such as GDP, investment, prices, productivity, and the direction of innovation (Dosi, 2013, 1982). This means that complex systems display other characteristics than the constituting elements: “the very fact individuals interact with each other causes aggregate behaviour to be different from that of individuals” (Kirman, 2011, 21). This is proverbially framed as the whole being more than the sum of its parts (Arthur, 2014) or “more is different” (Anderson, 1972). The ongoing reflexivity



among individual actions and patterns of action means that rational behaviour is not well defined. Actors continually adapt to the meso and macro outcomes, and the adaptive behaviour at the micro level contributes to changing the emergent properties (Arthur, 2014).

3.1.4. Evolutionary processes

Fourthly, complex systems are characterised by evolutionary processes where ongoing differentiation, selection, and amplification processes generate novel behaviour, actor types, and innovations that generate growth and increasingly complex patterns of interaction. Evolution is “a learning algorithm that adapts to changing environments and accumulates knowledge over time” (Beinhocker, 2007, 187). Inspired by Schumpeter’s theory of perpetual creative destruction, Nelson and Winter (1982) abandoned neoclassical notions of rationally maximizing behaviour resulting in stable equilibrium outcomes. According to their evolutionary economic theory, firms carry different ‘operating characteristics’ and adapt to the environment they act within (Nelson et al., 2018).

In the evolutionary view, the market is perceived as a selection process that rewards and punishes certain operating characteristics while actors attempt to replicate successful strategies. Yet, because of the adaptive behaviour and emergent properties, the successful strategies change over time (Beinhocker, 2007, 215). Echoing Schumpeter, Nelson and Winter (1982, 30) stated that adherence to the neoclassical concepts of maximization and equilibrium had “forced the theorists to greatly simplify and stylize the processes of R&D, industrial structure, the institutional environment, and so forth[, which] obscure what seems to us to be essential aspects of Schumpeterian competition – the diversity of firm characteristics and experience and the cumulative interaction of that diversity with industry structure”. We should therefore examine the evolutionary processes to obtain a better understanding of the system’s outcomes.

Additionally, history matters in evolutionary systems since “where you can go in the future depends on where you have been in the past” (Beinhocker, 2007, 212). The experience and network connections accumulated through evolutionary processes create endogenous heterogeneity between actors, which further conditions how they act in the future. While many



forms of change do not definitely change the system since their impact is either reversible or revocable through additional measures, history is driven by irrevocable changes (Setterfield, 1995). Crucially, irrevocable changes often relate to innovation and creation of new experiences:

“movement through historical time changes the stock of experience that agents possess, and experience accumulated since the initial conditions of a system existed cannot easily be eradicated” (Setterfield, 1995, 6).

This perspective relates well to Arthur's (2011) theory of technology as a recursive system of combinations of previous technologies that take advantage of some insights about the properties of the natural world. This conveys an image of a constantly growing web of combinations that can hardly revert to a previous state through unlearning. Technological evolution therefore epitomises the idea of historical time and substantiates why historical changes over time have decisive impact upon the technological possibilities at a future point in time. Economists in the evolutionary tradition have therefore emphasised the need to induce innovation with innovation policies rather than expect it to be an exogenous contribution to growth or decarbonisation or simply a function of R&D (Grubb et al., 2021b, 2017, 2002; Mazzucato, 2018, 2016a).

3.1.5. Non-equilibrium dynamics

Finally, the previous four characteristics carry implications for how complex systems behave at the system level. One core complexity insight is that complex systems feature non-equilibrium dynamics (Arthur, 2014; Beinhocker, 2007, 99). That is to say that they rarely fall to rest, and if they do, tranquillity itself may be a cause of change. Since the actors are always in an adaptive state attempting to find better solutions in their changing environment, which can lead to propagating changes in the system.

Complex systems are characterised by dynamic relationships between stock and flow variables with feedback effects across time (Beinhocker, 2007, 101). Feedback effects can either lead to path dependency when the past affects the future in ways that either reinforce continuity (negative feedbacks) or lead to sudden shifts when the past state reinforces a new direction of change (positive feedbacks). A system can therefore appear stable for a long while until a positive



feedback mechanism powerful enough to overcome the negative feedbacks is triggered, after which a sudden, non-linear change can occur. Complex systems, therefore, move between different stable states – or between periods of order and disorder (Johnson, 2011, p. 15).

Beinhocker (2007, 174) formulates a ‘punctuated equilibrium model’ inspired by complexity theory of biological systems. Complex systems usually evolve through “periods of quiescence or stasis interspersed with periods of change” (ibid., 173). These changes would be dependent on the network structure and, most significantly, on the fate and behaviour of the most connected actors, who biologists refer to as ‘keystone species’. Simulations have shown that network evolution often occurs in three distinct phases that emerge through sudden disruptions of the previous state. The first is a random or *experimental phase* without much structure, and changes occur without much effect. This seeming inertia is broken when “an innovation sends the network suddenly into a growth phase”, which triggers new innovations in a positive feedback loop. The *growth phase* often leads to the rise of new types of actors joining the ecosystem who self-organise and increasingly structure the system. The growth phase “eventually flattens out” as the network enters an *orderly phase* where changes are consolidated, the network is structured in a seemingly durable way, and few ‘keystone species’ take up central positions in the web of interactions. The orderly phase can endure for a while, but it is still vulnerable to new innovations or exogenous influences on the keystone species. The two key mechanisms behind changes are the “sparse-dense networks of interaction and catalyzing effects from individual nodes” (ibid., 174-175).

From a complexity policy perspective, it is commonly considered how to target ‘sensitive intervention points’ that can create self-reinforcing feedback effects, such as the policies that turned renewable energy cheaper than fossil fuel alternatives (Colander and Kupers, 2014; Farmer et al., 2019; Lenton, 2020; Otto et al., 2020; Sharpe and Lenton, 2021).



3.2. *Complexity, finance, and investment*

Economists working with a complexity perspective have generally been more focused on the destabilising role of finance (Battiston et al., 2016; Botta et al., 2020; Farmer et al., 2012; Keen, 1995; Kirman, 2011; Minsky, 1982; Pollitt and Mercure, 2018) than neoclassical economists who are constrained by equilibrium assumptions (Arthur, 2014; Vines and Wills, 2020) and assuming that the financial system merely moves savings around with some frictions (Zoltan and Kumhof, 2015). Evolutionary and complexity economics is therefore more suitable for incorporating the system-shaping role of finance that Schumpeter, Keynes, and Minsky proposed (Mazzucato and Wray, 2019).⁸

Schumpeter evoked the notion of the banker as the “ephor of the exchange economy” (Schumpeter, 1983, 41). Rather than neutrally shifting existing savings around to the most productive capital, he focused on the ability of banks to create “new purchasing power out of nothing ... in the name of society” (Ibid. 40-41) to finance innovative activities that require entrepreneurs to source existing productive resources. Financial decisions were, therefore, an important source of creative destruction that disrupted rather than facilitated economic equilibria (Schumpeter, 2013).

Following the Great Depression, Keynes (1964 [1936], 159) was more concerned about the tendency for financial speculation to disrupt productive investments: “When the capital development of a country becomes a by-product of the activities of a casino, the job is likely to be ill-done”. Synthesising Schumpeter’s focus on innovation and Keynes’ focus on reflexivity, which could lead to severe malfunctions, Minsky (1982) formulated a *financial instability hypothesis* which stated that *stability is destabilising*, since the validation of past investments through profits leads to more confidence in the future which increases debt-leveraged investments and financial fragility until a crisis erupts. This notion of the empirical nature of finance and its potential for bubbles is now more widely recognised among neoclassical economists, yet Brunnermeier and Oehmke (2013) find that neoclassical approaches to asset

⁸ Investments can be said to be injected into projects, but this is not substantially important in this study. Practically, undirected ties are preferable for analysing the connections between investors via projects.



price bubbles are more able to explain the persistence of existing bubbles than either their formation or bursting. Complexity approaches can help operationalising the Minskian framework (Farmer et al., 2012).

Minsky's view of the economy reflects the core tenets of complexity theory: "An ultimate reality in a capitalist economy is the set of interrelated balance sheets among the various units. Items in the balance sheets set up cash flows" (Minsky, 1975, 118). Capitalism is, therefore, an explicitly networked social structure because of the assets and liabilities that tie different organisations and individuals together, and the resulting network structures how the payments flow, what organisations can invest, and where financial crisis can emerge. Moreover, capitalism is an evolving complex system because of the way the financial structure continually changes, which conditions the corporate governance and propensity to invest and innovate in non-financial corporations (Minsky, 1989; Tymoigne and Wray, 2016).

Although speculation is often associated with trading in financial securities, in Keynes's view, investing in real capital assets is inherently also an act of speculation due to the fundamental uncertainty of the asset's ability to generate a cash flow during its lifetime (Minsky, 1975, 132). While the energy finance literature commonly reasons based on rationalistic and atomistic investors (e.g. Krupa and Harvey, 2017), Keynes (1964 [1936]) memorably explained private investment behaviour with reference to *animal spirits* – an image of the state of business confidence in the context of uncertainty. Fundamentally, Keynes challenged that private investment would be rationally guided by objective risk and return conditions. To him, investment depends on:

spontaneous optimism rather than on a mathematical expectation (...) as a result of animal spirits—of a spontaneous urge to action rather than inaction. (...) Thus if the animal spirits are dimmed and the spontaneous optimism falters, leaving us to depend on nothing but a mathematical expectation, enterprise will fade and die.

(Ibid., 161-162)



The state of business confidence is thus an emergent property in Keynes's framework where the propensity to invest depends on the level of investment, which leaves the economic system prone to gravitate towards self-fulfilling optimistic or pessimistic states. In conjunction with the organisational barrier literature, we should therefore expect investments in emerging technologies to be dependent on the state of confidence in the future of the technology in the business community. Indeed, the possible "obsolescence of a new invention" was explicitly identified by Keynes (1937, 213-14) as a source of fundamental uncertainty, which limits rational approaches to investment decision-making.

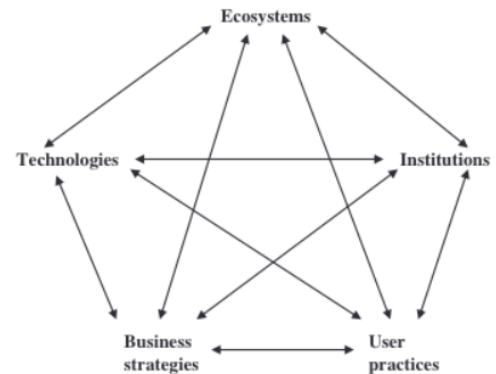
3.3. Sustainability transitions research, complexity, and finance

Sustainability transitions research (STR) is a rapidly growing research programme that uses interdisciplinary approaches to examine how "unsustainable consumption and production patterns in socio-technical systems such as electricity, heat, buildings, mobility and agro-food (...) require radical shifts to new kinds of socio-technical systems, shifts which are called 'sustainability transitions'" (Köhler et al., 2019, 2). STR shares a number of features with complexity theory in its focus on co-evolution among multiple elements of socio-technical systems, including "technologies, markets, user practices, cultural meanings, infrastructures, policies, industry structures, and supply and distribution chains", and various actor types with heterogenous resources and interests (ibid.). Moreover, there is a strong focus on how these co-evolutions results in path dependency and technological lock-ins (Seto et al., 2016; Unruh, 2000) and how unsustainable lock-ins can be broken. Finally, STR emphasises uncertainty and open-endedness stemming from innovation, politics, and cultural change (Köhler et al., 2019, 2).

STR has developed various analytical frameworks, including the Multi-Level Perspective (Geels, 2011, 2002), the Technological Innovation System approach (Bergek, 2019; Hekkert et al., 2007), Strategic Niche Management (Kivimaa and Kern, 2016; Schot and Geels, 2008) and

Transition Management (Loorbach, 2010). Broadly, Foxon (2011) finds that too little attention is granted to economic factors vis-à-vis the more social and technical aspects of transitions. He argues that *co-evolution* is a particularly useful concept for comprehending the dynamics of sustainability transitions and finds that is especially relevant to analyse the co-evolution of *technologies, institutions, business strategies, ecosystems, and user practices* (Figure 3.1). Each element has its own

Figure 3.1: Co-evolution among transition elements



Source: Foxon (2011, 2262)

internal dynamics that causally affect and are influenced by the other four. This co-evolution can lead to sustainability transitions being hampered by self-reinforcing lock-in among the elements.

Among the scope of economic factors, Geddes and Schmidt (2020, 1) find that the role of finance “is largely marginalised by the transitions literature”. In both the Multi-Level Perspective and The Technological Innovation Systems approach, finance is considered a resource that must be mobilised to invest in new technologies (Bergek, 2019; Karltorp, 2016; Karltorp et al., 2017), but the role of finance is vaguely theorised (e.g. *ibid.*, 3874). In a review of the Technological Innovation Systems literature, Bergek (2019, 209) finds that “Private funding is rarely explicitly mentioned”. In their STR review, Köhler et al. (2019) recommend that the role of finance capital is a topic for further research. Geels (2019, 197) finds that “more work should be done on (...) Financial reform” in relation to the Multi-Level Perspective. However, Naidoo (2020, 285) raises concerns regarding STR’s general adoption of orthodox theories of finance:

The sustainability transitions field positions finance neutrally. It assigns a background role to finance as a function inherent in user practices and as one of the resources critical for advancing transition processes. This neutral positioning masks the broader and multi-layered complexity of the political dimensions of the financial system. It is therefore critical to develop new framings for finance in the sustainability transitions field.

In a theoretical contribution, Geddes and Schmidt (2020, 5) attempted to integrate finance into the STR literature and the Multi-Level Perspective model (Geels, 2019; Geels et al., 2017). The



general model divides the socio-technical world into three layers (Geddes and Schmidt, 2020, 2): Niches are “protective spaces where path-breaking, radical innovations, such as low-carbon technologies, are produced and developed”. In order to affect the evolution of the economy, they must scale and deploy within the constraining context of the meso-level regimes, which make up the prevailing “selection environment, defined as the arrangement of established practices, sets of rules and organisational and cognitive routines that affect incumbent actors’ resistance to or compliance with system change“. Lastly, the prevailing regimes are embedded within the socio-technical landscapes defined as “a set of deep structural trends and technology-external factors” that are less easily amendable.

Geddes and Schmidt positioned finance as a meso-level regime “with its own actors and institutions, set of norms, organisational and cognitive routines“, which strongly shapes the potential for niche technologies to scale up and alter the economy. To Geddes and Schmidt (2020), one crucial question was whether technological niches – such as renewable energy technologies – will have to adapt to the financial regime to be deployed, or whether the financial regime can be “stretched” to accommodate the particularities and uncertainties of the niche technologies. In other words, whether finance can be re-institutionalised to suit the transition. They find that expansion of the role of state-investment banks is one option for changing finance rather than forcing technology developers to adapt to the prevailing inclinations among financiers to enable the particular niche technology in question.

This ‘regime approach’ highlights the Schumpeterian role of finance as ephor for the development of new innovation and identifies four factors that shape this niche-regime interaction: the technologies must offer acceptable risk and appropriate transaction sizes, the financial regime must have technological knowledge, but this is often under-developed for new technologies, and lastly, well-developed industry networks can help to get access to finance (ibid., 6-8). These are all useful building blocks, but they do not offer a theory of how finance itself operates. There is, therefore, a scope for developing Hall et al.'s (2017) adaptive theory of finance with complexity theory to inform how finance co-evolves with other transition elements (Figure 3.1).



3.4. Institutional mechanisms shaping the renewable energy finance system

It is considered “The Holy Grail of Complexity Science ... to understand, predict and control such emergent phenomena” (Johnson, 2011, p. 5) by analysing how micro-level behaviours generate systemic effects. However, the open-endedness of complex systems, which stems from adaptive behaviour, the importance of history, and the pervasiveness of disequilibrating feedback effects, means that prediction and control are largely unachievable goals (Beinhocker, 2007, 99). Rather than control, policymakers should consider how to influence the system through institutional design (Beinhocker, 2007, 324; Colander and Kupers, 2014), which requires an understanding of the networked reality and the mechanisms shaping its evolution (Ormerod, 2012).

Beinhocker (2007, 185) found that complex emergent phenomena have three root causes: adaptive behaviour, the institutional structure, and exogenous inputs to the system. Institutions are “integrated systems of rules that structure social interactions” as they “enable, facilitate, and incentivize as well as constrain activity” (Hodgson, 2015, 57-58). Crucially, Hodgson’s definition includes organisations as institutions that shape economic outcomes, while the institutional tradition within mainstream economics considers institutions as ‘rules of the game’ and organisations as the players (North, 1990).

Institutional perspectives tend to be better at explaining persistence than change (Lockwood et al., 2016; Pierson, 2004) but better integration with evolutionary perspectives can give more balanced explanations (Hodgson and Stoelhorst, 2014).

Gräbner (2017), therefore, identified a complementary relationship between institutional and complexity approaches in economics. Complexity approaches can benefit from the institutionalist emphasis on realism and inductive understanding of causal mechanisms in social systems, while complexity economics offers a systems perspective and analytical tools, such as agent-based models and network analysis, to analyse the impact (ibid., Radzicki, 2021). In this section, I, therefore, synthesise three hypothesised mechanisms from the complexity and RE finance literature to inform a complexity analysis of RE finance:



3.4.1. Mechanism 1: Bounded rationality

The RE finance literature has emphasised how investors are boundedly rational, which stems both from cognitive limitations and social biases and the inescapable uncertainty of the continually changing technological, institutional, and financial environment (Hall et al., 2017b; Wüstenhagen and Menichetti, 2012). The immaturity of the investor community in relation to knowledge of and confidence in emerging technologies is, therefore, likely to be a systemic barrier to the adoption and development of sustainable technologies (Hall et al., 2017).

3.4.2. Mechanism 2: Evolutionary processes

The state of uncertainty and institutional pressures to find clean technologies to mitigate climate change means that investors are involved in an evolutionary process experimenting with behavioural strategies that can be amplified through networks and imitation when successful solutions are found. This generation of knowledge and know-how means that heterogeneity among investors arises endogenously in the network. Network effects can reinforce these differences and create path dependency in the network and technological trajectory.

3.4.3. Mechanism 3: Actor heterogeneity

The RE finance literature showed considerable actor heterogeneity in the investor system both across sectoral groups and ownership forms and within these categories (Table 2.1), which can shape what technologies get deployed and the resulting ownership patterns (Hall et al., 2016). Private investors are strongly dependent on confidence in the returns on investment since sustainable energy technologies are long-lived capital-intensive assets that must be paid off during a fundamentally uncertain future (Keynes, 1937; Minsky, 1975; Schmidt, 2014). Changes in the state of expectations for new technologies among private investors, possibly because of the evolutionary processes, can, therefore, rapidly change their investment behaviour in a self-reinforcing manner.

The literature also suggested that, despite “myths” around public investments in clean energy (Meckling et al., 2022), entrepreneurial state investors can have a system-shaping impact on the

technological trajectory (Mazzucato, 2015; Mazzucato and Semieniuk, 2018) and the investor community through a number of channels (see Appendix B). State-owned enterprises can be lead adopters of new technologies because of less binding financial constraints and public purpose governance mandates (Benassi and Landoni, 2019; Jerneck, 2020; Steffen et al., 2020b; Tönurist and Karo, 2016). Their investments can advance early learning curve formation and bring technologies across the technological ‘valley of death’ after which more private investors see their economic potential (Grubb et al., 2017; Karltorp, 2016).

State investment banks (SIBs) can also have a system-shaping role (Griffith-Jones and Ocampo, 2018; Marois, 2021a; Mazzucato and Penna, 2016). Like SOEs, their investments can advance technological learning by increasing the market size for the industry, but they are also particularly well-suited to influence the evolutionary process of private financiers. Based on case studies (Geddes et al., 2018), Geddes and Schmidt's (2020) theorise of how SIBs can advance other investors’ propensity to invest via *learning-by co-investing*, *building a track record of new technologies*, and *trust signalling* in risky or large projects. Learning-by co-investing occurs when SIB participation enables its co-investors to become “familiar with ‘new’ projects, the technology and business models and the risks involved, [learn] how to better assess and mitigate them and how to reach financial close in new and unfamiliar project settings” (Ibid., 10). These mechanisms require the SIBs to be recognised as capable investors with sophisticated in-house expertise for doing due diligence analysis (ibid.). However, the impact of SIBs ultimately depends on the form of governance in place, which is a subject of social contestation (Marois, 2021b).

3.5. Towards a theory of renewable energy finance as an evolving complex system

The review of the foundations of complexity science in economics has provided a theoretical framework for advancing Hall et al.'s (2017) adaptive market hypothesis for energy finance. A complexity approach to RE finance requires attention to the heterogeneity of actors, their explicit interaction in networks, how the interaction produces emergent properties through evolutionary processes, and how the system’s outcomes can change in a non-linear manner between different states (Arthur, 2014, 2021, p. 20; Beinhocker, 2007). The adaptive market hypothesis shares

several complexity features, especially concerning evolutionary dynamics, but it is less useful for understanding other types of interaction than asset pricing in financial markets. Most importantly, complexity theory provides an established framework for analysing systems with widespread interaction in networks, which Hall et al. (2017) indeed show to be the case in RE in the UK.

The review also identified an opportunity for this complexity perspective to inform theories of how finance co-evolves with other elements of sustainability transitions (Geddes and Schmidt, 2020; Köhler et al., 2019a; Naidoo, 2020). The RE finance literature informed how three mechanisms are likely to shape how the system evolves: 1) bounded rationality, 2) evolutionary processes, and 3) actor heterogeneity in the investment behaviours of organisations across and within different sectors and forms of ownership. Two of the main outcomes of advancing the adaptive market hypothesis with complexity theory are the emphases on interaction in investor *networks* and the methodological need to study evolutionary processes *over time*.

Chapter 4

Methodology

The review of the renewable energy finance literature has revealed caveats regarding the role of finance in sustainability transitions and the state's role as an investor. Key contributions have pointed to the complexity of energy finance (Hall et al., 2017c) and the institutional role of finance as a constraint and enabler of technological change (Geddes and Schmidt, 2020), but these perspectives remain underdeveloped. Therefore, this dissertation has an explanatory ambition to develop a complexity-based framework that can be used empirically to improve understanding of the dynamics of renewable energy finance and the role of the state. Below, this general motivation is operationalised into five research questions, which call for a clarification of terminology and the scope of the inquiry. With an outset in the ontology and epistemology of complexity science, the chapter presents the research approach, design, case selection, and the periodisation structuring the analyses. This leads to an explanation of the dissertation's network analytical and qualitative research methods and a presentation of the data material.

4.1. Research questions

Sustainability transitions researchers have increasingly called for a more accurate theory of how finance and investments influence the decarbonisation of society's provisioning systems (Bale et al., 2015; Geddes and Schmidt, 2020; Köhler et al., 2019). The surveyed literature has shown how investments and financial conditions are key determinants of the cost of renewable technologies. Investments lead to deployment which enables learning-by-doing, economies of scale, and research and development in supply chains. The mechanisms lead to cost reductions that may endogenously spur further deployment through a learning curve relationship (Grubb et al., 2021a; Way et al., 2022). Moreover, the cost of finance is a substantial cost component, often adding between 30-50% to non-financial costs depending on the cost of capital (IRENA, 2022a). Fortunately, renewable energy investors can also learn-by-doing, which lowers the cost of

financing (Egli et al., 2019a, 2018). However, the “tacit knowledge and capabilities associated with deployment (...) are little charted” (Grubb et al., 2021a).

Recently, more scholars have called for adopting an adaptive systems perspective (Hafner et al., 2020; Hall et al., 2017; Naidoo, 2020) and a multi-level perspective on the financial sector’s co-evolution with technologies and institutional elements shaping transitions (Geddes and Schmidt, 2020), in addition to more in-depth studies of the role of state investments in energy technology (Elie et al., 2021; Mazzucato and Semieniuk, 2018). One important aspect to examine is the development of an investment community that is capable of assessing the risks of emerging technologies and able to finance them at a low cost of capital: “The need to grow a skill base of an investment community is the first structural constraint that requires adaptive processes to occur” (Hall et al., 2017, 292). To advance this research field, the main research question of the dissertation is:

RQ1: Main research question

RQ1: *What can be learned about how finance and investment influence sustainability transitions by analysing renewable energy finance as an evolving complex system?*

Hypothesis 1 (H1): *Finance and investment is not neutral to the way sustainability transitions develop. The complexity perspective enables a comprehensive analysis of which investors and what interactions among them have been decisive for the deployment of renewable energy technology. Ongoing learning and adaptation to changing circumstances among investors are fundamental mechanisms in sustainability transitions. Entrepreneurial state investors have a disproportionate role in shaping how these processes lead to mature technologies and systems change.*

The research is explanatory in the ambition to apply complexity theory to explain how renewable energy finance evolves as a system, yet also exploratory with respect to the exact mechanisms because of the sparse prior research with this perspective. The main research question is answered through empirical analysis and discussion based on the following four sub-research questions.

As explained below, OSW investment is used as a case study for analysing the role of finance and investment in the maturation of a sustainable technology. The case study can elucidate how investment patterns have historically evolved in conjunction with technological, regulatory, and politico-economic changes. Moreover, it enables a study of how tacit investment know-how is created through learning-by-doing and diffused through co-investments. The analyses enable a theoretical synthesis and a reconsideration of the role of finance and investment in sustainability transitions. Finally, it is discussed how the insights can be used in financial governance and innovation policy.

RQ2: Investment history, technological maturation, and political economy

RQ2: *How has offshore wind investment co-evolved with the technology over time, and how have these changes shaped the political economy of climate change?*

H2: *State-owned investors were early drivers of the industry's learning curve. This maturation attracted private investors, whose participation was enabled by public financial investors' co-investments. Technological cost-competitiveness and increasing private ownership of the parks were conducive to more ambitious climate policy.*

RQ3: Investment know-how diffusion

RQ3: *Which investors and interactions have been important for investment know-how creation and diffusion in the offshore wind sector?*

H3: *Entrepreneurial state-owned organisations have created and diffused early investment know-how in offshore wind and enabled learning by private actors via co-investment relationships with de-risking, capital provisioning, and educational benefits.*

RQ4: Sustainability transitions research

RQ4: *What is the role of finance and investment in sustainability transitions?*

H4: *Finance and investment should be considered co-evolutionary elements of sustainability transitions. The opportunities for financing emerging clean technologies influence and adapt to technological changes, institutional factors, and business strategies.*

RQ5: Policy and governance

RQ5: *How can insights from the complexity analysis motivate new ways of governing financial systems to support sustainable innovation and transition of economic provisioning systems?*

H5: *Governance of financial systems aiming to promote sustainable finance lack a focus on investor capabilities. State-owned investors can be creators and diffusers of investment know-how in the experimental and growth phases of new technologies.*

4.2. Operationalisation: Scope and terminology

This section defines the key terms *renewable energy finance* and *investment know-how* and operationalises what the application of complexity theory requires from the methodology.

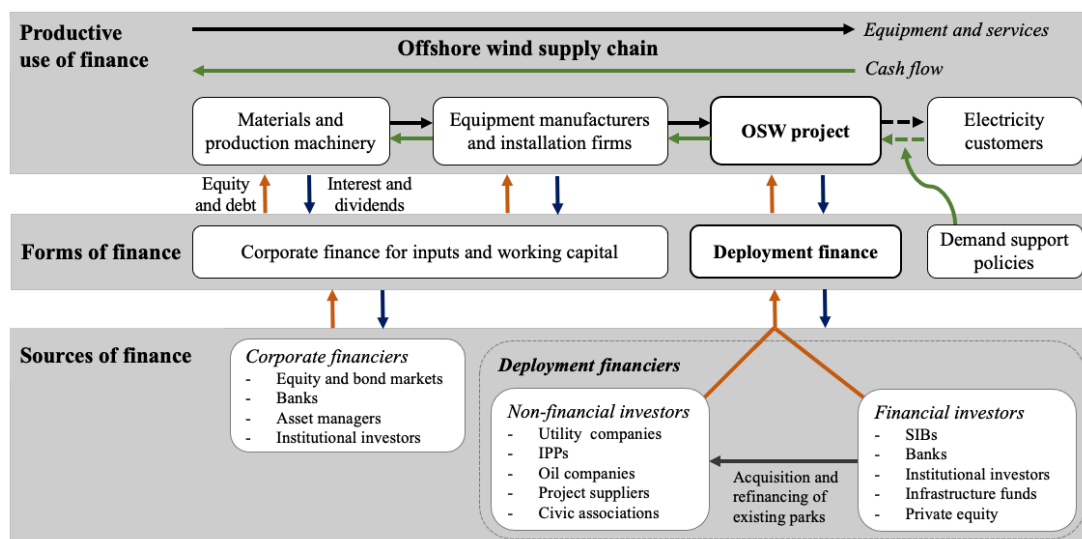
4.2.1. Renewable energy finance

It is commonly argued that sustainability transitions need a ‘greening of finance’ (UK Government, 2019). Consequently, greening finance has become a ubiquitous and hence imprecise term, which can encompass investments in numerous mitigation and adaptation activities as well as emission offsetting and divestment from fossil fuel assets. This opens a wide scope for greenwashing and uncertainty about the additionality of investment decisions. This dissertation focuses on *investments in renewable energy* (RE), which is a subset of the emission-mitigating ‘low carbon finance’ (UNEP, 2016). RE investments provide a clear causal path to

additional carbon mitigation by displacing fossil fuel energy sources from the electricity grid. Moreover, since renewable energy technologies have experienced remarkable cost reductions over the past 15 years (IRENA, 2022a) that have also enabled the decarbonisation of transport and heavy industry, it is important to understand the role of finance and investment for this technological group.

Although the activities of all elements in the supply and innovation chains need to be financed (Grubb et al., 2017), the scope of this dissertation is on *deployment finance*, which brings the final combinations of sub-technologies into final use in the economy. The reason is that from a cashflow perspective, deployment is the upstream cause that makes the entire industry invest, produce, organise, and innovate. While the most important technological and organisational innovations undoubtedly occur in the supply chain, Figure 4.1 illustrates how the suppliers rely on the cash flow from sales to OSW projects to finance their productive activities.

Figure 4.1: The importance of deployment finance for the offshore wind industry



Note: Own illustration. SIB = state investment bank. IPPs = Independent power producers. The populations of corporate and deployment financiers can overlap.

The last consideration regards the types of financing that are within the scope of the study. We can distinguish between fixed investment that creates new physical OSW projects and investment in existing assets where claims on the assets shift hands. This dissertation refers to the financing



of fixed investments as *primary finance*. Financing of existing assets takes two forms. One is *acquisition finance*, where a new actor buys a stake or the entirety of an operational wind farm (or where construction is underway). Debt provided to a leveraged acquisition is also categorised as acquisition finance. The other type, *refinancing*, is where banks or other debt providers provide new debt to an operational project, for instance, to replace expensive or expiring debt with cheaper or simply more debt. Providers of all three categories of finance are all referred to as *investors*, though the dissertation distinguishes between debt and equity investors when relevant. The ‘investor network’ and the ‘financial network’ are therefore used interchangeably since non-financial corporations such as utilities finance a large share of investments in RE.

4.2.2. *Investment know-how*

Given my emphasis on the generation and diffusion of knowledge of renewable energy investment in the energy and financial sectors, it is worth elaborating on this knowledge more precisely. Knowledge has for long been identified as a crucial input in growth in both neoclassical and neo-Schumpeterian growth theory – and increasingly also as an output in the proclaimed transition from industrialised to knowledge economies (Acemoglu et al., 2012; Antonelli, 2019; Lundvall and Johnson, 1994; Romer, 1994; Stiglitz and Greenwald, 2014). The dissertation is particularly concerned with the knowledge that enables investors to undertake large construction projects successfully, make sound risk assessments, and take the necessary precautions. Based on theory of knowledge, learning, and innovation (Loasby, 2002; Lundvall and Johnson, 1994), this type of knowledge is ‘know-how’ rather than ‘knowing that’.

‘Knowing that’ refers to facts, theories and relationships and is the subject matter of most education and the news. ‘Knowing how’ is “the ability to perform the appropriate actions in order to achieve a desired result, and includes skill both in performance and in recognising when and where this skilful performance is appropriate” (Loasby, 2002, 51). In other words, know-how is the latent ability to take action and achieve a desired result. Both types have indirect variants concerning knowing how to learn new knowledge or getting something done by others (also described as ‘knowing who’ by Lundvall and Johnson (1994, 28)).

Following Loasby (2002), ‘know-how’ is used interchangeably with ‘capabilities’ to cover the competencies built up in organisations and the ability to develop them over time. Strategic management scholars have distinguished between an organisation’s *resources* that are “Valuable, Rare, Inimitable and Non-Substitutable” stocks, including “process know-how, customer relationships, and the knowledge possessed by groups of especially skilled employees”, while *capabilities* “are hinting at process” and the use of resources to create and capture value (Katkalo et al., 2010, 1176).

Katkalo et al. (2010, 1177-1180), therefore, used the concept *dynamic capabilities* to refer to “the firm’s capacities to integrate, build, and reconfigure internal and external resources/competences to address and shape rapidly changing business environments”. They help firms identify opportunities for value creation, seizing them through the mobilisation of the requisite resources and through continuous renewal of the firm’s resources to match the changing environment (see also Teece and Pisano, 2003; Teece et al., 1997). Since the dissertation is concerned with the development of investment know-how around a new technology, it is also important to consider how the stocks of know-how are developed through interactions with users, suppliers, competitors, and researchers, as emphasised by the national systems of innovation literature (Jensen et al., 2007; Lundvall and Johnson, 1994).

The *investment know-how* necessary for planning and managing successful installations of renewable energy projects can be subdivided into two types of know-how. First, *fixed investment know-how* denotes the personal and organisational capabilities necessary for efficiently developing and managing the construction of new RE installations. This know-how includes making sound technological selections, developing at a low budgeted cost and without cost overruns and delays, and the ability to make up for unforeseen circumstances. *Financial know-how* refers to the ability to accurately assess the eventual return on the asset, including the risks involved. Investors must therefore be able to assess the expected revenues across the 20–30-year lifetime of the project (based on notoriously unpredictable energy markets) and the risks in the construction and operational phases. The particular risks for the selected technology case of offshore wind are reviewed in Appendix I: Risks in offshore wind investment.



Fixed investment know-how primarily resides in organisations that develop rather than provide external financing for RE projects. However, financial investors must also possess some fixed investment know-how to assess the financial risks and opportunities in a given project. Developer organisations likewise need financial know-how in order to be profitable businesses. They are likely to be more entrepreneurial and opportunity-focused, while external financiers who take on construction risk are likely to be more conservative and focused on risks in their financial assessment of potential investments (interview 2). Financial cost reductions can then occur through developer and/or financier learning-by-doing.

This capability perspective implies that deployment-oriented policies, whether CO2 taxation or targeted market creation, also operate by improving the stock of investment know-how in investor organisations. Different policies will have different impacts on this learning process. The processes around particular technologies will likely be different and non-linear because of the specific ways the know-how is generated and spread among potential investors.

In this regard, it is worth noting that complexity economists have emphasised that know-how – or tacit knowledge – “moves with enormous difficulty from brain to brain because it is unconscious and does not involve understanding”. It is created through “a long process of repetition, imitation and feedback” (Balland et al., 2022, 2). While most studies of innovation consider ‘knowing what’ codified in patent data, innovation scholars find that know-how is more important since “knowing how to do and change things is more difficult to learn, than it is to learn about facts and science” (Lundvall and Johnson, 1994, 28). To understand innovation and learning processes, we should therefore look beyond intentional R&D processes and focus on learning-by-*doing*, -*using* and -*interacting*, which are the typical sources of know-how (Arrow, 1962; Jensen et al., 2007).

The described properties of know-how mean that organisations can build up capabilities that are hard to imitate. This is a reason behind the formation of “durable user-producer relationships and network relationships [likely because] they give access to know-how” (Lundvall and Johnson, 1994, 30). Indeed, two of the core functions of innovation systems are the development and diffusion of knowledge through networks, which contribute to sustaining technological change (Hekkert et al., 2007). For the same reason, successful firms often develop and rely on the

absorptive capacity to acquire, assimilate, and exploit external knowledge inside the organisation (Cohen and Levinthal, 1990). Because of the active and interactive ways for creating and spreading know-how, the methodology should be attuned to account for investors' learning-by-doing and diffusion processes among networks of organisations.

4.2.3. *The ontology and epistemology of evolving complex systems*

The main goal of this dissertation is to make an ontological contribution to the ongoing theorising of the role of finance in sustainability transitions. Before we can regulate or govern finance to strengthen the green transition, we must have a clear conception of the financial system and how it operates. It has been proposed that energy finance is “an adaptive market” (Hall et al., 2017) that cannot find an optimal equilibrium and a “regime” (Geddes and Schmidt, 2020) which constrains technology deployment and maturation. Based on the literature review, this research programme is advanced by examining if renewable energy finance can be explained as an *evolving complex system* and what causal mechanisms this perspective can reveal. The research, therefore, needs to be aligned with the ontological and epistemological perspectives in complexity theory. Sheard and Mostashari (2009, 296) defined complex systems as:

systems that do not have a centralizing authority and are not designed from a known specification, but instead involve disparate stakeholders creating systems that are functional for other purposes and are only brought together in the complex system because the individual “agents” of the system see such cooperation as being beneficial for them.

In further detail, complex systems contain many autonomous and heterogeneous actors who interact and adapt to each other and the environment, a system boundary that is often hard to pin down, and they display emergent macro-level behaviour stemming from the interactions. The future behaviour is often non-deterministic and involves nonlinear dynamics. Over time, complex systems tend to increase their complexity through more feedbacks among the elements and increasing specialisation and capability formation (Ibid., 297).

Insofar as renewable energy finance has the characteristics of complex systems, we should see heterogeneous investors with different preferences, endowments, productivities, technological repertoires, learning processes, propensities to innovate, organisational setups, and corporate strategies (Dosi, 2013). The actors should be interacting in networks which leads to an evolutionary process where the actor composition, know-how, and technology usage change over time (Arthur, 2021; Beinhocker, 2007; Dosi, 2013; Foster, 2005; Foster and Metcalfe, 2012; Kirman, 2011).

This ontological focus on complex systems carries methodological and epistemological implications for how to produce valid knowledge of how the world works. The hypothetico-deductive approach of reasoning about how representative, rational actors optimise under constraints will not be able to elucidate the research questions in this dissertation. Instead, an analysis of complex systems requires research methods that can account for actor heterogeneity, interactions and disequilibrating feedback loops, such as system dynamics, agent-based modelling, input-output analysis, social network analysis (SNA), and co-evolutionary approaches (Foxon et al., 2013), and should seek inspiration from historical studies of the energy transition in question (Fouquet, 2016). The analysis needs methods that can detect feedbacks between micro-level behaviour and meso- and macro-level outcomes (Arthur, 2021; Dosi, 2013; Kirman, 2011). More precisely, the analysis should be able to answer to what extent interacting actors create emergent structures and outcomes, which they, in turn, adapt to through new patterns of interactions and innovations at the micro-level.

While agent-based modelling and simulations can provide valuable insights with regard to the impact of interactions and evolving routines and strategies on energy transitions (Barazza and Strachan, 2020; D’Orazio and Valente, 2019; Hötte, 2020; Mercure et al., 2016), the approach is limited by the fact that “interactions between agents are not calibrated to data” and “the emerging complexity rapidly obscures the nature of phenomena, and strongly depends on the definition of these interactions” (Pollitt and Mercure, 2018, 192-193). Moreover, emergent properties, i.e. “system behavior that does not depend on its individual parts, but on the multiple relations and interactions on all system levels”, where the exact causal mechanisms are unknowable cannot be computationally modelled, since the results stem from the inputs and the specified algorithm

(Tolk et al., 2018, 7). Formal models therefore need exploratory studies to obtain internal validity.

Because of these limitations and the exploratory purpose of this dissertation, the application of SNA methods on fine-grained historical data of interactions is preferable for conducting empirically grounded theory development (Lee, 2016). Evolutionary and complexity economists have emphasised the use of networks since they make the social reality of economic activities explicit (Beinhocker, 2007; Dosi, 2013), and transmissions through networks inexorably brings historical time into the analysis: “without such propagation, time disappears” (Arthur, 2021, 140). However, the availability of longitudinal and fine-grained data is often a binding constraint.

4.3. Research design and analytical approach

4.3.1. Research approach

The ambition of this research is to improve our understanding of how renewable energy technologies come to be supported by investments by analysing the history and social interactions of the investors who make the investment decisions. The theoretical review showed that these investment decisions have either been empirically examined at the micro-level at one point in time with a focus on cognitive limitations and biases or by assuming efficient financial markets that respond rationally to risk-adjusted return prospects (Hall et al., 2017). This dissertation intends to study the mechanisms that, over time, create organisations that can efficiently respond to price incentives and technological change. It is, therefore, an evolutionary and socially contextualising approach aiming to examine if a system-based ontology of renewable energy finance enhances our understanding of how investments are undertaken in emerging sustainable technologies. The foundational proposition is that investors can more efficiently respond to price signals if they have accumulated investment know-how and hence lower the needed level of de-risked revenues as they learn about the sector. The dissertation thus focuses on the intermediate causal mechanism of investor know-how that links price incentives in the market with investment decisions.



The philosophy of science underlying this dissertation is closely related to the propositions of critical realism and grounded theorising (Lee, 2016; Morgan, 2016) by basing explanations on the causal mechanisms and structures that produce economic outcomes and continual events that can be experienced empirically. Causal mechanisms are triggered by human intentionality in entities, while structures have an influence on how the events unfold. The critical realist perspective rejects the positivist search for law-like generalisations or hypothetical deductions of how the world operates. Since the continual flow of events (and non-events) are produced by actors with changing powers to cause changes and structures that can slowly change as a consequence of agency, causality is historically contingent. Moreover, mechanisms, observed and unobserved, overlap in complex ways that reduce the potential for definitive falsifications of theories. Theory development, therefore, needs historical grounding in observations of the mechanisms and structures that produce the events of interest.

The ambition is to explain the processes that lead to investment decisions rather than establish law-like generalisation or predict future outcomes. According to George and Bennett (2005, 137) causal mechanisms are “physical, social, or psychological processes through which agents with causal capacities operate, but only in specific contexts or conditions, to transfer energy, information, or matter to other entities.” A law-like theory of renewable energy investment could be that: if the risk-adjusted return is sufficient, then the investment is undertaken. The more mechanism-based inquiry in this dissertation posits: the level of risk-adjusted returns leads to investments *if the potential investors obtain sufficient knowledge of the technologies and firms in question to lower the estimated risks below their hurdle rates*. Mechanism-based inquiry thereby holds a “commitment to consistence with the micro level” (Ibid., 141), which is not adequately addressed by deductively modelling micro-level decision-making. Still, this does not mean that all explanatory weight needs to be placed at the micro-level. Emergent properties and structures shape how agency is exercised (Lee, 2016), which renders the approach suitable to examine complex systems.

This dissertation, therefore, heeds the call by George and Bennett (2005, 142-145) for “social scientists to discard stylized simplifying assumptions and build upon the most accurate micro-level mechanisms that can be discerned” by pushing the “movable border of the unobservable”.



Ideally, to examine social mechanisms, the data and methods should enable analysis of agent-agent and structure-agent interactions. This points to the need for a mixed methods approach (Creswell and Plano Clark, 2018) that includes social network analysis (Cronin, 2016; Wasserman and Faust, 1994).

4.3.2. *Research design*

The research design of this dissertation is a longitudinal case study of the development of offshore wind (OSW) as an economically viable renewable energy technology from an investment perspective. It is hence a within-case analysis, which “focuses not on the analysis of variables across cases, but on the causal path in a single case” (George and Bennett, 2005, 179). It attempts to create a coherent narrative of the historical evolution of the OSW market and, in the process, examine who have been the prominent investors, how the investors have been connected to each other and, in combination, to examine how a mature investor community has developed around OSW.

Since the dissertation is motivated by the theoretical development of the complexity perspective on energy finance introduced by Hall et al. (2017), a ‘plausibility probe’ case study is an appropriate choice of research design since they are “preliminary studies of relatively untested theories and hypotheses to determine whether more intensive and laborious testing is warranted” (George and Bennett, 2005, 75). The design is thereby inspired by the method of grounded theory where “researchers create their theory ‘directly’ from data ... [and] data collection, theoretical analysis, and theory building proceed simultaneously” (Lee, 2016, 39). In my research process, the relevance of the complexity perspective slowly dawned upon me as I examined the patterns of a database of renewable energy investments, which led me to study complexity theory in greater depth while considering how various research designs could contribute to further theory development.

This design draws on the four main strengths of case studies (ibid., 19-25, see also Flyvbjerg, 2006). First, case studies allow researchers to analyse with high conceptual validity between the theoretical concepts and empirical observations by using more contextualised observations than

statistical analysis across a large number of cases. Second, case studies' qualitative engagement with primary sources and the creation of new data can inductively inspire new hypotheses. Third, case studies are better suited to examine causal mechanisms than statistical studies of co-variation of two or more variables that happen to be coded in a database. It hence strengthens the validity of claims of causality to study the actual processes that create events. The last advantage is the ability to analyse complex causal relations such as path dependence and interaction effects. For the same reasons, case studies are better at asking “*whether* and *how*” a variable influenced the outcome than “*how much*” it mattered, i.e. the relative causal weight. The main challenge is to select a relevant case and reflect on its inferential limitations.

While an in-depth case analysis is therefore well-suited to develop the complexity perspective on renewable energy finance, quantitative methods can still be helpful for ordering and making sense of the actors and actions influencing the outcomes of interest. To obtain a comprehensive understanding of the selected case, the dissertation uses a mixed methods approach called “QUAN → qual = explain quantitative results” (Creswell and Plano Clark, 2018, 119), where quantitative and qualitative methods are implemented sequentially by first establishing quantitative results which are then explained using qualitative methods. More specifically, the quantitative results are based on descriptive analysis and social network analysis, which is considered an “inherently mixed [type of] analysis” (Ibid. 322), since the network relations can both be quantified and interpreted narratively based on visualisations.

4.3.3. *Case selection and the structure of the analysis*

As mentioned, this dissertation is inspired by Hall et al.'s (2017) proposition that energy finance should be considered an adaptive rather than an efficient market. Their initial analysis of the hypothesis was a case analysis of the conditions for renewable energy investment in the UK leading up to the 2013 electricity market reform. The strength of such a country-based within-case study is that it is easier to integrate the policy framework into the explanation. However, it can be difficult to isolate influences stemming from developments and policies in other countries, e.g. the availability of experienced investors.



To advance from this first probe into the empirical application of a complexity perspective, conducting a longitudinal case study with more emphasis on investment data would be complementary. Since investments in renewables are generally not constrained by borders, it would also be useful to examine investments in more countries. Both steps would provide a more comprehensive understanding of the financing behind renewables deployment but concomitantly sacrifices attention to the effects of the policy frameworks that change over time and vary across countries and technologies as a trade-off. Since the emphasis is on understanding financial systems, this prioritisation is warranted. However, closer integration with the effects of policy frameworks should be prioritised in future research, for instance, through comparative case analysis of investments in different countries. Finally, since investors and policy frameworks vary across technologies, the single case analysis will achieve a sharper focus by only focusing on one technology.

Onshore wind, offshore wind (OSW) , and solar PV are the most interesting cases to analyse. Other available technologies had matured significantly less (IRENA, 2022a), which limited the informational content in relation to understanding how investments and investor communities co-evolve with technologies. These non-cases could also be interesting future objects of analysis to understand their failures to mature through a complexity lens. The case is thereby selected based on the dependent variable to better understand the processes producing the still poorly understood phenomenon of competent investor ecosystems (George and Bennett, 2005, 23).

Among the three RE technologies, OSW is selected primarily for methodological reasons. For onshore wind and solar PV, the investment data linking investors and projects were only available for the years 2004-2017 and with a considerable amount of unidentified investors, possibly because of the large number of decentralised minor projects. For OSW, the same database could be combined with another database covering 2018-21 and the entire period before 2004 could be covered by manual data collection. OSW thus offers a unique opportunity to examine the entire history of deployment finance for a maturing sustainable energy technology. The full coverage is pertinent since complexity theory suggests that complex systems evolve with great sensitivity to early conditions and events that create path dependencies (Arthur, 2014; Beinhocker, 2007).



Moreover, as an impactful, low-carbon technology, it is substantially important to learn about how OSW developed. Many efforts have been invested in understanding the development and cost trends of OSW technologies (Díaz and Guedes Soares, 2020; Dismukes and Upton, 2015; Ederer, 2015; Gonzalez-Rodriguez, 2017; Junginger et al., 2020), but only recently has the cost of capital for offshore wind received significant attention as a source of cost reductions (IEA, 2019; Voormolen et al., 2016). Karltorp (2016) observed that OSW faced a ‘second valley of death’, i.e. the challenge of commercial upscaling, because of a perception of high risk and low reward among financial investors, especially in light of the long time required to pay back the investment. Insufficient know-how was one particular obstacle:

increased knowledge of renewable energy technology is needed among financial investors. This is despite that investors can be informed by consultancy and due diligence firms ... increased knowledge among investors might be needed in order for these to be able to formulate their need for consultancy services on renewables and to interpret and evaluate the acquired information. This knowledge could be acquired in many ways. One suggestion is that technology developers who have good knowledge of the technology, can take on the role to increase knowledge among investors by working more closely with them (ibid., 100, 106-107).

This points to the importance of diffusing investment know-how from early investors to the wider financial system. Karltorp suggested that novel business models and financial innovations could help OSW reach technological maturity, including emerging models for including pension funds as owners, increasing the share of public finance to stimulate private finance, and finding ways to obtain finance with bond issuance.

Since all technologies have different characteristics that change over time, the insights drawn from the historical evolution of OSW investment cannot be perfectly representative of other technologies nor a clear guide for predicting how OSW financing will evolve in the future. Still, there are certain features of OSW that suggest that lessons learned from its historical development can be relevant for the interpretation of the development of other contemporary technologies and the next generation of sustainable energy technologies. Most importantly, OSW is capital-



intensive, like most sustainable energy technologies that do not rely on high-cost fuels to operate (IEA, 2019; Schmidt, 2014). In addition, the resulting parks are long-lived, with up to 30 years of operation. In combination, this means that the perceptions of debt and equity investors matter greatly to the cost and possibility of constructing OSW.

Since OSW is installed in much larger projects and with additional risks (see Appendix I) than onshore wind and solar PV, the financial barriers are likely stronger for OSW. It is, therefore, more likely that uncertainty, path dependency, and network effects can be impactful for OSW, which is helpful for early theory development, but the hypothesis should be critically examined on more decentralised technologies (see chapter 8).

4.3.4. Periodisation of five investment phases

At the time of data collection, investments in OSW have occurred over an approximately 33-year span from 1989 to 2021. To create structure in the narrative of how OSW evolved and practically for making visual SNA intelligible, I have demarcated the 33 years into five phases. The breaks are based on significant events detected in the literature on the history of OSW (Backwell, 2018; Voldsgaard and Rüdiger, 2021) in combination with trends identified in the data material (see chapter 5). Also, two events in the system's environment – the great financial crisis (GFC) and the Paris Agreement — are used to separate the three middle phases to support the co-evolutionary perspective in the narrative. Here follows a brief introduction to each phase (Table 4.1).

Table 4.1: The five phases of offshore wind investment

Phase	1: 1989-2001	2: 2002-2009	3: 2010-2015	4: 2016-2018	5: 2019-2021
Title	<i>SOE exploration</i>	<i>Utility-led upscaling</i>	<i>State-led maturation</i>	<i>Post-Paris learning and diffusion</i>	<i>Offshore wind as a mainstream asset class</i>
Industry characteristics	Early experimentation with increasingly larger demonstration parks.	Larger parks, further ashore, in deeper waters, with rising costs. More networked investor system.	Ørsted (SOE) and SIBs are lead investors in a growing market. A financial core emerges. Institutional investors enter.	Rapidly falling costs. More financial investors in the network, who predominantly invest in existing assets.	Continually falling costs. Financials are dominant investors in new projects. Globalisation to East Asia and US
New investors	SOE and civic utilities. Civic groups	Utilities, banks, small developers, and SIBs	Institutional investors		Major oil companies
Notable events	First utility-scale parks (2000 & 2001)	First project financing with bank loans (2006) GFC (2008-09)	Paris Agreement (2015)	Borssele 1&2 and Krigers Flak project tenders (2016) and first zero-bid tenders (2017)	Normalisation of zero-bid tenders. Large projects in Taiwan, South Korea, and US.
MW financed	555	4,751	14,800	18,691	15,441
Active investors	14	87	173	209	207

Note: SOE: state-owned enterprise. SIB: state investment bank.



The first phase is called *SOE exploration* and spanned from 1989-2001. This was a period where Danish and Swedish state-owned and civic utility companies explored how onshore wind technology could be used at sea. This period displayed cost declines in the capital cost per MW as the initial challenges were overcome through learning, economies of scale, and early standardisation. The period is capped by two Danish utilities' (who were later merged with the SOE Ørsted, then DONG Energy) investments in the world's two first large-scale offshore parks – Horns Rev 1 and Nysted – following governmental instructions. These investments provided the know-how foundation for the subsequent scale-up phase (Voldsgaard and Rüdiger, 2021).

The second phase is *Utility-led upscaling* and lasted from 2002-2009. In this phase, the already active SOEs were accompanied by a small group of German and British private energy and utility companies. The period also saw banks finance smaller developers, while state investment banks (SIBs) provided early finance to both utilities and small developers. In this phase, large offshore wind farms became more mainstream, although the cost per installed MW increased – at odds with common learning curve trends (Junginger et al., 2020).

The third phase is named *State-led maturation* and spanned from 2010-2015. This period was marked by the aftershock of the Great Financial Crisis and strains on the balance sheets of private energy companies (Blyth et al., 2015). SOEs and SIBs invested countercyclically in the OSW sector and ensured continued deployment until costs started to come down. Institutional investors also entered the market by acquiring stakes in operational parks.

The fourth phase titled *Post-Paris learning and diffusion* lasted from 2016-2018. After the Paris Agreement costs fell rapidly (IEA, 2019; IRENA, 2022a). This was also the period where private financial actors became familiarised with the technology's investment characteristics, primarily through refinancing and acquisitions of existing parks.

Lastly, the fifth phase *Offshore wind as a mainstream asset class* covers the years between 2019-2021. This was a period where the private financial actors assumed a more dominant role, also in terms of finance for the construction of new projects, while public investors had a smaller role. Major oil companies were the novel type of actor in this phase.



4.4. Methods

The necessity of accounting for evolving patterns of interaction underlines the need to adopt methods compatible with a complex systems perspective (Arthur, 2014; Beinhocker, 2007; Foxon et al., 2013). The dissertation therefore applies social network analysis (SNA) (Scott and Carrington, 2011; Wasserman and Faust, 1994) to assess the complexities in the co-evolving financial subsystem of OSW finance. Financial connections are social relations of indebtedness and ownership and are therefore appropriate to analyse with SNA and social relations have been shown to influence business financing (Uzzi, 1999; Uzzi and Gillespie, 2002).

Basically, networks are made up of actors and/or events, mentioned as *nodes* or *vertices*, and their interconnections, mentioned as *ties*, *edges*, or *links*. Both nodes and ties can be attributed various characteristics to add information to the network, e.g. the monetary value of a financial relationship or the type of actor.

Critical realists have highlighted the ability to make otherwise hardly observable causal structures tangible for analysis as a strength of SNA (Buch-Hansen, 2014). Establishing causal mechanisms of theories “in principle requires consistency with the finest level of detail observable”. Consequently, detailed historical analysis of investor networks can contribute to developing a complexity theory of renewable energy finance that is substantiated by observed investment behaviour.. For the same reason, the network visualisations and statistical network analysis are complemented by qualitative methods to provide a more detailed picture of what is occurring at the micro-level of the network as it evolves.

4.4.1. Method 1: Network visualisation

SNA analysts often look to identify cohesive groups and actors with central roles in the network. One of the main SNA methods is network visualisation (Freeman, 2005). Network visualisations contain nodes that are either actors or entities they relate to (in case of so-called bipartite networks with two types of entities), such as social events or organisations, and connections between them, often referred to as ties or edges, that can either be directed or undirected depending on the nature of the phenomenon. Network graphs provide a vocabulary and models of social structures that

can render them objects for analysis (Buch-Hansen, 2014; Iacobucci, 1994). The data material in this dissertation creates bipartite networks since two types of entities – investors and OSW projects – are connected by undirected investment ties⁹.

The researcher can thereby identify individual roles as well as the social structures they are embedded within. Visualisations can convey specific and general data simultaneously, which is one “of the powerful communicative features of a network visualization” (Cronin, 2016, 238). Visualisation is, therefore, an important tool for preliminary analysis and inspection of pairwise interrelations between specific actors, and is commonly supplemented with statistical network measures (ibid., 250).

One important issue is how to place the nodes relative to each other so the pattern can both make the “pairs that are socially closest in the observed data (...) spatially closest in the graphic image” (Freeman, 2005, 248) and be reproducible. The analysis does not discriminate among social proximity between any two pairs of investors¹⁰. Instead, it uses a force-directed algorithm to place the nodes relative to each other based on their common interlinkages (Fruchterman and Reingold, 1991). The nodes with a direct tie and more connected nodes in common will then be closer to each other. Each rendering will not be identical, but the main formations and characteristics of the network will be the same.

Network visualisation will be used in chapter 6 to narrate and interpret the history of OSW investment according to the five phases presented above. The bipartite networks show how each particular investor is invested in one or more projects and how this makes it directly connected to other investors in the same network and indirectly connected to the wider web of projects and investors through direct partnerships. The colours of the investors are used to indicate the ownership form (public, private or non-profit) and sector (financial or non-financial) of the organisations. The project deals and the ties to them are coloured by the financial category, i.e. whether it is primary finance, acquisition finance, or refinancing. One project can be represented

⁹ Investments can be said to be injected into projects, but this is not substantially important in this study. Practically, undirected ties are preferable for analysing the connections between investors via projects.

¹⁰ This could for example be done by weighing the connections by the value of investments.



more than once in a graph if it, for example, has been constructed and refinanced during the same phase. The sizes of the nodes are used to show the volume of each node's total investment in the phase relative to the top investor in the phase. The sizes thereby provide a proxy for learning-by-doing among the investors. The relative sizes of nodes can be used to compare the volumes of investment within each phase but not across phases since the top investor (i.e. the reference point) will have invested different amounts. The relative ranks can still be compared, i.e. who were among the top investors in the phases. The size of the project deals reflects the total volume of capital invested by the investors.

4.4.2. *Method 2: Network statistics*

In chapters 6 and 7, the OSW investor network is also analysed with statistical methods. Chapter 6 uses measures of network ties and density in each phase to strengthen the historical analysis of the investor network's evolution. Chapter 7 uses network reachability analysis to examine how investment know-how could be created and diffused through co-investment ties *through time*. The network statistics use a bipartite projection of the network, where the projects are turned into ties among the investors, who are then the only nodes in the network. One exception is the backward reachability measure, which focuses on investors' reach to past projects rather than to past investors.

Statistics for static networks

SNA features certain widely used metrics of the network structure and each node's position in the network. The network size is measured by the number of active investors in a given phase. The *network density* measures the observed number of ties among active investors as a share of the maximum possible number of ties among these actors¹¹ (Jackson, 2010, 51). This gives an impression of the cohesiveness of the network, although the same density can be created by different distributions of ties among the actors, which is why further measures and inspections

¹¹ Formula: Actual connections / (nodes * (nodes-1) / 2).



are useful (Cronin, 2016, 248). A more cohesive network can ensure better exploitation of resources and experiences in the network and facilitate economies of scale via specialisation. In contrast, less connectivity among groups can facilitate the exploration of new ideas that can spread via nodes linked to both (or more) separate groups (ibid.)

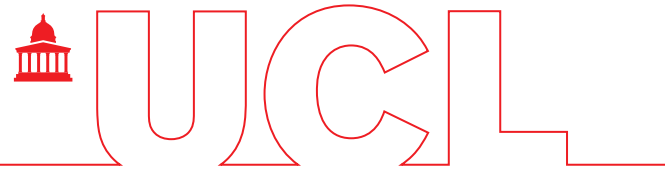
The most straightforward measure of a node's centrality is its number of direct ties, known as *degree centrality*. Nodes with more ties generally have better access to information, opportunities, and potential for influencing the network. However, all ties and nodes are not equal in the network. Therefore, other centrality measures can be used to capture other forms of influential positions. *Betweenness centrality* counts the number of shortest paths among all pairs of nodes in the network that pass through each node, which provides an impression of the node's role as a broker or intermediary between different parts of the network – even if it has few ties (Freeman, 1978)¹². *Eigenvector centrality* weighs each node's degree centrality by the centrality of its neighbours' centrality (which is, likewise, weighted) (Jackson, 2010, 67-68). Degree centrality is used in chapter 6, while betweenness and eigenvector centralities are reported in Appendix F to increase the robustness of the interpretation.

Reachable paths and sets

In chapter 7, the analytical focus shifts to the connections *between* the five phases and the longitudinal flow of know-how in the network. The main analytical challenge is that investment know-how is real and impactful on the cost of capital but largely unobservable. To analyse the phenomenon, the analysis has to use a proxy for where know-how is created and examine the ways it can flow between investors in the network.

From a learning-by-doing perspective, we should expect that the investment know-how is created when new projects are financed. I, therefore, use each node's connections to past construction projects as a proxy for how much know-how they can have absorbed. Since this know-how is likely transferred between investors as they co-invest, the time-respecting temporal networks can

¹² The count of appearances on shortest paths can also be normalised by dividing by the total number of shortest paths among all nodes in the network (Jackson, 2010, 65).



show how investors are, directly and indirectly, able to source know-how through their investment partners. This is called reachability analysis through the walkable paths in the network.

Walkable paths between nodes in a network are a common element used to measure a node's integration in the network (Iacobucci, 1994). The length of the paths to other nodes measured by the number of ties and the number of reachable nodes express how closely connected a node is to other nodes in the network. The more reachable nodes and the closer they are, the more likely the actor is to have more informational resources and influence. In temporal reachability analysis, the paths *must respect the timing of interactions* to draw valid conclusions about what is reachable. These paths can stretch both forward and backward in time.

For any node in the network at a particular point in time, its forward-reachable set of nodes in the network is defined as “the set of nodes that can be reached from an initial seed via a path of temporally ordered edges” (Armbruster et al., 2017, 328) and the backward reachable set is conversely the set of nodes that could reach the node since a previous point in time.

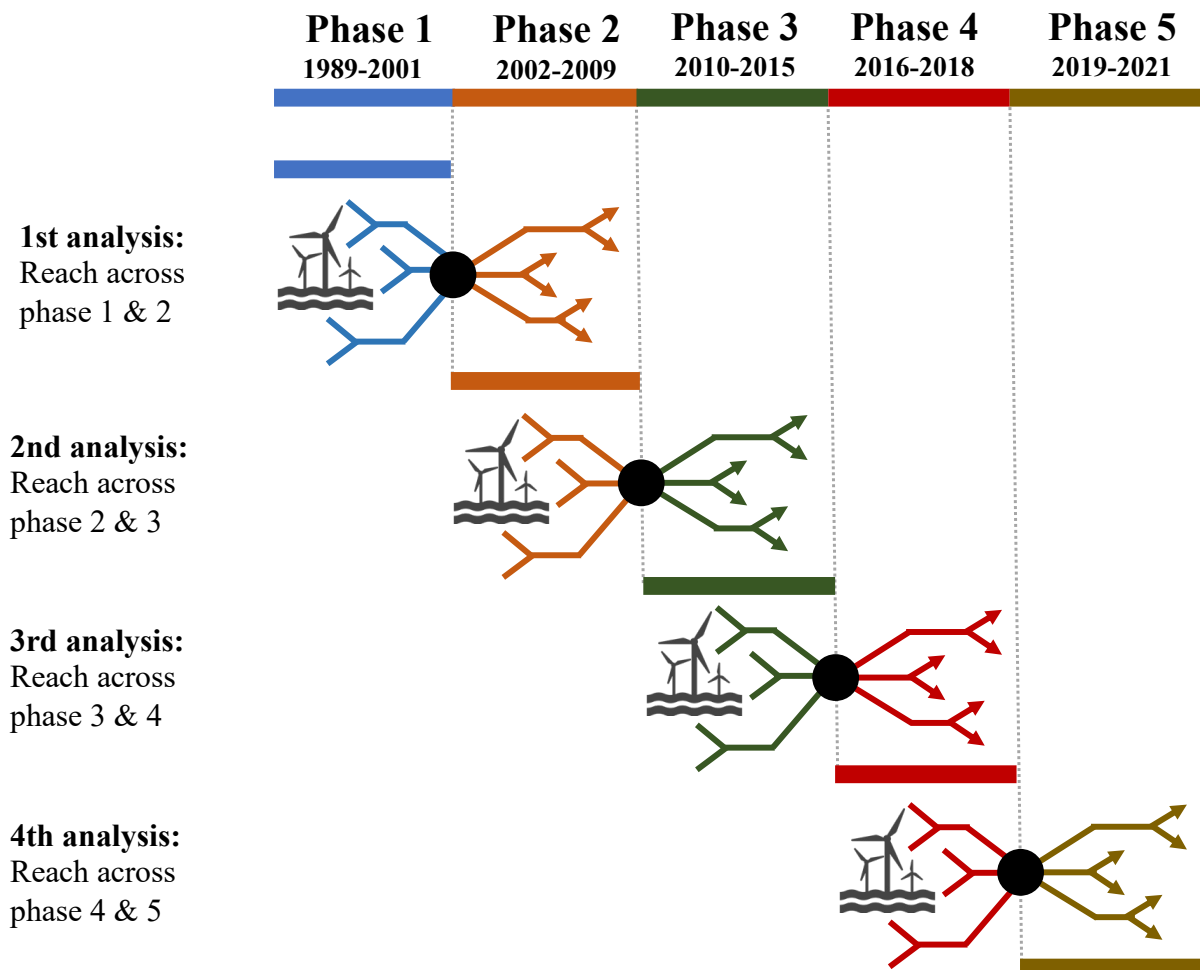
Calculation of reachable paths has been used to study the transmission of sexually transmitted diseases (Anderson et al., 2021; Morris et al., 2009), citation networks (Hummon and Dereian, 1989), and patent networks to find main paths of technological development (Gwak and Sohn, 2018). However, to my knowledge, reachability analysis has not been used to study how investment know-how can be transferred via cooperative relationships.

By using the time-respecting network paths, we can take advantage of the temporal granularity of the data on an annual basis while using the five phases to structure the focus of the analysis and keep the length of the paths reasonable. This limits two issues with decay: Previously generated know-how will become outdated over time, and not all know-how will be transferred through interactions.

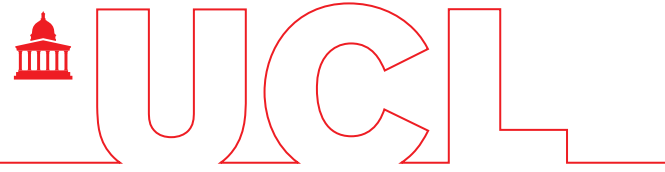
For these reasons, I use the reachable sets to calculate proxies for each investor's *know-how exposure* to previous learning and potential for *know-how diffusion* to other investors. The four sub-analyses in chapter 7 each take a viewpoint from the four breaks between the five phases of OSW investment. Figure 4.2 illustrates how the analysis is designed to use backward reachable

sets to measure each investor’s exposure to know-how generated from the construction of new parks in the most recent phase. Similarly, the forward reachable sets of investors provide a measure of the subsequent potential for influencing the state of know-how in the investor community. The black node at each break between phases represents all the active investors in the two adjacent phases.

Figure 4.2: Investors obtain know-how from previous projects and diffuse the know-how



Note: The figure illustrates how the analysis at each break between the five investment phases examines how each investor (the representative black nodes) could have been influenced by the know-how generated from the investments in new parks in the previous period and how this know-how could subsequently be diffused through co-investments.



By default, the reachable sets in the OSW investor network contain both parks and investors, since investors are connected via their investments in parks. To improve the indicators for the analysis, I filter the reachable sets, so the backward sets only contain the reachable investment deals for new parks (directly or via co-investors) since they are the main *sources of know-how*. The forward sets are filtered to only contain the reachable investors (via parks) since they are the *destinations of know-how*.

More specifically, I use the backward set of each investor to identify which previous parks they could have been influenced by, either through their own direct learning-by-investing or interactively by absorbing the know-how previously obtained by their co-investor. Primary financing creates know-how because of the involved planning, construction and commissioning processes, while refinancing and acquisition financing can be pathways for know-how diffusion of existing know-how among co-investors.

For each investor, I calculate the sum of MW capacity in the set of reachable parks. This enables me to calculate each investor's *reachable MW out of the total new MW financed in the previous phase* as the proxy for know-how exposure (equation 1). Investors who have either directly financed more capacity or co-invested with other investors who have done so in the previous phase will thereby get a higher reachable share of the total new MW, which is the know-how base for the subsequent phase. We can thereby identify which investors have likely obtained investment know-how from the previous phase, which can be used to invest more efficiently in the following phase.

$$Knowhow\ exposure_{t_{end}} = \frac{\sum_{t_{start}}^{t_{end}} MW_D + MW_{indirect.1} + MW_{indirect.2} + \dots MW_{indirect.n}}{\sum MW_t} \quad (1)$$

Where:

MW = New MW capacity financed.

t = each of the first four phases (see above). *Start* and *end* indicate the first and final years of the phase.

D = direct investments in new MW by investor.

$indirect.1$ = previous investments in new MW by co-investors.

$indirect.2$ = previous investments in new MW by co-investors' co-investors.

$indirect.n$ = previous investments in new MW by the investors most distantly within reach.

Considering the forward reachable sets, each investor's know-how can be shared with its investment partners during the project planning and due diligence phases and later diffuse wider with the investment partners' ensuing co-investments with third parties. The forward reachable set can thereby indicate which investors have had the largest potential for influencing other investors' investment know-how through co-investments. I, therefore, calculate the second indicator for know-how diffusion as *the reachable share of active investors in the subsequent phase*. An investor who co-invests more and together with other co-investing investors will grow a larger forward reach and potential for know-how diffusion.

$$Knowhow\ diffusion\ potential_t = \frac{\sum_{t_{start}}^{t_{end}} INV_D + INV_{indirect.1} + \dots INV_{indirect.n}}{\sum INV_t} \quad (2)$$

Where:

INV = Active investors in offshore wind

t = each of the latter four phases. *Start* and *end* indicate the first and final years of the phase.

D = direct co-investment partners.

$indirect.1$ = investors indirectly reachable via direct co-investment partners.

$indirect.n$ = the investors most distantly within reach through co-investment network.



Together, these two measures provide indicators for how much investment know-how each investor may have absorbed and how far that know-how may be diffused through co-investments, measured at the four points in time between the five phases.

4.4.3. *Method 3: Qualitative sources*

The presentation of the network methodologies has highlighted the strengths of combining both specific information about particular actors and events and general insights about the structure of the wider social context. The network methods can still be too ‘meso’ to provide a valid account of what is occurring within the network and driving the changes. From a causality perspective, it is an advantage to have temporal data, but it needs to rest on a solid micro-foundation about the activities in the network. Therefore, the dissertation uses a mixed methods approach in the analyses in chapters 6 and 7. The qualitative data is sourced from reports, academic research, news media, and interviews.

I conducted two exploratory expert interviews (Döringer, 2021; Menz, 2003) with two persons with intimate experience from the history of OSW investment (more below). Preliminary SNA disclosed that the investor network consists of two interrelated sub-systems. There is a core based on bank financing of smaller investors through project financing, refinancing, and acquisition of existing projects. Other financials, including SIBs and institutional investors, are also present here. Around this financial core, there are a number of loosely connected utility companies who finance their investments on their own balance sheets, i.e. from retained earnings, asset sales, and equity and bond issuance. Furthermore, institutional investors and capital funds acquired stakes in projects from both the balance sheet and project finance investors. I was therefore looking for experts with experience from each of these two sub-strands of OSW investment.

Both interviews were transcribed and coded based on the focus points in the two main analyses, including how project financing occurs, what information is shared among investors during financial negotiations, details regarding historical events, and the role of Ørsted, banks, SIBs, and oil companies. These insights contributed as background information for the development of

the narrative (cited as interview 1 and 2) and selected quotes were inserted in the analyses and discussions.

4.5. Data

4.5.1. Data sources

4.5.1.1. Investment data

This dissertation combines three sources of OSW investment information into a comprehensive database that covers the entire period of investment from the first offshore wind farm, Vindeby, in operation from 1991 in Denmark, up to and including all investments in 2021. Data for the period 2004-2017 are based on the Bloomberg New Energy Finance (BNEF) database and data for 2018-2021 were sourced from the IJGlobal database. The IJGlobal database has also been used to crosscheck if any projects were missing in the BNEF database. I manually collected the investment information for the period before 2004 through various publicly available online sources by cross-checking a number of lists of the earliest projects and then searching for investment information.

Table 0.5 and Table 0.6 in Appendix K: Database descriptions describe the content of the resulting database (after data handling). It contains 1,815 ties between investors and projects, out of which 54% are participations in the construction of new parks. The remaining ties are nearly evenly split between acquisitions and refinancing. There are 904 nodes in total, divided between 423 investors and 481 investment deals. Some 46% of the deals were primary financing of new projects, which accounted for 68% of total investment volumes. The same park can give rise to more than one deal if it gets refinanced or acquired in the pre-development phase or after commissioning. Some 28% of the investors are state-owned, yet they have invested 42% of total investments (for any financing type). Similarly, energy and utility companies make up 28% of the investor group and have invested 41% of the capital.

The BNEF and IJGlobal databases are both proprietary, owned by Bloomberg and IJGlobal. Consequently, the data can only be shared with the consent of the owners. This study has permission to use the data through its involvement in the MOBICA Project at the UCL Institute for Innovation and Public Purpose. To avoid using data in a way that would disclose the databases to the public, the nominal investment values of investors are not listed in the dissertation. Instead, the information is used to size nodes in SNA according to their relative investment values (section 6.2 and 7.4).

Another reason for using the investment data to signal proportionality among investors and projects rather than analysing the specific values is the fact that the values must be interpreted with caution. BNEF and IJGlobal algorithmically estimate project values when it is not publicly disclosed based on the disclosed information of similar projects. This is a non-transparent process, but provides the best available estimates. The less reliable part is that in the BNEF database, the individual investor shares and values in the total deal values are often missing. For equity investments, 20% of the entries have no disclosed investor share. For debt investments, the share is 73%. However, it is known that banks commonly provide debt on the same terms ('tickets') (Guillet, 2021).

Another limitation is that lenders are underrepresented as BNEF ascribes the entire investment to the equity investors if no debt providers are publicly disclosed (Mazzucato and Semieniuk, 2018). A related issue is that it is not possible to observe where the funds for RE projects financed directly on a developer's balance sheet (i.e. corporate finance, often by utilities) came from. The funds could come from retained earnings, assets sales, or issuance of bonds or equity. On the other hand, the possible external sources of finance do not take construction risk directly, as they have recourse to the entire balance sheet of the corporation and are hence not as decisive for the deployment of technologies. Moreover, bond finance is generally ill-suited for taking construction risk in OSW since it is a one-off interaction, while construction projects require ongoing interactions among developers and debt providers (Guillet, 2022).



4.5.1.1. *Qualitative data sources*

I combine the SNA results with qualitative accounts and descriptions of events, which in turn develops the SNA interpretation further. Preliminary SNA is used to identify crucial events and actors, which are studied in further detail based on company and project descriptions on industry websites, such as power-technology.com and 4COffshore.com, news articles, reports by government agencies, policy organisations, industry organisations, and large investors (Backwell, 2018; Danish Energy Agency, 2017; EWEA, 2013; Green Giraffe, 2019; Guillet, 2022, 2021; IEA, 2019; Jennings et al., 2020; Ørsted, 2019; WindEurope, 2017), and academic research on offshore wind innovation and deployment (Ćetković et al., 2017; Geddes et al., 2018; Jacobsson and Karltorp, 2013; Karltorp, 2016; Kern et al., 2014b, 2015; Mercure et al., 2021b; Reichardt et al., 2016; Reichardt and Rogge, 2016; Wieczorek et al., 2013).

The first interviewee (cited as interview 1) was Christian Skakkebæk, who has exceptional experience with OSW investment from the utility sector as Senior Vice President in DONG Energy (later Ørsted) and the infrastructure fund manager Copenhagen Infrastructure Partners (CIP) that develops energy infrastructure with funding from institutional investors. From 2001-2010 he was Senior Vice President in DONG Energy with responsibility for Corporate Affairs (Legal and Procurement) and in 2011-2012 Country Manager for the UK and Head of Asset Management. As chapter 6 shows, DONG Energy/Ørsted¹³ has been a pioneer and persistent top investor in OSW, why Skakkebæk can provide unique historical insights about how this leading position was established. Since 2012 he has been founding Senior Partner in CIP together with a group of executives from DONG Energy who used their investment know-how to establish energy infrastructure funds with funding from institutional investors to develop OSW projects (and other energy infrastructure).

The same group had pioneered the inclusion of pension funds in DONG Energy's OSW projects, which has otherwise been identified as a barrier to investment (Ameli et al., 2019). Skakkebæk thus offered valuable insights on the general history of OSW, the operations of one of the crucial actors in the network, and first-hand experience with the later tendencies towards a more

¹³ Including the utilities that were merged into DONG Energy in 2005.



financialised model for OSW investment. I have previously interviewed Skakkebæk for a case study of the company's strategic reorientation towards OSW (Voldsgaard and Rüdiger, 2021), which meant this second interview benefited from a spirit of continuing a fruitful conversation. The interview was based on a semi-structured scheme (Appendix C) where Skakkebæk received the main questions beforehand. It lasted one hour.

The other interviewee (cited as interview 2) was Jérôme Guillet. Guillet has been a pioneer in the other section of OSW investment, i.e. project financing between banks and smaller developers. From 2002-2010 he was Head of Energy and Structured Finance at the Franco-Belgian bank Dexia. Together with a team at Rabobank, Guillet provided and organised finance for the first instances of project finance for OSW in 2006, 2007 and 2009 and hence turned OSW 'bankable'. From 2010 to 2021 he was director of the newly established OSW financial advisor Green Giraffe (2019, 23), who advised on nine of the 17 parks that were project financed from 2009-2015. They advised on five deals in the following three years. Guillet, therefore, offered the two benefits of having been an early entrepreneur of bank finance in OSW and later advised on a large share of the bank-financed projects, thus obtaining rare, centralised experience with the changing financial conditions for OSW. Before the interview, I had a chance to read his recent report on the history of OSW finance (Guillet, 2022), which enabled me to ask more in-depth questions of relevance to my dissertation and address less explored topics, such as the role of SIBs. The interview followed the same semi-structured scheme (Appendix C) and lasted for approximately 2.5 hours.

4.5.2. Data collection and handling

Compared to more sociological uses of SNA, this study benefits from analysing objective organisational and/or contractual social relations (Cronin, 2016, 241). Still, there is a challenge with the disclosure of business-sensitive information that can include participation and investment values. The one limitation I could improve through imputation was the missing distribution of the total deal values among the disclosed participants. Following Mazzucato and Semieniuk (2018), I imputed the missing individual investor data based on the weighted (by investment values) average of debt-to-equity shares in the deals where data were disclosed, which



was 0.75. The debt-to-equity ratio has increased over time, which is why the sizes may slightly overestimate the sizes of debt investors in the earlier phases and likewise underestimate them in the later phases (Guillet, 2021; Figure 5.6). The imputed debt and equity totals were distributed equally among the listed debt and equity financiers. This will underestimate investors that are prone to invest more than their co-debt or co-equity providers. I consider that this underreporting is strongest for SIBs who tend to provide larger sums than banks in project financing.

Another issue was that several investor's organisation types were wrongly categorised. The common issues were that public banks were categorised as private banks (e.g. German state-owned Landesbanken and Sparkassen banks and the Korean Development Bank), Chinese SOEs were listed as private, and cooperative pension funds were listed as private. Regarding the projects, many projects in the BNEF database were separated into sub-deals by way of their titles (e.g. a unique deal name for each investor acquiring a stake in a project). This meant the projects had to be consolidated by adding identical titles, so the network would reflect the connections between investors via the projects they acquired together.

For the manually collected database from 1989-2003, the time of final investment decisions was rarely disclosed. The historically important Rødsand 1 park took 1.5 years to construct (June'02 – Dec'03). I, therefore, coded the investment decision to occur two years before commissioning.

4.6. Summary

This dissertation aims to examine how a capable investor community around OSW deployment has evolved and the implications for theorising sustainability transitions and governing financial systems. The methodology uses an exploratory approach to theory development through a within-case study of OSW investment. The theoretical lens of complexity theory contains ontological and epistemological implications for how to approach the research question, including the use of methods that can analyse how heterogeneous actors interact in networks. Therefore, visual and statistical network analytical methods are used in a mix with qualitative methods that can provide a sound micro-foundation for interpreting the network's evolution.

PART 2: ANALYSIS

Chapter 5

The sectoral trends in offshore wind investment

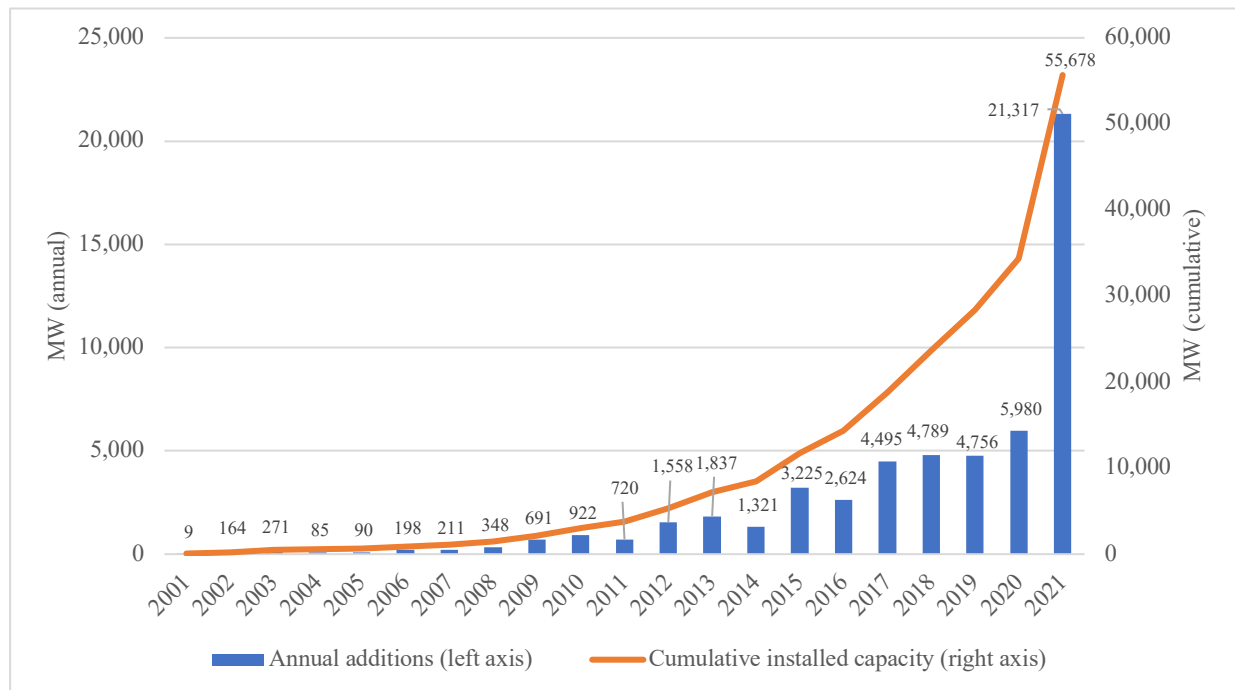
In this chapter, I analyse the central trends in OSW investment and costs between 1989 and 2021 and provide a brief introduction to the risks in the sector. The sectoral trends are aggregate outcomes that were directly or indirectly affected by investment decisions in the investor community. In the complexity framework, these outcomes can be interpreted as emergent properties of the micro- and meso-level dynamics among the investors. The chapter thereby provides partial answers towards RQ2: *How has offshore wind investment co-evolved with the technology over time, and how have these changes shaped the political economy of climate change?* Chapter 6 complements the aggregate perspective with micro- and meso-level analysis.

5.1. Deployment of generation capacity

Figure 5.1 displays the annual additions and cumulative global capacity of OSW installations. The cumulative 55.7 GW installed capacity in 2021 has ratcheted up in periodic step changes with some cyclicity at each level. From the 76 MW of various demonstration parks installed before 2002, the annual deployment between 2002-2008 ranged from 85-348 MW. From 2009-2011 new deployment ranged 691-922MW, and from 2012-2016 the span was 1,321-3,225 MW. From 2017-2020 between 4,495-5,980MW was deployed, while 2021 was remarkably elevated by a dash in China for completing farms before a generous subsidy scheme expired. Therefore, the 21 GW added in 2021 is not a new regular deployment rate, as evidenced by the 17 GW being under construction at the end of 2021, which will be completed in different years. By the end of 2021, there were 215 offshore wind farms in operation, of which 110 were located in Europe,

103 in Asia, and 2 in the US. Around 40% of the capacity in operation was installed in China (WFOW, 2022).

Figure 5.1: Annual additions of offshore wind capacity and cumulative growth (2001-2021)



Source: IRENA (2022). **Note:** There were 76 MW installed by 2001, including the year's 9 MW addition.

In Figure 5.1, we can see OSW has been a slowly developing technology with a weak exponential trend. Electricity generated from OSW in 2018 was only 22% of IEA's Sustainable Development Scenario's production in 2025 and 11% of the target in 2030. IEA, therefore, finds that annual deployment should quadruple by 2030 (IEA, 2019). Since the Sustainable Development Scenario is not aligned with the Paris Agreement, deployment should arguably be increased further (IEA, 2021a). In this context, China's sizeable addition in 2021 was welcome but unlikely to be a new trend. BNEF (2022) forecasts annual MW additions will fall to 13.4 GW in 2022 and steadily increase to 25 GW annually from 2025, which would sum to a 10-fold increase in cumulative capacity to approx. 500GW in 2035.

The changing geography of OSW deployment is depicted in Figure 5.2. At the turn of the century, Denmark was the dominant site for offshore wind, with 76% of installed capacity, with the rest split between Sweden and the UK. Denmark's expansion with the first two large demonstration parks, Horns Rev 1 and Nysted 1 (each ca. 165 MW), in the early 2000s, further entrenched Denmark's leading position and initiated the wider commercial adoption of OSW (Dedecca et al., 2016).

5.1.1. UK's protective space for large-scale OSW

The UK has become a leader in OSW deployment by taking advantage of its geography containing one-third of Europe's OSW potential. The Renewables Obligation (RO) scheme incentivized renewable energy production from 2001 by rewarding generators with one RO certificate per MWh, which retail power providers were required to submit in proportion to their sales to the public regulator, thereby subsidizing renewable energy (Kern et al., 2014b). Despite initial perceptions of the UK as a renewables "laggard," a series of policy initiatives eventually created a "protective space" for OSW (ibid.). The UK overtook Denmark's lead in installed capacity in 2008 (Figure 5.2). The Dutch, Belgian, German, and Irish governments also created niche markets for OSW in the mid-2000s, but the UK became the dominant growth market (Fagerberg and Normann, 2022; Kern et al., 2015). The UK's share of cumulative deployment peaked at 56% of all installed OSW by 2012.

The capital cost of OSW increased from £1.5m/MW to over £3.0M between 2004 and 2009. The rising costs of materials and labour and the falling exchange rate for sterling were main reasons, but costs were also elevated because of more difficult deployment conditions and limited competition while the sector industrialised (Greenacre et al., 2010). It was predicted that the cost of electricity from OSW would decrease by 20% from 2010 to 2025, from £145/MWh to £115/MWh, and potentially even to £95/MWh in an optimistic scenario (ibid., xii). In 2012, the government's Offshore Wind Cost Reduction Task Force set a £100/MWh target for 2020. Nonetheless, the 2019 CfD auction saw the lowest bid at £39.65/MWh, demonstrating a significant reduction in costs (BEIS, 2019, see also Figure 5.7 below), not least because of the



UK's decision to provide extensive demand- and supply-side support for OSW (Kern et al., 2014b; Mercure et al., 2021b).

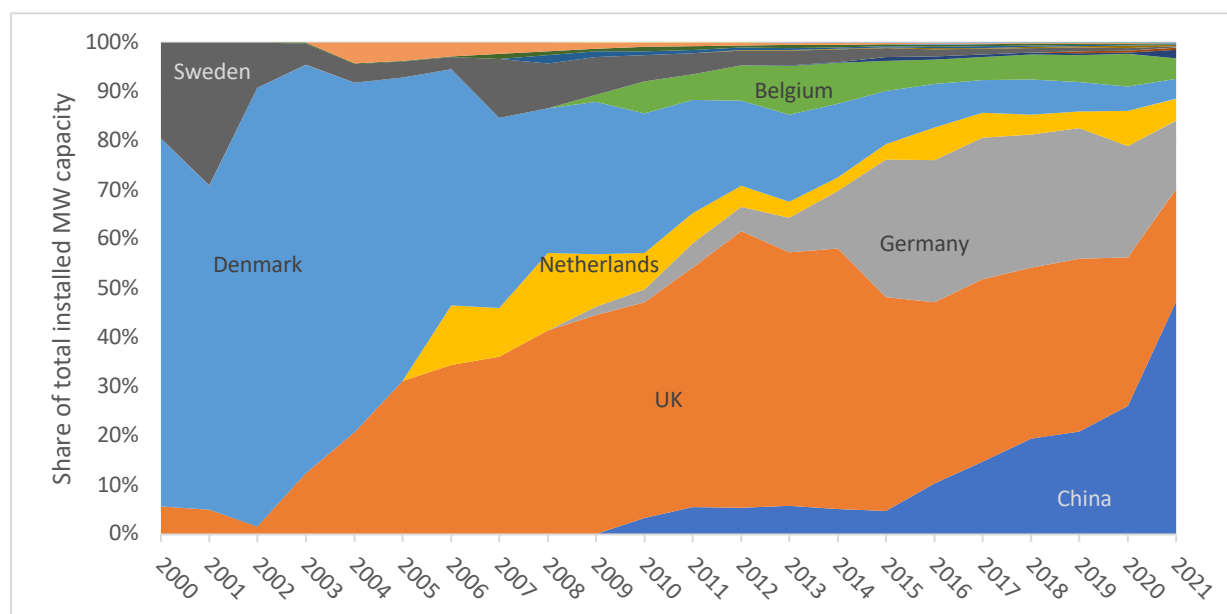
The UK Crown Estate, which owns the seabed, held three leasing rounds for offshore wind between in 2000, 2003 and 2008, respectively allocating 1.1GW, 7.2 GW and 32GW, thereby showing the long-term economic opportunities (Ørsted, 2019). The Crown Estate also participated as a co-investor with £80 million (Kern et al., 2014b). Changes to the RO scheme in 2009 and 2010 doubled the RO certificates received by OSW, but the value of RO certificates remained variable and exposed OSW to market risk, contributing to a higher cost of capital than the fixed-price schemes used on the continent (Higgins and Foley, 2014; Kern et al., 2015).

The uncertainty for investors was alleviated in two ways by the UK's electricity market regulator Ofgem. First, Ofgem effectively stabilised the RO certificate price around £45 by adjusting the obligation on the suppliers and the 'buy-out' price that suppliers could alternatively pay to fulfil their obligations (Toke et al., 2008; Jennings et al., 2020, p. 21). When OSW started to receive two RO certificates per MWh, generators typically earned around £140 - £150 (ibid.).

Secondly, Ofgem established a framework for investments in transmission to the grid where the developers could conduct the construction before being obliged to sell off the asset in a competitive tender managed by Ofgem. This provided incentives for cost efficient construction and lowered the risk of delays (Kern et al., 2014b). In addition, this model secured a low cost of capital for the long-term ownership of the assets (Mercure et al., 2021b).

Ofgem had historically been emphasising the market-oriented aspects of electricity market design so, according to one government minister, they "had to get OFGEM to stop being pedantically market driven" (quoted in Toke, 2011, p. 528). The resulting changes contributed towards making the UK the country with best conditions for OSW investment around 2010 according to KPMG, E&Y, and one academic study (Prässler and Schaechtele, 2012).

Figure 5.2: The changing geography of the cumulative stock of offshore wind capacity



Source: IRENA (2022)

The UK introduced the Electricity Market Reform in 2013 to increase competition and reduce the cost of capital for offshore wind projects (Grubb and Newbery, 2018). This was achieved through contracts for difference (CfDs), which offered fixed-price remuneration for 15 years through auctions, forcing developers to compete on cost while providing price certainty. Contrary to governmental expectations of a 0.4%-point WACC improvement, Newbery (2016) found that CfDs reduced the WACC by 3% for onshore wind, saving £75 billion on investment support up to 2020. Previous studies have also shown that long-term stability and credibility, rather than generosity, attract external finance for renewable energy investments (Breitschopf and Alexander-Haw, 2022; Criscuolo and Menon, 2015; Dukan and Kitzing, 2021). The UK has prioritized maintaining the finance-friendly CfD scheme over exposing projects to electricity market risks through auction designs, unlike continental European countries (Fitch-Roy, 2016; Jansen et al., 2022).

Thirdly, the UK implemented industrial policy initiatives to co-finance RD&D projects among developers, academic institutions, and industry research organizations. Up until 2007, “learning by interacting between British knowledge institutes and project operators occurred only



occasionally”, although it had been “crucial to the success of the Danish wind industry” (Smit et al., 2007, p. 6438-6439).

The UK Government spent £450 million between 2008-2015 on funding schemes for offshore wind RD&D (see Appendix H: UK offshore wind industrial funding schemes), such as the Carbon Trust’s Offshore Wind Accelerator, to solve the technical difficulties of the UK market’s harsh maritime environment and locations at greater sea depth (Jennings et al., 2020; Kern et al., 2014b, p. 641; Madsen, 2014; Prässler and Schaechtele, 2012). The Carbon Trust’s more than 150 projects included developer-led and co-funded research in cables, electrical systems, foundations, logistics, operations and maintenance, and yield and performance. The research partnership attracted major developers such as the companies now known as SSE, RWE, Ørsted, ScottishPower Renewables, E.ON, EnBW, Vattenfall, Equinor, and, more recently, the oil majors Shell and Total Energies. The initiative has so far resulted in an estimated 15% cost reduction on offshore wind (Carbon Trust, 2018).

Lastly, the UK Government also launched a Green Investment Bank (GIB) in 2012. However, as will be discussed in chapters 6, 7, and 9, the GIB largely failed to make a catalytic impact on OSW deployment by focusing too much on acquisitions of existing assets (Geddes et al., 2018).

5.1.2. Diversified deployment

In the wider policy context, EU negotiations led to the 2009 Renewable Energy Directive with a binding 20% renewable energy target for 2020, allocated across member states who had to develop national plans. This provided the anticipatory demand necessary to invest in complex supply chains that could deliver “a new generation of blades, towers, nacelles, substations and the foundations needed to support them” (Ørsted, 2019, 12). The UK’s target of 15% of final energy consumption from RE encouraged the government to double RO certificate allocation to less mature technologies, incl. OSW (Mercure et al., 2021b).

In the aftermath of the great financial crisis, Germany gradually became the most expanding market, reaching 29% of total cumulative deployment in 2016, once the *Energiewende* policy programme became adjusted to also encourage offshore wind (Kostka and Anzinger, 2016;



Rechsteiner, 2021; Reichardt et al., 2016). The German expansion occurred alongside continued expansions in the UK, Netherlands, Denmark, and Belgium – and now also China, which possessed 10% of global capacity in 2016. After the Paris Agreement in 2015, OSW deployment increased markedly, since only 21% of the total capacity in 2021 was installed by 2015.

This post-Paris Agreement period from 2016 onwards saw a more diversified deployment pattern, with large additions in the UK, Germany, Netherlands, and China. Following China's large addition in 2021, 47% of the total capacity was installed in China. UK hosted 23%, Germany 14%, and approx. 4% in each of the Netherlands, Denmark, and Belgium. The last few years were also characterised by new markets opening in Vietnam, Taiwan, South Korea, Japan, France, and the US.

Economic geography shapes the feedback between politics and technology development (Schmidt and Sewerin, 2017). For offshore wind, the deployment pattern has generally been shaped by the geography of shallow waters and strong winds in Northern Europe and existing industrial bases around onshore wind (MacKinnon et al., 2019). These factors have contributed to determining where demand-side policies that subsidise and/or guarantee the price of electricity generated have been implemented, but the UK also shows that a strong demand pull can come without a strong domestic industrial base for offshore wind (Ćetković et al., 2017). However, it's too simplistic to conclude that deployment is solely driven by geography and demand-side policies since the presence of demand-side policies is also contingent on deployment capabilities that can deliver offshore wind at a tolerable cost to electricity consumers or the public finances.

This cost limitation is exemplified by the “wavering support for offshore wind in the Netherlands“, where the initial support scheme in 2003 with higher subsidies for OSW was cancelled and later replaced with a new scheme in 2007 (again altered in 2010) that benefited cheaper renewables such as onshore wind (Fagerberg and Normann, 2022, 23). Similarly, in 2011 the UK government placed an annual cap on levy-funded spending on low-carbon electricity support until 2020/2021 to prevent a political backlash against renewables support in the context of austerity policies (Jennings et al., 2020, 22; Lockwood, 2016).

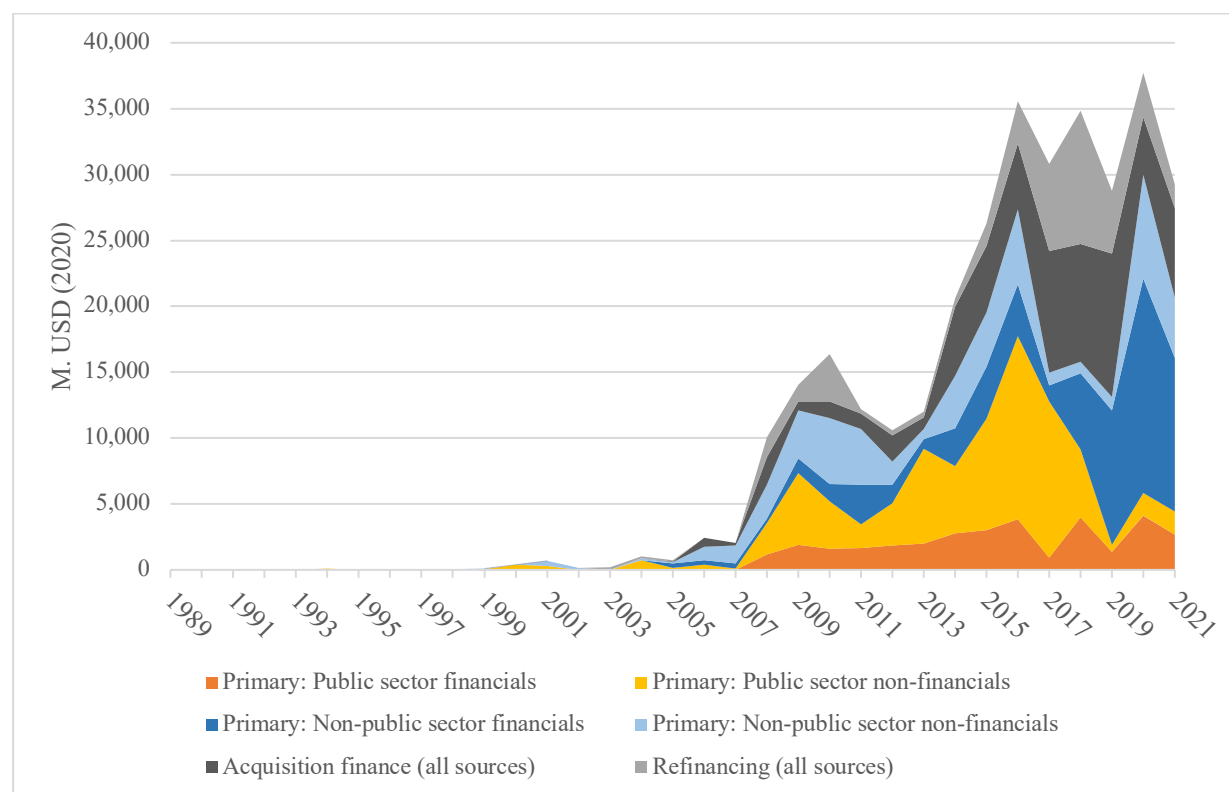


5.2. Investment trends

All the net additions to the installed capacity required financing to move from the planning phase over construction to commissioning and operation. This creates a period of variable length between the ‘financial close’ or ‘final investment decision’, where the financing among the involved actors is agreed upon, and the construction phase is finalised. Figure 5.3 shows how this financing has occurred since the very first OSW park was commissioned in 1991. The graph distinguishes between the three types of financing, primary financing, refinancing, and acquisitions, and separates the primary financing for new projects by industry and broad ownership groups (differentiated by colours).

As for the annual capacity additions, we see a general trend towards larger annual primary investments, but the investments have a stronger cyclical character. We see three notable primary finance peaks in 2009, 2016, and 2020 and a minor early rise in 2000 and 2001 in relation to the first two utility-scale projects (Voldsgaard and Rüdiger, 2021). All three peaks were followed by contractions in financing activity in the following years, most rapidly after 2016.

Figure 5.3: Annual finance for offshore wind by type of finance, sector, and ownership type



Note: There are three types of financing: *Primary financing* of new parks and *refinancing* and *acquisition* of existing parks. Primary finance is grouped by industry and broad ownership groups. The non-grey areas thus sum to the total primary financing. Non-public investors include both privately-owned companies and non-profits such as cooperative banks and member-owned pension funds. Public ownership denotes state or local government ownership (incl. multilateral and supranational development banks).

Source: Bloomberg New Energy Finance, IJGlobal & author's own data collection.

However, between the latter two peaks, there was a large increase in the refinancing and acquisition investments in existing projects. Most financing for refinancing and acquisition was provided by private financials (Appendix D: Figure 0.5 and Figure 0.6). Refinancing activity expanded from 2016, possibly caused by a combination of the expiry of debt issued in the investment surge around the GFC and to take advantage of the falling cost of debt (IEA, 2019). The expansion of acquisitions from 2017 suggested a rapid change in attitude among financial investors towards the attractiveness of owning OSW assets.

Considering the changing composition of primary financing, the majority source of investments alternated through the cycles between public and private non-financial companies that were



mostly utility companies. From the bottom of the investment cycle in 2012, public non-financials were the main driver behind the investment upturn towards 2016. Non-public (i.e. private and civic) non-financials again became more central in 2020 and 2021 following five years of low investment activity, however, this was more driven by oil companies than utility companies.

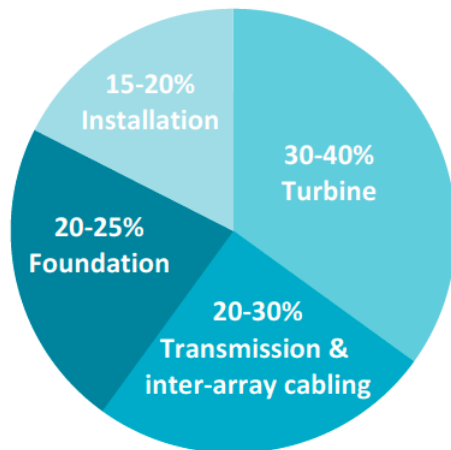
Non-public financials entered the market in the 2000s but first had a quantitative impact between 2009-2012. This group maintained a steady but small presence until 2017, after when they rapidly financed a majority of investments. In 2020 and 2021, they provided approx. 55% of primary financing, and even 78% in 2019, where the total was lower. From a complexity perspective, this sudden change resembles a phase shift where the object changes character in a non-linear fashion. Lastly, public financial institutions have provided a steady level of financing since 2008, although with larger co-movement with the investment cycles than the non-public financials.

5.3. Cost trends

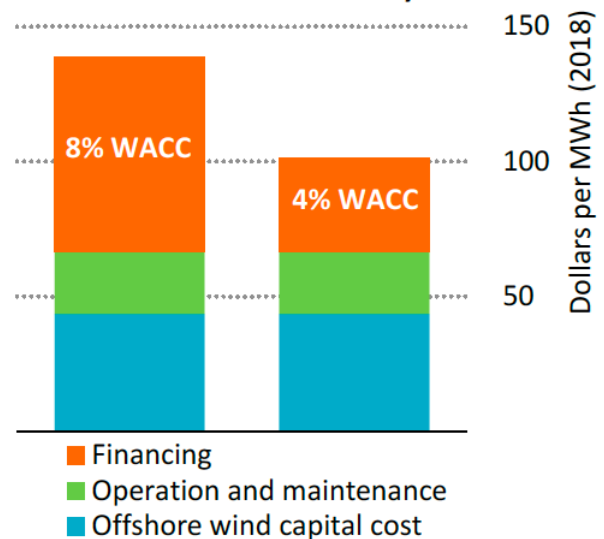
In this section, I present the cost profile and historical cost trajectory of OSW. Figure 5.4.B shows how the cost of electricity from offshore wind stems from three sources: the *capital cost* (also known as *total installed cost*), covering equipment and installation (panel A), the *cost of operation and maintenance* of completed farms, and the *cost of financing* the capital cost (also known as the *cost of capital*). The capital cost is dominated by the cost of turbines (30-40%), half the cost is divided between foundations and transmission and cabling, and the remaining 15-20% is made up of installation cost. Panel B shows how the weighted cost of capital (WACC) can possibly be the source of 30%-50% of the cost of producing electricity. This underlines the importance of understanding how the cost of capital can be reduced for sustainable technologies like OSW (Schmidt, 2014).

Figure 5.4: Cost profile of offshore wind

A. Indicative shares of capital cost by component



B. Levelised cost of electricity



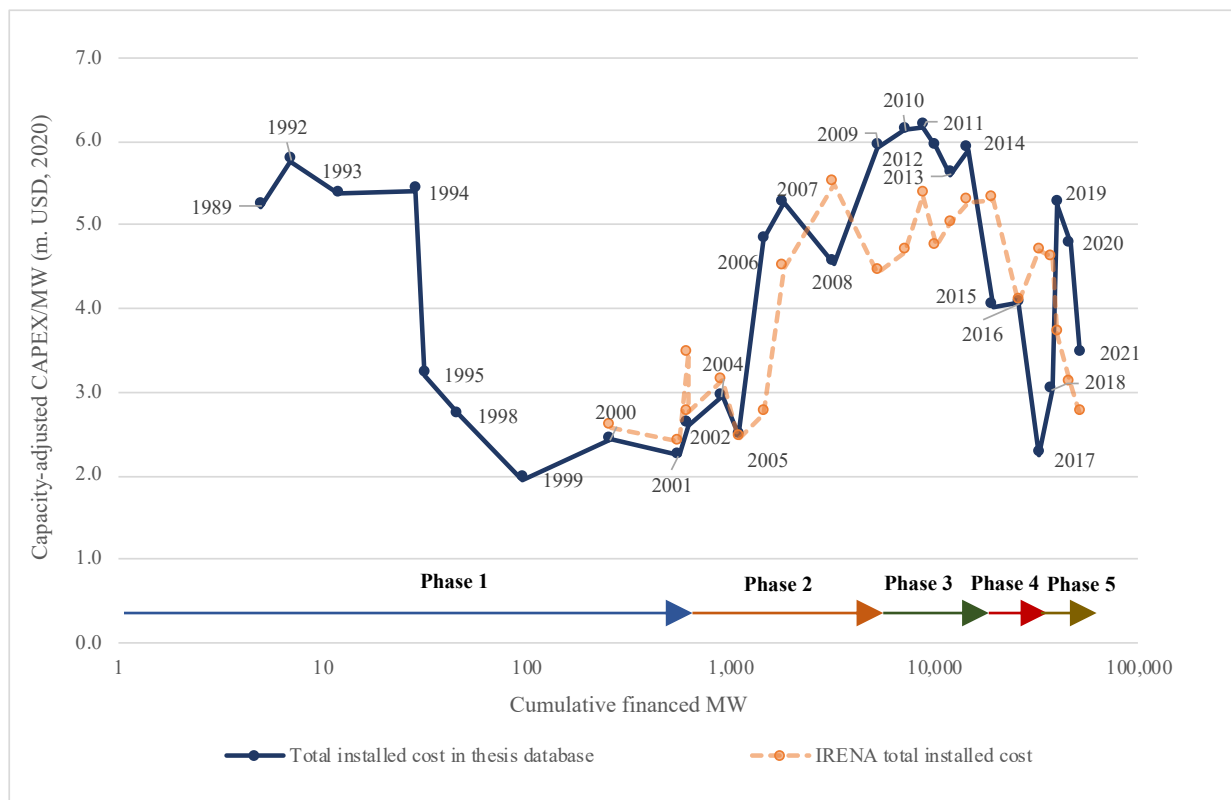
Source: IEA (2019, 24). **Note:** WACC = weighted average cost of capital.

5.3.1. Technological cost trends

Let us turn to the historical development in the total installed cost per MW capacity, which reflects the technological progress and exogenous cost impacts from materials, labour, and currency fluctuations (Junginger et al., 2020). While technologies often follow smooth downward-trending learning curves (Grubb et al., 2021a; Way et al., 2022), Figure 5.5 shows that OSW has faced considerable challenges along the way toward price competitiveness by plotting the cost/MW by cumulative financed capacity. The chart shows both the cost trend based on my compiled database and IRENA's (2022) cost database, which show the same tendency. IRENA's costs are measured by the year of commissioning, while my database measures at the time of the final investment decision, which explains the lag between the curves. We can identify two cycles of learning that contributed to my demarcation of the five phases of OSW investment. The first occurred through the 1990s as the concepts behind the demonstration parks were improved and more powerful turbines were developed. From the early 2000s, costs rose markedly to a first peak in 2007 and even higher in 2011. This was a period of 'fundamental innovations'

incl. foundation types and adjustments to improve the durability of turbines at sea (Jennings et al., 2020, 10).

Figure 5.5: The two offshore wind learning cycles



Note: The X-axis is log scaled. CAPEX = Capital expenditure on the construction of the project. The capacity adjustment weighs the cost per MW by the size (MW) of each project, so the cost of larger projects influences the cost estimate more. The IRENA cost databases measure the capacity-adjusted cost per MW based on the year of commissioning, which explains some of the discrepancy between the curves. There is a general time lag based on construction time and variations because of projects with construction duration diverging from the average.

Source: The combined investment database behind this study (manual collection, BNEF, and IJGlobal) and IRENA (2022b, 108).

This increase occurred based on a variety of factors, including greater challenges installing OSW further ashore and at greater sea depths, which raised demands for equipment durability and the design of foundations and transmission cables, and rising materials cost (IRENA, 2022, 104; van der Zwaan et al., 2012; Voormolen et al., 2016). For these reasons, learning processes were still ongoing, but overwhelmed by the difficulties and exogenous cost pressures. Voormolen et al.



(2016) also note that costs were elevated because of the limited competition in the turbine market that was dominated by Siemens. My previous research has shown that DONG Energy (later Ørsted) had the industry's first bulk supply agreement with Siemens, which gave DONG Energy certainty of supply to strategically pursue OSW investments and Siemens the order book necessary to industrialise its production (Voldsgaard and Rüdiger, 2021). This arrangement, which to some extent cornered the market, likely contributed to the elevated turbine prices.

After a prolonged period of high costs, there was a rapid decline between 2014 to 2017. The total installed cost rapidly fell because of a mix of technology improvements and maturing supply chains (IRENA 2022, 101). From 2012 onwards, a dedicated offshore wind industry emerged with more experienced developers and a more robust supply chain that consolidated into fewer companies (interview 2). This led to fewer delays and cost overruns. Some of the innovations that delivered lower costs were larger turbines (3.6MW-8MW), longer blades, less steel-intensive foundations, digitised remote operations and maintenance (Ørsted, 2019). Jennings et al. (2020) find that 24.5% of cost reductions stemmed from better installation processes, 36.5% from foundations and cables, and 35.5% from turbine innovation.

One major policy-based reason was the trend towards tenders for price support granted to the lowest bidders increased competition and efforts to reduce costs, and the revenue certainty also reduced the cost of capital (Jansen et al., 2022; Jennings et al., 2020; Mercure et al., 2021b). However, this also reoriented the industry away from 'fundamental innovations' and towards incremental innovations (Jennings et al., 2020; Backwell, 2018, 114). In the most recent years, the two cost databases have diverged.¹⁴ The dissertation database is mostly elevated in 2019-2021 because of projects in the new markets in Taiwan and France.

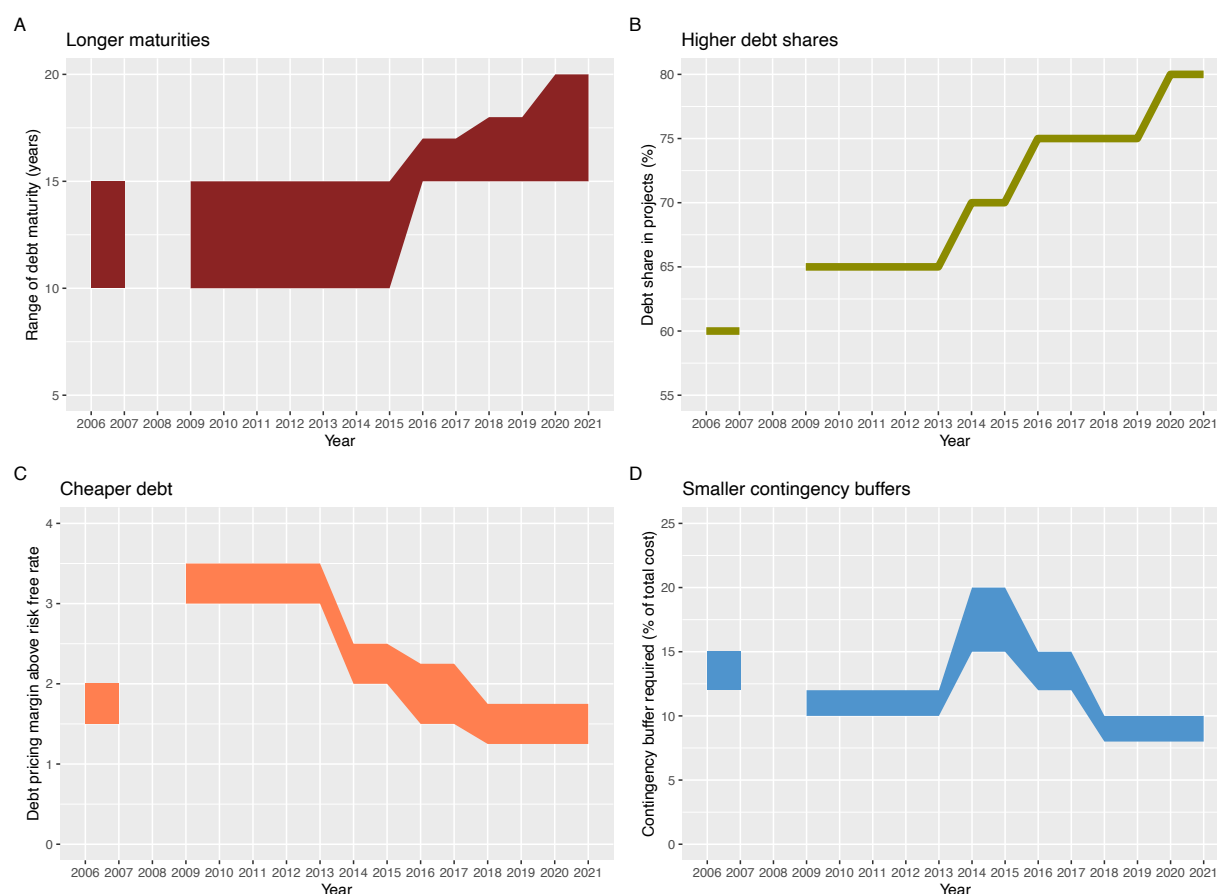
5.3.2. *Financial cost trends*

As indicated above, the cost of capital is a crucial determinant of the cost of electricity for OSW. Figure 5.6 shows the conditions for raising debt in project finance entities, often used by smaller

¹⁴ One reason is the construction lag, but 2019 should be expectedly be closer. IRENA's estimate for 2019 was also markedly higher in previous editions of their database.

developers (Guillet, 2021). We see that project financing was established in 2006 and 2007 with a relatively small price margin of 1.5%-2% above the risk-free rate set by monetary policy, although lenders would only finance 60% of construction costs, repaid over 10-15 years, and with relatively high contingency buffers imposed on the project.

Figure 5.6: Easing financial conditions for using debt in project finance



Source: Own illustration based on Guillet (2021). **Note:** There are interruptions in the bands because no project financing occurred in 2008.

No project financing took place in 2008 because the GFC disrupted financial market conditions and some small developers and banks. On the other side, the cost of debt rose with a small easing on debt ratios and contingency budgets. This phase was considered as a financial ‘valley of death’ because it was unclear if the cost of financing would keep OSW uncompetitive and if the

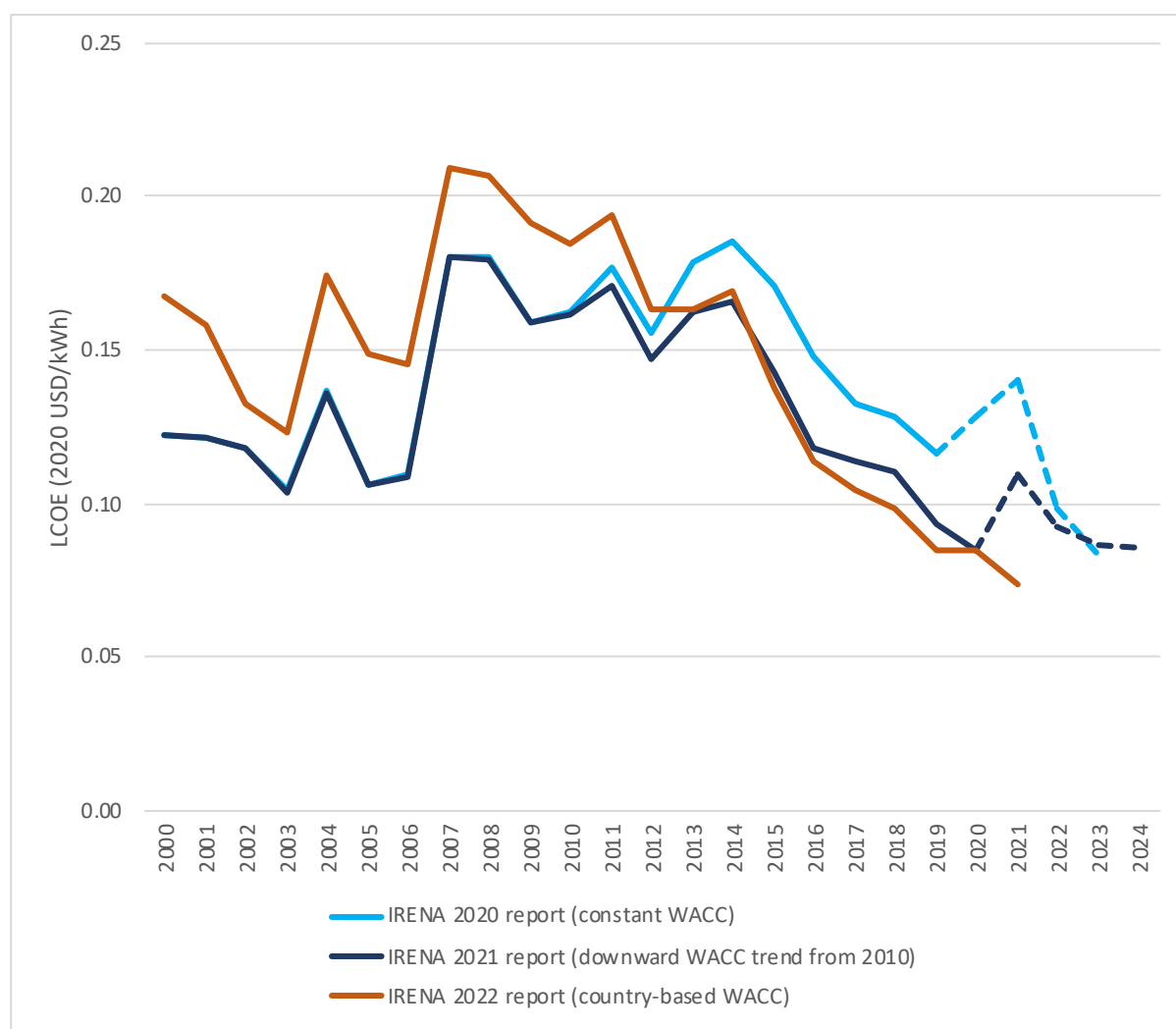
available volumes of capital would suffice for the increasing scales of OSW parks (BNEF, 2010; Karltorp, 2016). The financial cost data in Figure 5.6 is not differentiated by market, but it is noticeable that after the introduction of CfD auctions in the UK in 2013, the conditions for debt financing gradually improved, although contingency buffers became elevated in the mid-2010s. Voormolen et al. (2016) estimated that the UK's policy framework until 2014 resulted in a WACC of 12-13.5%, while the WACC in the Netherlands and Belgium was 2.5-3%-points lower and the WACC in Denmark was 4.5%-points lower. It therefore makes sense, given the size of the UK market, if the introduction of CfDs had a driving influence on the average cost of debt.

On average, the IEA (2019, 41) estimated that the cost of debt fell from above 6% in 2010 to below 3% in 2018, evenly split between lower monetary policy easing and a smaller premium for low-risk projects, while the premium for high-risk projects increased. In addition, from 2015, the cost of raising equity finance for Europe's main developers fell from around 8% to 4%, which contributed to lowering the WACC for OSW¹⁵.

As indicated by Figure 5.4, the cost of capital can have a major impact on the cost of producing electricity with OSW. Until 2020, LCOE estimates by multilateral organisations have generally assumed constant WACC rates, only distinguished by using a 7.5% WACC for OECD countries and China and 10% in the rest of the world (IRENA, 2020). The light blue line in Figure 5.7 shows how, under this assumption, OSW had become 37% cheaper in 2019 than the highest point in 2014 but not cheaper than in the early 2000s (see also Table 0.1, Appendix A).

¹⁵ This was likely driven by Ørsted's rapidly rising stock price, following a partial privatization by the Danish government. In practice, investors often use organization-specific hurdle rates to make investments decisions rather than their cost of issuing equity (Helms et al., 2020).

Figure 5.7: Large impact on the cost of electricity from offshore wind by different cost of capital assumptions



Note: Dashed lines are projected years. There were no projected years in the 2022 report. WACC: weighted average cost of capital. In the 2020 report and previous iterations, IRENA assumed a 7.5% WACC in OECD countries and China, and 10% in the rest of the world. The 2021 report inserted a downtrend by assuming a WACC of 7.5% in 2010 for the OECD and China, declining to 5% in 2020, and for the rest of the world a WACC of 10% 2010, falling to 7.5% in 2020. The 2022 report adjusts the LCOE measure according to the estimated WACC for 100 different countries across the entire period (IRENA, 2022, 183).

Source: IRENA (2022, 2021, 2020).

In 2021, IRENA (2021) assumed a falling cost of capital from 2010, which turned 2007 into the most expensive year and resulted in a 48% cost reduction in 2019 (53% in 2020). In 2022



(IRENA, 2022, 183), the methodology was refined to account for country differences through time in terms of domestic market maturity and general financial conditions¹⁶. This made the earliest years 11-40% more expensive, while the estimates after 2015 were lower, which led to a 60% cost reduction in 2019 (65% in 2021). On this basis, around 2/5 of the LCOE cost reduction appears to stem from the falling cost of capital (Table 0.1, Appendix A)¹⁷. This underlines the importance of studying how this falling cost of capital was achieved in the investor community. Regardless of the assumed cost of capital, Figure 5.4 shows how the expansive market created in the UK until 2014 (Figure 5.2) was crucial for allowing the OSW sector to mature technologically and in terms of investment know-how, which set the technology up to experience rapid cost reductions from 2015 onwards.

5.4. Finance and offshore wind's two valleys of death

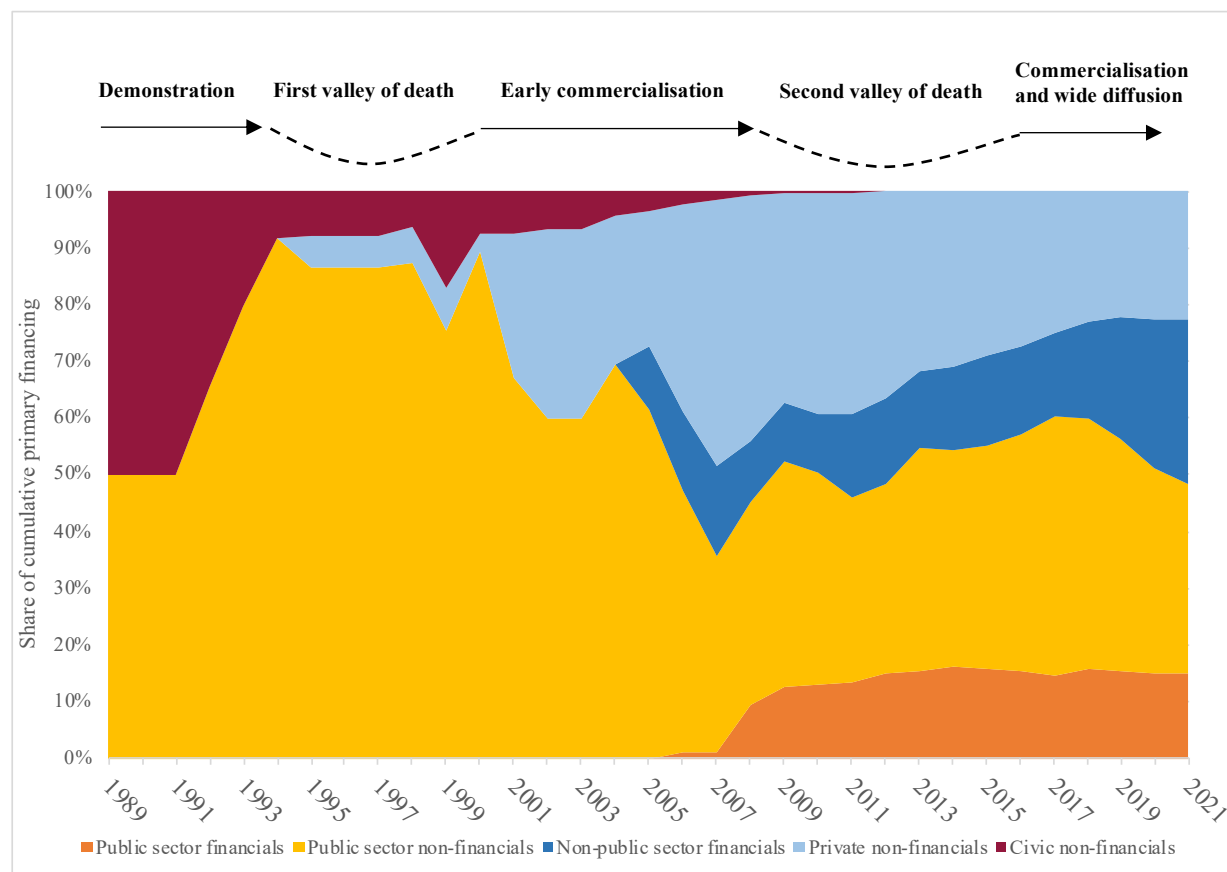
These aggregate trends portray a remarkable story of how a technology has matured from its first demonstrative deployment in 1991 to a cost-competitive technology in 2021. One report finds that to reach net zero emissions in 2050 in a cost-efficient pathway, average annual OSW investments need to rise ten-fold from USD 18bn in 2017-2019 to 177bn during 2021-2050, resulting in a total investment of USD 5.3tn. (IRENA, 2021, 102)¹⁸. In other words, a case of how a niche technology can change the socio-technical regimes shaping our provisioning systems (Geels, 2019). Considering the cost and investment trends, there appear to have been two periods that decisively shaped the trajectory of the sector: the first investments in large parks that were followed by a growth in deployment, private investment, and costs; and the period after the GFC with elevated installed and financial costs. Following BNEF (2010) and Karltorp (2016), we can understand these two phases as the technological and financial valleys of death. Figure 5.8 maps these two phases onto the cumulative primary financing (i.e. the annual data from Figure 5.3) with the non-financial investments grouped by public, private and civic ownership.

¹⁶ Country estimates ranged from 1.5% in Denmark to 7.4% in Vietnam.

¹⁷ Calculated as (37%-60%)/60%

¹⁸ Average annual investments in the net zero scenario in onshore wind is USD 212 bn. and 237bn. in solar PV.

Figure 5.8: Primary finance and the two valleys of death



Source: Dissertation database. **Note:** Own illustration with inspiration from Grubb et al. (2017, 29), Karltorp (2016, 98), and BNEF (2010). ‘Non-public financials’ includes both private and civic financial investors, e.g. coop. banks and pension funds.

Public and civic investors undertook most of the investments in the experimental demonstration period. In 2000 and 2001, the public and private investments in the two first utility-scaled parks moved the industry into a growth phase as the technology was demonstrated to work on a large scale, although one of the parks was perceived as an economic failure because of severe technical issues (Smit et al., 2007; Voldsgaard and Rüdiger, 2021). In the early commercialisation stage, costs rose, but new geographic challenges were faced, and fundamental innovations for offshore deployment were developed. Private financials were also attracted to the market.

Following the GFC, the market expanded based on demand-pull policies (Figure 5.1) but the costs of supporting OSW were becoming politically untenable (Lockwood, 2016). Through most of the financial valley of death, public investors had an increasing share of the investments.



Public financials had approximately the same share of primary financing as non-public financials between 2012-2017. This was the moment of a phase shift in the investor composition, where non-public financiers became dominant. Notably, the private financial companies' attraction to financing first the existing parks with refinancing and acquisitions and, subsequently new construction (Figure 5.3) coincided with a downward trend in installed cost (Figure 5.5). Public investors had thereby invested countercyclically in a double sense: the investments stimulated the crisis-ridden European macro economies, and they countered the elevated costs in the industry, thereby contributing to the eventual fall in installed and financial costs.

5.5. Summary

This chapter has reviewed the main trends over the lifetime of OSW investment, which I interpret as emergent properties of the interactions in the OSW industry. The total installed cost of a MW capacity has been going through two learning cycles before reaching cost competitiveness with fossil fuel sources in recent years. The high CAPEX-OPEX ratio means that OSW has been extraordinarily sensitive to the available cost of capital, which in turn has co-evolved with the maturation of the industry and the changing policy frameworks, not least in the UK. The periods of falling costs attracted new private investors, which contributed to further learning and market expansion, while entrepreneurial state investors stood out as important for bringing OSW across the technological and financial valleys of death.

Several of the risks in OSW, reviewed in Appendix I: Risks in offshore wind investment, turned out to be smaller in OSW than feared, which became apparent when track records were formed, and the performance could more easily be assessed. Generally, OSW developers have been successful at lowering construction and operational risks compared to other energy infrastructure classes, which over time made it “a very attractive asset class, leading to increased competition amongst financial players and thus more attractive terms for both debt and equity” (Guillet, 2022, 7, 59), which contributed to the sharply falling LCOE (Figure 5.7). We thus see the contours of a co-evolution among investors, technologies, business strategies, and institutional market frameworks (Foxon, 2011), which will be examined with emphasis on the investors in the following chapters.

Chapter 6

From cradle to a mainstream asset class: A network analysis of how offshore wind technology matured and became financialised

6.1. Introduction to the historical network analysis

This chapter is dedicated to examining the history of how offshore wind (OSW) developed into a mature renewable energy sector by examining all investments in the entirety of OSW projects from the first park commissioned in 191 until the end of 2021. It addresses RQ2: *How has offshore wind investment co-evolved with the technology over time, and how have these changes shaped the political economy of climate change?* by complementing the aggregate perspective in chapter 5 with analysis of important investment events (micro-level) and network formation (meso-level).

The answer provides three contributions to our understanding of how sustainability transitions occur (Geels et al., 2017). First, the results provide historical insights into how investments in the deployment of OSW technology have matured the technology along its learning curve. Second, the technology case analysis sheds light on the relationship between finance and technological development. Third, the detailed analysis of OSW investment patterns displays some of the financial micro- and meso-level mechanisms that shape the material foundation of the political economy of climate change.

The history of offshore wind energy has often been told as a side story to general wind technology with a focus on turbine producers (Backwell, 2018; Owens, 2019), or the importance of demand-side policies and regulatory actors for bringing down costs over time through deployment (Fagerberg and Normann, 2022; Kern et al., 2014b; Mercure et al., 2021b), or the innovation systems that facilitate the cost reductions in the supply chains (Jacobsson and Karltorp, 2013; Reichardt et al., 2016; Reichardt and Rogge, 2016; Wieczorek et al., 2013). However, Karltorp (2016) provided a valuable contribution to an investor-focused inquiry by analysing the difficulty of mobilising enough cheap finance during OSW's "second valley of death" after the GFC. This



analysis complements these contributions by focusing on the dynamics and interactions in the investor ecosystem, which have led to an increasing pace of deployment and falling cost of capital (chapter 5). The argument is that if there are few capable investors, demand-side policies must be strengthened to stimulate investments and hence become more expensive to consumers and/or the state. Thereby, this perspective contributes towards understanding the financial supply-side of the economy's co-evolution with demand-side policies.

This case analysis is a special opportunity for seeing a complex system of interacting heterogeneous actors evolve over time (Beinhocker, 2007), which has contributed to the emergent property of falling costs of decarbonisation. In addition to these complexity properties, the analysis also offers a clearer understanding of how important entrepreneurial state investors, including SOEs and SIBs, have been to the development of the OSW industry (EWEA, 2013, 19; Geddes et al., 2018; IEA, 2019, 40-41).

6.1.1. The asset foundation of the political economy of climate change

Deciding on ways to approach transitions in energy production and use is inherently a process that depends on and reconfigures power resources in society (Stirling, 2014). By studying the full period of OSW investment, the research provides a new perspective on the creation of assets that cumulatively change the political economy of climate change. Using asset specificity to explain climate change politics is gaining traction among scholars (Colgan et al., 2021). The background is more widespread questioning of whether the most impactful hindrance to ambitious climate policies has been international free-riding concerns, as proposed by public goods reasoning. Instead, political economists suggest the main obstacle is found in distributional politics and the uneven distribution of power resources in favour of fossil-based interests at the national level (Aklin and Mildemberger, 2020). This suggests we should develop a clearer understanding of how particular climate-related assets are created and distributed among actors with political influence. Also, the possession of climate-related economic assets may be a powerful source of political influence because of the resulting financial resources and control over major investment organisations, such as oil companies or large renewable energy



companies, that can either be used for political lobbying and more fossil fuel-based investments or for climate-friendly investments (Christophers, 2022b; Green et al., 2021).

Colgan et al. (2021) propose “a dynamic theory of climate politics based on the present and future revaluation of assets”, arguing that the balance between climate-*harmful* and climate-*vulnerable* assets at the levels of each actor and each sector explains the dynamics of climate politics. According to this dissertation, we should expect politics to change as more actors become negatively exposed to climate change impacts. One example is near-shore real estate which could turn financial institutions towards a more climate-friendly stance in their lobbying efforts.

However, this formulation of the theory leaves out climate-*friendly* assets, which are arguably a more potent source of economic power and concentrated interests that shape politics compared to climate-vulnerable assets, where the future impact on particular assets is subject to strong uncertainties.¹⁹ Conversely, as clean technologies become deployed at scale and a major source of profits in the economy, they provide a clear new basis for forming green ‘winning coalitions’ which can alter political trajectories (Meckling et al., 2015; Pahle et al., 2022). New powerful coalitions with concentrated interests in the transition are politically necessary to overcome the entrenched interests in the oil and gas sector which stand to lose USD 1.4tn in lost profits in a 2 °C scenario based on stated policies (Semieniuk et al., 2022).

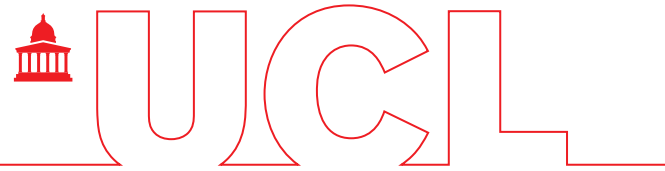
Schmidt and Sewerin (2017, 3) posit that although scholars have achieved a better understanding of policy-induced technological change (e.g. Breetz et al., 2018), “policy-induced technological change as a driver of policy change in other jurisdictions is hardly considered at all.” Therefore, to reflect on how sustainable technological change affects the political economy of climate change, we should study how sustainable assets are created and who holds and owns them. Hitherto, climate change has largely been a “blind spot” in international political economy, despite offering insights regarding the “spatial or scalar qualities of finance” (Paterson, 2020) that are useful for understanding the political economy of asset creation.

¹⁹ Colgan et al. (2021) indeed uses an example of how the car industry may change their political allegiances as they hope to profit from new climate-friendly production assets: “For example, whereas car manufacturers have traditionally resisted climate policies, some companies hoping to profit from the shift to electric vehicles now support policies that they used to resist”.



Braun and Koddenbrock (2022, 17) conceptualise the power of finance as originating in the trio of creation, trading, and enforcement of financial claims. The construction of new OSW parks requires the creation of financial claims on the projects' future revenues. While these creditor and owner claims are a source of power within the industry, they also shape the interests of the involved investors and make up a material resource base, which can be leveraged to affect the political system in alignment with these interests. According to Langley (2021) 'assetisation', i.e. "the contingent processes which turn all manner of things into assets", has become a focal point for understanding the changes in power and economic inequality under contemporary capitalism, although the production of assets remains "an empirical 'blind spot' [because of] an over-emphasis on secondary exchange and speculative trading on prices". Christophers (2020) shows how the UK economy became increasingly structured to produce economic rents to the holders of infrastructure, patents, natural resources, and contracts. Braun (2022) points to the irony of labour-based pension funds contributing the 'assetisation' process despite its negative downstream consequences on workers and consumers.

Although Schumpeter (1983) emphasised the empowering role of finance as modern ephors for entrepreneurs looking to upset the technological status quo, the political economy of finance literature reminds us that this process also produces and reproduces national and international power structures (Strange, 2004). The ephors behind the financing are also powerful political actors, which has implications for decarbonising the economy: "The strategic question is whether immensely powerful actors will enrol in the project of financing de-carbonization strategies and, in political economy terms, tip the balance of power further in favor of those pushing for a low carbon economy" (Newell, 2019, 37). However, "Seeking to engage and enrol finance capital in these ways comes with many limitations and contradictions" including decarbonising with only "modest re-arrangements in modes of regulating and governing technology and social systems (...) but without disrupting dominant distributions of economic and political power" (ibid., 29, 37). Gabor (2021) argues that the world is decarbonising in a 'modest' way according to a *Wall Street Consensus* policy paradigm that socialises the risks and privatises the rewards of the sustainable assets created to the benefit of private financial interests.



The OSW case offers empirical micro- and meso-level insights into how this process of green financial asset creation unfolds, which calls for further studies concerning the causal mechanisms between sustainable asset creation, actor interest formation, sectoral political realignments, and climate politics (Colgan et al., 2021).

6.1.2. Structure and methodology

The chapter proceeds by analysing the financial networks in each of the five phases of OSW investment (see chapter 4 and Table 4.1). Graphical network analysis is used to display the network structures and the relative investment volumes of the active actors. The networks show how the investors are interlinked through co-investments in OSW projects, which together determine the centrality of each investor in the network. The investment deals are distinguished by three categories of financing: Primary financing in new construction projects (green triangles), refinancing of operational parks (brown triangles), and acquisition of operational parks (purple triangles). The investors are coloured to show their exogenous heterogeneity, i.e. whether they are in public, private, or non-profit ownership and if they are in the financial or non-financial sectors of the economy.

After the five sub-sections on each of the phases, the following section looks at the entirety of the evolutionary process to derive conclusions about the investor system's properties and history.

6.2. The phase-by-phase evolution of the investor network

6.2.1. Phase 1: SOE exploration (1989-2001)

The first phase called *SOE exploration* spans from 1989-2001. The network graph in Figure 6.1 shows how this was a period where especially the civic Danish utility companies that would



merge into Ørsted (then DONG Energy)²⁰ and the Swedish state-owned utility company Vattenfall explored how onshore wind technology could be deployed at sea with seven and six projects, respectively. The private German energy companies RWE²¹ and E.ON²² also obtained early experience with OSW projects, and, like Ørsted, did so by acquiring two energy companies. RWE got to construct the 60MW North Hoyle while E.ON became a participant in the 166 MW Rødsand 1 with Ørsted in addition to its co-investment with Vattenfall and Shell in the Blyth pilot project in the UK.

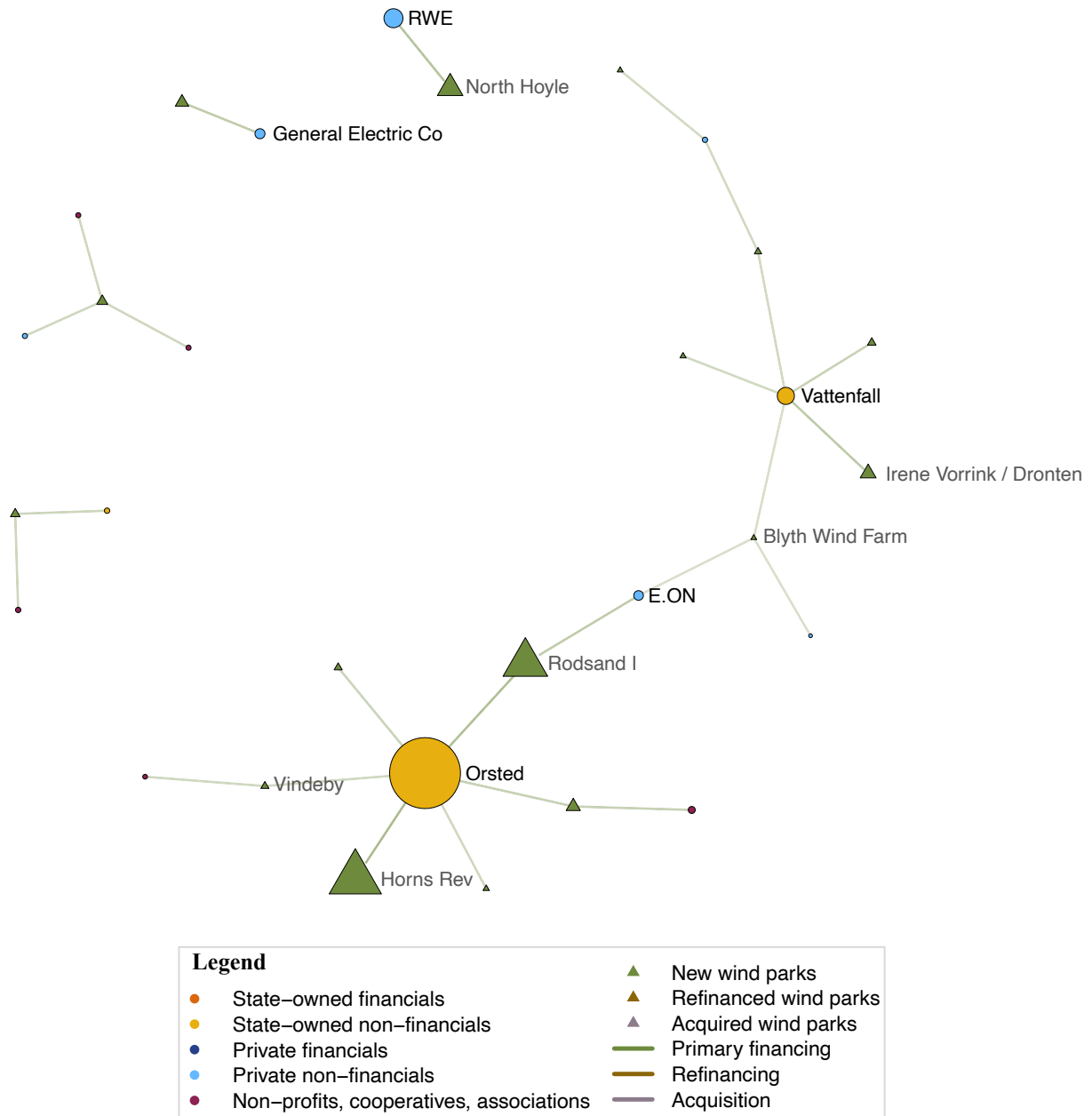
Besides E.ON bridging between Vattenfall and Ørsted, there is little network activity in this phase. Ørsted and Vattenfall cooperate with minor investors on a few projects and two Danish projects are undertaken by mostly civic investor groups. Lastly, General Electric financed Ireland's first project Arklow Park, which the turbine manufacturer used to deploy the world's first turbines with more than 3MW capacity. The learning in this phase was thereby more based on experimentation through learning-by-doing in separation than collaborating with other investors. This may be because of the lack of experience offered by potential partners and that projects were small enough not to warrant cooperation for economic reasons.

²⁰ DONG Energy (later renamed Ørsted) was formed in 2005 by the merger of the SOE DONG (Danish Oil and Natural Gas) with the consumer and municipality owned utilities and transmission operators Energi E2, Elsam, Elkraft, and Københavns Energi in response to market liberalisation. Displaying the companies in the consolidated post-merger form in the figure shows how Ørsted inherited unmatched organisational know-how from learning-by-investing in phase 1.

²¹ Via its acquisition of Innogy in 2002 that had invested in North Hoyle in 2001 (Wind Power Monthly, 2003).

²² Via its acquisition of Sydkraft in 2001 that invested in Rødsand 1 in 2001.

Figure 6.1: SOE exploration (phase 1: 1989-2001)



Source: Dataset compiled from BNEF, IJGlobal, and own data collection.

The first offshore park, Vindeby (5MW), was financed by the joint venture of East-Danish energy utility Elkraft (later merged into Ørsted) and the cooperative utility company SEAS which had also supported Johannes Juul's impactful turbine innovation in the 1950s and 1960s ; Owens,



2019, 91). Vindeby was followed by several small-scale parks ranging from 2-17 MW capacity, including Lely, Tunø, Irene Vorrink, Bockstigen, Utgrunden, and Blyth. The scale increased to a new level with Middelgrunden (40MW) which was built in 2000. Middelgrunden was the world's largest park until the first two utility-scale OSW parks Horns Rev 1 (160MW) Rødsand I (166 MW) were financed in 2000 and 2001²³. The two parks were constructed by demand from the Danish Minister for Energy and the Environment in exchange of requested permits to expand coal capacity by the two largest utility companies that were later acquired by Ørsted (Smit et al., 2007; Voldsgaard and Rüdiger, 2021).

The two parks stand out due to their unprecedented sizes, together totalling 60% of the total financed capacity by the end of 2001. They demarcate the transition to phase 2 of OSW investment since they were crucial innovation events that contributed to the market and investor network moving from the initial experimental phase to a growth phase that would span phases 2 and 3. One former Ørsted executive described the two parks as “the mothers of all large-scale offshore farms” (Voldsgaard and Rüdiger, 2021, 34). This was a period focused on making fundamental innovations that would enable offshore wind to become competitive in the future (Jennings et al., 2020). One important feature of the state-directed approach in Denmark was to create a portfolio of large-scale projects²⁴ that would contribute to developing the supply chains and solutions for offshore deployment.

This portfolio approach to industrial policy, rather than developing one big demonstration project, was crucial for the development of OSW. While Horns Rev 1 became “widely perceived as a “disaster” due to technological issues resulting in excessive cost” (Voldsgaard and Rüdiger, 2021, 34), Rødsand 1 became the blueprint for how to deploy OSW at scale. Horns Rev 1 was especially impeded by the Vestas turbines used. The turbines were not insulated to handle the harsher conditions offshore. This required 75.000 maintenance trips by helicopter, and all 80 nacelles were eventually taken back to shore for repairs (Backwell, 2018, 104). Vestas sustained large financial losses during this episode and subsequently had expensive difficulties with their

²³ Assuming a two-year gestation period before commissioning.

²⁴ Three additional large-scale projects were cancelled after the change of government in 2001.



gearboxes in two large UK projects, which left Vestas with a low appetite for OSW until it re-entered the market in 2014 in a joint partnership with Mitsubishi (Ibid.).

Meanwhile, the Rødsand I wind farm was successful and provided a template for future large scale wind farms. The turbine supplier Bonus was acquired by Siemens in 2004 and has since dominated the offshore wind market reaching an 85% cumulative market share in 2013 (Backwell, 2018, 104). Siemens's next iteration of the Bonus turbine became "for many financiers the only 'bankable' machine in the market, particularly between 2010 and 2012" (Ibid., 103), which shows how finance can constrain the directionality of technological innovation (Geddes and Schmidt, 2020).

Although external financiers may have a conservative influence, phases 1 and 2 generated a number of foundational innovations (Jennings et al., 2020). From the Danish portfolio approach, new blueprint technologies emerged that would spark optimism and enable the ensuing growth phase. The series of bankable Siemens turbines became one of the lasting consequences of the Rødsand I project. While Horns Rev 1 was a commercial disappointment, it pioneered steel monopile foundations and the first use of an offshore transformer station connected to the grid via the, at the time, thickest submarine cable ever produced.

Still, the mixed economic and technological outcomes of the two parks underline the extent to which uncertainty and path dependency are important factors in the green technology space (Grubb et al., 2021b, 2017). Without the two projects that were initiated by governmental directives, it is uncertain how OSW would have evolved. Following the financing of Rødsand 1 in 2001, it took three years before additional projects of 90MW or larger were financed. Nine projects above this size were financed between 2004 and 2007, in time to benefit from the experiences generated at the end of phase 1, before the market expanded in 2008 and 2009.

In summary, phase 1 showcases the dynamics between investments and technology development in the earliest phase of learning curves. Offshore wind was an example of how innovation is combinatorial (Arthur, 2011) as onshore wind technology was adapted to marine conditions and combined with oil and gas technologies, such as monopile foundations, and electricity transmission technology, such as cables and transformer stations. The first phase proved through trial and error that OSW could be deployed at a large scale while the installed cost had trended



downwards (Figure 5.5). Rather than a simple matter of economic incentives, the market was pushed towards its growth phase because of government directives to public and civic owned utilities in Denmark. Importantly, a small number of utility developers emerged from phase 1 with early advantages from learning-by-doing, which they could take advantage of in the ensuing phase.

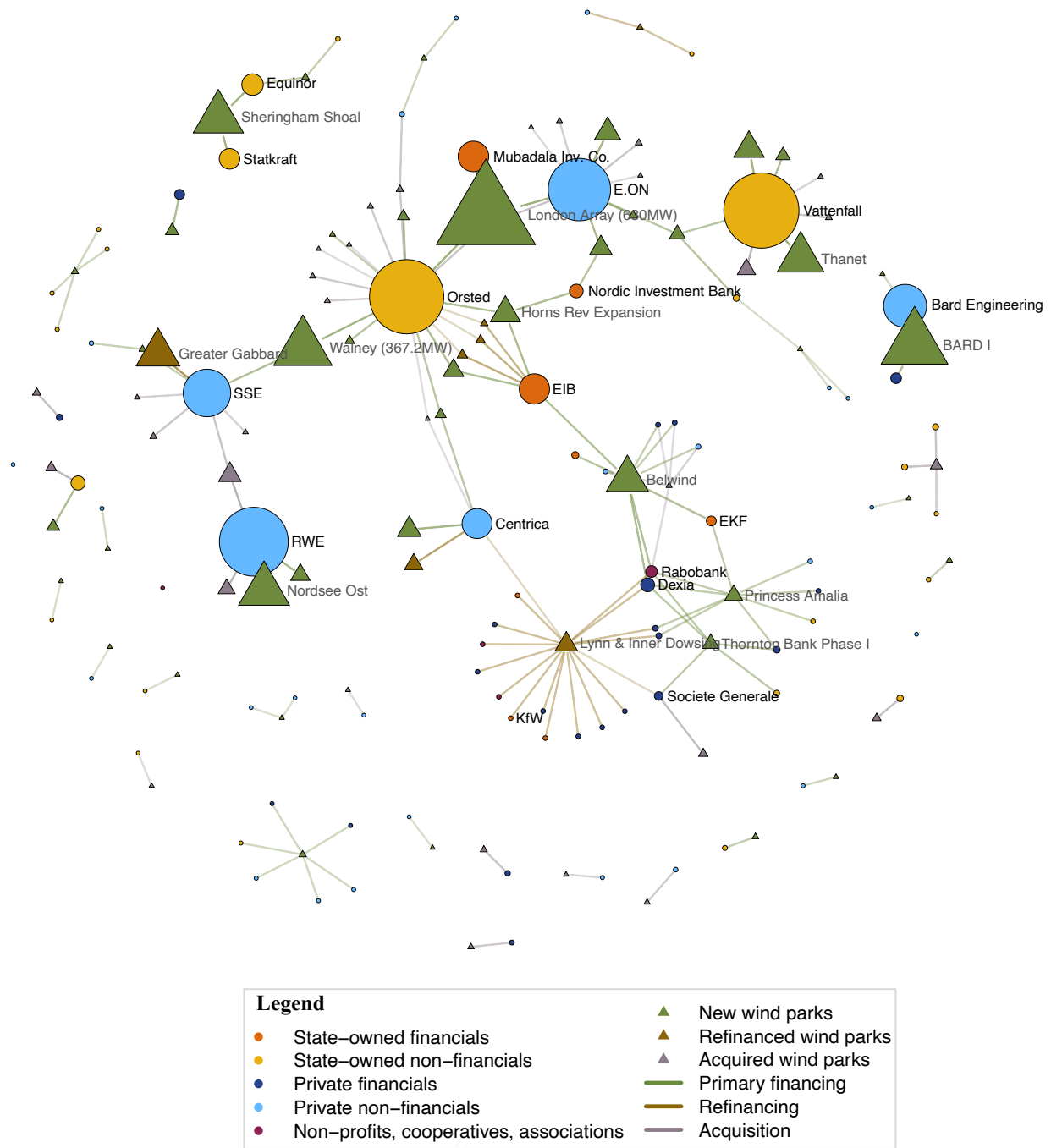
6.2.2. Phase 2: Utility company-led upscaling (2002-2009)

The second phase, *utility company-led upscaling*, spanned from 2002-2009. This was the phase of early commercial adoption of OSW (Dedecca et al., 2016), with most expansion in the UK followed by Denmark, the Netherlands, and Sweden (Figure 5.2). In this period, the two SOEs Ørsted and Vattenfall remained prominent investors in new parks while the investor network grew and became more diversified in terms of investor types and the distribution of investments between more investors. Moreover, the seeds were sowed for an eventual change in the political economy of climate change as commercial banks entered the market. All in all, phase two was a disorderly growth phase where the investor network was in flux while the costs of deployment increased as the investors attempted to continue the development of large scale-parks under increasingly difficult geographic conditions.

Considering the changing composition of active investors, the group of leading utilities increased as the two incumbent SOEs were matched in terms of capital volumes invested by a small group of German and British private energy and utility companies, most notably RWE, E.ON, SSE, and Centrica (Figure 6.2). In this group, RWE and E.ON could also draw on their experience from the first phase as they entered the era of large-scale OSW parks.²⁵ BARD Engineering also launched its technologically ambitious BARD1 project far from shore and with all components developed and supplied in-house (Kostka and Anzinger, 2016).

²⁵ In 2008 SSE acquired Airtricity which was involved with the development of the Arklow Bank park in Ireland.

Figure 6.2: Energy and utility company upscaling (phase 2: 2002-2009)



Source: Dataset compiled from BNEF, IJGlobal, and own data collection.



Commercial banks also entered the market as Dexia and Rabobank pioneered the use of project finance to make OSW ‘bankable’. Dexia and Rabobank developed a conservative approach to contracting, which lowered the risks sufficiently to get acceptance from their internal credit committees (Guillet, 2021). Chapter 7 considers project financing in greater depth as it was a key financial innovation for spreading investment know-how in the financial sector. Finally, public financials entered the market. The Mubadala sovereign wealth fund of the United Arab Emirates provided equity to the large London Array project (630 MW)²⁶, while state investment banks (SIBs) provided finance to both the bank-based and utility-based clusters of the network.

A main tendency in the investor community was that it became more common to co-invest with others in the network. Figure 6.2 displays how the investor community became considerably more heterogeneous while some central investors became more networked compared to phase 1. These are two fundamental properties of complex systems, which create the potential for emergent properties and non-linear dynamics (Beinhocker, 2007). The increase in interactions was driven by different considerations. Larger utility companies used co-investments to share risks, pool capital, and learn through cooperation from projects of growing size (interview 1). Smaller developers needed willing banks to realise the early project licenses they had acquired (interview 2).

The main formation in the network consequently had two clusters: one was based on cooperating utilities, seen in the upper part of Figure 6.2, which primarily invested in the hastily expanding UK OSW market (see section 5.1.1). The other cluster was based on smaller developers and bank finance, in the lower part of the network, which invested more in the European continental markets offering more price certainty. It has been argued that the market uncertainty under the RO scheme was more acceptable to utility developers rather than independent power producers or financial investors (Grubb and Newbery, 2018, p. 8; Kern et al., 2014b), which is corroborated by the investment data. However, with the political OSW targets towards 2020, utilities would have to access considerable amounts of external finance, which called for market design innovation in phase 3.

²⁶ Through its subsidiary energy company Masdar.

One early example of cooperation between utilities in the UK market was in 2004 when Ørsted co-invested in the Barrow project (90MW) with Centrica, who had an early strong position in the UK market. It is Ørsted's (2019, 12) own interpretation of this period that: “Along with the increasing size of offshore wind farms, utilities began partnering with each other on a project-by-project basis, to gather know-how in offshore wind energy projects and share risk.” SSE got an opportunity to absorb know-how from RWE via their shared pre-construction acquisition of the Greater Gabbard project (504 MW) in 2008. The tendency towards increasing scale and interactions among heterogeneous investors culminated in 2009 with the record-breaking London Array park (630 MW) where Ørsted, E.ON, and Mubadala sovereign wealth fund invested together, and EIB provided its largest loan to date in 2010 to fund Ørsted’s contribution to the construction budget (EWEA, 2013, p. 31)²⁷.

In the continental market, Rabobank and Dexia’s arrangement of project financing for Princess Amalia (2006), Thornton Bank (2007), and Belwind (2009) attracted the first group of bank financiers to OSW. Project financing allows banks to assess projects on a stand-alone basis and manage the risks through extensive transparency regarding project management and risk allocation through contracting with suppliers (Steffen, 2018). However, as chapter 7 expands upon, because of the banks’ unfamiliarity with this new market, SIBs were important de-riskers and capital providers in this nascent phase. The Danish export credit agency EKF assumed significant risk on behalf of commercial banks for Princess Amalia (120MW) and Belwind (165MW), while EIB provided a large share of the capital of the latter. The smaller Thornton Bank (30MW) was completed without SIBs.

The EIB was one of the bridges between the bank- and utility-dominated clusters of the network because of its five co-investments with Ørsted. In addition, The Nordic Investment Bank contributed to Ørsted’s Horns Rev Expansion and E.ON’s Rødsand II, both in Denmark. The other link between the two clusters in the network was created by Centrica’s refinancing of its operational park at Lynn and Inner Dowsing in 2009. The low risk of refinancing a farm after construction enabled sixteen banks to commit financing to the project, which freed up capital for

²⁷ EIB’s loan is included as a refinancing loan in phase 3, since the construction was underway.



Centrica. This group included Dexia and Rabobank who had experience with project finance from the two previous projects.

In terms of the political economy of climate change, this period was crucial for changing the mode of asset creation in OSW. First of all, OSW projects increased almost sixfold in size. This was one techno-economic step towards OSW becoming an attractive target for institutional investors, who are generally disinclined to invest in small projects due to the high transaction costs compared to the amount of funds they need to place. Secondly, commercial banks entered the market because project financing could sufficiently alleviate the construction risks through agreements with contractors and contingency planning. This meant that the banking sector got a commercial interest in the continued expansion of OSW. Thirdly, private utility companies expanded their businesses to OSW, so the technology deployment became less dominated by state-owned economic interests and planning. This also enabled their shareholders in the capital markets to benefit. Several companies traditionally vested in electricity generation from coal or even oil and gas exploration (Ørsted) could, therefore, foresee a future with sizeable, stable revenues from new large-scale parks.

On the other hand, the role of the European states increased by the early catalysing roles of the three SIBs. Also, the utility that strategically pivoted the most towards OSW was the SOE Ørsted. Following the merger of several utility companies involved in OSW and increasing momentum for climate policy in the EU, the SOE decided in 2008 to go all-in on renewables and focus on OSW because of the unparalleled investment know-how the utility had accumulated (Voldsgaard and Rüdiger, 2021). At this point, OSW investment was still primarily a business for non-financial investors.

Regarding technological innovation and the economics of OSW, the second phase presented new difficulties spurred by constructing farther ashore and at greater sea depth in a market context of rising costs for materials, notably steel, and currency revaluations (Junginger et al., 2020). The expansion of the market led to a range of new challenges across the supply chain that called for new specialised solutions, for example, with regards to installation vessels, competition, and industrialisation to bring the costs down again (Guillet, 2021; Voldsgaard and Rüdiger, 2021).



The second phase spurred more collaboration among developer companies with the purpose of combining balance sheet strength, sharing risks, and exchanging know-how. Also, a major strategic partnership between Ørsted and Siemens announced in 2009 gave Ørsted a guaranteed supply of 500 offshore turbines with 1.8GW capacity in total (Ørsted, 2009), which meant it would have certainty of supply to execute its strategic pivot while Siemens reached the economic scale required to industrialise its offshore wind turbine production (Voldsgaard and Rüdiger, 2021).

6.2.3. Phase 3: State-led maturation (2010-2015)

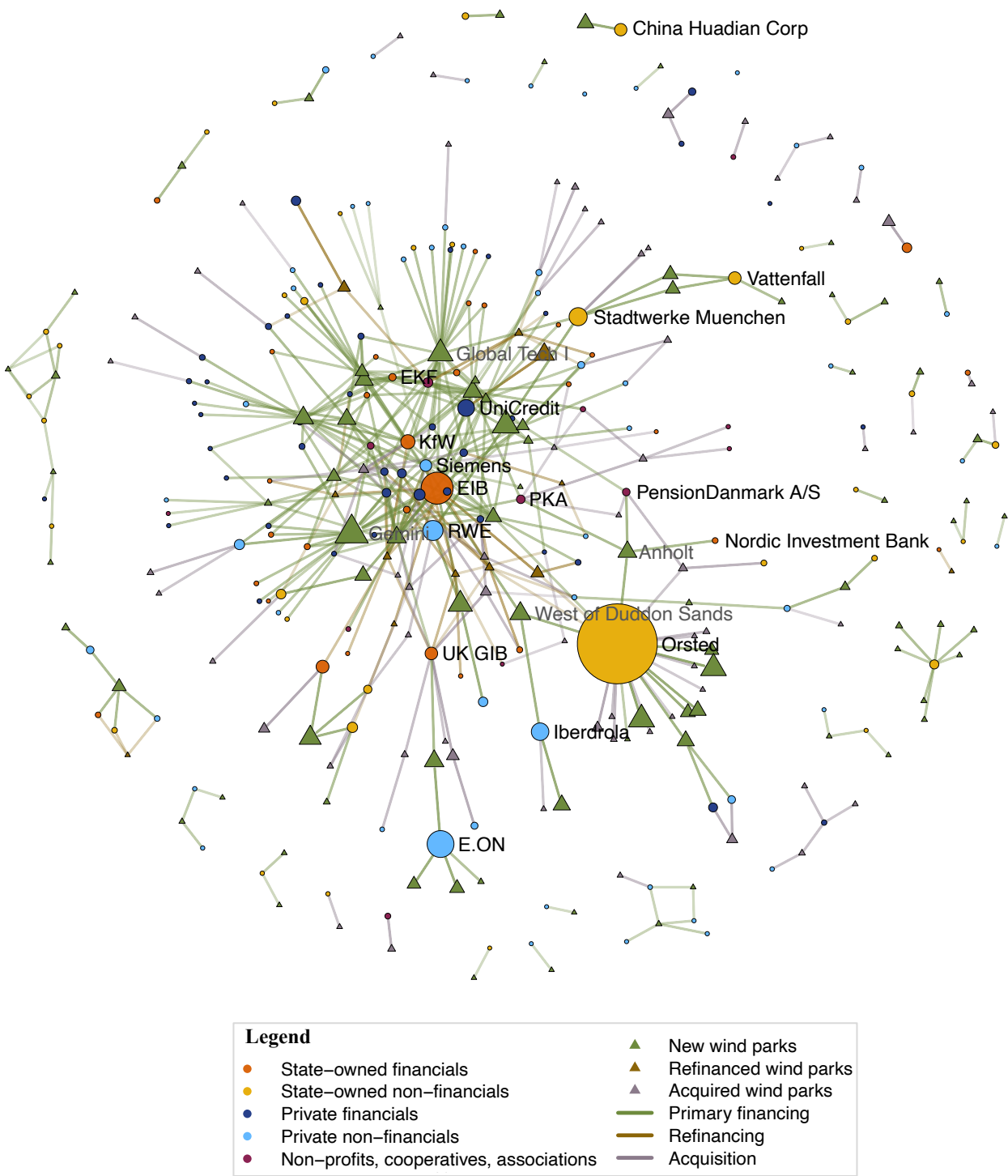
The third phase is titled *State-led maturation* and stretches from the early recovery from the GFC in 2010 to the Paris Agreement was reached at the end of 2015. The title reflects the fact that the SOE Ørsted became the clearly largest investor following its strategic pivot to OSW late in phase 2 (Voldsgaard and Rüdiger, 2021), while the EIB was the second-largest investor and continued to hold a central position in the network together with the German SIB Kreditanstalt für Wiederaufbau (KfW). Considering the demand side of the global OSW market, the UK market initially grew most rapidly as a consequence of the protective niche that was established from 2008-09, not least the doubling of RO certificates awarded to OSW from 2009 (Kern et al., 2014b). Two of the largest projects in the investor network (Figure 6.3) were the two +500MW projects in the UK, Greater Gabbard and Gwynt y Mor, that received final investment decision in 2010 from, respectively, RWE and SSE with debt from EIB and the trio of equity investors RWE, Siemens, and Stadtwerke Muenchen. Simultaneously, the German market expanded with a series of 200-400MW projects, with the 400MW Global Tech 1 from 2011 being a noticeable early investment by a consortium of eight equity investors and seventeen debt providers. In Denmark, Ørsted invested with two pension funds and the Nordic Investment Bank in the 400MW Anholt project in 2011. The Dutch Gemini project from 2014 almost matched the London Array project with its 600MW and was financed by four equity investors, incl. the suppliers Siemens and Van Oord, and fourteen debt providers. As the German projects reached commissioning, the German market jumped from 5% of cumulative capacity in 2012 to 28% in 2016, although still trailing the UK's 37% (Figure 5.2).



Although the market was state-led on the demand side via the strengthened RO scheme in the UK and feed-in tariffs and fixed-price auctions on the European continent, it was also state-led from the supply-side. On the financial supply-side, SOEs and SIBs responded to the price signals and were willing to take risks at the scale required to advance the learning curve of the industry. Figure 5.8 showed how state-owned investors increased their share of primary investments in this phase, which amounted to a financial valley of death for OSW (Karlton, 2016).

Figure 6.3 displays how the investor network grew significantly denser in this period. In the previous phase, investments were primarily undertaken by sole utility investors with a few collaborations with other utilities or a SIB. In phase 3, we see the formation of a networked core in the middle, mainly made up of numerous financial investors, Siemens, and RWE. This network structure reflects that project financing had taken hold and was used extensively in continental Europe (Guillet, 2022). No single commercial bank would be willing to take full risk exposure to a whole OSW park, so these financing deals were highly interactive events, often with ten investors or more. Global Tech 1 even had 25 investors. Project financing was consequently conducive to spreading familiarity among financial investors with the characteristics of investing in OSW. However, at the same time, the GFC reduced banks' appetite for risk, so the EIB and KfW were needed and became the two largest financial investors at the core of the network.

Figure 6.3: State-led maturation (phase 3: 2010-2015)



Source: Dataset compiled from BNEF, IJGlobal, and own data collection.



On the outskirts of the network core, there are five utilities with substantial investments, who mostly relied on balance sheet financing: E.ON, Vattenfall, Ørsted, Iberdrola, and Stadtwerke Muenchen. RWE is closer to the core because of co-investments with two utilities on each side of the core and due to its use of project finance in 2015 to raise capital from ten and eleven banks for its Nordsee and Galloper projects.

Ørsted stands out as the period's largest investor. Ørsted and Centrica did use project financing for one project in 2012 following a protracted negotiation process, but their unwillingness to let banks scrutinise their project management led British bankers to deem for years that OSW was too risky to finance (interview 2). So, developers in the UK had to search elsewhere for funding until RWE had success in 2015 raising loans from banks for its Galloper project, however only from one UK bank.

Besides the funds they raised on their balance sheets by bond and equity issuance, the developers obtained financing from SIBs, who became even more important to the network in terms of the volume of capital they provided and by integrating the network through their high rate of participation. The EIB invested in 19 deals, only surpassed by Ørsted. KfW completed 14 investments, and the newly established UK SIB, the Green Investment Bank (GIB), which invested for the first time in 2012, completed 11 deals. Four out of the seven most active investors in terms of deals were state-owned entities. The other three in the top seven in terms of the number of investments were Siemens, which used its financial arm of the conglomerate to provide finance to its own turbine customers, Rabobank, who took advantage of its early lead in the market, and the Japanese bank Mitsubishi UFJ Financial Group (MUFG).

Unlike the EIB and KfW, the GIB was positioned in the periphery of the network since it invested with a particular focus on acquisitions of stakes in operational parks as a way to provide capital to developers for their next project rather than by co-financing projects directly. It is unlikely that the GIB filled a gap in the financial market at this point (interview 1). As examined in greater detail in chapter 7, Ørsted pioneered the inclusion of pension funds as long-term owners of OSW parks. The characteristic of OSW parks as long-lived assets with de-risked revenue streams by the market design meant that, with the right guarantees by the original owner, the parks would become similar to their familiar fixed-income assets, such as sovereign bonds. Ørsted would



make a capital gain on the acquired stake by having completed the risky construction process and thus raise capital for new projects. Figure 6.3 shows the pension funds PKA and PensionDanmark who were among the connectors between Ørsted and the financial core of the network.

One interesting deal providing insights into market dynamics in phase 3 was the 400MW Anholt park in Denmark, where Ørsted secured a historically high level of subsidies²⁸ (partly because of no willing competitors in the bidding process) and obtained financing from the Nordic Investment Bank (NIB). NIB provided its largest loan to date based on experience from lending to Ørsted's Horns Rev Expansion and E.ON's Rødsand II. Ørsted's project manager explained the importance of the SIB getting involved:

"Generally, DONG Energy [i.e. Ørsted] has had good access to financing during the current economic downturn. However, raising specific financing for large offshore wind projects is in general cumbersome due to the scale of the projects and the fact that it is a new industry. The appetite and capacity of the financial institutions to provide financing for these types of projects have been affected to some extent by the financial crisis, and we are pleased that NIB made available financing for our Anholt Offshore Wind project" (NIB, 2011).

In 2011, during the construction process, Ørsted sold 50% of the ownership to the two aforementioned Danish pension funds. The year before, PensionDanmark had also acquired a 50% stake in the operational Rødsand I park. As the Danish Energy Agency (2017, 33) recounts, this initiated a process where institutional investors gradually became knowledgeable enough to eventually take on construction risk:

"Through innovative partnerships with experienced industrial investors like utilities, institutional investors come to grips with the inherent risks. The first Joint Ventures of this type saw institutional investors enter only after successful commissioning, but now there is a growing confidence on the side of institutional investors" (Danish Energy Agency, 2017, 33)

²⁸ DONG Energy received 1,05 kroner pr kWh for 12 years, which added 66% to the amount granted two years earlier (0,63 kroner pr. kWh) to E.ON's Rødsand II in Denmark.



This is also how Ørsted (2019, 12) perceived the learning dynamics among institutional investors: “This demonstrated a growing understanding of offshore wind farms as a new asset class and greater confidence in the projects being delivered on time and on budget.” Given the reluctance of banks to provide credit, getting institutional investors like pension funds involved was an important capital recycling mechanism for utility developers to raise funds for new investments. The practice of selling stakes with guarantees to the new financial owners, e.g. limiting the price risk, became known as ‘farm-down’.

From a complexity perspective, this practice was a self-organising feature of the investor system, where utility investors learned to navigate the heterogeneity among actors in terms of appetite for risk (interview 1). Institutional investors who preferred to wait for a park to become operational – and therefore less risky – would pay a substantial premium for avoiding the construction phase that neither suited their risk profile nor was a well-understood form of risk. The SIBs also assumed an enabling role by stepping in to provide considerable amounts of finance for construction, which could later be recycled by sales of ownership stakes to more risk-averse institutional investors.

Moreover, this interactive and adaptive behaviour among the different types of investors was a co-evolutionary response to two factors. The first co-evolutionary factor was the increasing sizes of offshore wind farms, which increased the need for raising external finance. This, in turn, made the sector’s development more sensitive to financial conditions. Secondly, as Hall et al. (2017) pointed out, financial sub-markets such as energy finance are influenced by and have to adapt to wider financial conditions.

Phase 3 was marked by the aftershock of the GFC and the resulting strains on the balance sheets of utility companies (Blyth et al., 2015; Jacobsson and Karltorp, 2013). Private non-financial corporations, such as RWE, Bard Engineering, Siemens, Iberdrola, and E.ON, were relatively minor investors compared to Ørsted and the EIB, and the risk premia added by banks to the cost of debt in project financing rose (Figure 5.6). The increasing use of project finance meant that project risks were being transformed into counterparty risk against the contractors who provided more guarantees. In conjunction with the push to lower costs through economies of scale in a smaller-than-anticipated market, the financial attention to counterparty risk increased mergers



and acquisitions in the supply chain (interview 2). In 2016, the offshore turbine market “had consolidated into four Western turbine manufacturers: Siemens-Gamesa, MHI-Vestas, GE and Senvion, plus several Chinese players” (Backwell, 2018, p. 112).

At the same time, Ørsted adaptively took advantage of the low interest rates in money and bond markets set by central banks, which meant institutional investors were searching for returns in new ‘alternative’ asset classes. Some institutional investors hence realised they had to obtain the know-how to invest in new fixed investment projects to restore their level of returns and Ørsted’s legal and financial teams found a model for structuring the risks so OSW became sufficiently de-risked for pension funds (Voldsgaard and Rüdiger, 2021).

The political economy impact of phase 3 was equivocal. In one sense, it showed how the green transition could be accelerated by public investments as Ørsted and the SIBs were the period’s lead investors. This challenges the model based on previous technology transitions by Perez (2002) where the deployment of new infrastructure and energy technologies were fostered by exuberant waves of investments by optimistic private financiers. The history of OSW suggests that, for capital-intensive sustainable energy technologies, public investments were indispensable for reaching the point of steadily falling costs along a learning curve, which finally arrived again during phase 3 (IRENA, 2022, Figure 5.5). This raises the question of whether a shift to private investments was even necessary since SOEs and SIBs demonstrably had access to capital and investment know-how to expand the sector and lower the cost of electricity. However, this was ultimately a transition pathway not taken (Foxon, 2013; Geels and Schot, 2007).

The Danish government would not provide additional equity funding for Ørsted to finance its expansion, which turned the SOE towards asset sales and stock issuance acquired by Goldman Sachs and domestic pension funds (Voldsgaard and Rüdiger, 2021). The SIBs were generally governed to attract investments by private financiers (often on de-risked terms where the SIBs took riskier debt tranches, interview 1). Consequently, although phase 3 was decidedly state-led, the phase instead became the effective starting point for widespread private financial funding and ownership of the OSW sector by international banks, institutional investors, and capital funds.

In summary, phase 3 saw state-owned actors taking lead roles as investors in OSW, while other types of investors kept more reluctant roles. This assertive investment behaviour by the state-



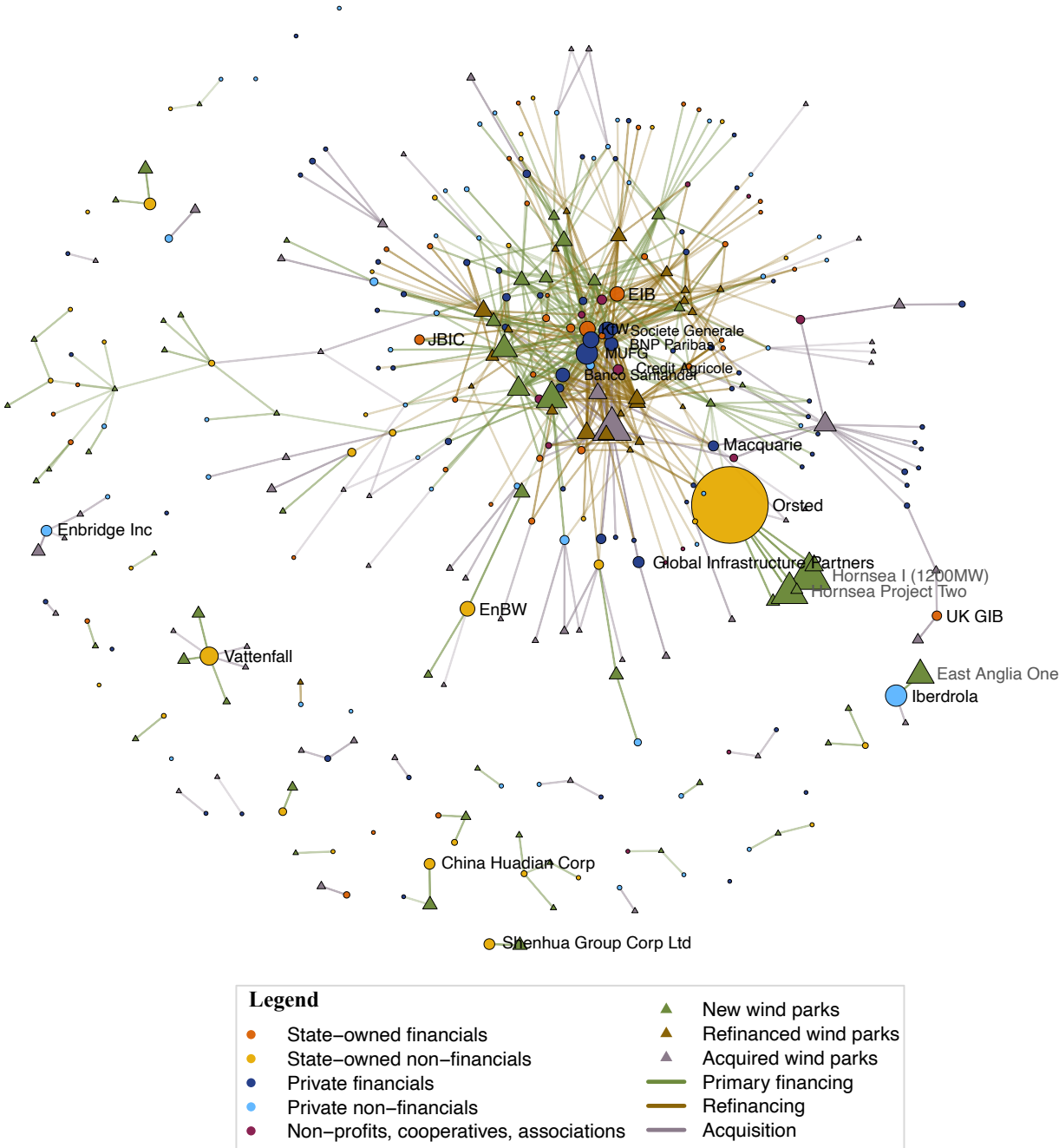
owned investors was important for leading to a new phase of falling costs (Figure 5.8), which provided new hope for the future of OSW in deep decarbonisation scenarios (IEA, 2021a). Despite the shaken financial sector in the aftermath of the GFC, the period also saw private financial actors taking central positions in the network and financial innovations enabling institutional investors to recycle the capital invested by developers in operational farms.

6.2.4. *Phase 4: Post-Paris learning and know-how diffusion (2016-2018)*

The fourth phase, titled *Post-Paris learning and know-how diffusion*, spanned from 2016-2018. The phase was characterised by private financials becoming dominant actors in the OSW investor network. However, the private financials were more engaged with financing existing assets through refinancing and acquisitions, as it offered a low-risk way to gain familiarity with the large and capital-intensive assets being created by the investments in this sector. Ørsted still dominated the sector in terms of primary investments in new projects (Figure 6.4).

The network maintained the basic structure from the previous phase with a core of primarily financial investors and a periphery of loosely connected utility investors, while the network generally became denser because of the larger number of deals involving the financial investors in the core. Within this structure, the composition and distribution of the investment volumes across the actors had also evolved. The SIBs had been the main investors when the network core emerged in phase 3, but Figure 6.4 shows how the core had increasingly become dominated by private banks, incl. MUFG, BNP Paribas, Societe Generale, and Banco Santander. The EIB and KfW were still prominent investors, but more on par with the private banks in terms of capital invested and network connectivity, considering all types of financing. They remained leading financial investors in terms of primary financing (Figure 7.3).

Figure 6.4: Post-Paris learning and know-how diffusion (phase 4: 2016-2018)



Source: Dataset compiled from BNEF, IJGlobal, and own data collection.



In the periphery, we see that Ørsted remained the clearly largest investor, but the growing sizes of the central private financials show that they came relatively closer to Ørsted's investment value. Ørsted's largest investments were the Hornsea 1 (1.2 GW) and 2 (1.4 GW), and Borssele I and II (752 MW). In addition, the utility developers Vattenfall, Iberdrola, and EnBW continued to invest, although mostly in isolation from the network and on a scale close to the private banks in the core. Ørsted and Vattenfall created two of the period's cost breakthroughs. Ørsted's Borssele I and II won the Dutch government's auction in 2016 for a fixed-price contract with a strike price of 83 USD/MWh, and shortly after, Vattenfall's Krigers Flak won the Danish government's auction at only 57 USD/MWh (IEA, 2019, 26). These reductions from the LCOE level between 150-200 USD/MWh indicated that OSW was finally on a learning curve – and a steep one (Figure 5.7).

Turning to the investment behaviour of the financial actors in Figure 6.4, they predominantly refinanced (brown ties) and acquired (blue ties) existing projects rather than provided primary finance for new projects (green ties). We can see how the EIB and KfW were located on the upper half of the network, characterised by relatively more primary financing, while the private financials were closer to the half with more refinancing and larger acquisitions.

As mentioned in chapter 5, developers undoubtedly took advantage of the falling interest rates and likely had expiring debt from the construction of the project. I also interpret this pattern as a co-evolutionary strategic response in the private financial sector to the Paris Agreement and the early signs of a downward trend in OSW costs. These two political and techno-economic trends were both encouraging signals for the future viability of OSW as a major decarbonisation technology. Hence, this was a moment that spurred private banks and fund managers to seek more know-how of OSW as an asset class that would be able to profit from the global sustainability transition of the energy sector.

This learning process was facilitated on the demand-side by the widespread use of auctions for fixed-price contracts, which de-risked the operational assets and hence attracted capital at a low cost of capital to owners looking to refinance with more and cheaper debt or sell off ownership stakes. These price schemes successfully attracted institutional financial investors and banks that were otherwise too risk-averse in relation to OSW (Christophers, 2022a; Hall et al., 2016;



Mercure et al., 2021b). Although institutional investors mostly acted as capital recyclers after project completion, some pension funds began to take on construction risk and hence obtained the same cash flow at a lower cost (interview 1).

Some acquisition deals exemplified this broader trend. In 2016, the capital fund Macquarie used debt from 12 banks to leverage its own funds to acquire a stake in the 573MW Race Bank park from Ørsted. In 2017, two cooperative pension funds PKA and PFA likewise used debt from 10 financial companies incl. Blackrock, the SIB EKF, insurance companies, and Macquarie, to acquire a stake in Ørsted's 659MW Walney Extension park. The most remarkable deal was arguably the US private equity firm Global Infrastructure Partners' £4.46bn acquisition of 50% of Ørsted's Hornsea 1 project. Citigroup and MUFG led a group of 17 financiers who provided 4/5 of the acquisition value in loans. With its 1.2 GW and the sizeable price tag for the stake, the Hornsea 1 project epitomised how offshore wind was becoming a mainstream asset class that international financial investors could fund with vast sums of capital. Meanwhile, the UK GIB mimicked this investment behaviour by continuing to buy stakes in operational farms. The SIB bought stakes in Lynn and Inner Dowsing with Blackrock in 2016 and in Lincs in 2017 before being privatised in a sale to Macquarie (BBC, 2017).

Phase 4 thereby brought both new dominant actors and new financial practices that increased the density of the network. The investor ecosystem underwent rapid change in co-evolution with politics and technology. In complexity terms, this can be understood as a phase shift in the investor network since its composition, practices, and financial logics changed over a few years. Nonetheless, 65% of finance for new projects was still provided by state-owned investors (Figure 5.3), so the investors seeking to acquire low-risk operational projects were still dependent on the risk-embracing attitude of public investors. Still, there was a symbiosis between the two types of investors since the sales of ownership stakes after completion provided the developers with funds for new investments. This thorough change in the network was an indication of a transition from the network's disorderly growth phase towards a more 'orderly' phase with a more stabile composition of actors (Beinhocker, 2007)

Considering the political economy aspects of this phase, Schmidt and Sewerin (2017,1) found "the Paris Agreement might ultimately represent a paradigm shift from cost-minimizing to



opportunity-seizing, and thus from a focus on emissions to a focus on technologies” in the logic of climate policy. This ‘opportunity-hypothesis’ corresponds to the attraction OSW assets had in this phase on large capital funds and international banks. On the other hand, Allan et al. (2021) argue that “Paris was not the *cause* of this shift; rather, it reflected changes set in motion by green industrial policy”. Indeed, the preceding history of OSW deployment supports the position that green industrial policy on both the demand and supply sides had brought the technology on the verge of a tipping point by setting off a virtuous spiral among deployment, falling installed cost, and falling cost of capital (J. I. Lewis, 2021), which the Paris Agreement bolstered.

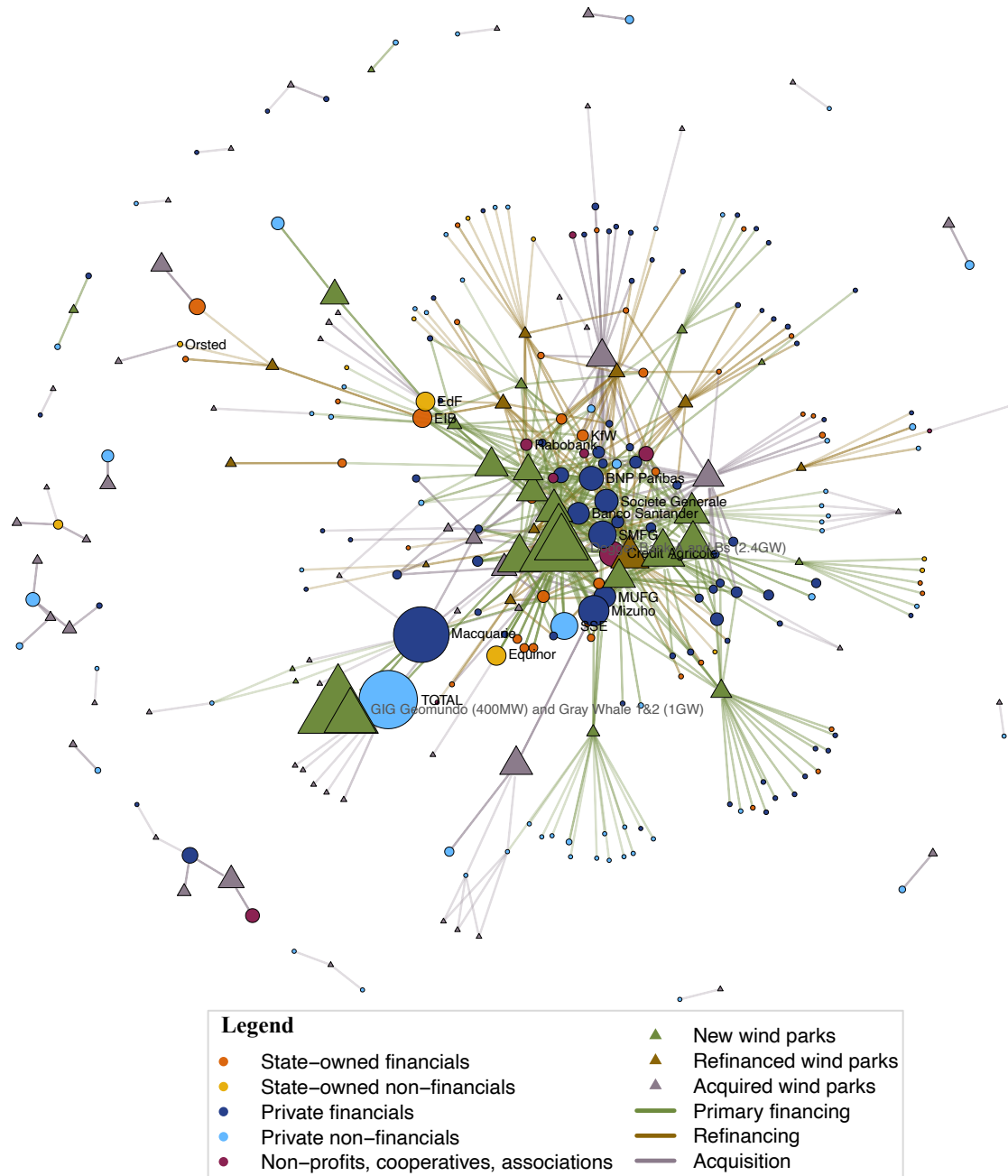
From an asset-based perspective, phase 3 showed how OSW could create large assets that could generate substantial, long-lasting, and de-risked cash flows for institutional investors and capital funds. The changing composition and relative sizes of actors in phase 4 imply that the asset-based interests of financial investors were likewise undergoing change. With the entrance of these quintessential actors of financial capitalism, such as Macquarie, with around USD 500bn of assets under management, it was becoming clearer for financial investors that it would be possible to transition towards net zero greenhouse gas emissions while preserving the existing social structure of financing and ownership with the emergence of new classes of profitable, low-carbon assets like OSW (Newell, 2019).

6.2.5. *Phase 5: Offshore wind as a mainstream asset class (2019-2021)*

The fifth phase, *Offshore wind as a mainstream asset class*, covers the investments during 2019-2021. This was a period where the private financial actors assumed a more dominant role, also in terms of finance for the construction of projects while public investors receded. It showed how the financial ecosystem had evolved to the point of maturity where public investors were no longer needed.

The structure of the network in Figure 6.5 resembles the one in the previous phase, with a dense financial core and a few large investors in the periphery. The core had been balanced among private and public financials, but in phase 5, it became dominated by private and cooperative commercial banks.

Figure 6.5: Offshore wind as a mainstream asset class (phase 5: 2019-2021)



Source: Dataset compiled from BNEF, IJGlobal, and own data collection.

Note: Dogger Bank A & B deal has been downsized to the size of the second largest deal to avoid over-crowding the centre of the network.

Considering the deal activity, non-state financial actors fill the entire top 11 in terms of investment deals completed, followed by KfW as the first state-owned actor based on its 9



participations. The main private banks in the core in terms of investment values and counts included the Japanese investment banks Mizuho, Sumitomo Mitsui Financial Group (SMFG), and MUFG and the French banks Societe Generale, Banco Santander, and BNP Paribas, and the cooperative banks Rabobank and Credit Agricole also had central network positions and relatively large investments.

In the periphery, there were five noticeable investors, incl. the utilities SSE and Electricité de France (EdF), the oil companies Total and Equinor, and the capital fund manager Macquarie. Total and Macquarie shared the lead investor role in Ørsted's absence, strongly reflecting their investments in South Korea. One reason for Ørsted's inactivity was that the SOE had initiated several large-scale investments in the preceding 3-year phase but, at the same time, Ørsted and experienced pension funds were complaining about the profit-squeeze from the aggressive competition from major oil companies seeking to get a late foothold in the market (Frandsen, 2021; FT, 2021).

BP also invested in phase 5 and Shell has recently won auctions for seabed leases in the UK (FT, 2022a, 2021), but the major French oil company Total was most noticeable in Figure 6.5 as the largest investor in the fifth phase. This leading role was based on two large projects in Korea with Macquarie and the 1.1GW Seagreen project in the UK with SSE and debt from twelve banks. The Norwegian SOE Equinor had invested on an ongoing basis since its first major investment in 2009 but scaled up its investments after the Paris Agreement, particularly through its co-investments with SSE in the 3.6 GW Dogger Bank project in the UK, which was also supported by a remarkable club of 31 banks. It appeared the potential for sustainable investments identified in the large balance sheets and cash flows of the major oil companies was being realised (Green et al., 2021), although this potential has been met with scepticism regarding their willingness to sustain less profitable investments compared to oil and gas (Christophers, 2022b).

Another significant characteristic of the fifth period was that the private financials moved from a capital recycling role in the system (by refinancing and acquiring operational assets) to a role as primary investors in new projects, as evidenced by the larger prevalence of green ties in the core of Figure 6.5 (see also Appendix D: Figure 0.4). Public investors only provided 18% of total finance during these three years.



This was both the consequence of strategic pivots and financial innovations. One strategic move was the infrastructure fund Macquarie's decision to gain OSW investment know-how by acquiring the UK GIB in 2017, which enabled it to become one of the largest primary investors in this period. An example of financial innovation was the Copenhagen Infrastructure Partners (CIP), which creates funds for institutional investors and invests the raised capital in new OSW projects where they plan and manage the development through contracts with suppliers. CIP is thereby one example of how a lack of suitable investment vehicles for institutional investors (Ameli et al., 2019) was becoming less of a constraint as the investment ecosystem adapted and self-organised.²⁹

The changes characterised above amount to a relatively swift financialisation of the OSW investment sector. Instead of entrepreneurial state actors such as SOEs and SIBs and private energy companies that had patiently developed the market, it was becoming dominated by private financiers and hence the logics of money manager capitalism (Minsky, 1989), which makes decisions based on total quarterly returns. The long-term de-risked revenue streams of OSW fit into these portfolios, but it is uncertain how much appetite there will be in the future as electricity markets are re-risked and if it will impact the willingness to deploy components based on newer technological iterations, such as floating foundations and +20MW turbines (Jennings et al., 2020).

While public financing diminished relative to private finance, its purpose was also changed. The EIB, which provided decisive financing during the scale-up of OSW (phase 2) and the push towards maturity (phase 3), moved to the periphery of the financial core, while export credit agencies become more prominent public financials. In phase 5, the Danish export credit agency and KfW (also active in export credit) were central to the network³⁰. The French, Swedish and Norwegian export credit agencies also entered the field to support their domestic companies' roles in OSW deployment. This changing nature of public financing vehicles reflects a shift from deployment support and hence technology development towards export promotion in a more

²⁹ I return to CIP in chapter 7 to provide a stronger empirical grounding of what is transpiring in the financial interactions.

³⁰ In the core of the network, we also find the state-owned banks Lloyd's (UK) and ABN AMRO (NL) that are run as commercial banks after nationalisation during the financial crisis rather than as strategic public banks.



globalised market for OSW (Figure 5.2), where export credit availability remained an important competitive parameter for a country's OSW developers and equipment manufacturers.

6.3. Looking across the phases: Maturation from cradle to a mainstream asset class

In this section, we look across the five periods to apprehend some of the trends over the full period of OSW investment. The purpose is to examine the complexity aspects of the investor network in greater detail and conclude on the relation between OSW financing and the political economy of climate change.

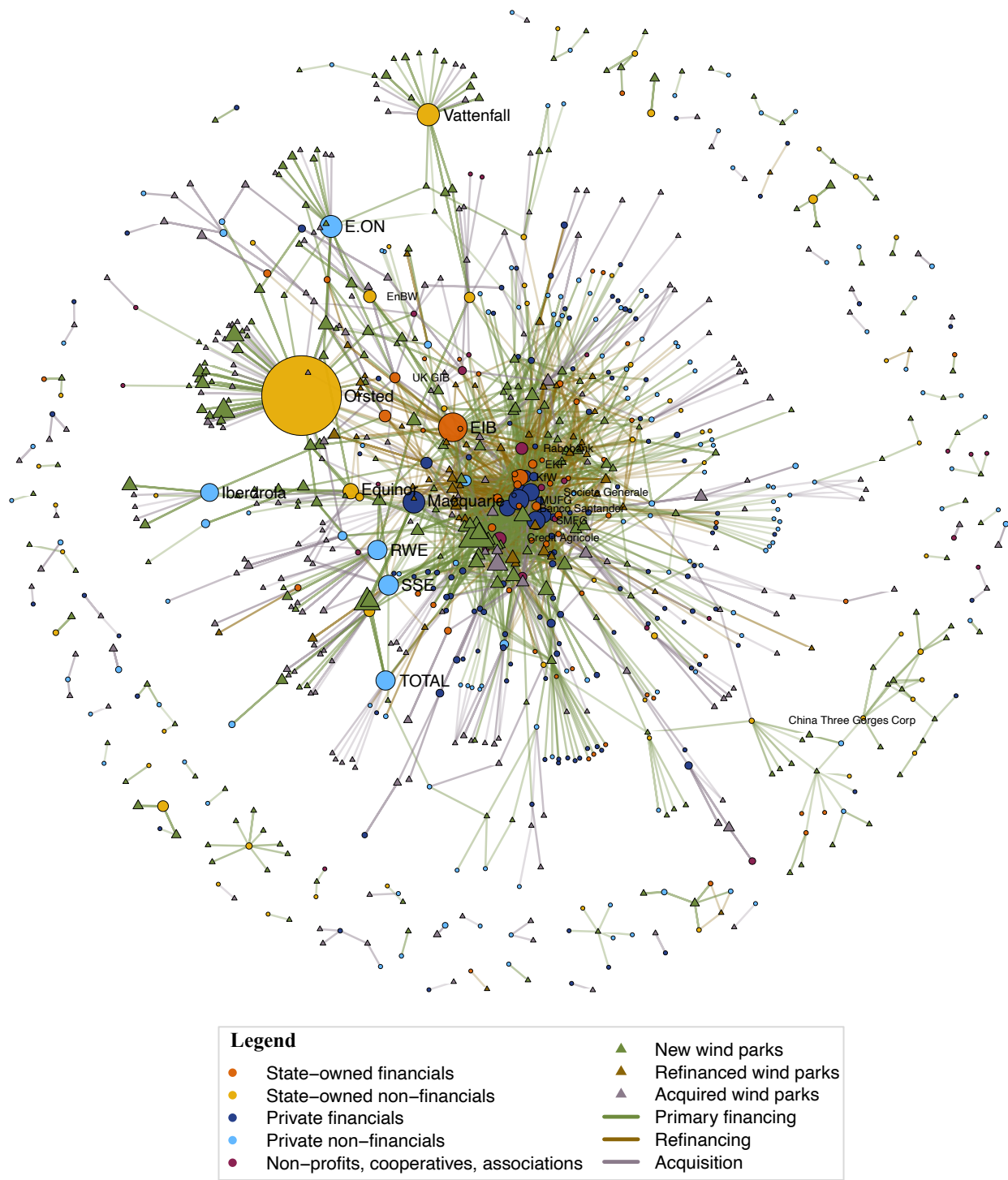
6.3.1. Assessing the full-period network

Figure 6.6 shows the combined investor network for the entire period from 1989-2021, where OSW energy went from its technological cradle to a mainstream asset class. It gives an impression of the network's structure and the most important investors for the deployment of OSW³¹, although the timing and iterations of the network must be kept in mind.

Because of the network structure in the three latest phases, the full network has a dense core dominated by a cluster of large banks that have financed project financing, refinancing, and leveraged acquisitions. The dominant banks are mostly private French and Japanese banks, but we also see KfW, EKF, and the two cooperative banks, Rabobank and Credit Agricole. Unsurprisingly, Ørsted stands out as the lead investor with three times more investments than the second largest. Perhaps more surprisingly, the second place is held by the EIB, which was 30-50% larger than the third tier consisting of utilities, private banks, KfW, Total, and Macquarie. If only primary financing is considered, the private banks fall to a lower tier than the utility investors (Appendix E: Figure 0.9), since they were more active in providing finance for refinancing and acquisitions (Appendix E: Figure 0.7 and Figure 0.8).

³¹ Although each dollar of investment was likely more technologically and know-how-wise impactful in earlier than later periods. For instance, Rabobank's smaller size does not reveal its importance for bringing project finance to OSW.

Figure 6.6: The full-period offshore wind finance network (1989-2021)



Source: Dataset compiled from BNEF, IJGlobal, and own data collection.



The leftward periphery of the network is characterised by the loose clustering among the major energy and utility companies, such as Ørsted, Vattenfall, RWE, SSE, and E.ON who have historically been the drivers of investment. The EIB is positioned on the upper-left edge of the financial core because of its many co-investments with utility developers in the periphery, especially Ørsted, while the private financials have predominantly invested via project financing often sponsored by smaller developers and invested in existing projects. In this sense, EIB has taken an intermediate role between the financial capital in the core and the production capital in the periphery and thereby held a special role as both a large-scale investor and a hub for know-how dissemination across the two investor clusters. The EIB has therefore likely contributed to the gravitation of investment activity towards the financial core in phases 4 and 5 because of its intermediate structural role in the network.

6.3.2. *Network growth dynamics*

Descriptive network statistics can provide a better appreciation of how the network grew over time. Table 6.1 shows how the total number of ties and actors changed from phase to phase. The network started out with 11 ties among 14 investors and, hence, a density of 12%, i.e. the share of potential ties that were actually present³². The density dropped to 7% in phase 2 as the number of actors increased by 73 (521%), thus increasing the potential for ties by 4,011%, while the actual number of ties increased by 243 ties (2209%). The largest increase in the number of ties was 933 (367%) in phase 3, while the number of investors almost doubled from 87 to 173. In the last two phases, the rates of nominal and relative increases in ties and investors slowed. The number of investors in phase 5 was even two fewer than in phase 4. This meant that the network stopped growing but became increasingly dense, reaching 12% density in phase 5.

³² The density in phase 1 is overestimated because of the consolidation of Ørsted's pre-merger utility companies.

Table 6.1: The growth of the offshore wind investor network

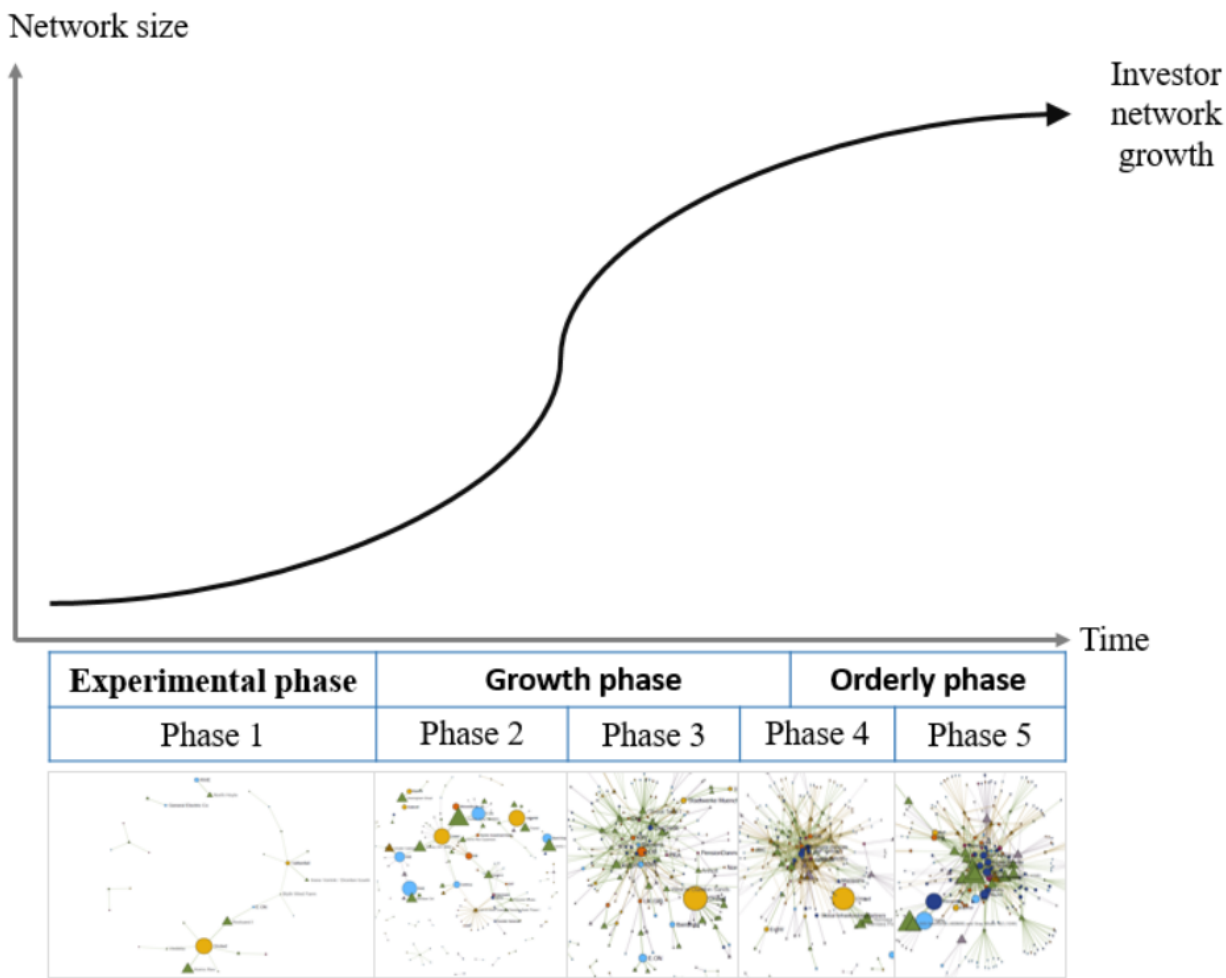
	Total ties	Change in total ties	Change in total ties (%)	Active investors	Change in investors	Change in investors (%)	Network density (%)*
Phase 1	11	11	-	14	14	-	12%
Phase 2	254	243	2209%	87	73	521%	7%
Phase 3	1187	933	367%	173	86	99%	8%
Phase 4	1988	801	67%	209	36	21%	9%
Phase 5	2644	656	33%	207	-2	-1%	12%

Source: Dissertation database. **Note:** *The network density expresses the amount of observed ties as a share of the sum of potential ties among all active investors.³²

Beinhocker's (2007, 174; see chapter 3) presentation of the punctuated equilibrium model of how complex systems regularly go through experimental, growth, and orderly phases is helpful for describing the evolution of the investor network in OSW. Figure 6.7 illustrates how phase 1 was an experimental phase where several small demonstration parks were deployed to test the use of onshore wind technology in the marine environment. The decision by the Danish government in the 1990s to deploy OSW in +100MW parks was the innovation that sent the OSW network into a growth phase. This spanned phases 2 and 3, where the number of ties grew by 2209% and 367%, while the number of active investors grew by 521% and 99%. During this growth, new 'keystone species' came to dominate the network. In the first two phases, it was utilities, and in the third phase, SIBs became the most important network actors in terms of connections and investment volumes, while Ørsted remained the lead investor.

Phase 4 was also part of the unstructured growth as private banks, and other types of financial investors became more dominant financiers at the core of the network. This change of composition and importance was also a sign of the orderly phase that seemingly emerged in phase 5, predominantly characterised by private financing of new projects. The growth in the number of investors stalled to 22% in phase 4 and minus 1% in phase 5. At the same time, the number of ties grew by 67% and 33% in the two phases, which led to growing network density.

Figure 6.7: Three stages of complex system evolution for offshore wind



Note: Based on Beinhocker's (2007) account of the punctuated equilibrium model and the visualised networks in this chapter.

This appears to be a solid financial structure for the deployment of OSW at a relatively low cost of capital on a medium-term horizon because it is not, to the same extent, relying on a few specialised investors. Nonetheless, complexity theory suggests that even orderly systems may be vulnerable to sudden changes in activity if the keystone actors are unable to handle changes in the environment or innovations in the network (ibid., 175). For instance, the resolute entrance of oil majors could change the order in the general OSW industry under re-risked electricity markets (interview 2). I will discuss these concerns further in chapters 9 and 10.



6.3.3. *Network effects and path dependency in the investor composition*

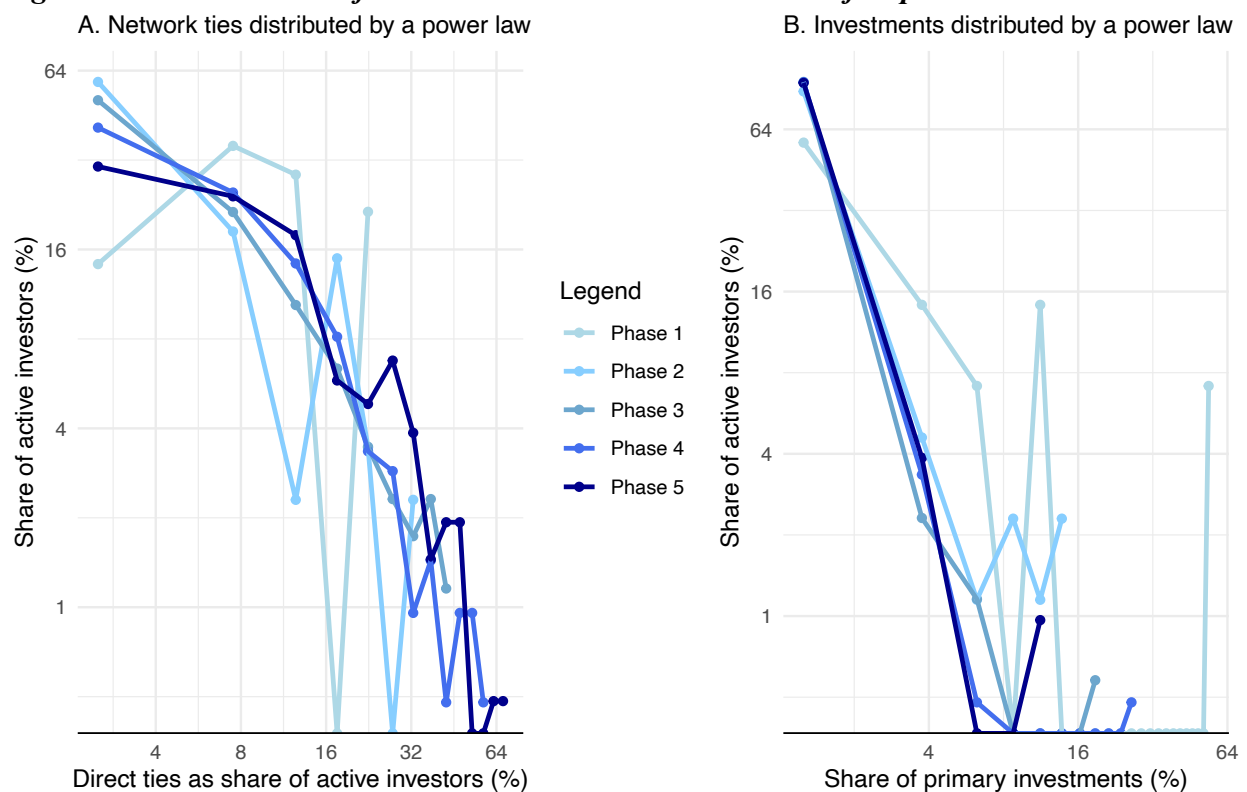
Let us now examine the distribution of ties and investments in the network in greater detail across the five phases. Since neoclassical theories of finance commonly reason based on a representative investor (Hall et al., 2017; Kay and King, 2020), this implies that most investors are more or less equally equipped to undertake investments. Complexity theory suggests that there is normally strong heterogeneity among actors and that network effects and evolutionary processes constrain and enable the behaviour of any particular actor (Beinhocker, 2007). Therefore, it is often inappropriate to analyse finance by considering a representative investor.

In the complexity view, systems are typically producing oscillations and emergent properties if they are characterised by networks with power law distributions that structure how information and influences spread. Power law distributions are heavily right-skewed distributions where most observations have low values while a long and narrowing right-side tail contains only few observations with high values. Power law distributions are produced when one quantity changes relatively in proportion with relative changes in another variable. Power distributions generally result from endogenous processes that contain a ‘the rich get richer’ dynamic (Barabási and Albert, 1999). Based on the reviewed theory of know-how formation, we would expect those who invest in obtaining an experience-based advantage through learning-by-doing to be better at identifying business opportunities, new technologies, and complete the projects more efficiently. Network theory suggests that more networked and successful actors also attract other actors who want to benefit from the resources of the incumbents (Wasserman and Faust, 1994).

This behavioural pattern of preferential attachment provides a social mechanism through which the previously successful investors obtain more opportunities than investors with smaller track records. In OSW, this could occur by experienced developers being offered to acquire a stake in a project or obtaining cheaper access to finance so they can win in competitive auctions because of greater trustworthiness as partners. For banks, a strong track record could lead them to becoming invited to the club of banks in project financing or even for the role as lead arranger for the deal by the developer (interview 2, Guillet, 2021). We should therefore expect the OSW network to display power law distributions and a path-dependent pattern of active investors.

In Figure 6.8, the distributions of network ties and investments are displayed for each of the five phases based on histogram plots. The Y-axis counts the number of investors in the observational ranges as a share of all active investors in each phase. The X-axis shows the numbers of direct ties to other investors (via projects) and amounts of primary investments as shares of the phases' totals. The data points are placed on the centre value of the histogram bins. Each axis is transformed to a logarithmic scale, which visually changes power law distributions to straight downward trending lines.

Figure 6.8: Distributions of network ties and investments in the five phases.



Note: The figures show the histogram distributions of active investors in each period across intervals of network ties and investment volumes. The intervals for network ties are each of 5% of the network size and 2.5% of all primary investments. The data points are placed at the middle value of the histogram intervals. Both axes are log-transformed, so a straight downward-trending line reflects a power law distribution, highly skewed towards smaller values.



The downward-trending lines in panel A show that the network ties are generally close to power distributions. In the experimental first phase, with few investors, the distribution is closer to a short horizontal line, implying that it was more common to have a moderate reach and rarer to be an isolated or highly central investor. In the subsequent four phases, the distributions were closer to a power law. Here, only 3% or less of active investors were within the top intervals (of each 5%) in each phase. In phases 4 and 5, the tail is longer and narrower, with 0.5% of investors placed in two intervals with direct ties to more than 60% of the network. As the end point of the distribution curves moves further down and outward for each phase, the network effects create increasingly superior network positions for a few advantaged investors.

This supports the hypothesis that there are endogenous mechanisms in the network that create self-reinforcing success for the incumbents or potentially for aggressive newcomers who strategically manage to get included in the core of the network. On the other hand, the distribution in phase 5 is also less steep, with a lower top point and a larger share of the investors with ties to 25% or more of the network than in previous periods. This indicates that although a few investors became increasingly well-connected (in the tail), there was another tendency of a broadening ‘middle class’, as it apparently became easier to achieve a medium-wide reach than in earlier phases. The large deals around the financings of Dogger Bank with more than 30 participants were likely a main cause of this shift. Concomitantly, the ability to attract so many investors to a single deal was a sign of OSW being regarded as a more mainstream asset class by the banks.

In panel B, we see that the distribution of investment volumes among active investors in each phase also generally followed power laws. For all phases except the second, there were several intervals without observations before reaching the investor with the most primary investments in each phase. We know from the visualised networks that this was because of Ørsted’s unparalleled level of investments in phase 1, 3, and 4, while Macquarie and Total invested at a much higher level in phase 5 than the rest of the network. In phase 2, it was more even among the largest developers and EIB.

The distributions in phases 1 and 2 were generally less steep than in the three later phases, although Ørsted (i.e. the pre-merger utilities seen consolidated) was a strong outlier in phase 1 with more than 50% of investments. From phase 3, the top points of the curves move upward to



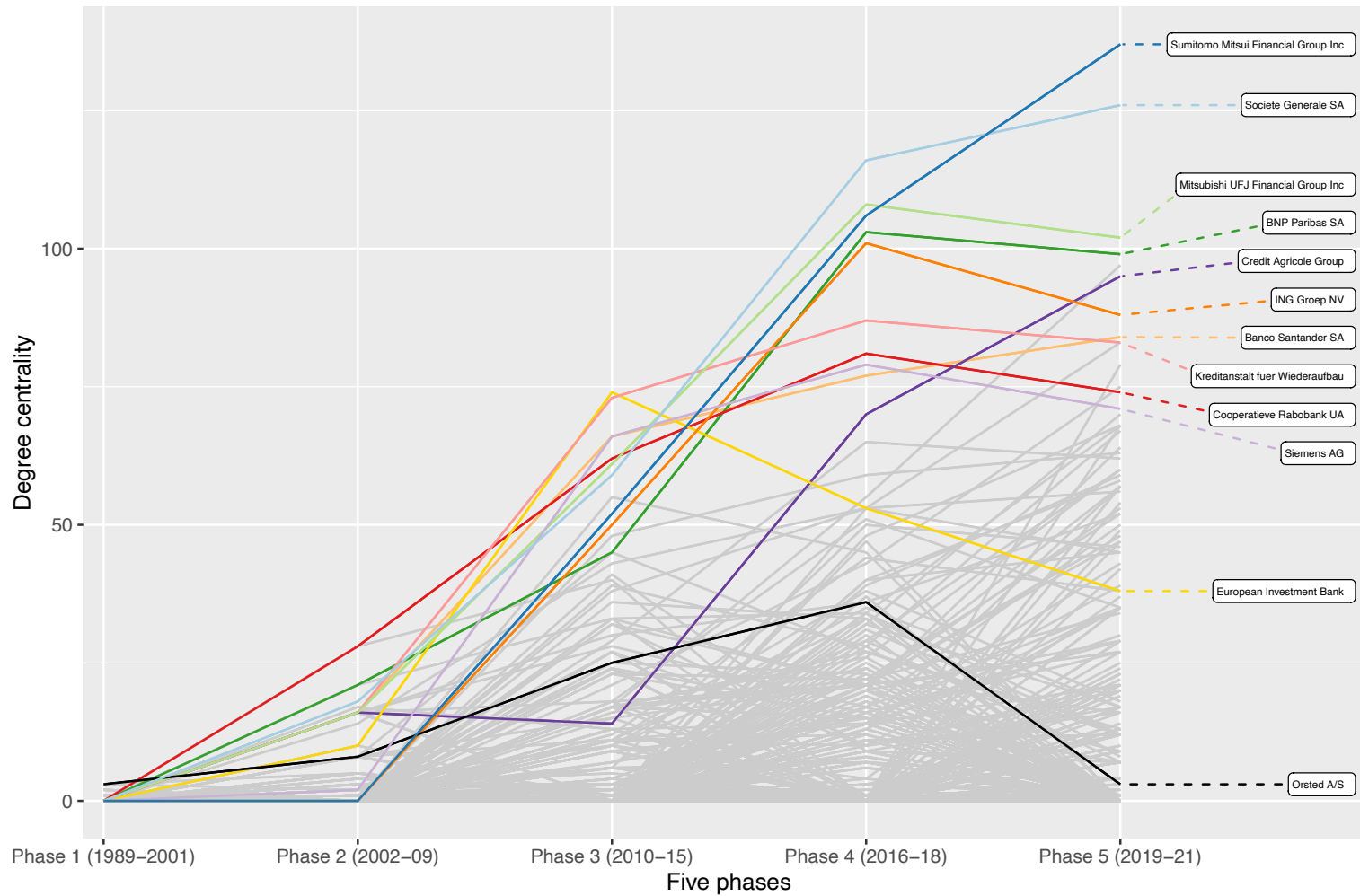
around 95% of active investors providing only between 0-2.5% of primary investments. Meanwhile, the tail lengthened in phases 3 and 4, where the top investor provided 17.5-28% of total primary finance, before the tail shortened again in phase 5. The tail shortened because there were two top investors, instead of just one, who each provided 10-12.5% of all primary financing in phase 5.

The network, therefore, featured a tendency for a few investors to invest vastly more than most other active investors. On the one hand, this skewed distribution means that a lot of know-how could be created cumulatively through learning-by-doing concentrated in a few organisations. On the other hand, this is also a fragile structure, where a lot of know-how and a continually high level of investment may be dependent on the strategy and survival of the top investor.

Together these two sets of distributions support that the OSW investment network has been structured according to power laws where few investors dominated in terms of either investments or network connections. One may ask if these skewed distributions impact the development of the network in a path-dependent way by perpetuating the composition of dominant investors and ‘making the rich richer’. We already noted how Ørsted came to dominate investment in phases 3 and 4 based on its strategic decision to take advantage of the lead in investment know-how it had acquired during phases 1 and 2 (Voldsgaard and Rüdiger, 2021). So, how about the degree of perpetuation in terms of network ties?



Figure 6.9: Degree centrality of offshore wind investors in the five phases (1989-2021)



Note: Degree centrality calculates the number of co-investment ties to other investors via offshore wind projects and not the number of ties to projects. The lines are coloured for the ten investors with highest average degree centrality. In addition to the top ten, Ørsted A/S is highlighted with black and the European Investment Bank is highlighted with yellow due to their roles as important investors (cf. chapter 6).



Figure 6.9 shows how the number of co-investment ties to other investors via a project, i.e. the unimodal degree centrality, has evolved for all investors in OSW in the five phases. The ten investors with the highest average degree centrality across all periods are highlighted, while Ørsted and EIB are added because of their important roles as capital providers. The most connected are all banks except for Siemens, whose investments placed itself “in a strong position to provide more of its turbines and maintenance services to offshore wind projects” (EWEA, 2013, 24). The chart shows that there has been a strong persistence among the most connected investors between phases 2 and 5, since the highlighted investors are taking up the positions as the most well-connected investors, although a few other investors do enter the top in single phases. This resembles the tendency identified in industry life cycle research that earlier firm entrants are less likely to exit the market as the industry matures because of a stronger proclivity for innovation and the ability to overcome new business challenges (Klepper, 1997; Klepper and Simons, 2005)³³.

Seven out of the ten investors with the most connections in phase 2 were also in the top ten with the highest average number of ties across all phases. This indicates a path dependency based on strong sensitivity to early events. In this case, the banks who decided to participate in the earliest project financings generally became the leading banks in the mature market. Since the utilities generally invested on their balance sheets, the banks did not interact directly with more experienced investors in the first deals. Still, they did get an important head start relative to other banks with regards to examining the risks in OSW construction projects and structuring the contracts to avoid a loss when negative surprises occur.

The pattern was similar in phase 3, where nine out of the twelve of the most connected investors were from the all-time top ten. This suggested that the banks who learned about project financing for OSW in phase 2 drew advantage of this know-how in the following phase. A new trend was that the two top investors were the SIBs, EIB and KfW, which were noted as visually central to the emerging financial core of the network during phase 3. One reason was that they were simply

³³ However, since the industry life cycle literature focuses on industrial product markets, I find it less applicable to organisations that invest in energy infrastructure and depend on improving know-how and organisational process innovations, rather than product innovations.



investing in more projects, but in addition, they may have been able to attract less experienced investors to participate and hence widen their reach. It has been noted that KfW had “been successful in attracting commercial lenders to take construction risk in a number of the projects. KfW’s experience and robust due diligence has undoubtedly contributed to this” (EWEA, 2013, 31), which exemplifies the potential for SIBs to have an educational and trust-signalling role in financial systems (Geddes and Schmidt, 2020)

The investor persistence trend continued in phase 4 as the top ten was identical to the all-time top ten, although in a different order. The EIB fell out of the top while the number of interactions for the top investors all rose. Credit Agricole achieved five times more co-investors, while BNP Paribas doubled its count of ties. Societe Generale was the most well-connected bank, with 116 co-investors in the network, followed by the two Japanese banks MUFG and SMFG.

The general trend towards more connections stopped for the most connected investors in phase 5. Only four of them increased their degree centrality despite the total number of ties increasing by 1,312 (33%) from phase 4, while the number of active investors remained stable. Figure 6.9 shows that the growing density mostly occurred by more investors entering the middle range with 40-75 ties. The group of investors with the largest gain from phase 4 to 5 include a mixed group of financials, incl. East Asian banks and capital funds, export credit agencies, and international banks such as Standard Chartered, Barclays, and Deutsche Bank.

The ten most well-connected investors across the phases still made up ten out of the fourteen investors with the most connections in phase 5. So, while the second tier of investors broadened, the path dependency at the core of the network persisted. Phase 5 thereby shows a maturation of the network since the network became less reliant on a small group of specialised banks.

Measures of betweenness and eigenvector centrality show similar persistent patterns in the dominance of a small group of investors (Appendix F: Figure 0.10 and Figure 0.11).

6.3.4. *Offshore wind investment as a prism for the political economy of climate change*

As mentioned above, political economists increasingly understand climate politics through the lens of domestic distributional struggles and the properties of the assets on the balance sheets of



the most powerful individual and collective actors (Aklin and Mildenerger, 2020; Colgan et al., 2021). Following Colgan et al. (2021), we should expect the asset composition on the balance sheets of particular investors and within sectors to shape political dynamics. Investors can ‘flip’ in their political stance when they achieve a larger share of assets compatible with deep decarbonisation. Likewise, sectors can ‘realign’ their lobbying impact if a sufficiently influential group of constituent firms flip to favour decarbonisation. Therefore, different interests in *if* and *how* decarbonisation should be expected as a consequence of specific asset profiles.

This chapter sheds new light on these asset-driven political dynamics. One main political economy implication of the shifting trends in the investor network is the changing economic basis for the financial sector to engage as a constructive force in public policymaking. In the third phase, the first wave of private banks and institutional investors gained familiarity with this emerging asset class. The combination of falling costs and the Paris Agreement then led to a big push by private financiers to enter the offshore wind business to reap the benefits of a head start before OSW would get deployed at a scale commensurate with the Paris Agreement. This change of composition in the investor ecosystem again feeds back to politics by making the interests of private finance aligned with more OSW deployment. In other words, the interests of finance were becoming aligned with an accelerated green *transition* – but not a green *transformation*, which would challenge “the position of private wealth owners in the social system” (Keynes, 1937, pp. 213–214; Newell, 2019).

Most notably, we saw an organised expression of this tendency with the establishment of the *Glasgow Financial Alliance for Net Zero* (GFANZ) at COP26 in 2021, whose members pledged to align their \$130 trillion in assets under management with a net zero emissions target in 2050. However, recent efforts to make GFANZ membership conditional on comprehensive carbon finance disclosure, 2030-transition plans, and a halt to financing new coal projects have caused the support among investors to waver (Financial Times, 2022a, 2022b, 2022c). Most recently, the GFANZ appears to have cut ties with the UN framework ‘Race to Zero’ that sought to impose these constraints (Financial Times, 2022d). It appears the ‘green asset channel’ discussed in this chapter has a positive feedback effect on the political support for further creation of de-risked



green assets, but only insofar as it does not constrain their financial business opportunities in the fossil fuel sector.

Despite the historical role of public investments in the development of OSW, we are generally seeing the role of the state being restricted to a de-risking regulator that facilitates the creation of assets with favourable risk-reward properties for institutional investors – a new “Wall Street Consensus” for how to structure the green transition (Gabor, 2021). Nonetheless, the case study shows the contours of a contrasting alternative to the Wall Street Consensus model in the expert investor roles occupied by a few public utilities and SIBs. The reasoning behind the general preference for private investors is their believed superior ability to assess risks and economise on their resource use to the benefit of shareholders. Paradoxically, the general tendency in OSW has been the opposite, with public investors displaying the most dynamic capabilities (Kattel and Mazzucato, 2018; Teece and Pisano, 2003). An alternative approach based on a “Green New Deal State” (Gabor, 2021; Nersisyan and Wray, 2021) could therefore take inspiration from the in-house investment expertise and successful embrace of technological risk by the SOEs and SIBs in OSW. Instead of focusing on levelling the playing field for private competitors, countries or clubs of countries could establish SOEs for deploying new sustainable technologies and circumscribe competition between private companies to the supply chains. SIBs could be reconfigured to co-finance and provide external due diligence on the projects, rather than working to attract private finance.

6.4. Summary

In continuation of chapter 5, this analysis has further pursued an answer for research question 2: *How has offshore wind investment co-evolved with the technology over time, and how have these changes shaped the political economy of climate change?* Taking a view across the entire lifespan of OSW deployment, the analysis has documented how OSW investment has transitioned through five phases. The first two phases were dominated first by the public and civic utilities, which were later merged into Ørsted, and then by a small group of public and private utilities in the second phase. A few private banks also entered the market with the de-risking support of



SIBs, but the main impact was that they established OSW as a ‘bankable’ technology before the GFC.

In the third phase, Ørsted and two SIBs, EIB and KfW, were the most important investors in terms of capital volumes and number of participations. After the Paris Agreement in 2015 and the incipient maturation of OSW technology, private financial investors became increasingly attracted to invest in OSW parks because of the low risk and large asset sizes and the emerging prospects for OSW to become a key decarbonisation technology. First, they predominantly took positions in operational assets, either through refinancing or acquisitions, and became familiar with the investment properties. In the last phase (2019-2021), financial investors became the dominant primary investors, which conveyed that OSW had finally become a mainstream asset class.

Although OSW undoubtedly matured because of demand-side policies, it is clear from the investment patterns that all investors do not react equally to new opportunities and challenges for sustainable technologies. Rather, there were strong tendencies for a few investors to have disproportionate shares in investors and/or network ties. This suggests there are endogenous mechanisms in investor systems that can be activated to reinforce tendencies to learn and invest. However, in the development of new technologies, there are strong negative feedback effects from the uncertainty that work against these dynamics, which can explain the slow initial growth before the sudden changes into the growth phase and the orderly phase.

In this regard, it is difficult to counterfactually envision OSW overcoming its cost headwinds and getting on a low-cost trajectory without the persistent presence of entrepreneurial state investors like Ørsted and the SIBs who were strategically focused on OSW. At the very least, the process would have been considerably protracted in their absence. This finding adds more granularity and depth to previous studies that have found state-owned organisations being more risk-embracing with regard to renewable energy technologies (Mazzucato and Semieniuk, 2018; Steffen et al., 2020b). Chapter 7 analyses their role in know-how creation and diffusion more closely.

Considering the literature on OSW, this network analysis has contributed to understanding its history by shedding light on the investment dynamics that have driven the technology towards



maturity. This investment and deployment focus complements other historical accounts that have emphasised the role of learning by doing and specialisation in the supply chains and innovation systems and the price schemes that have supported the deployment (Backwell, 2018; Jennings et al., 2020; Junginger et al., 2020; Kern et al., 2014b; Mercure et al., 2021b).

Theoretically, the study's complexity perspective contributes towards an adaptive understanding of renewable energy finance (Hall et al., 2017), which is considered in further depth in chapter 10.

The third contribution is politico-economic and based on the relationship between the finance-technology nexus and climate politics. There has been increasing attention to the formation of green “winning coalitions” (Meckling et al., 2015; Pahle et al., 2022) and how asset specificity shapes climate policy outcomes (Colgan et al., 2021). This network analysis provides an empirical window for understanding the asset-based micro-foundations of the financial sector's pivot to net zero emissions pledges: If the world's largest assets managers and institutional investors can profit from the green transition at a low risk, the sector's influence on climate politics and global governance is likely to become more climate-friendly. It is nonetheless unclear how the financial sector would react if policymakers decided to embark on a more ambitious investment schedule by scaling up the financial capacities of state-investment banks and state-owned energy developers.

Chapter 7

Raising green animal spirits: Know-how diffusion in the investor network

7.1. *The capability foundation of green animal spirits*

In the previous chapter, we gained an understanding of the evolution of the offshore wind (OSW) investor network. However, it remains unclear how investors developed the perception of their ability to assess and undertake risks in different OSW industry stages. This chapter addresses this issue by exploring (RQ3): *Which investors and interactions have been important for investment know-how creation and diffusion in the offshore wind sector?* By analysing the investment behaviour of these investors, this chapter will contribute towards the main research focus on the OSW industry's evolutionary processes of learning, adapting, and interacting through investments (Beinhocker, 2007).

The renewable energy finance literature typically assumes rationalistic and atomistic investors, while Keynes (1964 [1936], 161-162) used the concept of animal spirits to explain the variability of investment behaviour in the context of fundamental uncertainty. The difficulty of assessing the value of an investment means that subjective perceptions and social influences are main mechanisms behind investment decisions (Kay and King, 2020). However, the theoretical framework in Chapter 3 suggests that improving investors' investment know-how, including their abilities to assess and mitigate risks, can promote animal spirits. In other words, a capability theory of the investor is proposed. In other words, *a capability theory of the investor*³⁴ is proposed.

As argued in chapter 3, the investors' capabilities to assess and handle risks are crucial for sustainable investments in renewable energy technologies, which have a high CAPEX-OPEX ratio, long lifetimes, and a thin track record to develop expectations from (Schmidt, 2014). Furthermore, investors must know the broader innovation trends in the sector since emerging

³⁴ With inspiration from the capability theory of the firm (Teece and Pisano, 2003; Teece, 2019).

technologies can become obsolete due to breakthroughs in rival technologies, creating a coordination issue that can work against sustainable technologies. Immature investment communities have been identified as a systemic barrier to sustainable investments (Ameli et al., 2019; Hall et al., 2017).

For OSW, it has been argued that “increased knowledge of renewable energy technology is needed among financial investors” (Karlton, 2016, p. 106). However, this barrier is not a static condition since investors can learn by doing (Egli et al., 2018). Innovation theory finds that learning also occurs through various forms of interaction with users, suppliers, and competitors (Jensen et al., 2007; Lundvall and Johnson, 1994). Karlton (2016, p. 107) suggested that to remedy the know-how barrier in OSW, “technology developers [i.e. manufacturers and project developers], who have good knowledge of the technology, can take on the role to increase knowledge among investors by working more closely with them”.

We should therefore focus on how *green animal spirits* can arise through learning-by-doing and interactions in investor ecosystems. Green animal spirits refer to the urge to invest in emerging sustainable technologies despite uncertainty. This increases the possibility of deploying niche technologies at scale so their learning curve potential can be explored at a low cost of capital to avoid a prohibitive cost of electricity production. While investments in unproven technologies can rise due to financial “frenzy” (Perez, 2002), this chapter considers green animal spirits a phenomenon based on improved abilities to analyse risks and potential. Thus, the chapter aims to develop a capability-based theory of green animal spirits, inspired by Keynes.

7.2. The micro-level dynamics of offshore wind investment

This section explains financial practices encountered in this study. The expert interviews and Guillet (2022) provided insight into how interactive learning mechanisms worked in OSW financing partnerships. In the early phases, utilities co-invested for capital preservation, risk sharing, learning from others, and internal blame avoidance (see chapter 6). Balance sheet finance was often preferred by utilities to avoid intrusive demands for transparency and risk control from banks (interview 2).



Project financing involves protracted negotiations that shape project structure and management. Skakkebæk (interview 1) explained timing and sequencing of interactions. Typically, developers and equity investors cooperate with banks 3-8 years before financial close, followed by construction initiation. Banks are included in planning about 1.5 years before financial close, while lead arrangers prepare financing process by selecting and inviting banks to participate in cooperation with developers' financial advisors who have a central role in structuring financing (interview 2). During this 1.5-year period, banks scrutinize project plans, supplier contracts, risk allocations, technology choices, insurance deals, production forecasts, market forecasts, cash flow, and management team know-how (Guillet, 2022). Guillet described the different approaches to investing between equity investors and banks:

Investors are looking at 'how do we make this work? How do we get the upside?' Banks say 'what happens if things go wrong? And then, can we still be paid? Can I be paid even if investors lose their money?' So, banks look at downside scenarios and check if there's still enough money to salvage.
(interview 2)

Banks estimate cash flow based on conservative assumptions and assess project risk profile, resulting in requirements for contingency budget size, offered debt ratio, and price of debt (spread or margin above reference monetary policy rate) after extensive due diligence and negotiation between equity and debt investors. Generally, higher contingency, less debt leverage, and higher cost of debt result in a higher WACC and smaller returns on equity, as more expensive equity will be used (interview 1).

In project finance, club deals with banks are the predominant mode of financing. A lead arranger is selected by developers to bring together a group of potential banks for the deal. "When you do a club deal (...) it's a lot harder to do because, obviously, you need everybody to agree to the exact same terms at the same time" (interview 2). Financial contracts are lengthy and complicated and "the devil is really in the details" throughout the documents (interview 2). To avoid delays or increased loan costs from a conservative bank, the lead arranger or financial advisor may involve more banks than required. This fosters competition and keeps banks in check, but the availability of capable banks can sometimes be limited. SIBs have been helpful in this regard as



they are willing to invest larger amounts and thereby reduce the number of banks required for the project (interview 2).

On the other hand, if the arranger has too many interested banks, “it's probably because you don't have an aggressive enough financial structure” (interview 2), e.g. with higher debt ratio, lower spread, warranties or other technical covenants. Skakkebæk notes that “If the project starts to become attractive there comes a ‘lemming effect’ where everyone wants a piece of the pie and then the spread falls” (interview 1).

Consideration of suppliers, including turbine technology and risk allocation, is a central part of the process. The choice of turbine technology can have industrial and technological implications, as a Siemens turbine was considered the only “bankable” machine in the market between 2010 and 2012 (Backwell, 2018, p. 103). Increased demand for guarantees and warranties has turned project risks into counterparty risks, leading to consolidation in the industrial ecosystem to increase suppliers' financial robustness (interview 1).

The 1.5-year period before each financial close allows for learning-by-investing and co-investing with experienced participants. However, capable banks are more likely to be invited due to their ability to offer better terms and experience with handling idiosyncratic risks in OSW, which is a positive feedback effect on capabilities. Newcomers can hope to be included by offering more aggressive terms or using existing network relationships with the developer (interview 2) to absorb know-how and move closer to the core of the investor network.

Banks impose requirements upon the fixed investment know-how of developers by scrutinising project management capabilities during due diligence. According to Guillet, there is a steep cliffside in terms of know-how: “If you're above the cliff, then the market is plentiful. If you're below the cliff, you get nothing” (interview 2). Non-capable developers have had their projects stopped and eventually acquired by more capable developers (interview 2).

After the club deal is settled, participating banks may sell some of their exposure to other banks (‘syndication’), but they remain involved in the project to monitor progress during construction. “Debt providers get ongoing updates as they get cash calls to make funds from the loan available.



Then they check if the funds go to the planned purposes” (interview 2). Thus, project finance banks gain a strong learning feedback effect as their risk assessment is tested during construction.

The financial negotiations and planning processes facilitate the creation and transfer of investment know-how among investors. These processes have a positive feedback loop, as "learning-by-investing" and "learning-by-co-investing" give investors a relative advantage over less experienced investors. This improves the ability of developers to construct projects, reduces the cost of electricity, and enables banks to participate in club deals on more favorable terms. As the industry's investment know-how grows, projects can be built with fewer complications, more debt leverage, smaller credit spreads, and smaller contingency budgets. This downward pressure on the cost of capital reinforces the effect of policies that de-risk revenue from production in OSW.

The approach relies on co-investments as the main mechanism for transferring tacit investment know-how between organisations. However, other diffusion mechanisms operate in parallel. According to Guillet (interview 2), a small number of key individuals have been essential for the organisations' know-how. For instance, banks only provide financing if they recognize successful project management teams. Likewise, the core banks had to establish dedicated teams before investing at scale in OSW.

The use of advisory services is another mechanism for know-how diffusion, with a few dominant advisory firms in OSW. Technical advisors assess a developer's plans, while financial advisors help developers obtain bank finance and devise supplier contracts. The know-how in these adjacent services is also held by a few individuals. For example, only one person was considered a bankable insurance advisor, and Guillet was the director of the Green Giraffe financial advisory firm, which advised on over half the project finance deals completed between 2009-2015.

7.3. Methodological approach

The analysis uses reachability analysis, as described in section 4.4.2. The backward and forward reach metrics are calculated for each investor at the four breaks between the five phases of OSW investment (Table 4.1) and mixed with qualitative data (Creswell and Plano Clark, 2018). A more



practical introduction to the reachability method is found in Appendix G, which uses Ørsted as example. This analysis considers the forward and backward reaches across one pair of adjacent phases at a time. This provides a systemic perspective on how the know-how flows in the network have likely evolved. In the four charts, the vertical axis displays each investor's backward know-how exposure from the new parks in the previous phase. The horizontal axis displays each investor's potential for forward diffusion to other investors in the subsequent period. We thereby get four impressions of which investors have been important know-how generators and bridges across the five investment phases.

7.4. The diffusion of offshore wind investment know-how via networks

7.4.1. Path analysis across phase 1 and 2: Few solid bridges

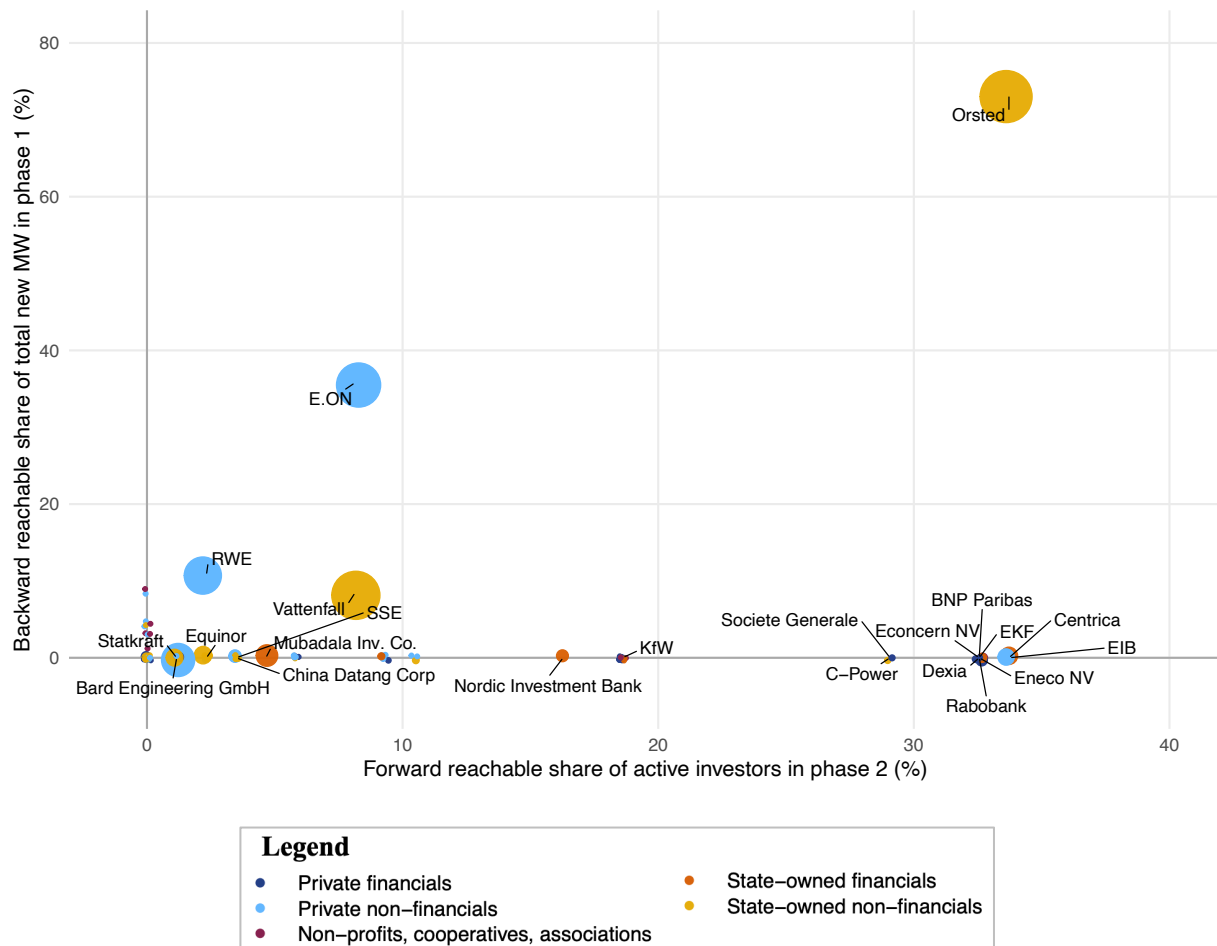
This section considers what the reachable sets of all active investors at the demarcation between phase 1 (1989-2001) and phase 2 (2002-2009) can elucidate about the know-how flows across these early periods of OSW investment. The juxtaposition of know-how exposures and know-how diffusion potentials in Figure 7.1 reveals four main insights regarding these two periods. First, the early pioneers in OSW investment and the fragility of know-how flows between the two first phases become more clearly identifiable. Second, project finance with banks emerges as an important alternative to the utilities' balance sheet financed projects, which promotes cost discipline and prudential risk management and opens a way to finance at a cheaper cost of capital. Thirdly, the impact of the great financial crisis (GFC) shows the importance of precedents in financing in relation to successful project financing undertaken before the crisis disrupted the financial sectors globally. Fourth, we get a clearer impression of how SIBs can buttress the early large-scale deployment of emerging sustainable technologies.

7.4.1.1. Few early carriers of know-how

One of the main characteristics of Figure 7.1 is that only a few active investors in phase 2 held most of the exposure to the MW installed in phase 1. The Danish SOE Ørsted stands out with

exposure to 73% of the 556 MW total new installed capacity in phase 1. This was almost entirely based on direct investments, most notably in Horns Rev 1 and Rødsand 1 which were the harbingers of the ensuing growth phase in OSW. Ørsted's superior know-how base formed rather accidentally through a disorderly merger-rush in 2005 where Ørsted (then DONG Energy) ended up owning utilities that separately had pioneered the early OSW market.

Figure 7.1: Know-how exposure from phase 1 (1989-2001) and diffusion in phase 2 (2002-2009)



Note: The Y-axis displays the share of total installed offshore wind capacity (MW) in the preceding phase that each investor could have obtained know-how from through their backward co-investment networks.



The X-axis shows the share of total active investors in the ensuing phase, whose know-how each investor could have influenced through their forward co-investment network. The size of the nodes reflects the relative amount of capital invested in new parks, i.e. not refinancing and acquisitions, in the ensuing phase. The largest node size for the largest investor is fixed across the four charts, while the underlying nominal investment amounts can variate. 556 MW were financed in phase 1. The data has been adjusted to account for that E.ON's backward reach could not span utilities that would first merge with Ørsted (then DONG) in 2005. This means it could not benefit from the know-how from Middelgrunden (40MW) and Horns Rev (160 MW). **Source:** Dataset compiled from BNEF, IJGlobal, and own data collection.

This know-how base would cause Ørsted's management to pivot strategically to OSW in 2008 at the expense of its activities in coal, gas, and oil (Voldsgaard and Rüdiger, 2021). The German utility E.ON could reach 36% of the MW installed before 2002 based on its participation in Blyth in the UK and the co-investment with Ørsted (then DONG) in Rødsand 1. Besides a few minor investors who left the market, such as Danish energy cooperatives, General Electric, and Shell, only the utilities RWE and Vattenfall made up a third tier with backward reaches to around 10% of the installed capacity.

Among these investors carrying know-how into phase 2, Ørsted stands out as the one with superior potential for having influenced the investors by having a forward reach of 34% of active investors, while the other three utilities could reach less than 10%. This result reflects the network patterns we saw in Figure 6.1 and Figure 6.2, where utilities generally preferred to invest alone on their own balance sheets or together with other utilities to learn and reduce risk exposures. This finding is complemented by Figure 0.13 (Appendix G), which shows Ørsted's early forward reach was mainly caused by its co-investments with the EIB and Centrica, who were both involved with early instances of bank financing of OSW.

Along the X-axis, we find the investors who did not invest in phase 1, ordered by their forward reach. The widest reach is held by EIB and Centrica at 36%.³⁵ EIB's reach was large because of its connection to Ørsted and its involvement in some of the first uses of project financing. The

³⁵ They have the same reach as Ørsted since both invested with Ørsted in 2004.



banks and developers who pioneered project financing in the Netherlands and Belgium make up the second tier on the X-axis with 29-32% forward reach.

Centrica achieved a large reach mainly because it refinanced its Lynn & Inner Dowsing farm in 2009 with 15 banks³⁶, including the German SIB KfW, and one US private equity firm. The financiers who only participated in this deal reached 18% of active investors. With smaller reach, we find investors who initiated or contributed to projects with balance sheet financing, such as Chinese and Norwegian SOEs, the experimental Bard Engineering firm that sourced all components in-house, the Nordic Investment Bank (NIB), which provided loans for both Ørsted's and E.ON's wind park expansions in Denmark, and the UAE sovereign wealth fund, Mubadala, which co-invested in 2009 with Ørsted and E.ON in the large new London Array Park (630 MW).

The node sizes in Figure 7.1 reflect the finding from chapter 6 that energy utility companies were the major investors in the second phase³⁷ when offshore wind projects were scaled up, and 4,569 MW were deployed in total. Moreover, this deployment was mostly accomplished by investors with know-how from past projects (8%-73% exposure to past MW). Nonetheless, the project financiers located on the X-axis generated important learning-by-doing that would contribute to the future evolution of the investor network.

7.4.1.2. The introduction of project financing

The large difference in forward reach between most of the utility investors and the banks and smaller developers who had >18% investor reach shows the advent of a new, more interactive financial model: project financing. Project financing entails the establishment of a project-owning entity, which obtains financing from both equity and debt providers. The debt providers do not have recourse to the equity providers' balance sheets in case of failure to repay loans, which is why banks effectively assume construction risk with this model.

³⁶ The group included public, private and cooperative banks.

³⁷ In chapter 6, the node sizes also included capital invested in refinancing and acquisitions, in addition to primary financing.



These more networked financing events with multiple investors, incl. banks, developers, and additional equity sponsors, created early opportunities in phase 2 for learning about OSW investment that could slowly propagate in the financial sector. One cause was the “quirk of history” (Guillet, 2022, p. 18) in the OSW industry that small developer firms won the rights to a substantial amount of the early OSW sites. Unlike the large utilities, they did not have the capital available to construct a full OSW park and were therefore forced to seek external financing.

As mentioned before, commercial banks did generally not have an appetite for risk in a still unproven technology and industry. The two main banks that organised the first instances of project financing in the Netherlands and Belgium were Dexia and Rabobank. The expert interviewee Jérôme Guillet was employed with Dexia. He utilised his previous experience with project finance in the natural gas industry in the context of Dexia’s early positive experiences with onshore wind financing, which was less risky and complicated compared to OSW.

Project financing was a potential way to finance projects by smaller developers, but it required “intrusive” transparency in project management so banks could perform their due diligence. The banks would need to be able to assess the risks of construction issues and whether the project teams had the right know-how to handle eventual problems as they arose without jeopardising debt repayment. This required rapid learning as well as optimism. It is worth examining a few early investments to understand how learning was generated and diffused early on.

Princess Amalia (2006) was the Netherlands’ first offshore wind farm, and the first occasion commercial banks assumed risk under construction and commissioning phases without recourse to the sponsors’ balance sheets. This reflected a growing trust that the developers’ and contractors’ fixed investment know-how would lead to construction on time and on budget. This confidence had been cast in doubt after equipment manufacturers declined to assume responsibility for ‘turnkey’ completion, i.e. ready-to-operate parks (interview 2). The various aspects of offshore wind park construction were too dissimilar, without any dominant cost component that would make any single contractor willing to take responsibility for the delivery and performance of the full project.



This lack of guarantor was solved by Princess Amalia's project developers "carefully constructing a web of contracts parcelling out the various risks to [the construction phase counterparties] best able to absorb them" (ibid., 22). This contract management role increased project development costs compared to pure balance sheet financing as it required deep and transparent due diligence and placed a new type of risk on developers (and ultimately their debt providers) of managing the interface of the project risks being allocated in cases of overlooked and unallocated risks.

Princess Amalia was, therefore, one of the most important diffusion events in phase 2 as it both pioneered project financing in offshore wind and convened nine investors³⁸ (Wind Power Monthly, 2006). Crucially, the Danish export credit agency (EKF) was included based on the intended deployment of Vestas turbines. Guillet (2022) described how EKF provided:

a substantial portion of the contingent funding to the project ... This helped create larger buffers for adverse scenarios and allowed the commercial banks to be more comfortable taking the overall construction risk: with no funding beyond the committed buffers available to solve possible problems, having these buffers mainly funded by EKF provided substantial additional comfort to all.

This was an early case of catalytic de-risking investment by a SIB, as it enabled the first project financing, which would serve as a template for later projects.

Next year, Belgium's first, but smaller, offshore wind farm Thornton Bank (2007) reached its 'financial close', i.e. collective decision to invest. Like Princess Amalia, it had Rabobank and Dexia as debt providers³⁹. Thornton Bank had other developers and debt providers involved, so Rabobank and Dexia stood out as crucial learning bridges for spreading familiarity with the project finance model. Both projects ran into severe and costly construction issues (ibid.), but the

³⁸ Incl. EKF, Rabobank, Dexia and French SOE EdF.

³⁹ Rabobank, Dexia, Societe Generale, Investec and the developer C-Power.



project teams found workable solutions and saved expenses in other areas, such as by installing during autumn and winter.

In addition to displaying abilities to overcome problems, the timing of these transactions was important for the evolution of the investor network. They took place in the generally positive investment atmosphere before the GFC when investors were both optimistic in general and open-minded to OSW based on positive experiences from investments in onshore wind and the success of Rødsand 1. Therefore, attracting financing became easier, although this situation would change a few months later (ibid.).

7.4.1.3. *The path dependency of positive precedents*

These two instances of project financing provided important positive precedents that would make it easier for banks to approve lending to OSW after the GFC and regulatory responses had generally limited banks' appetite for risk and leverage. Following the GFC, investors became more reluctant to lend, and margins increased. As Figure 5.6 showed, banks used a 1.5-2.0% premium in addition to the risk-free base interest rate before the GFC, and the mark-up rose to 3.0-3.5% during 2009-2013. This shift meant that OSW did not benefit from the general reduction of monetary policy interest rates during the crisis (interview 2).

Notwithstanding, the market for private financing did not freeze up for several reasons. Banks focused on their core, low risk markets, which included the Northern European countries that promoted the deployment of OSW by subsidising and de-risking demand and through SIB investments. Importantly, the two early project-financed parks provided positive reference points for subsequent investments. Guillet (2022) describes their impact:

For a lot of reasons, lenders love (successful) “precedents” – something that has been done before and has worked is a lot easier for them to approve again and do again. Part of that is that once you have made the effort to understand a particular technology, or regulatory framework, or category of risk, it is much easier to assess a project that falls in the same basket. Part of it is that a

history of profitable transactions in a sector is more conducive to doing more business in that same sector than if losses have been incurred. A less flattering reason is that banks prefer to be wrong in groups than right alone – so doing something that a lot of other peers are doing already is seen as reputationally safe.

These insights into the sociology and psychology of offshore wind investors underscore how important the timing of the first successful instances of bank financing with construction risk was. Without positive precedents from the pre-GFC era of financial optimism, smaller project developers may not have been able to fund their projects following the GFC.

Moreover, the quote reveals the peer effects and group psychology that sway investors to go with the direction of the rest of the industry. The quote above echoes Keynes: “Worldly wisdom teaches that it is better for reputation to fail conventionally than to succeed unconventionally” (Keynes, 1964 [1936], 158). This is coherent with the theoretical insights from complexity and Keynesian economics that describe finance and investment as self-reinforcing mechanisms that over short periods can move towards booms or busts when “animal spirits” raise or lower business confidence (Ibid., 161) – rather than adjusting towards an optimal equilibrium.

These impacts of positive precedents, experience, and group dynamics suggest that advancing deployment of new technologies should be one principle of policy pursuit of raising green animal spirits. This adds to the arguments for front-loading sustainability transitions, including advancing technological learning curves (Way et al., 2022) and the longevity of installed capital goods (Vogt-Schilb et al., 2018).

Yet, it was not given that these projects would turn out to be positive precedents for the future. Previous projects had experienced technical problems, including the serial defects on gearboxes at Horns Rev 1 (Ørsted), flaws in the wielding of the foundations at Greater Gabbard (SSE & RWE), and disputes with ill-suited oil and gas sector contractors at Barrow (Ørsted & Centrica), but they were constructed with balance sheet finance of the utilities why “much less public or semi-public information was made available about them” (Guillet, 2022, p. 10). Therefore, commercial banks were generally in a weak position in terms of know-how regarding how to



ensure they would be repaid. European banks were familiar with project finance from other industries but not the particular challenges with offshore wind construction.

Rabobank and Dexia, therefore, led an extensive, year-long due diligence effort with the developer team, contractors, insurers, and technical advisors to ensure the developer planned for as many plausible contingencies as possible and would have time and capital buffers to sustain delays and unforeseen costs. For instance, the project should be able to withstand delays of the construction phase into the winter months, which in turn implied they would have to wait for warm weather to return next spring due to the harsher conditions and thus risk the unavailability of construction vessels also used by the oil and gas industry. The conservative approach by the banks led the developers to have all contracts with risk-mitigating clauses in place before the start of construction, which became the norm in later project financing (*ibid.*, interview 2).

Princess Amalia and Thornton Bank both experienced significant problems in the construction phase, which led to delays and ad-hoc solutions that jeopardized the future willingness of banks to take on construction risk. The Dutch park ran into problems as the construction crane was damaged beyond repair as it fell over on the quayside, which led to several months of delay that pushed construction into the harsher winter season. When the concrete foundations of the Belgian project were being filled with sand, the tube that was supposed to house the cables within the foundation collapsed under the pressure and prevented the connection to the grid. Both issues were solved with custom solutions that led to delays and additional costs.

Although these project-specific issues had not been identified in the planning phase, the contingency buffers were sufficient to deliver the projects on time and within budget⁴⁰ (*ibid.*). Besides the importance of their timing, the sector benefited from the substantial variation between the two early, succeeding projects. There were different developers, different turbines and other contractors, and different regulatory regimes in different countries – and yet both turned out well, thereby signalling the robustness of the fixed investment know-how in the sector.

⁴⁰ The Princess Amalia project team managed to construct on milder days in the winter season and thus allowed some catch-up on the delays, since no construction had been planned for in this season as a conservative assumption.



7.4.1.4. *State investment banks enter as counter-cyclical and entrepreneurial investors*

In 2009, the final year of phase 2 and the beginning of the post-GFC era, the financial sector had become more reluctant to finance OSW. EKF had previously shown how SIBs could play an enabling role by providing the riskiest debt and guarantees for Princess Amalia, but 2009 showed that SIBs could also enable the market by taking a more volume-based and countercyclical role.

There were two important multi-party financing events this year, the Belwind Offshore Wind Farm (2009) and the non-recourse refinancing of Centrica's Lynn & Inner Dowsing Wind Farm (2009) that both transpired as the GFC was shaking financial markets and the prospects for electricity demand. Centrica refinanced its recently completed 194 MW project, whereby the 15 debt providers benefited from the first large investment opportunity for absorbing know-how from the UK market without taking construction risk.

Meanwhile, the financing of Belwind was more noteworthy as the developers and sponsors required banks to assume construction risk despite the heightened state of uncertainty. Also, its 165MW was larger than the combined size of the two previous project-financed parks. Belwind "replicated a lot of what had been done in the earlier two projects" (Guillet, 2022, p. 25) by using the same contractors as Princess Amalia and by being positioned in Belgium. The lead investors again contained Rabobank (equity and debt) and Dexia (debt), despite the latter going bankrupt in the process because it was permitted to proceed with the investment following a public bailout. Another influential event occurred when the main developer Econcern went bankrupt just before construction began, which required the banks to identify the key staff to be transferred to a new project organization with new investors (ibid.).

Yet, the main financial innovation at Belwind was the inclusion of EIB who assumed non-recourse construction risk in offshore wind for the first time, as it built on previous experience with less risky debt deals with Ørsted⁴¹. In this early phase, commercial banks were still

⁴¹ The EIB had provided debt refinancing to three of Ørsted's (i.e. predecessor companies before mergers) completed projects, Horns Rev I and Rødsand I (both DK), and Gunfleet Sands (UK), and primary debt financing with recourse to Ørsted's (then Dong Energy) balance sheet for Barrow (UK) and the Horns Rev Expansion (DK).



reluctantly taking on new forms of risk exposure and would resist supporting projects relying on more than 50-60% debt financing (Figure 5.6), which translated into a higher WACC. Yet, with EIB's involvement in combination with extensive loan guarantees by EKF, Belwind was financed with a 70% debt ratio, which lowered the WACC for the project, although the cost of debt had risen to between 3-8%⁴². Together, EKF and EIB assumed the risk on 70% of the debt provided to Belwind (EIB, 2009; IJGlobal, 2009).

Belwind was, therefore, an early example of the critical importance SIBs would have for getting OSW financed through the difficult third phase (2010-2015). Through these critical engagements, EKF and EIB had an early impact on how the financial ecosystem would evolve by helping to establish the project finance model, which is reflected in their high forward reaches in phase 2 (Figure 7.1).

In short, the transition from phase 1 to 2 was characterised by the continued investment by the investors with the most know-how exposure from phase 1, while the EIB and EKF contributed to the self-organising processes in the bank sector working to provide financing for smaller developers in the Netherlands and Belgium. The timing of the first instances of project finance established important positive precedents before the GFC, which paved the way for more bank involvement in the subsequent growth phase.

7.4.2. Path analysis across phase 2 and 3: More network paths emerge

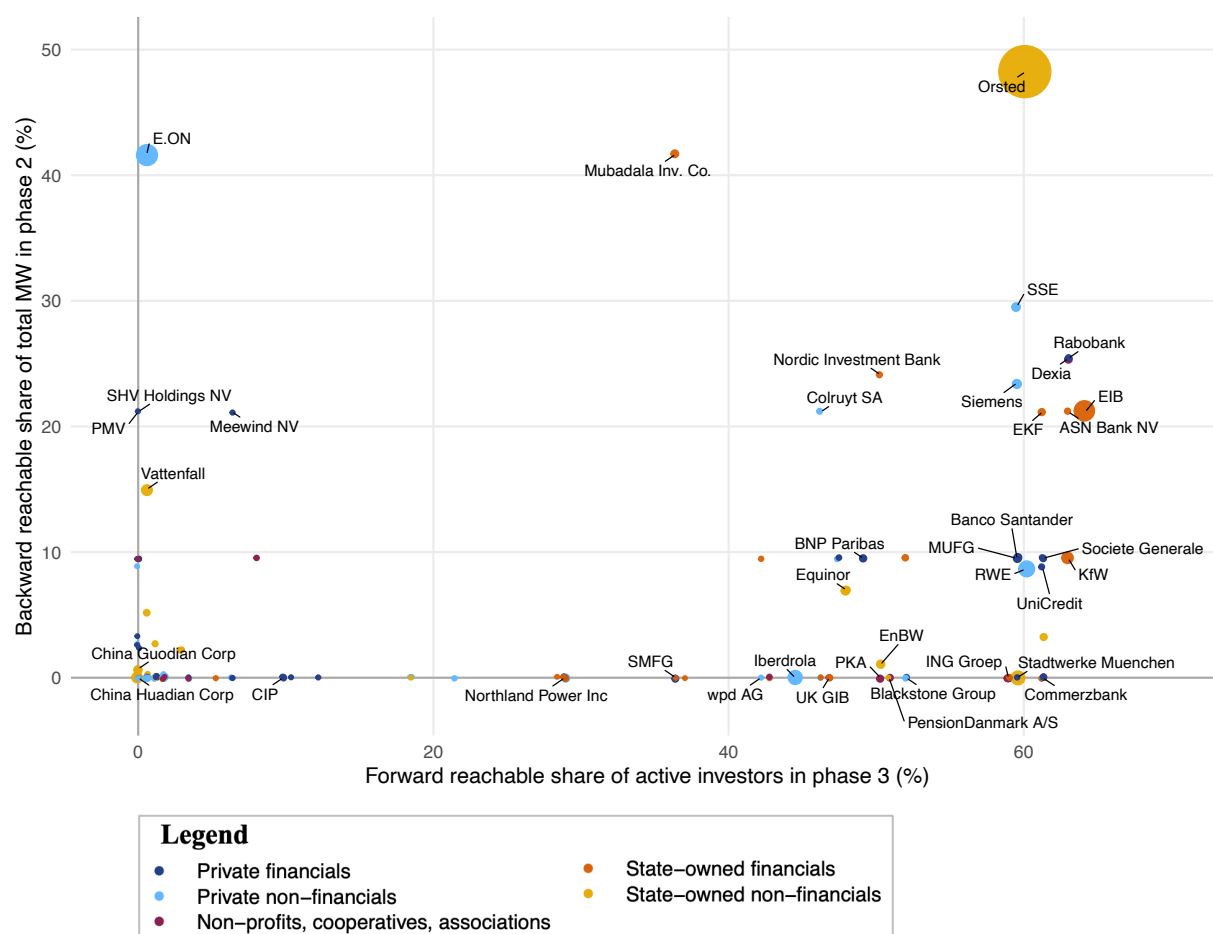
At the boundary between phase 2 (2002-2009) and phase 3 (2010-2015), some new trends appeared in the evolution of the investor network. There were 1) a more diversified flow of know-how based on the new market entrants in phase 2, 2) a robust response to adversity in the sector, including higher cost and construction difficulties, 3) SIBs in more central and expertise-based roles, and 4) financial innovations to include institutional investors in the network.

⁴² Under the combination of de-risking by EKF and pessimistic financial market circumstances the senior debt was priced at 3.0-3.5% above risk free rate on debt, debt committed to cover contingent expenses costed additional 0.5%-points, while the mezzanine debt tranches came at a cost of 6-8% (IJGlobal, 2009).

7.4.2.1. A more diversified flow of know-how

The right side of Figure 7.2 displays how the investor network had evolved and become increasingly populated by investors with combinations of high forward reach (approx. 60% of active investors in phase 3) and varying degrees of backward exposure to OSW installed in phase 2. Ørsted again stands out as the main know-how bridge between the two phases, with a backward reach to 48% of capacity installed in the previous phase (2,204MW out of 4,569MW). Ørsted's partners in the 2009 London Array project, E.ON and Mubadala, have a similar 42% backward reach but considerably less forward reach compared to Ørsted.

Figure 7.2: Know-how exposure from phase 2 (2002-2009) and diffusion in phase 3 (2010-2015)



Note: See the note for Figure 7.1. 4,569 MW were financed in phase 2.



Yet, while Ørsted was the only investor with both high forward and backward reach in phase 2, twenty-two investors had a reach to between 7%-30% of past MW and above 40% of the investors in phase 3. The upper group in this formation contains a mixed group of investors. Rabobank and Dexia are there because of their central roles in establishing project finance in OSW, and who built upon their experience by being centrally placed investors in the phase 3. In addition, the group contains the three SIBs who supported the first growth phase (i.e. EIB, EKF and NIB). Especially, EIB stands out with the largest investor reach (64%) and second most capital provided for new parks in phase 3, only surpassed by Ørsted (by nearly a factor of 3). In addition, the group contains two smaller developers and Siemens, who used investments to secure turbine supplier contracts⁴³.

Further below, with approximately 10% in backward reach, we find a group predominantly consisting of private international banks, including Societe Generale, Banco Santander, Unicredit, MUFG and BNP Paribas, two smaller developers, and KfW, which was among the top investors in phase 3 in terms primary investment and forward reach. It was not accidental that these private banks were involved. French banks were historically experienced with project financing, and they were staffed by French engineering graduates who were educationally well-equipped to understand the technicalities of energy and infrastructure investments and conduct mathematically demanding financial assessments (interview 2).

Moreover, the Japanese banks generally possessed ample foreign currency liquidity (ibid.), plausibly based on Japan's many years of balance of payment surpluses. These banks used their early know-how advantage in OSW to seize upon the growing opportunities for project finance. Guillet (2022) recounts the dynamics in the early phase of project financing in OSW:

The market was built around a few sectorial pioneers (Dexia, Rabobank) and experienced project finance lenders ..., and slowly attracted a wider universe

⁴³ Sometimes equity investment was demanded by the financial advisor/lead arranger bank as a competitive parameter (interview 2).



of banks that have less experience but are willing to follow the lead of the core banks. In that sense the sector has followed the traditional route of growing maturity that new sectors typically do.

Hence, the network had an endogenously developing group of ‘core banks’ with a know-how advantage in relation to assessing projects, structuring contracts, and the technological tendencies in the sector.

This is a source of path dependency in the evolution of investor ecosystems since well-connected actors can leverage the learning obtained from their investments and interactions to prosper in the future. Indeed, Figure 7.2 shows a tendency for investors who had high know-how exposure in phase 2 to also possess high forward reach in phase 3. Generally, the investors with wide access to early know-how prospered as OSW financiers in this phase. Moreover, less knowledgeable investors would exhibit a tendency for preferential attachment towards these investors to lower their own risk, which would further improve their position in the investor network (Barabási and Albert, 1999). For instance, one interview revealed that Iberdrola’s first primary investment in OSW was a co-investment with Ørsted and EIB in West of Duddon Sands in 2012, motivated by a desire to absorb know-how from Ørsted (interview 1, see also Figure 6.3). Iberdrola would later become a main investor in OSW without co-investors. In addition, Figure 6.9 showed a tendency for banks with many ties to obtain more ties as the network grew.

There were also successful newcomers with high forward reach positioned towards the right end of the X-axis. Above 40% of forward reach, there is a diverse mix of investors. The largest investors were the three utilities, Iberdrola, EnBW, and Stadtwerke München. The market was also joined by less prevalent investor types such as US private equity firm Blackstone, Danish cooperative pension funds PKA and PensionDanmark, and the UK’s SIB, the GIB, that was created in 2012. On the left end of the axis, among others, there are Chinese SOEs, which continued to invest largely in isolation and Copenhagen Infrastructure Partners (CIP). CIP was founded by a group of senior managers at Ørsted who had developed the utility’s integrated approach between financing and developing (more below) and now attempted to capture market shares as a combined financial fund manager backed by institutional investors as a ‘greenfield’



developer of new projects (interview 1). It was thereby a financial innovation aiming to overcome the structural barrier of inadequate investment vehicles (Ameli et al., 2019), which exemplifies the self-organising behaviour of the investor system.

7.4.2.2. Responding to adversity

A second characteristic of the third phase was that the investor community proved resilient in the face of adversity. As mentioned, developers had generally proven capable of overcoming and learning from the issues they inescapably faced with basic technological uncertainty and immature supply chains that often had to rely on ill-suited contractors from the oil and gas sector. The market was in the process of advancing from the experimental and technology-oriented phases 1 and 2 to the more industrialised and cost-focused phase 3 (Jennings et al., 2020; Voldsgaard and Rüdiger, 2021). The cost focus was prompted by the rising costs through phase 2 which had plateaued after the GFC (Figure 5.5) under concerns about the willingness of policymakers to continue the generous subsidies required at the time (Lockwood, 2016).

Several issues in the emerging German OSW market raised concerns. Particularly the instance when Unicredit had to take over the technologically ambitious, though failure-ridden, 400MW BARD1 park that ended up completed three years behind schedule with a cost overrun of around EUR 3bn. BARD1 was challenged by its sponsor, Bard Engineering, making all components in-house rather than relying on the best suppliers in the market. Also, the site was located 90 km from shore, which was far beyond what had been attempted before. Unicredit had provided a EUR 200M loan in 2008 before financial markets were hit by the GFC, and the bank saw itself forced to recapitalise and eventually take control and finish the project when Bard Engineering went bankrupt in 2013 (Guillet, 2022).

While BARD1 stood out as the most problematic project, the wave of five 288-400MW parks that would commence construction in Germany between 2009-2012 would, to a smaller extent, share its fate with cost overruns and delays (Kostka and Anzinger, 2016). Three of the parks had cost overruns between 8-30%, while BARD1 went 93% above budget and was deemed an “expensive disaster” by The Economist thus casting doubt on the future of OSW in the German

Energiewende policy programme. Moreover, the constructions were delayed by 6-24 months due to technological, environmental and transmission challenges (Ibid., 176).

The transmission system operator TenneT was obligated to provide subsea transmission cables for the offshore parks, but Tennet and its main supplier, Siemens, could not keep up with the synchronised wave of parks that were completed around 2013 and 2014. They struggled both with discoveries of wartime material on the seabed and getting the direct current transmission technology working, as it was more suited for the long distances off the coast in Germany. This led to foregone revenue for the generators, which would eventually be 90% reimbursed by TenneT, who raised tariffs on the consumers to fund the cost (Ibid., 162, 170). One study finds that the German developers' struggles to keep construction on budget and schedule contrasted with Ørsted "because [Ørsted] have achieved the scale to build integrated supply chains which helped them solve logistical and financial problems that other wind park developers faced" (Ibid. 179). In other words, Ørsted's learning-by-investing resulted in superior fixed investment know-how. To reduce exposure to such risks, banks markedly increased their contingency budget requirements between the years 2014-2017, after when they fell below the pre-2014 level (Figure 5.6). To avoid scepticism spreading in the investor community from the difficulties in the German market and the generally elevated costs, SIBs had a key role as accumulators and diffusers of technical and financial expertise.

7.4.2.3. State investment banks as trustworthy partners

The three SIBs, EIB, KfW, and EKF, all exhibited high forward reach in phase 3 and noteworthy backward reach in phase 2 (Figure 7.2). Their considerable involvement stems from three main causes. Skakkebæk explained that they were more risk-embracing than other actors. While banks preferred senior debt, which is first in the creditor hierarchy, SIBs were more willing to provide mezzanine or junior loans, which would be serviced after senior debt (interview 1). Guillet and Skakkebæk both argued that one of the main strengths of the SIBs was their ability to provide much larger loans per project than banks, which lowered the need for finding banks with high



OSW know-how, which were still in short supply in phase 3 (interview 2). A third reason was their extensive accumulation of know-how, which made them trusted co-investment partners.

One example where the risk-taking by SIBs facilitated know-how diffusion was when the EIB financed the German Global Tech 1 park (400 MW) in 2011 (Figure 6.3). The eight equity sponsors received loan finance from a consortium of 17 financials incl. the EIB and KfW. The bank consortium provided \$347m, while EIB provided a separate loan of \$128m. Crucially, the EIB also set up a \$514m loan guarantee for the remaining banks and thereby de-risked their participation, which enabled a wide range of investors to learn at low risk (Power Technology, 2014).

A few years later, another high-profile instance of project financing showed how the investor ecosystem was maturing. The sponsors behind the 600 MW Gemini park (2014) in the Netherlands, which at the time was the world's largest project, had to raise EUR 2.2bn in debt via the largest project finance structure to date in OSW. Guillet, who advised on the deal, recounts that it was “so much larger than anything that had ever been done. So we effectively needed every single bank that understood offshore wind to join, including EIB and EKF” (interview 2). They assembled a consortium of 12 banks, out of which EIB provided one-third of the debt, in addition to support from three export credit agencies (Guillet, 2021, 2014).

After the Gemini deal, Guillet inferred that the willingness to participate among lenders indicated that the wind market was “deal-constrained rather than liquidity-constrained” (Guillet, 2014). In other words, the investor ecosystem and fixed investment know-how of developers had co-evolved to a new level of maturity, although SIBs still played a substantial role in terms of providing capital and de-risking adverse scenarios. The Gemini park opened ahead of schedule and below budget in 2017 and was later refinanced at lower rates to increase profitability for the sponsors (Renewables Now, 2017), which further raised confidence in the sector's ability to scale up and be profitable.

The third strength of SIBs was that their wide engagement in the sector also gave them a network-based advantage for building up investment know-how. Their central positions in the network stemmed from the fact that until 2017, at least one of EIB, KfW, and EKF participated in 18 out



of the 21 new farms that were project financed with bank debt. Skakkebæk explained that the impact of SIBs occurred on the backdrop that “most of the banks were not very competent in this area in the beginning – some have become very competent by now though. Having someone with expertise who had participated in nearly all transactions and knew how things were, it was huge and provided robustness to the deals” (interview 1).

Skakkebæk complimented EKF as “super competent at financing offshore wind compared to other similar actors. Comparing with the Department of Energy in the US, they are lightyears ahead. It is a question of knowledge of projects that one accumulates. They understand risk in a different way” (Ibid.). This know-how base led to signalling effects in the investor community: When EKF “are in [a financing deal] taking a chunk of the risk, it is also a stamp of approval because they have extensive experience in the same way as the EIB has done it. It neatens the project and makes it look attractive to investors.” (Ibid.)

Considering KfW, Moslener et al. (2018) find that the German SIB’s success as a strategic investor also stems from its “extensive technical and engineering expertise”, which distinguishes it from commercial banks. When the KfW initiated a dedicated offshore wind financing programme in 2011 for supporting projects with up to 50% of the necessary borrowing (KfW, 2015; Kostka and Anzinger, 2016, 157), it already had one of the “top teams in the OSW sector” in its commercial lending branch, IPEX⁴⁴ (interview 2).

Another case study finds that KfW’s investments in its internal expertise in OSW were crucial for filling the “expertise gap” in relation to identifying, assessing, and mitigating risks in the German developer and investor communities, which had rendered it “very challenging to source finance” (Geddes et al., 2018, p. 165; Karltorp, 2016). KfW invested in most German OSW parks in addition to some investments in the UK, Netherlands, and Belgium and worked closely with

⁴⁴ However, the maximum leverage they would accept for projects in the promotional programme meant that most KfW lending continued through the regular channel (interview 2).



developers and insurers in the planning phase. Its technical staff built up know-how capabilities by getting first-hand experiences:

KfW staff actively visit sites and investigate innovative technology to develop their expertise. As one developer said ‘KfW know renewable energy inside out...they have a real technical grounding in understanding how renewable energy works’ (ibid., 165).

Not only the developers benefited from KfW’s know-how base. The case study also found that KfW had an important educational and signalling role for the commercial banks curious to engage with this emerging infrastructure asset class:

Banks especially had a lack of knowledge and KfW IPEX regularly took the lead role in syndicates, helping to educate participating banks on the risks involved. Interviewees described KfW IPEX as ‘a real opinion leader’ where they are known to be ‘the technical bank’ in any consortium. IPEX’s due diligence processes, risk assessments and registers are considered throughout the industry to be ‘technically excellent and accurate’. They then bring these processes and knowledge to other investors, helping them to become familiar with the risks (Ibid., 165-166).

Because of the combination of investments in internal technical and financial expertise and a track record of large-scale capital investments in OSW, KfW’s decisions to invest signalled the soundness of the targeted projects to the wider investor community (Geddes et al., 2018).

The EIB had a similar business reputation based on its internal due diligence processes and in-house technical staff (EIB, 2022, interview 2). The arrangers of project financing had to weigh off the extra work that it entailed to include EIB and KfW since “they had their own due diligence and other guarantees and documentation requirements which could be very painful” (interview 2). On the other hand, the project could obtain cheaper financing compared to the marginal banks that would otherwise set the terms, and their inclusion would also signal the soundness of the project: “some would say if it's been vetted by EIB then it's good enough for us. So, it sort of



helped to bring some of the second-tier banks in and some of the German banks (...) But in terms of what they required, I don't think they did more than the technical advisors we were using, other than somewhat formal requirements [like massive MonteCarlo simulations]" (Ibid.). Insofar as these SIB procedures created further reasons for optimism, they could be used as an argument with the banks for improving commercial terms, e.g. a reduction of the contingency budget (Ibid.).

The main financial and technical advisors in OSW formed "good relations" with the EIB's technical team and included them pre-emptively in due diligence processes. Remarkably, the EIB experts "were willing to do that early due diligence even without knowing if they would be part of the financing in the end or not" (Ibid.). So, the SIBs formed an integrated part of the rather centralised process of know-how generation in project financing around the core banks and the few trusted advisors in the sector.

7.4.2.4. Integrating institutional investors through financial innovation

While the continental European OSW market developed with more reliance on project financing, this mode of financing had difficulties emerging in the large UK market. When Ørsted, Centrica, and Siemens sought finance for their Lincs project, they were in difficult negotiations over three years from 2009-2012 with the project financing banks over how much transparency regarding contracts and contingency plans the project owners should offer. The construction was well underway when they finally reached an agreement, however, it left "a bitter taste to all" and "London-based bankers and investors saying publicly and wrongly, for several years, that construction risk could not be financed even as their continental colleagues were doing multiple transactions" (Guillet, 2022, p. 31). Successful project financing in the UK first occurred for the Galloper project in 2015, which was mentioned in chapter 6 as a signal of the maturation of the investor ecosystem. There was, until then, a bifurcation in the investment capabilities between the UK and continental European financial systems and an apparent mismatch between the utility investors active in the UK and the available sources of finance – although the EIB partially filled this gap.



As Ørsted needed capital to finance its investments and project finance was deemed unattractive to Ørsted's business model, the SOE pioneered financial engineering of balance-sheet financed projects in the UK and Danish markets (Voldsgaard and Rüdiger, 2021). The company saw great potential in recycling the capital previously deployed in farms under construction or in operation by selling minority stakes to institutional investors such as pension funds – a model known in the industry as 'farm-down' (interview 1). The CEO at the time, Anders Eldrup, explained "States do not really have the money, the banks do not want to lend, and the energy companies do not earn what they once did. But institutional investors like insurance companies and pension funds have the money" (Adolfson, 2011). The 'farm down' practice would allow Ørsted to earn capital gains by taking projects through the risky construction phase and sell ownership stakes once they entered the long low-risk operational phase.

One illustrative example was when Ørsted in 2016 sold "a 50% stake in its upcoming [\$1.1 billion] 258MW Burbo Bank Extension to Danish pension fund PKA and Lego owner Kirkbi for [\$1 billion]" (IJGlobal, 2021). In other words, the project *doubled in value* by clearing the construction phase and became attractive to more risk-averse investors with a lower cost of capital. The adoption of this capital recycling practice would later allow balance sheet developers to submit more aggressive bids in contract auctions by anticipating these windfall profits (Guillet, 2022).

This financial innovation is the reason why we see pension funds emerging on the horizontal axis in Figure 7.2. The financial technique was pioneered in 2010 when PensionDanmark acquired 50% of the once ground-breaking Rødsand 1 park in Denmark in a deal where Ørsted de-risked the cash flow that the pension fund would receive in case of volatile electricity prices. A few months later, the Dutch pension fund for the healthcare industry PGGM and a fund managed by Triodos Bank acquired nearly half of Ørsted's Walney project (UK) that was under construction⁴⁵. Ørsted de-risked their investment by providing construction guarantees and a

⁴⁵ The UK utility SSE had acquired a 25% stake in 2009 before the construction commenced. PGGM and Triodos would only provide little liquidity for the ongoing construction, but would subsequently refinance their ownership stake with bank loans and repay Ørsted for its share of the cost (Offshorewind.biz, 2010).



power purchase agreement for their share of the output, so Ørsted would carry the market risk (Offshorewind.biz, 2010).

Next year, PensionDanmark and the PKA pension fund acquired half of Ørsted's yet-unfinished Anholt project under similar conditions (Adolfson, 2011). This started a learning process within the pension funds, and in 2013 PKA and Industriens Pension assumed construction risk when they invested equity in the project-financed Butendiek farm in Germany. In 2014 the latter two pension funds, together with two other Danish pension funds, bought a 50% stake in Ørsted's Gode Wind II project before construction started. PKA also provided non-recourse debt to the Gemini project mentioned above, and later acquired a stake in the aforementioned Burbo Bank park in 2016. PKA's managing director recounted their changing capabilities and role in the investor ecosystem:

“we normally go for greenfield [i.e. construction] projects because although the risk is higher, so are the returns. And because we have done several projects we think we can handle that risk, and therefore we will go for the higher returns. (...) When we did our first wind farm deal we could get higher prices as there were few other such investors out there. What we have now done is to move down the risk curve.” (Recharge News, 2017).

Ørsted had thereby found a de-risking formula for ‘mobilising’ its domestic institutional investors, who, in turn, learned from the experience and began to offer more patient risk-embracing capital to the offshore wind market.

In summary, the third phase of OSW investment from 2010-2015 was critical since the investor community had to mature to drive down the financial and installation cost of OSW. This occurred while facing an elevated cost level that raised doubts about the political willingness to sustain the market as well as the continually distressed macro-financial context in Europe (Guillet, 2021). Nonetheless, the transition from phase 2 to 3 saw an increasing pluralism in the investor ecosystem, with more types of investors accumulating know-how. A core of commercial banks and three SIBs had particularly large roles in integrating the network.



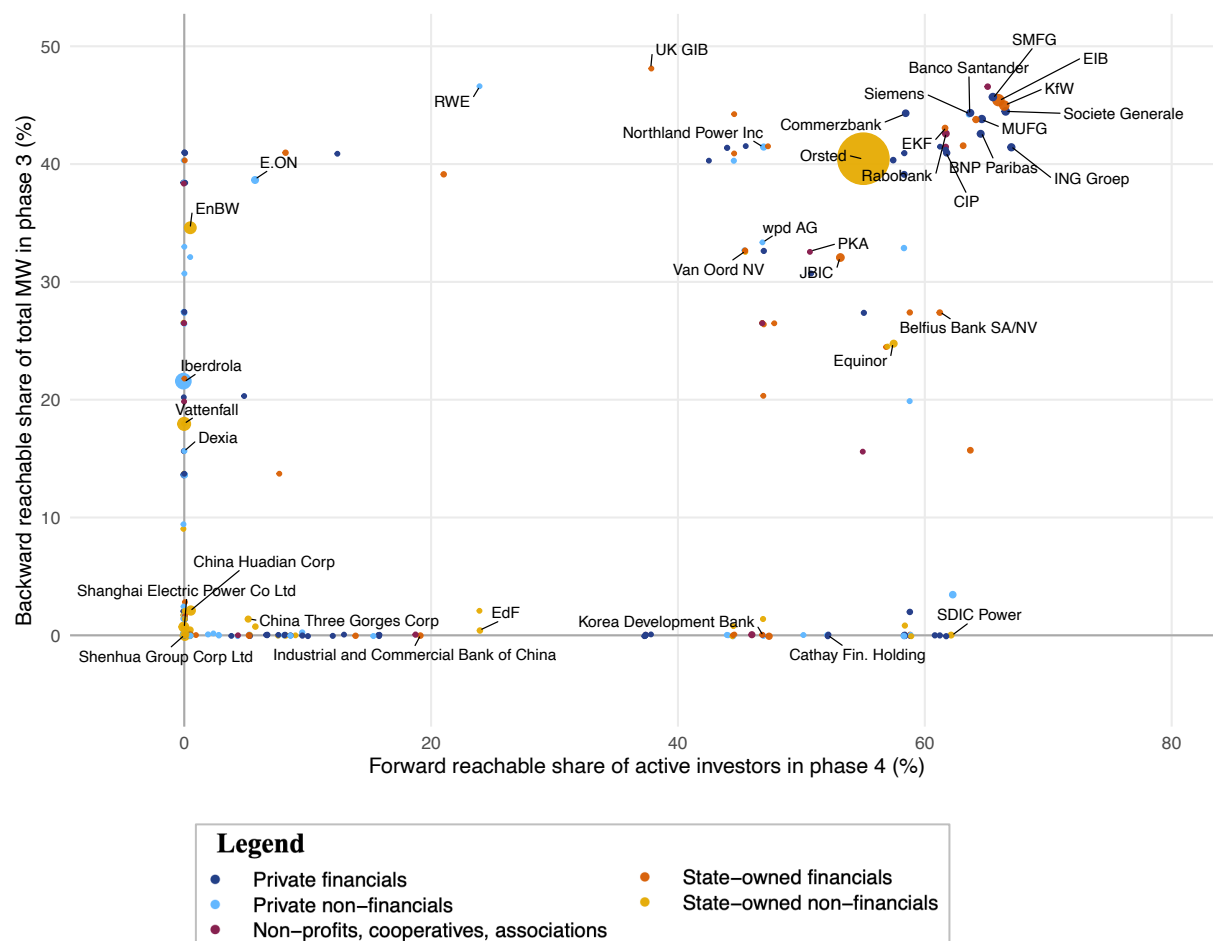
7.4.3. Path analysis across phase 3 and 4: Financial learning and engineering

In contrast to the previous phases, the next transition between phase 3 (2010-2015) and phase 4 (2016-2018) occurred in the positive atmosphere following the Paris Agreement reached in December 2015 and with a long-awaited falling cost trend for OSW (Figure 5.5). As we saw in chapter 6, the combination of OSW finally bending the cost curve during phase 3 and the positive political feedback signals attracted much larger private investment activity in OSW in phase 4. This occurred disproportionately through investments in existing assets via refinancing and acquisitions. In chapter 6, this was interpreted as part of a learning process as more investors became familiarised with OSW as an asset class. The structure of know-how flows in Figure 7.3 shows there was a consolidation of a dense financial core with high backward and forward reaches, a divergence in the strategies guiding the SIBs, and finally, a new wave of financial innovation that enabled the financialisation of OSW investment described in chapter 6.

7.4.3.1. Polarisation of the know-how flows

While Ørsted was clearly the main know-how carrier into phases 2 and 3, the structure of know-how flows changed markedly in phase 4. Figure 7.3 shows that the active investors in phases 3 and 4 cluster together in four relatively polarised groups. In the upper right corner, we see a large formation of investors with relatively high backward reach (25-47% of the 14,473 new MW financed in phase 3) and forward reach (43-67% of active investors). Within this formation, there is a consolidated core with the highest reaches on both metrics. In the bottom-left corner, we again see a concentration of Chinese SOEs with little connectivity, although now with larger investments, in addition to many smaller investors.

Figure 7.3: Know-how exposure from phase 3 (2010-2015) and diffusion in phase 4 (2016-2018)



Note: See the note for Figure 7.1. 14,473 MW were financed in phase 3.

Closer to the right end of the horizontal axis, we see new entrants that have also managed moderate-to-high forward reach. The group partly reflects the growing globalisation of OSW with the investments by Taiwanese Cathay Holding, Chinese SDIC Power, and the Korea Development Bank.

Along the vertical axis, we see the investors who either left the market, or pursued a strategy of investing in isolation. Most notably, this group contains five major utility investors with moderate-to-high backward reach: Vattenfall, Iberdrola, EnBW, E.ON, and RWE. The first two



invested in isolation. EnBW and E.ON could reach around 1% and 10% of the network. These four utility investors could rely on their previous learning-by-doing and their own balance sheets to invest. RWE could, more moderately, influence up to ca. 25% of the active investors because of its use of project finance in phase 4.

One reason behind their isolation, besides their accumulated know-how, could be the increasing competition in the sector, which could make them disinclined to cooperate closely with competitors as in phases 2 and 3. For instance, Jennings et al. (2020, 10) find that in the UK, “Knowledge sharing has decreased with the competition generated by [the contracts for difference auctions after 2013], but there are still pockets of cooperation.” For instance, Ørsted and Equinor have forward reaches to around 56% of active investors because of their co-investments. Equinor’s forward reach primarily stems from re-financing its Dudgeon wind farm, while Ørsted used project finance for Taiwan’s first large-scale park and re-financed three UK parks’ loans from banks and SIBs.

One structural difference from the previous phase is the absence of a vertical belt of investors on the right side, especially closer to the bottom. This is an indication of the network effects intensifying during the maturation of the investor community, where those who manage to invest with the core banks and SIBs are directly or indirectly exposed to much more of the network. These effects set them in an advantageous position for investing more and learning from the network.

7.4.3.2. *The know-how core*

Taking a closer look at the core of investors in the upper right corner, there are 21 financial investors, Siemens, and Ørsted, who again was the largest investor in new parks in phase 4. Furthest up in the corner, EIB and KfW are the second and third largest investors in the core group. Hence, while the private financials became considerably more active investors in this phase, the SIBs still maintained their system-shaping roles as leading liquidity providers and know-how conduits for new projects in phase 4.



The financials in the core comprise most of the banks that already had a know-how advantage from phase 2, incl. MUFG, Rabobank, BNP Paribas, Banco Santander, and Societe Generale. It also contained some of the newcomers in phase 3 who managed to get wide exposure to the know-how available, incl. Mizuho, Sumitomo Mitsui Financial Group (SMFG), ING Groep, Commerzbank, and the capital funds CIP and Macquarie. These private financials were most notable in this phase for their network reach rather than for their investment volumes. However, Societe Generale, SMFG, MUFG, ING Groep, and Banco Santander, surpass the experienced utilities E.ON and SSE in terms of primary finance, thus signalling a transition towards financial investor dominance.

Although the core contains many banks with similar reach, the interview with Guillet suggested that it was still relevant to distinguish between *core banks* and *second-tier banks*. Core banks have a strong enough know-how base to arrange the club deals and facilitate the main due diligence of the project. Second-tier banks generally have some experience with OSW and are confident enough in the expertise of the lead banks to co-finance projects⁴⁶ (interview 2). Almost all of the fifteen banks Guillet considers as main banks are found in the financial core in Figure 7.3, while only four of the twenty-four second-tier banks are included: ING Groep, Caixa Bank, Mizuho, and Lloyd's⁴⁷.

One example of self-organisation in the investor network was the emergence of Copenhagen Infrastructure Partners (CIP) in the financial core, which addressed the barrier of a lack of 'financial vehicles' for institutional investors to channel their capital through (Ameli et al., 2019). Christian Skakkebæk, who co-founded CIP as a financial OSW developer with a group of other financial executives and experts from Ørsted⁴⁸, explained that they continued with the organisational model they had developed in Ørsted with close cooperation between the three

⁴⁶ Guillet (2022) lists the core and peripheral banks. His categorisation is corresponding to the results of the network analysis and it is used to validate the interpretation of the network.

⁴⁷ These four banks are among the seven highest ranked among the second-tier banks, so the method is largely in congruency with expert judgment.

⁴⁸ Following a public controversy where the CEO was terminated for providing what was deemed too generous salaries for this particular group.



branches of engineering, finance, and the legal team (interview 1). Ørsted was at first dominated by its engineers, which is also the case for some of the other utility developers. Engineering dominance can hinder both cost discipline and holistic considerations in the development and construction phases regarding how the project can obtain cheap finance from the financial ecosystem (Ibid., interview 2). Moreover, CIP relied, to a large extent, on funding from the Danish pension funds they had cooperated with during their time at Ørsted. CIP's rise is thereby also an example of the know-how flows that occur through staff movement, a factor that the network analytical method does not capture.

There is a more scattered band of investors below the core with significant involvement in OSW in phases 3 and 4. A common characteristic is that the members of this band are predominantly not private financials. Instead, it's a mix of developers, contractors who invest, public banks, and non-core private banks, and institutional investors. Some of the largest primary investors were the GIB, the Japanese SIB JBIC and the Norwegian SOE Equinor. A large share of investors in this segment were mainly refinancing or making acquisitions of existing assets.

7.4.3.3. Comparative state investment banking

The low forward reach of the UK's GIB (38%) compared to other SIBs (EIB, KfW, EKF; 62-67%) illustrates Marois' (2021) argument that public banks can take vastly different roles in society depending on how they are designed and governed. The GIB is a case in point as it, since its inception in 2012, prioritised investments in existing assets by refinancing two projects and acquiring ownership stakes in five projects. However, it also provided primary financing equity for the Rampion and Galloper farms in 2015 before being privatised in a sale to the Australian capital fund manager Macquarie in 2017 (BBC, 2017). The GIB thus imitated the role played by more risk-averse institutional investors with the intention of freeing up capital for developers (Geddes et al., 2018, 166). In this sense, it shied away from taking risks and instead supported the realisation of large capital gains for developers following the riskier construction phase. Skakkebæk holds the view that the GIB “came too late” and instead “crowded out a market that



actually was beginning to have interest”. It would have made more of an impact to “have taken marginal risk”, i.e. the de-risking of primary financing taken by the continental SIBs.

Another alternative would have been to have invested more with equity during the construction phase and share the rewards. While a strategy of long-term public ownership of energy infrastructure could make strategic sense, it is incoherent with an unwillingness to take on risk in the construction phase and only acquire it after construction. The UK GIB undoubtedly accumulated both valuable assets and internal investment expertise. But because of the applied strategy and subsequent privatisation of the assets and capabilities, it displayed a more neoliberal mode of public banking compared to EIB and KfW’s risk-embracing and know-how diffusing model, which was itself quite accommodative to private financial interests by insisting on their inclusion, rather than financing the projects themselves⁴⁹.

7.4.3.4. Financial engineering to increase debt leverage

The transition between phase 3 and phase 4 also gave rise to another wave of financial innovation that would contribute to lowering the cost of OSW power. One method was post-construction refinancing. Refinancing was used early on but reached another level of scale in phase 4 as a large wave of 22 projects had cleared their risky construction phases and could be refinanced on more favourable terms, incl. better pricing, higher leverage ratio, and less intrusive commitments regarding project management (Guillet, 2022)⁵⁰.

Refinancing after construction was adopted for both balance sheet- and project-financed parks. Refinancing on better terms would enable project owners to pay out “special dividends” since the increased gearing would free up invested equity and capital gains (Ibid., 70). Like Ørsted’s ‘farm-down’ technique, refinancing after construction on better terms gives project owners an

⁴⁹ EIB has historically been used to promote market-based finance (Mertens and Thiemann, 2018) and public-private-partnerships (Howarth and Liebe, 2021).

⁵⁰ Before 2016, a total of 18 projects had been refinanced.



expectational financial windfall they could use to bid down the required revenue support in public auctions.

Belwind became the first project-financed park to be refinanced in 2015. Gode Wind and Meerwind also refinanced in 2015 and were the first to be refinanced by institutional investors and project bonds with public rating (thereby tradeable on financial markets), respectively. Capital markets are generally not well-suited to finance projects with uncertain construction processes since lenders' engagement is often required to deal with unforeseen circumstances, while bond financing is based on a "fire and forget" approach, where the creditor is no longer involved after funding is provided (Guillet, 2022, p. 69).

So, capital markets are better suited for refinancing operational parks, while the creation of these assets depends on a more interactive creditor-debtor relationship that requires deep knowledge of the borrower's operation and abilities to monitor and respond to both positive and negative events that could change the drawdown schedule for the loan (interview 2).

The tendency to increase leverage also prevailed in the acquisition market, where financial investors used debt leverage in separate holding companies ('holdcos') to make more aggressive bids for stakes in projects in operation or under construction. This is a financially more aggressive way to acquire ownership of OSW projects where the buyer finances itself with debt to obtain a higher return on the (smaller amount of) equity invested and, hence, enable higher valuations.

These leveraged acquisitions were pioneered in 2012 by two Japanese banks, Mizuho and SMFG, who debt financed Marubeni's acquisition of the Gunfleet Sands park in the UK. And in 2014, the duo, together with the Japanese SIB JBIC, financed Marubeni's acquisition of 25% of Westernmost Rough. In the same deal, UK GIB acquired another 25% ownership from Ørsted, while it was still under construction.

In 2015, Macquarie adopted this model for its acquisition of a stake in Baltic II in Germany from EnBW, where MUFG, two German public banks, and Siemens provided the debt. Macquarie went on to use the model again in 2016 when it acquired a stake in the Race Bank park from Ørsted with debt from twelve commercial banks. In 2017, the Danish pension funds PFA and PKA also adopted the technique to acquire half of the 659 MW Walney Extension from Ørsted.



The recent culmination of this trend was the US-based infrastructure fund Global Infrastructure Partners' leveraged acquisition of half of Ørsted's size record-beating 1,218MW Hornsea 1 (UK), while it was still under construction. Examination of the sources of acquisition finance shows that civic institutional investors (e.g. pension funds) were only a minor source of acquisition finance, while banks in cooperation with leveraged private equity and infrastructure funds were more active (Appendix D: Figure 0.6).

These leveraged transactions are another example of how elastic the financial system can be when green animal spirits have taken hold in the investor community. This tendency to increase debt leveraging through financial innovations was at the root of Minsky's financial instability hypothesis (see chapter 3) (Minsky, 1982). It is commonly believed that both banks and institutional investors simply move existing savings around. However, banks create money as they extend their balance sheets in the act of lending (McLeay, et al., 2014; Ryan-Collins et al., 2017; Werner, 2016), and capital funds use the banks' ability to create money to leverage their own funds (Sissoko, 2017). In the described deals, this enables institutional investors to own more offshore wind assets with their investable funds, although the resulting cash flow must first service the incurred debt. Therefore, the question in the green finance literature regarding if enough finance is available to fund the green transition (Polzin and Sanders, 2020) is arguably too static. If the investors understand the risks of the projects and the resulting expected risk-adjusted returns are sufficient, funds can and will likely be made available.

In summary, the transition from phase 3 to 4 shows how the financial ecosystem matured from the state investment bank-driven phase 3 to a system with a know-how hub of mostly financial investors. Private financials became central to the know-how flows through a mix of primary financing, refinancing, and acquisitions. More financial innovations, such as refinancing and leveraged acquisitions, were used to increase the leverage of investors in OSW, which contributed to higher valuations of projects. SIBs were still important actors in this core of the network and in terms of capital volumes invested, but less pronounced relative to the commercial financial institutions.



7.4.4. Path analysis across phase 4 and 5: Private financials dominate the know-how flows

In the continued process of financial maturation from phases 4 to 5, there were three main properties: First, private and cooperative financials came to dominate the know-how flows and primary investment. This also implies markedly reduced roles for SIBs that appeared to have played out their functional role. Second, the entrance of investors from the oil and gas sector raises new questions about the future and robustness of OSW deployment. Third, although Chinese SOEs had generally invested in isolation, a few connections to the network emerged in the fifth phase.

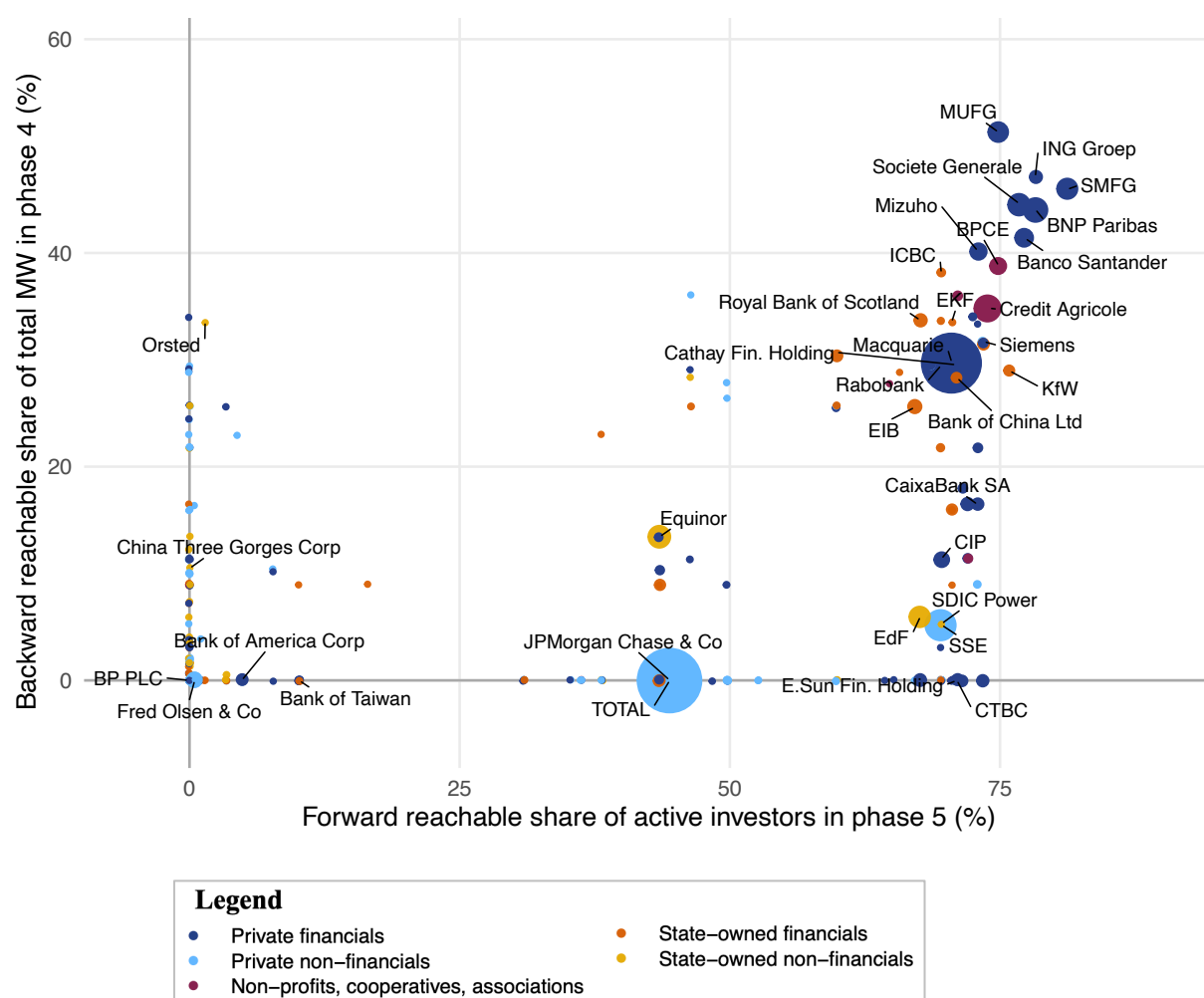
7.4.4.1. A mature private investor network with diminishing roles for SIBs

The main tendency in phase 5 was that the presence of private financials became more pronounced. We learned from the previous analysis that the fourth phase contained a large wave of refinancing and acquisition activity, which was followed by a larger share of primary investment undertaken by private financial investors (Figure 5.3). I hypothesised that these steps were integrated parts of a learning process that allowed financial investors to gain familiarity with the industry at low risk.

Figure 7.4 shows that this is a plausible interpretation. The financial core from phase 4 is no longer an isolated formation. Rather, it is a tilted vertical formation of 90 investors with forward reach of 65%-81% and with a wide span of backward reach from 0% to 51%. This relatively common level of forward reach suggests that the diffusing network effects were stronger in this period since so many investors could obtain a large forward reach by connecting to the network. One reason was that the increasing size of projects meant more investors had to collaborate to provide enough finance. The financial network thus co-evolved in response to this techno-economic property as there were 11 projects with 20 or more investors in phase 5. Another reason was the opening of new markets where local investors sought know-how and capital from

international sources. For instance, the lower parts of the formation contain a number of Taiwanese investors, including Cathay, E.Sun, and CTBC, and the French SoE EdF, which undertook project finance with the core of the investor network and, in a short time, obtained a wide network reach.

Figure 7.4: Know-how exposure from phase 4 (2016-2018) and diffusion in phase 5 (2019-2021)



Note: See the note for Figure 7.1. 18,690 MW were financed in phase 4.



Considering the vertical formation in greater detail, the upper part contains investors with both high exposures to the new parks that were financed in phase 4 and the highest potential for influencing investors in phase 5. In contrast to the fourth phase, the know-how flows were dominated by six private financials⁵¹ who used their central positions in the previous phase to become the most well-connected investors who had backwards reaches above 40% of new MW and forward reaches above 75% of active investors. Moreover, these banks became among the top primary financiers only superseded by the oil companies Total and Equinor, the utilities EdF and SSE, and the financials Macquarie and Credit Agricole.

In the second tier, with a backward reach between 20-40%, the top private banks had displaced the EIB and KfW from their roles as the most central investors. EKF had a similar second-tier role as in the previous phase. The two EIB and KfW were still notable investors in terms of capital volumes, but there were 15 investors who provided more capital than the EIB and 32 who provided more than the KfW. KfW managed a larger forward reach because of its export credit agency branch that financed outside of Europe, most notably in the increasing number of projects in Taiwan.

It appears that the risk-insuring export credit agency roles were more in demand in this period compared to promotional lending, as there was also increased activity from the Swedish, Norwegian, Canadian, UK, Chinese, and French agencies, while EKF remained active and relatively well-connected. This makes sense in relation to the increased investments in new markets with unfamiliar political, regulatory, and supply chain risks (see chapter 5 for a risk review).

The second tier also included some of the largest investors in Macquarie and Credit Agricole, followed by the Japanese bank Mizuho and the French cooperative bank BPCE. The capital fund manager Macquarie had considerable exposure to the MW installed in phase 4 and it had, in addition, obtained know-how by acquiring the GIB, which was rebranded as its Green Investment Group. This provided organisational capabilities to make a strategic move into OSW.

⁵¹ MUFG, ING Groep, SMFG, BNP Paribas, Banco Santander, and Societe Generale.



Lastly, the second tier also contains a relatively large number of commercial public financials, such as Royal Bank of Scotland, ABN Amro, Bank of China, and two German Landesbanken that are owned by regional governments. The public banks thus appeared to contribute to the financing of OSW like regular commercial banks and take comparable shares in the financing. However, the data suggests the EIB still functioned as a larger capital provider than commercial banks in European projects. Based on the evolution of the network and expert interviews (1 & 2), this role was no longer strictly needed, although EIB possibly still provided cheaper loans than the marginal banks it displaced from the club deals.

This tendency of diminishing importance of SIBs may be in accordance with a political strategy to reorient the SIBs to scaling up new technologies and attracting new private investors to these new technological niches, such as hydrogen, energy storage, geothermal, and carbon capture. Another strategic option would be to complement this catalysing function with a more public value-oriented strategy where SIBs keep on financing public infrastructure to recoup the infrastructural rents to public balance sheets and/or let them flow to the users, e.g. via cheaper electricity.

7.4.4.2. Major oil companies: Transferable know-how or a systemic disruption?

As mentioned above, the two final phases can be described as a process of financialisation, where private financial investors came to dominate offshore wind investment. Another emerging trend was the entry of major oil companies as Total, BP, and the Norwegian SOE Equinor became more notable investors. This tendency is, on the surface, positive news since there has been both hope and scepticism regarding the potential for redirecting oil companies' investments to accelerate the deployment of renewable energy based on their existing capabilities in offshore construction projects and their large cash flows (Christophers, 2022b; Green et al., 2021).

However, even with these investments, it still resembles more of a hedging strategy to avoid ESG criticisms rather than corporate transformations (Ibid.). Moreover, Christophers (2022b) points to the irony of organising the green transition to relying on the continued extraction of fossil fuels. Nonetheless, Total's and Equinor's willingness to deploy floating wind is likely to provide



useful opportunities for advancing the learning curve by experimenting with technology options, industrialising production, and learning-by-doing.

An additional concern could be that insofar the oil majors are more motivated by their corporate image than financial returns and they turn out to be organisationally ill-equipped to develop large OSW parks, it may lead to disruptions in the otherwise orderly evolutionary pattern (Figure 6.7). I will return to this concern in the discussion chapter.

7.5. A systemic view on flows and accumulation of know-how

The reachability analysis of know-how accumulation and diffusion has shed new light on the co-evolution of investment and technological development from a systemic point of view. Common reasoning on the role of the financial sector assumes a rational, solitary investor balancing objective risks and rewards (Hall et al., 2017). However, the use of temporal network analysis has enabled an exploration of the importance of relationships for know-how formation and the unevenness of connections in the investor ecosystem (Lundvall and Johnson, 1994). This brief discussion considers three main themes of the analysis: The fragility of early know-how creation, self-organisation and robustness, and the importance of investment capabilities.

7.5.1. The fragility of early know-how formation

Although the evolution of OSW financing and the co-evolving cost reductions can rightfully be seen as a positive story because of the resulting cost reductions, it is also a tale of caution because of the fragility of know-how accumulation and diffusion in the first three phases. The distributions of backward reach (Figure 0.12, Appendix F) shows that there were power law distributions in phases 2 and 3, while there were more U-shaped distributions in the last two phases. The distributions of forward reach had U-shaped distributions in all four phases. This indicates that the network effects from the adaptive behaviour were relatively well-suited for spreading know-how around, but that the know-how from the first two phases was highly concentrated in few organisations, which slowed the network's maturation.



The results from the know-how diffusion analysis indicate that there were three fragile inflection points that all turned out favourably. However, each could potentially have disrupted the process towards the cost reductions that developed from around 2013. The three path-determining events were: 1) early investments by state-led utilities that created the first utility-scale parks in the early 2000s, 2) the development of positive project finance precedents before the GFC, and 3) the large financial and technical support provided by SIBs during the growth phases of OSW in phase 2 and 3. By examining these instances, it is possible to draw lessons with some applicability to the development of other sustainable energy technologies.

First, the overall trajectory was dependent on the experiences from the initial large-scale demonstration parks, especially Rødsand 1 and Horns Rev 1 that were demanded by the Danish government in the 1990s as a conditionality for granting permission to the regional utilities to expand coal power capacity (Voldsgaard and Rüdiger, 2021). If those initial investments had not been undertaken, the industry would likely have gotten off to a considerably slower start.

These investments also concentrated specialised know-how in a single organisation following the merger between Ørsted (then DONG) and the civic utilities in 2005. Having only one solid know-how bridge also implies a fragility of know-how accumulation during the technology's early deployment. For instance, if Ørsted had not pivoted towards OSW in 2008, it is unclear if other companies would have assumed this lead role. Moreover, Ørsted stood out from the other investing utilities in phase 2 by co-investing more with others, incl. the EIB that helped resume project finance after the GFC (Figure 6.2).

The early stage of technology development thus faces a twin challenge of developing organisations with a high level of know-how and a dedicated strategy while also balancing this specialisation with know-how diffusion to allow for more experimentation and competition (Balland et al., 2022). It is hence worth contemplating if SOEs are sufficiently exploiting their organisational potential for driving the early stages of learning curves in other technologies.

Secondly, the introduction of project financing by Dexia and Rabobank was a financial innovation that enabled OSW projects to be directly financed by banks. But this innovation was contingent upon the de-risking and capital provisioning by EKF and EIB, in addition to the



beneficial timing ahead of the GFC (interview 2). Without these pre-GFC project finance deals, it is a plausible counterfactual that the Dutch, Belgian, and German markets would have developed at a considerably slower pace and only through investments by the incumbent utilities. This would have weakened competition and slowed cost reductions. This form of fragility suggests that front-loading efforts to deploy a new technology increases resilience against exogenous shocks because of the importance of positive precedents.

Thirdly, the importance of the SIBs stretches far beyond their initial de-risking and capital provision for the first project-financed parks. Rather, the results show that they were important countercyclical investors following the GFC, which enabled sufficient amounts of capital being available. Since there were limited commercial banks with sufficient investment know-how to invest in OSW, large projects required too many banks compared to what was available. The SIBs willingness to take larger stakes hence reduced the need to include incompetent banks.

Moreover, their inclusion often de-risked projects both financially by taking more riskier stakes and by providing guarantees, but also through signalling based on their reputation as capable investors in OSW (Geddes et al., 2018; Geddes and Schmidt, 2020). Their large investments in technical expertise in-house and sectoral knowledge from financing most of the project-financed parks meant that SIBs were recognised as sophisticated and trustworthy investors and that the projects they were participating in were sound. If investments had dried up following the GFC, the industrialisation and specialisation of the industry supply chain would unlikely have developed at an equal pace and thus jeopardised the realised falling costs after 2015⁵².

7.5.2. *Self-organisation and robustness*

Although the analysis of reachable network paths raises concerns about the fragility of know-how flows in the earlier phases of technology development, it also shows that the investor network can develop robustness through increasing returns to experience, self-organisation, and

⁵² In terms of installation cost per MW capacity. Improved capacity factors contributed to falling LCOE after 2011 (IRENA, 2021, 101).



network effects. The gradual development of a group of experienced and networked investors increased the possibilities for more developers and more projects in OSW as they could access affordable external finance as well as source know-how from the financiers.

The graphs above displayed an enduring presence of a core of mostly financial actors. Certain commercial banks that were centrally involved in phases 2 and 3, such as Rabobank, MUFG, Société Générale, Banco Santander, and BNP Paribas, ended up among the top investors with the widest reaches in phases 4 and 5, and a few SIBs were prominent actors from phase 2 to 4. This suggests that once learning processes advance sufficiently, they become self-reinforcing and reach a threshold where SIBs and SOEs are no longer important for the continued deployment of the technology at low cost.

In other words, early accumulation of know-how appears to create staying power in the network as a consequence of an experience-based competitive advantage. This path dependence in the composition of network actors is likely a source of robustness once a critical mass of experienced investors is reached.

The network topology in the latest phase appears robust due to the multitude of networked, homogenous, and experienced actors. On the other hand, this could also indicate a systemic risk to offshore deployment. If deployment becomes overly dependent on major international banks, it also becomes more exposed to the global financial conditions, which these institutions are thoroughly embedded within, and which could possibly channel financial instability to the OSW sector.

Changes in sectoral conventions and sentiments stemming from either financial instability or narratives regarding market trends could lead private financiers to deprioritise investments in long-term and capital-intensive investments such as OSW. States should therefore contemplate how to ensure resiliency in investments in an adverse scenario where private financiers become reluctant. One approach would be to maintain state-owned organisations with high levels of investment expertise that could flexibly scale up investments if the green animal spirits became ‘dimmed’.



7.5.3. *Towards a capability-based theory of green animal spirits*

This chapter has an inductive aim to provide theoretical insights for how sustainable niche technologies can come to face favourable and constructive financial conditions that enable them to scale and mature. The motivation stems from a tendency in the literature to assume atomistic and rationalistic investors (Hall et al., 2017) and thereby disregard the uncertainties, path dependencies, and complex patterns of interactions that shape which investors that have the dynamic capabilities to invest in emerging sustainable technologies (Teece and Pisano, 2003). This propensity to invest in technologies with thin track records resembles Keynes' image of animal spirits that steer the private decisions to invest despite vast uncertainties. Yet, in my work towards a theory of *green animal spirits*, I have emphasised the creation and absorption of know-how that enables investors to take well-understood risks on sustainable technologies despite their often thin track records rather than because of waves of exuberance (Perez, 2002).

The results from this analysis suggest that the creation of investment know-how through learning-by-doing and diffusion through co-investments are crucial parts of raising green animal spirits in the investor community. Experience from financing previous projects and the experience of business partners make investors more capable of assessing the risks of different technologies, suppliers, geographical locations, electricity market frameworks, and risk allocations in contract negotiations. This experience ameliorates the uncertainty and provides the investors with a foundation for assessing the long-term value of the investment. The results indicate that finance can have a non-linear impact on the realisation of projects:

As the track record built up and was very positive, banks became more comfortable with the risks and slowly offered more competitive terms. (...) The sector is like a high plateau – transaction[s] that do not meet the standards (in terms of contractual structure, due diligence and economics) simply do not happen, but if you reach the requisite level of quality, then liquidity becomes plentiful and banks compete on commercial terms like pricing or, increasingly, underwriting (Guillet, 2022, p. 68).

More risky projects did not simply receive financing at higher interest rates to compensate for the risks. Projects had to live up to the standards commensurate with the know-how and appetite for risk in the banking community to enter the construction phase – otherwise, they would not go ahead. Although the know-how created a demanding ‘high plateau’, it was both preferable to a level that was higher and perhaps unattainable if the investors had been less sophisticated or at a much lower level because of financial exuberance. Instead, OSW investors avoided both prohibitive costs and bad precedents: “like equity investors, nothing lowbrow has been done by lenders: terms have slowly improved, but without any drop in standards” (ibid.). The evolution of the OSW investor system thereby appears to have found the proverbial middle-of-the-road towards maturity.

Industrial policy is commonly concerned with developing new industrial and technological capabilities (Rodrik, 2014) through market creation (Mazzucato, 2016), such as the German *Energiewende*’s feed-in tariffs for renewable energy, or targeted R&D support. However, the presence of investors capable of responding to price signals is often taken for granted. To avoid large subsidies to cover an excessive cost of financing, there could be more focus on establishing the investment capabilities that allow new innovations and deployment of technologies to be financed (Mazzucato and Wray, 2019). Historically, industrial policies have addressed this by using credit guidance in the financial system (Bezemer et al., 2021; Kedward et al., 2022; Mikheeva and Ryan-Collins, 2022).

Shaping of the financial sector’s capabilities was also a less-recognised part of the *Energiewende* where public promotional banks provided between 33% and 41% of annual finance for renewable energy between 2010-2017 (D’Orazio and Löwenstein, 2020). KfW, the largest of the promotional banks, usually provided capital to renewable energy by on-lending cooperation through local intermediary banks, who also received advice on how to conduct risk assessments (Griffith-Jones, 2016; Yildiz, 2014). These local banks, in turn, contributed to increasing local and civic ownership of the installations (Hall et al., 2016).



7.6. Summary: How a renewable energy investor community matured

This chapter has pursued the second sub-research question (RQ3): *Which investors and interactions have been important for investment know-how creation and diffusion in the offshore wind sector?* The purpose was to improve our understanding of how potential investors become confident enough to invest in large-scale deployment of new sustainable technologies, which enables learning curves to develop. Or, with inspiration from Keynes, to obtain a better understanding of how to raise *green animal spirits* among investors.

The analysis used network reachability metrics (Bender-deMoll and Morris, 2021) to examine how network connections helped investors obtain and diffuse investment know-how to other investors over time. These evolutionary learning processes cumulatively resulted in a mature investment community for OSW as an emergent property of the system. A mixed methods approach was used by combining the structural focus of the network analysis with qualitative evidence from events and experiences at the micro-level described by expert actors in the network. This was used to produce a coherent and micro-grounded narrative about how the investor network matured.

In the early phases, the know-how accumulation process was fragile since the know-how created through learning-by-doing in the 1990s and early 2000s was primarily concentrated in the Danish utilities that were merged into Ørsted (then DONG Energy). Ørsted co-invested with other utilities and the EIB, so its know-how had pathways to diffuse to the wider investor community. The results, therefore, suggests that innovation policymakers should both prioritise to advance the large-scale deployment of new technologies and balance the resulting specialisation with mechanisms for diffusing the know-how to a wider range of potential investors.

In phase 2, more utilities joined the market, and the financial innovation of project financing enabled banks to finance smaller developers. This innovation helped to grow the market and impose cost discipline, but it was also a fragile point in the evolution of the network since only two deals were completed before the GFC. Industry experts emphasised that these positive precedents and the existence of banks with first-hand experience enabled a positive path dependence after the great financial crisis when banks lowered their risk exposure by focusing



on core markets and sectors. OSW had become bankable, but the analysis also showed that the SIBs had a fundamental role in the wake of the crisis by providing sufficient volumes of capital, taking additional risks compared to commercial banks, and as trustworthy investors based on their extraordinary technical in-house capabilities and stringent requirements for due diligence.

From that phase onwards, the cost of offshore wind began to follow a steep learning curve and the private investors gradually formed a financial core, which eventually overtook Ørsted and the SIBs' central roles as know-how hubs in the network in phase 5. This self-organising growth of capable private investors suggests that the investor system had become robust and not dependable on the continued investments of policy-oriented SIBs or a few pioneering banks. On the other hand, the increasing homogeneity in the investor landscape may also add systemic risks, for instance, if the organisational models of the private financiers or the emerging major oil companies are unable to adapt to re-risked electricity markets or become conduits of external financial shocks.

The results of the analysis contribute towards a capability-based theory of green animal spirits, or how the financial sector can become more prone to invest in new sustainable technologies at a low cost of capital. It has developed the notion of know-how as an interactive form of knowledge (Jensen et al., 2007; Lundvall and Johnson, 1994) embedded in investing organisations and highlighted the fragilities inherent to the process of creating investment know-how through industrial policy.

Moreover, the analysis has shown how SOEs and SIBs can have catalysing effects on technology development both for starting up new learning curves and for accelerating deployment in the growth phase when the track record remains thin (Geddes et al., 2018; Geddes and Schmidt, 2020; Mazzucato and Penna, 2016). Although revenue support schemes are important for creating markets where investors can experiment and learn, the schemes also need investors with the capabilities to respond effectively to the incentives. SOEs and SIBs can be an underutilised policy lever with a view to keeping down the policy costs needed to cover uncertainty-induced risk premia in the cost of capital.



PART 3: DISCUSSION AND SYNTHESIS

Chapter 8

Methodological evaluation

This chapter evaluates the methodological robustness of the analytical chapters. The results are evaluated by their construct validity, internal validity, external validity, and reliability (Yin, 2018, 41-47). This will reveal the strengths and weaknesses of the results before drawing analytical, theoretical, and policy-oriented conclusions in the following chapters.

8.1. Construct validity

The first concern regards whether the analysis has empirically captured the theoretical phenomena towards which the main research question (RQ1) directed the research. The key concepts in RQ1 were 1) finance and investment, 2) renewable energy finance, and 3) evolving complex systems. Additionally, RQ3 specified an interest in 4) investment know-how.

Finance and investment were satisfactorily measured in the OSW case because of the dataset encompassing nearly all, if not every, participation in OSW investments between 1989-2021. One deficiency was that the estimates of investment values in China were likely downward biased since only 7% of total investments were ascribed to Chinese projects, despite 47% of total OSW capacity in 2021 was installed in China. This underscores the observation from chapter 6, that the Chinese part of the network is less well-understood.

A strength of the database was the inclusion of refinancing and acquisition deals, so the analysis could cover both primary financing of new fixed investments and the broader notion of ‘investment’ that includes financing and ownership of existing assets. The analysis did not

include the corporate financing of the balance sheet financiers, i.e. the equity and bond issuance that utilities more commonly use. On the other hand, the owners of these securities did not have to take on construction risk as they had recourse to the entire balance sheet that also receives cash flows from numerous operational assets besides the upcoming OSW project (interview 2).

The cost of capital of the investments was inherently difficult to ascertain, as evidenced by IRENA's (2022a) efforts to improve WACC assumptions (Figure 5.7), because it requires access to confidential business information, such as club deals between lenders and intra-organisational hurdle rates (Helms et al., 2020). This limitation was ameliorated by using data collected by one of the central financial advisory firms in the industry (Figure 5.6) and the estimates by IEA (2019) and IRENA (2022a).

Renewable energy finance was analysed through the subset of OSW financing. This case selection left out onshore wind and solar PV, which were the two other main types of renewable energy that have matured over the last three decades. The analysis, therefore, directly revealed insights about parts of renewable energy financing, but the selection raises questions about the results' external validity and representativeness regarding other RE technologies (more below).

The core purpose of the research was to assess if a complexity-based ontology of renewable energy finance was useful for the scientific production of knowledge of sustainability transitions. The construct validity in relation to the concept of evolving complex systems was, therefore, of key importance. Although a complex system is inherently an abstraction, high construct validity was achieved by combining network-based methods, qualitative methods, and suitable data material that could detect features known from complexity theory (Bale et al., 2015; Beinhocker, 2007; Creswell and Plano Clark, 2018). This mixed methods design improved the likelihood of recognising the features of evolving complex systems described in chapter 3 insofar as the features were present. Moreover, the identification of aggregate level developments in chapter 5 enabled analysis of emergent properties of the micro- and meso-level investment behaviour in the network.

The focus on investment and financing meant that co-investment interactions were prioritised, which supported an organisational perspective on know-how creation and diffusion (Katkalo et

al., 2010). The qualitative methods showed that other forms of interactions took place that also influenced know-how formation. Substantial know-how was held by contractors (out of which some were also investors, such as Van Oord and Siemens), and know-how was also exchanged through staff changes, the use of external advisors (Green Giraffe has for instance been a prominent financial advisor), and through industry organisations and state-sponsored know-how exchange initiatives, e.g. the UK's 'The Offshore Wind Accelerator' from 2008 (Jennings et al., 2020, 10). UNEP (2020) has also analysed how investors are connected via sectoral green finance initiatives. The full richness of complexity in the case was thereby not encompassed.

Lastly, the research was methodologically challenged by the theoretical importance of tacit investment know-how. The operationalisation in chapter 4 contributed with some conceptual clarity, but the generally low observability of know-how limited the strength of the conclusions that could be drawn in chapter 6. It would have required multiple in-depth case studies to observe the actual absorption, integration, and further development of new know-how in organisations, which would still be challenging due to the tacit nature of know-how (Loasby, 2002). For example, some micro-level insights regarding Ørsted, the historically main investor in OSW, were obtained by Voldsgaard and Rüdiger (2021) in a case study.

On the other hand, this would not have been a viable research strategy for understanding the *systemic* processes around the creation and diffusion of investment know-how that shape the deployment and cost of new sustainable technologies. The network reachability analysis developed a useful new method for assessing each investor's *potential* for absorbing know-how generated in the past and influencing the future of the network. Seen in relation to each other, their reachability scores indicated the structural importance of know-how flows as a source of staying power and, thus, a resource for their competitive advantage in the investor network. This relation between know-how exposure and persistence should be studied in greater depth, incl. with statistical methods. The expert interviews contributed to the validity of the system-level observations of know-how flows, which reaffirmed the strength of using multiple sources of evidence (Yin, 2018, 41-47).



8.2. *Internal validity*

The internal validity concerns the ability to draw valid conclusions regarding the hypothesised or observed causal mechanisms in the case study. Often this requires pattern matching, explanation building, and consideration of rival explanations (Yin, 2018, 41-47). The ability to draw valid conclusions regarding the dynamics of OSW investment was greatly enhanced by the data material, which covered all investments in OSW from the very first park until the end of 2021. The longitudinal perspective enabled observations of structural changes in investment patterns, which made it possible to analyse hypothesised adaptive behaviour unfolding empirically (Hall et al., 2017).

The high coverage of investment activity reduced the possibility of systematic biases or randomness in the data collection leading to unrepresentative conclusions for the case. Importantly, since complex systems are known to be sensitive to early conditions and early events (Arthur, 2014), it was a strength to include the first years of OSW investment through manual data collection. This data availability was identified in chapter 4 as a methodological advantage related to selecting OSW as the case to study because the comprehensive coverage would make it more useful for theory development (Flyvbjerg, 2006).

As explained in chapters 3 and 4, this dissertation aimed to examine to what extent renewable energy finance could be analysed as an evolving complex system, and what this perspective would reveal about the causal mechanisms connecting market incentives to market outcomes. Based on theories of complexity and know-how, it was expected that price impacts were contingent on the dynamic capabilities and interactive behaviour of investors. This logical model suggested the investor system's historical evolution would be a strong contingent variable affecting the relation between prices and outcomes since it is the investing organisations who respond to demand-pull policies and who determine the cost of capital.

The mixed methods approach provided a substantiated account of the complexity features of OSW investment through time, which strengthened the internal validity. At a structural level, the visual network analysis showed how the investments were undertaken by a changing web of heterogeneous organisations interacting through co-investments. The changes in the network



were congruous with the punctuated equilibrium model known to characterise how complex systems evolve (Beinhocker, 2007). Moreover, the micro-level data supported the notion that evolutionary processes were taking place with continual adaptation to the sectoral and exogenous business circumstances, which led to a number of financial innovations and the entrance of new types of investors such as banks, SIBs, institutional investors, and major oil companies.

As mentioned, the reachability analysis in chapter 7 provided an initial structural analysis of know-how formation. The qualitative data supported the interpretation that know-how is created through learning-by-doing and diffused through co-investments. For instance, in 2012 Iberdrola co-invested with Ørsted in the West of Duddon Sands project to obtain investment know-how (interview 1) that could be used in its subsequent investments in 2014 and 2016 without other partners. Also, the investors that the methodology found to be core and second-tier actors were highly congruent with the ranking of investors by Jerome Guillet (2022), which provided an expertise-based validation of the methodology. Still, the reachability method should be further developed and strengthened with more micro-level observations (more below).

A rival hypothesis regarding the observed important role of state investors was that the public investors simply crowded out private investors who would have undertaken the investments in the absence of state investors. First, I argue that the qualitative data showed that, after the GFC had erupted, there was a lack of banks with sufficient know-how ('core banks') to provide the required volumes of finance and provide riskier portions of debt. SIBs were important for filling this gap and attracting less experienced banks. Second, the claim in the dissertation is not so much that OSW would never have matured without sizeable state investments around the two 'valleys of death' (Figure 5.8). Rather, the timeline was markedly advanced by the entrepreneurial state investors. Private investors could hypothetically have responded to sufficiently high and de-risked subsidies, but the rapid learning curves of onshore wind and solar PV meant that OSW could have fallen too far behind to be considered a competitive RE technology. Also, there could be concerns regarding the political willingness to meet the higher policy costs (Lockwood, 2016). The impact of state investors could be further ascertained by examining the role of state investors in onshore wind and solar PV (more below).



However, I find that one aspect was not sufficiently illuminated: the determinants of the evolutionary process of entry, retention, and exit among investors. The analysis attempted to improve understanding of the main trends and actors in the network without systematically using the financial accounts of the firms. Some mechanisms were possible to discern: The initial large-scale investments in Denmark were exogenously initiated by government demands. The strong presence of French banks seemed more endogenous based on their established expertise with project finance. And the relatively slow start of utility investments in the UK market has been attributed to market liberalisation (Ćetković et al., 2017). However, the entry patterns could have been more systematically analysed. In relation to retention, chapter 6 showed how there was path dependency in the actor composition in the core (Figure 6.9), which indicated there was a self-reinforcing cycle between experience and financial performance. Exits were less transparent to analyse without the use of financial results, although the large BARD1 project showed how insufficient investment know-how and too large risks could bankrupt developers.

While the research has strengthened the understanding of mechanisms connecting demand-side policies and outcomes, it was not quantified or process-traced in detail how particular national market frameworks led to domestic investment outcomes. Preliminary research for the dissertation included the development of a relational hyper-event model (Lerner et al., 2021; Lerner and Hâncean, 2021; Lerner and Lomi, 2022), which could potentially be revised to include both network effects, organisational characteristics, business results, and policy frameworks.

In summary, the analysis provided a strong internal validity for the capability- and interaction-based causal mechanisms that were hypothesised to connect market prices and investment outcomes. The alternative explanation, which favours abstracting from the investor system by assuming a representative investor, was found to miss the causal mechanisms that produce the financial conditions at any given moment in history. While it may be useful for analysis at a specific moment in time, the assumption hides the importance of system interventions to promote a financial structure more conducive to supporting the effectiveness of climate policies.

8.3. *External validity*

The external validity concerns the possibility of drawing valid generalisations regarding the role of finance for other technologies. As any process occurring in historical time, OSW evolved under some distinct circumstances. Chapter 5 considered how the continually revised market frameworks and industrial policy initiatives were crucial for expanding a niche market, lowering the cost of capital, and developing the technological solutions required to overcome geographical challenges and bring down costs. Consequently, the lessons learned about the role of the evolving investor landscape (which also contributed to deployment and financial cost reductions) are not certain to apply to the next generation of sustainable technologies in niche markets today.

First, in line with the adaptive view on RE financing (Hall et al., 2017), the financial and political environment around investing in clean technologies has evolved since the most important investments were made in OSW. Financial investors have evolved as a consequence of the lessons learned from financing the first generation of RE technologies, such as solar PV and wind power, and the general political-economic shift towards a green industrial policy and the Paris Agreements have gradually changed the business narrative to focus on opportunities rather than costs (Breetz et al., 2018; Mathews, 2020).

As a tangible sign of change, climate-tech companies raised \$165 billion from listed and private sources in 2021, including startups raising \$53.7 billion from venture capital and private equity (BNEF, 2022b, 2022c, 2022d). The financial conditions are hence closer to the ‘frenzy’ conditions common to historical techno-economic transitions (Perez, 2002). Still, this enthusiasm has a direction and attention. The head of the US Department of Energy’s Loans Office for instance notes that although concentrated solar power has matured well, there is “no enthusiasm” for innovation among private investors who instead focus on “solar PV panels and other things” (Bloomberg, 2022).

These evolutionary dynamics imply that, overall, there may therefore be less unfilled potential for state investors to exploit because of increased private investment. However, the herding tendencies of private investors may leave unexploited niches for state investors to catalyse development – especially for technologies with more relevance for decarbonisation from 2035

and onwards such as hydrogen production and usage, long-term energy storage, advanced geothermal energy and direct air carbon capture. In addition, the more matured private financial sector could cause the catalysing effect of early public investments to be stronger for niche technologies because of enhanced network and learning effects.

The second aspect that conditions the potential to see similar complexity dynamics as in the history of OSW relates to the characteristics of the technologies in question. Although each technology has distinct characteristics, Table 8.1 categorises OSW and other energy technologies according to capital intensity and centralisation of deployment. It also distinguishes between 1st generation technologies (that become cost competitive in the 2010s) and 2nd generation technologies that are currently in the process of maturation.

Table 8.1: Comparing capital intensity and centralisation of sustainable energy technologies

<i>Technology characteristics</i>	More capital-intensive		Less capital-intensive	
	1 st generation	2 nd generation	1 st generation	2 nd generation
Centralised	Offshore wind Concentrated solar power Hydro power Regular nuclear power plants	Advanced geothermal Tidal & wave power Nuclear SMR	Open-loop geothermal	Electrolysers & electro-fuels Long-duration energy storage Utility-scale heat pumps DACC
Decentralised	Onshore wind Solar PV		Light electric vehicles LEDs Smart grid & demand flexibility	Heavy electric vehicles CCS

Notes: The less capital-intensive technologies have relatively higher operational costs, mostly for electricity. CCS = carbon capture & storage. DACC = direct air carbon capture. **Source:** Own categorisation with inspiration from IRENA (2022).



OSW has a capital-intensive cost profile and is deployed in large, centralised installations. These properties are shared with other energy technologies. Among other 1st generation sustainable energy technologies, concentrated solar power (CSP) and hydropower have a similar combination of high capital intensity and centralisation as OSW. Hydropower is a fully mature technology, but CSP could potentially see further cost reductions from more investments by entrepreneurial state investors (IRENA, 2021, 38). Onshore wind and solar PV are more decentralised, which could mean that state investors were less important because of the smaller amount of capital needed per project.

High capital intensity (CAPEX-OPEX-ratio) increases the demand for up-front financing of the future income stream, since there is little ongoing operational expenditure that can be serviced by income. More centralised deployment, i.e. in projects with more total capacity, amplifies the effect of capital intensity by raising the volume of financing required for a project to be realised.

More decentralised technologies could more easily be deployed by splitting up the financing on more actors, as seen in the citizens- and local bank-funded investments in onshore wind and solar PV in Germany (Hall et al., 2016). Still, it does not follow, that the financing of decentralised technologies is not a complex phenomenon. Preliminary analysis of the investment data for onshore wind and solar PV also gave the impression of a highly networked investor system with central roles for utility companies and SIBs. Furthermore, research has shown that financial learning-by-doing has occurred among investors in onshore wind and solar PV (Egli et al., 2018), which indicate the presence of evolutionary processes around these technologies as well. Yet, it could be a different kind of complexity dynamics playing out around decentralised, capital-intensive technologies.

For decentralised, capital-intensive technologies, the main complexity challenge is to spread investment know-how to a large number of financiers. For instance, KfW conducted large-scale on-lending through the banking system and provided around a third of funds for all RE investments in Germany at the height of its RE expansion from 2010-2013, which enabled the local banks to get familiar with the new risks (D’Orazio and Löwenstein, 2020; Griffith-Jones, 2016; Hall et al., 2016).



For centralised capital-intensive technologies, the challenge is rather to create and spread the know-how to the right investors with large investment budgets to instigate non-linear changes in investment patterns when know-how thresholds are crossed. Unlike for decentralised technologies, there is less room for investment experimentation because of the capital volume and the larger financial risk assumed per lesson learned from a project. The complexity perspective on finance could therefore potentially contribute to an understanding of why onshore wind and solar PV matured quicker than OSW and why other centralised technologies have not yet been commercialised on a larger scale.

As a general heuristic, in the circumstance of high capital intensity and centralised deployment financial conditions become more important and the evolution of the investor network around the technology is likely to display more complex dynamics, for instance with long, path-dependent stagnation and, possibly, and an eventual boom if negative feedbacks are overcome.

The less-capital intensive sustainable energy-related technologies generally use considerable amounts of electricity during operation and are hence dependent on low electricity costs for economic viability. Several 2nd generation technologies, including hydrogen production, energy storage and DACC, will also depend on attractive financial conditions for achieving cost competitiveness through the direct effect on LCOE and indirectly on technological learning based on increased deployment volumes. The complexity insights drawn from OSW are likely relevant to this subset of technologies with lower capex-opex ratios, however it must be considered how the use rather than production of electricity changes the picture. The market for electrons is well-established, international, and fairly standardised, why entrance barriers for boundedly rational investors should be lower. Although, electricity prices are hard to predict, the risks in relation to investing in electricity generation may be more easily understood than for hydrogen production or DACC, where the future customers are harder to identify with certainty.

The decentralised and less-capital intensive technologies, such as EVs, local demand flexibility technology (smart grid integration), CCS, and LEDs, are generally assisting firms (and households) fulfilling their primary objectives, e.g. with more energy efficiency or less carbon emissions, rather than producing the product of the firm. These decisions are less dependent on

the financial conditions, and more on the firms' cost-benefit analyses. There could still be an inefficient rate of adoption for this category, but this has likely more to do with satisficing behaviour or too low pricing of carbon emissions than risk aversion with regard to strategic investments (Grubb et al., 2015). The combination of decentralised deployment and lower capital-intensity therefore likely makes the complexity approach used in this dissertation to analyse RE investment less applicable to explain the dynamics for this type of technologies.

In summary, the proposition of considering RE finance as an evolving complex system can in this study only be evaluated for the subsystem of investments in OSW. RE finance is much broader and spans numerous technologies, different investor communities, and it occurs at different points in time, which implies the financial sector and technologies are undergoing change. The next chapter discusses the extent to which complexity theory provided a useful framework for understanding the history of OSW investment and it will be up to further research to determine the external validity in relation to other technologies and RE finance in general.

This chapter suggests that the insights drawn from OSW are likely partially applicable to other technologies, especially capital intensive and centrally deployed technologies. In these cases, financial conditions play a stronger role for deployment, more capital is at risk per project and the micro-foundations of complexity, incl. interaction among boundedly rational heterogeneous actors, are likely more impactful. Section 9.2.3 discusses the potential for entrepreneurial state investors to make a similar impact as in OSW for technologies with similar characteristics.

8.4. Reliability

Finally, the reliability of the research concerns the reproducibility of the analytical results. I have attempted to account for the analytical process in a transparent way, which facilitates the reproduction of results. One of the main obstacles to their reproducibility is the proprietary status of the BNEF and IJGlobal databases used to construct the dissertation database. Sharing the data requires the consent of the owners, e.g. by acquiring access. Interested researchers can visit the author in Copenhagen to examine the data analysis if warranted by a scholarly purpose.



Another obstacle regards how the compiled data material has been adjusted by imputing the missing distributions of investments among participants, and investor characteristics have been corrected. This process could lead to differences if others attempted to recreate the database from the same sources. Again, correspondence with the author can clarify possible differences. These two concerns regarding the data do not subtract from the analytical results, but they limit the scientific process.

Another factor weakening the reliability is the low number of primary interviews used. I managed to obtain two expert interviews with actors who had extraordinary historical experience and expertise with the balance sheet and project finance clusters of the OSW investor network. However, I had sent interview invitations to some of the core banks, KfW and EIB, but did not receive responses. While the two interviewees had expert knowledge, it also adds some arbitrariness to rely on only two interviews. Further research would benefit from more interviews from different types of organisations. To make up for this weakness, the analysis also incorporated research that had conducted interviews with additional OSW investors (Geddes et al., 2018; Geddes and Schmidt, 2020; Karltorp, 2016; Kostka and Anzinger, 2016).

The last reliability concern relates to the demarcation of the five investment phases. As mentioned in chapters 4 and 5, the periodisation was based on a combination of outcome trends, impactful events in the sector, and exogenous changes affecting investment in OSW. There is always some arbitrariness when subdividing a longer period into smaller periods, but the selection helped to narrate the changes that emerged when inspecting the data. For instance, Jerome Guillet (interview 2) supported the division of the first three phases but suggested combining phases 4 and 5 because of the maturation happening across both phases. However, I decided to maintain the separation because of the large difference between financial investors' propensity to refinance and acquire projects in phase 4 and provide primary finance in phase 5. This helped to understand the sequence of changes in the network.

The periodisation had more of an analytical impact in the know-how diffusion analysis since the backward and forward reachable sets can be sensitive to the point in time where they were measured from. For instance, investing with an experienced investor in the first year in the



subsequent phase would not generate know-how exposure from MW installed in the past phase, which the same co-investment would have done the year before. On the one hand, the selected years were not biased by being based on the results since the periods were selected before the diffusion results were known. However, the method should be developed to show forward and backward reaches on a rolling annual basis to avoid arbitrariness related to the selected years of measurement.

8.5. Summary

In summary, the analysis has operated with high levels of construct validity and internal validity, which make the conclusions regarding the causal mechanisms operating in the OSW investor network well-substantiated. The external validity of the conclusions to other energy technologies is more challenging to assess. Still, there are reasons to believe that complexity features and SIBs have also been important for onshore wind and solar PV, which are more decentralised technologies. In the future, the lessons from OSW could be even more pertinent for the emerging group of centralised sustainable technologies since OSW shares this characteristic. The reliability has been acceptable, but more interviews could strengthen the interpretation of events at the micro level. The know-how diffusion analysis would benefit from being conducted on a rolling annual basis.

Chapter 9

Analytical synthesis: Renewable energy finance as an evolving complex system

In response to the main research question, the analytical chapters have examined how our understanding of renewable energy finance could be improved by adopting a complexity perspective, as suggested by Hall et al. (2017) and Hafner et al. (2020), to analyse how OSW deployment has been financed. The database containing all OSW financing deals from the very first park until the end of 2021 offered the analyses a hitherto unseen combination of detail richness and comprehensive temporal coverage for an RE finance analysis. The unique data material allowed the research to interrogate the economic complexities in the political economy of climate change, where investors face the need to deploy long-lived, capital-intensive, sustainable energy technologies with largely unproven track records.

The first part of the chapter discusses how the analyses contribute to the RE finance literature by advancing the theory of energy finance as an adaptive market (Hall et al., 2017) with a complexity economic framework. The second part considers how the analyses have addressed the gap in the literature regarding the role of entrepreneurial state investors in RE finance (Elie et al., 2021) and their role in shaping the evolution of the complex system. The third part discusses what this perspective suggests for the future of OSW investment.

9.1. Offshore wind financing analysed through a complexity lens

Throughout this study, we have examined what could be gained by accounting for complexity properties and evolutionary processes in RE finance. With an ontology founded in complexity theory, the research design and methods enabled the analyses to detect and analyse some of the complexity properties through three network analytical methods: Graphical network analysis visualised how financing patterns have evolved over time and enabled identification of dominant actors in the system. Second, network statistics showed the growth trends of the network and the

path dependency in the composition of dominant actors. Third, network reachability analysis extended the graphical analysis by examining which investors have most likely been the main know-how generators, carriers, and diffusers across the five phases of OSW investment.

This section evaluates to what extent the analyses supported the notion of OSW financing being an evolving complex system and what the analytical implications are.

The complexity literature surveyed in chapter 3 highlighted five defining complexity characteristics (Beinhocker, 2007): Heterogeneous actors, explicit network interaction, evolutionary processes, emergent properties, and non-linear dynamics. While some of these characteristics are difficult to observe and trace empirically (Tolk et al., 2018), the applied methodology allowed the analyses to capture pertinent aspects of the investment process and go beyond reductionist reasoning based on perfectly rational or representative investors.

While generalisations are necessary for formal analysis, empirical studies of the depth and breadth of nuances and actors are useful complements since such studies are closer depictions of the world where policies are implemented. Disregarding these complexities may lead to futile attempts to change inertial systems and missed opportunities for achieving transformational impacts (Grubb et al., 2021b; Lenton, 2020; Sharpe and Lenton, 2021; Smith et al., 2020). The following sections consider what the analyses have brought to light about the five characteristics of complex systems (summarised below in Table 9.1).

9.1.1. Heterogeneous actors

In line with the surveyed RE literature, the dataset and network analysis revealed a plethora of heterogeneity in the OSW investor community. The diversity in the dataset was reduced to six main investor types to bring important distinctions to the foreground. Within industrial sectors, the analysis highlighted the division between financial and non-financial corporations since we would expect each sector to specialise in each of the two types of investment know-how: fixed investment know-how and financial know-how. More specifically, non-financial corporations would develop the know-how for developing parks on time and within a cost-efficient budget,



while financial investors would specialise in the ability to assess whether an investment would pay off even in adverse scenarios. For instance, the analysis revealed that large utility companies were less risk-averse than commercial banks.

The other main distinction was drawn among three categories of ownership forms: Public, private, and non-profit ownership, which contributed to analysing the institutional roles of entrepreneurial state-owned investors (see the next main section), private finance, and institutional investors. There were large differences among the same formal types of actors. However, there was a tendency for state-owned investors to invest relatively more in the two technologically and financially challenging phases for the maturation of OSW (Figure 5.8).

In addition to exogenous and formal differences between the active investors, there were also endogenous sources of heterogeneity as the investors developed large differences in capabilities to invest in OSW. Beinhocker (2007) emphasised how bounded rationality leads to evolutionary processes where actors act via rules of thumb under the constraint of biases. From this outset, actors learn from the feedback received from the environment, which becomes important for developing superior strategies and long-term survival. This evolutionary source of heterogeneity is elaborated below.

In short, the basic condition for complexity in heterogeneous actors was plentifully present in the OSW case.

9.1.2. Network interaction

Network interactions among such heterogeneous actors are a second condition for the existence of complex phenomena (Arthur, 2014; Beinhocker, 2007; Ormerod, 2012). The research design was developed to bring the networked reality of OSW investment into light by using the aforementioned trio of network analytical methods. Together they revealed OSW finance to be a highly networked phenomenon through the co-investments in OSW projects and with the ties and investments distributed according to highly skewed power laws (Figure 6.8).



The graphical analysis in chapter 6 displayed how an integrated investor network grew up from the pioneering investments in phases 1 and 2. One network insight was that a few SIBs were indispensable for keeping the network together and growing it during the difficult phase 3, after the GFC when liquidity became scarcer and the technological cost of deploying OSW reached its highest point. Out of these experimental and growth-oriented phases came the maturation of the investor ecosystem with an increasingly dense network and a core of experienced financial investors that overtook the previously dominant role of non-financial investors and SIBs (Figure 6.5 and Figure 6.7). The aggregate data in chapter 5 also showed this tendency toward financialisation of deployment (Figure 5.3), but without the network methods, it was not possible to appreciate how interactive and evolutionary a process in the investor system that had brought about the new phase.

These changing patterns of interaction became even clearer in the know-how diffusion analysis in chapter 7, where the backward and forward reachable sets showed how each investor was structurally positioned in the network to absorb existing know-how and influence the rest of the network over time. We could thereby see considerable endogenous heterogeneity in how the investors interacted with the rest of the network and thereby contributed in different ways to the spreading of investment know-how.

While this network perspective provides an initial step towards an empirical approach to studying the maturation of sustainable investor ecosystems, it is a significant advance compared to the isolated, rationalistic, and representative investor implied in the CAPM model (Appendix A, chapter 3). As Kay and King (2020) pointed out, this mainstream model assumes that investors only differ in their appetite for risk – but not in their abilities to assess the risk and handle radical uncertainty. This view neglects the evolutionary processes that generate these capabilities that work as an antidote to the paralysing effect of uncertainty.

9.1.3. *Evolution*

This leads us to the evolutionary characteristics of the OSW financial network. Evolution concerns the processes of differentiation, selection and amplification that are endogenous

mechanisms for creating novelties and new patterns of interaction in the network. Rather than optimal decision-making, evolution works as an algorithm based on the strategy: “I will try lots of things and see what works and do more of what works and less of what doesn't” (Beinhocker, 2007, p. 216). Economic development is a learning process (Balland et al., 2022), and one required component is the maturation of the investor community through learning since “Effective finance for industry firms is best provided by finance providers that understand the activities to which they are lending” (Busch et al., 2018, 122). In accordance with the evolutionary perspective, learning-by-doing has been identified in RE finance (Egli et al., 2018).

When dealing with immature technology, the crucial issue is, therefore, to get the first step – “try lot’s of things” – set in motion. Chapter 6 showed how the punctuated equilibrium model could make sense of how the OSW financial network evolved over time (Figure 6.7).

The initial experimental phase of OSW deployment transitioned into a growth phase following the innovation of the first utility-scale parks deployed in Denmark. The utilities (that soon after merged with Ørsted) were directed by the Danish government to provide crucial initial differentiation in the energy sector by deploying the first large demonstration parks. Rodsand I (2001) became “the mother of all offshore wind parks” on a utility-scale, while Horns Rev I (2000) was regarded as a failure, which underscores the need for a portfolio approach in green industrial policy (Rodrik, 2014; Voldsgaard and Rüdiger, 2021). This ‘visible hand’ of the state thereby created the conditions for learning the early lessons that would send the sector into its growth phase.

The subsequent growth phase brought a lot of engineering ingenuity in phase 2, where new technologies, such as foundation types and turbine models, were tested and deployed under increasingly difficult marine conditions. This up-scaling phase and its experimental approach to “foundational innovation” was underpinned in the UK by the generosity of the ROC market design (Jennings et al., 2020) and feed-in-tariffs elsewhere, although we also saw experimental projects with major financial difficulties, most notably the BARD1 project in Germany (chapter 7). In this phase, we also saw the utility companies co-investing to build up early know-how and pool their capital and the pioneering use of project financing by a small group of core banks.



The growth phase continued during phase 3, where the important new “keystone specie” (Beinhocker, 2007, p. 173), the policy-based SIBs, rose to prominence in the network as a decentralised adaptive response to the deteriorating financial circumstances and the techno-economic conditions within OSW, which required larger single projects to be financed. The growth phase of the network can be said to have given way to an organised phase during phase 4, as the increasingly dense network became consolidated around a core of private financials as new keystone species (Table 6.1). The main new actor type in the network came with the resolute entrance of major oil companies, most notably Total, which could crowd out institutional investors and experienced developers that are unwilling to compromise with their hurdle rates.

The transition between the growth and the orderly phases was likely caused by a combination of an increasing and more dispersed stock of financial know-how, falling costs of technology and finance, and the Paris Agreement, which changed the foundation for forming long-term expectations of business opportunities. Financial innovations such as refinancing, ‘farm down’ selling of ownership stakes to institutional investors, and leveraged acquisitions have contributed to the dispersion of know-how and the falling cost of capital, which again lowered the cost of electricity (Figure 5.7).

9.1.4. Emergent properties

The fourth characteristic of complex systems is the emergence of higher-level properties that cannot be explained with reference to the characteristics of the components: ‘more is different’ (Anderson, 1972; Arthur, 2014; Dosi and Roventini, 2019; Foster, 2005; Kirman, 2011). Chapter 5 identified four main emergent properties of the OSW investor network:

1. The oscillating patterns of annual investments (Figure 5.3)
2. The shifting composition of investment sources (Figure 5.8)
3. The installed cost of OSW capacity (Figure 5.5)
4. The cost of capital (Figure 5.6 and Figure 5.7)



In line with a co-evolutionary perspective on sustainability transitions (Foxon, 2011), the emergent properties are not solely resulting from interactions in the investor network but from the network's mutual influence upon and adaptation to other transition elements, including institutions, technologies, business models, user practices, and natural ecosystems.

First, the annual level of investment in new OSW parks has been on an upward trajectory with considerable oscillations around the trend. Figure 5.3 displayed how annual primary financing (i.e. for new parks) was negligent before accelerating in the 2000s with ensuing peaks in 2009, 2016, and 2020. The analyses showed how this volatile pattern was strongly influenced by SOEs and SIBs that, in correspondence with general political aims to increase OSW deployment, invested around the technology's two 'valleys of death': the demonstration of technological viability at utility-scale and the challenge of sources enough finance following the GFC until the cost of OSW began to fall (Figure 5.8; BNEF (2010); Karltorp (2016)).

After the technological valley of death had been crossed, the normal size of OSW projects scaled up beyond 100MW during phase 2. It became increasingly difficult for investors to finance the projects on their own balance sheets, especially for independent power producers, but utilities also co-invested in this phase. In addition, the reduced appetite for risk among banks after the GFC created more interdependency in the investor ecosystem. Each investor had to find a constellation of a sufficient number of investors with OSW know-how and the willingness to fund a specific project on terms that would still leave a return on equity (chapters 6 and 7).

The drop in investments from 2009 to 2012 coincided with the increasing reluctance of private banks to finance OSW (interview 2). One of the few primary investment decisions at the bottom in 2012 was Ørsted, Centrica, and Siemens' attempt with project finance which was dragged out for years because of the banks' conservative approach (Guillet, 2022). The peak in 2016 was driven by Ørsted's investments which were in part funded by sales of ownership stakes to institutional investors and financing by the EIB and NIB.

The second emergent property was the changing composition of the active investor community, which was displayed in Figure 5.3 and Figure 5.8. There were notable phase shifts in the composition. The early civic and state-led investments led OSW into the growth phase, where



private utilities for a period became the dominant investors, with a minor role for private banks. Although, for a few years in this period, around 2009, SOEs were the largest investors⁵³. From 2012 the pendulum swung back as SOEs and SIBs became the more dominant investors in the countercyclical investment cycle that peaked in 2016. The network then experienced another phase shift into the financialised phase from 2019-2021. This rapid change can be interpreted as the consequence of OSW cost reductions, the Paris Agreement, and increasing familiarity with investments in OSW among financial investors following the evolutionary processes described above. Also, the development of a group of highly experienced ‘core banks’, that had already been involved in the first instances of project financing before the GFC, provided a lead investor group for the ensuing financialisation, which attracted less experienced banks as the market matured.

The third emergent property was the falling cost of installing a MW of OSW capacity (Figure 5.5). While the investors in the network were motivated to earn enough from OSW parks to achieve their applied hurdle rates for the return on investment, most were not explicitly motivated to lower the future cost of OSW through learning-by-doing or enabling economies of scale in the supply chain. After the technological experimentations in the 1990s and 2000s, developers were searching for marginal ways to improve upon their previous projects, especially by “sticking to the plans”, rather than promoting more ground-breaking innovations (Backwell, 2018, p. 114; Jennings et al., 2020). Nonetheless, the industry used the demand to accumulate know-how and devise better solutions, especially larger turbines, which would eventually bend the cost curve. One exception to this tendency was Ørsted which worked in a strategic partnership with Siemens to industrialise the OSW supply chain to lower the costs of OSW (Ørsted, 2009; Voldsgaard and Rüdiger, 2021). The switch to auction models for revenue support also supported this mechanism by increasing the competitive pressure among developers, which would be passed down through supply chains (Jennings et al., 2020; Mercure et al., 2021b).

⁵³ One major reason was Ørsted’s investments in the major London Array project.



One of the positive feedback effects that became stronger as the industry matured was the fourth emerging property: the falling cost of capital (Figure 5.6, IEA, 2019). Two of the mechanisms were the increasing financial investment know-how and fixed investment know-how, that both improved through learning-by-doing and learning-by-co-investing in the network. As the network reachability analysis in chapter 7 showed, the presence of investment know-how that would allow the cost of capital to fall was the result of a fragile learning process centred on a few crucial organisations, most notably Ørsted, the private banks who pioneered project finance, and three most active SIBs.

These learning mechanisms occurred in conjunction with the increase in revenue certainty because of regulatory changes in the large UK market from the Renewables Obligation scheme to auctioning of fixed-price contracts. This regulatory tendency towards auctions turned external financiers more confident in the potential for investing profitably in OSW (Jansen et al., 2022; Mercure et al., 2021b).

In short, the OSW sector produced emergent properties that cannot be properly explained without reference to the interactions among investors and evolutionary learning processes embedded within the networked structure of co-investments.

9.1.5. Non-linear dynamics

The last aspect of complexity to consider is to what extent the OSW investor network contained or caused non-linear dynamics (Beinhocker, 2007). In other words, if there were feedbacks between the stocks and flows in the system over time (dynamic) and different rates of change with high sensitivity to initial conditions and path dependencies (non-linear). The OSW network can be said to have exhibited non-linear dynamics in two respects. First, the ongoing flow of investments generated a growing cumulative stock of know-how (chapter 7) and network capital in the form of network connections (chapter 6) that endogenously became distributed unevenly among the investors according to their varying investment activities (Figure 6.8). This stock of know-how and relationships, in turn, affected the conditions and propensities for undertaking investments since it modifies the investors' fixed investment know-how to construct a project on



budget and time, as well as their financial abilities to identify a sound project plan and enable it through credit provisioning. This was reflected in the persistence of investors who had many connections in the earlier phases among the top investors in the later phases (Figure 6.9).

This stock-flow relationship has contributed to the non-linear investment pattern since a higher stock of investment know-how requires fewer subsidies and revenue guarantees to incentivise new investments, reflected in the recent trend to zero-bid auctions. Improved fixed investment know-how lowers the cost of deployment, while more financial know-how lowers the risk premiums placed upon projects by external financiers and internally by utilities in relation to their institutionalised hurdle rates (Helms et al., 2020).

Secondly, regarding path dependency, a few impactful series of events have had disproportional impacts on the trajectory of offshore wind investment. In line with the complexity-informed focus on initial conditions, the early investments by Ørsted, the utilities that would merge with it in 2005, and some minor investors created an early stock of know-how and took OSW across the technological valley of death.

As mentioned in chapter 6, this was a source of fragility in the historical development of OSW, since the investments were demanded by the Danish government. The second source of fragility was that two instances of project financing were completed by Rabobank and Dexia before the GFC, which provided vital positive precedents for future bank involvement after the GFC. Thirdly, the presence of SOEs and SIBs that scaled up investments after the bottom in the investment cycle in 2012 were important for bringing OSW on a learning curve that generated rapid cost reductions.

Until this point, OSW was deployed against severe negative headwinds: first technological uncertainty, then rising costs, and thirdly the GFC, where the high costs plateaued. The combination of demand-side pull and persistent strategic investors eventually led to induced innovation and sufficiently lowered the cost of capital to set off a learning curve with endogeneity between deployment and falling costs.

From the financial innovations and interactions during phases 3 and 4, a more orderly structure of financing appears to have emerged in phase 5. The network evolution seems to have



culminated with a permanent structure around a considerable core of experienced financial and non-financial investors who will keep on investing in this now-mature technology. This suggests that the technology-investment nexus has settled in on a productive kind of path dependency, where OSW can be financed in accordance with the requirements of net zero transition scenarios.

However, as discussed below, the recent entry of the major oil companies Total, BP and Shell could disrupt this otherwise orderly financial structure. The oil companies' relatively low level of OSW experience and low connectivity with experienced investors (chapter 6), in combination with relatively large initial investment commitments, could increase the risk of severe project issues. Moreover, their high bids for seabed leases could jeopardise the project economies, especially as the regulation is trending towards more price risk (Pahle and Schweizerhof, 2016). The large scale and synchronous production of power from OSW could create depressed sales prices as a new emergent property, which could send dampening feedbacks back into the investor system.

In summary, OSW investment has displayed all five features of evolving complex systems, which are summarised in Table 9.1. The complexity perspective has thereby provided a clearer understanding of how the aggregate results in the sector were emergent properties of the investor network of heterogeneous investors that continuously evolved. The investors were all dependent on the demand-side policies that created the market pull. In addition to this well-known fact, the analysis shows that the demand-side policies were also dependent on the evolutionary processes that eventually created a supply-side capable of financing OSW without the formerly large role of SIBs and SOEs. These insights open the financial supply side as a subject for policy-making in sustainability transitions.

Table 9.1: The complexity characteristics of offshore wind investment

Complexity characteristics	Offshore wind finance
Heterogeneous actors	Different industrial sectors, ownership forms, attitudes to risk, capabilities to invest in offshore wind, visions for the future of offshore wind, access to capital, i.e. financial strength, and attitudes to project transparency.
Network interaction	Utilities co-investing with other utilities, SIBs, and later institutional investors through divestments of minority stakes. Generally increasing amounts of co-investments – especially including SIBs and project financing banks. SIBs as important hubs between project financiers and balance sheet investors.
Evolution	Evolutionary mechanisms shaping behaviour: Learning-by-investing, know-how diffusion through co-investment, increasing returns to experience, preferential attachment, adaptive self-organisation to external and endogenous constraints, incl. financial innovation.
Emergent properties	Changing investment levels. Phase transitions in the investor composition and network structure (from the dominance of utilities to SIBs to private finance). Falling technological costs driven by deployment. More favourable conditions of financing, incl. cost of capital and tenors.
Non-linear dynamics	Positive feedbacks effects between the flow of investments and the stock of investment know-how. Path-dependent sensitivity to impactful events, incl. early utility-scale demonstration parks, project financing being established in reference deals before the GFC, and SIB investment strategies after the GFC.

Note: Characteristics based on Beinhocker (2007).

9.1.6. Towards a complexity theory of renewable energy finance

So, what is gained from studying RE finance with complexity theory? The original motivation was Hall et al.'s (2017) proposition that by considering energy finance as an *adaptive* rather than *efficient* market, we would be better equipped to understand why emerging RE technologies faced difficulties being deployed at a large scale. The authors found that co-evolution between behavioural constraints, the investment circumstances in the energy sector, and financial market structures produced a disorderly market for financing RE. Especially, three key structural issues



were holding back capital market investment: “lack of a mature community of investors, mismatches between investment and fund manager timescales, and lack of suitable investment vehicles” (p. 293), which would require the investor landscape to change through entrance and exits of different investor types as well as by incumbents adapting and learning.

The analyses in this dissertation have advanced their ‘adaptive market hypothesis’ by further examining the mechanisms in operation over the course of the entire lifetime of deployment of a single RE technology. In this sense, the study achieved a more comprehensive systems perspective on the evolution of the investor network in spatial and temporal terms, while it sacrificed some of the policy context specificity that Hall et al. (2017) managed to integrate with the case analysis of offshore wind in the UK around the adoption of the Electricity Market Reform. While Hall et al.’s (2017) research was more deductive, reasoning from abstract theories of capital markets, the rich data available for this dissertation has enabled a more inductive approach to examine RE finance. Moreover, the use of network analytical methods has been instrumental in assessing the dynamics of RE finance.

This expanded perspective enabled the dissertation to answer questions regarding the role of finance beyond capital markets. Four aspects were advanced through further dialogue with the complexity economics literature (chapter 3): The scope of finance, the role of networks, investor learning, and emergent properties. The latter three have been explained above, so here I will consider how the complexity perspective is helpful for understanding RE finance in greater breadth and depth.

Chapter 3 suggested that the concept of energy finance as an evolving complex system may be more suitable than the ‘adaptive market’ concept because capital markets may not be expected, in the first place, to be a compatible source of finance for renewables. Rather, we should expand the focus of our theory of finance beyond capital markets. As demonstrated in the analytical chapters, the financing depends to a large extent on balance sheet financing, project financing with transactional deals among clubs of banks, and bespoke ownership sales to de-risk the specificities and uncertainties in such large construction projects and unforeseeable electricity market circumstances. Capital markets are not well suited as source of finance, since it is



conducted in a “fire and forget” manner without a relationship between creditor and debtor after the financing takes place (Guillet, 2022, 69).

Project bonds were first used in 2015 to finance Ørsted’s Gode Wind 1 project, and by 2021 only eleven OSW project bond transactions had been completed, out of which seven provided funding for the construction of new projects. Out of these seven series of bonds, only *one* had a credit rating which rendered it fit for public market exchange rather than private placement outside of public markets (Credit Agricole, 2021, 7-9). In concurrence with the adaptive market hypothesis, capital markets have not been important sources of capital, so we should theorise beyond this particular form of financing.

Utilities do use capital markets to finance their balance sheet-financed projects with bonds and equity that are traded on stock exchanges. Unfortunately, these one-step-away financial arrangements on the liability side of utility company balance sheets could not be integrated into the network analysis. On the other hand, the capital markets do not stand out as an important causal force in the deployment of offshore wind because they did not take on construction risk. Bond and equity holders have had recourse to the earnings from all the operation assets on a company’s balance sheet. Hall et al. (2017, 286) also acknowledge that the common statistical tests of the adaptive market hypothesis in the literature were “impossible for RE finance as no publicly quoted exchange or secondary market currently exists”, which is why they resorted to more qualitative methods.

Capital markets may become more relevant in the future as the financial sector’s predisposition to ‘Minskian’ financial innovation carries on, but for the development, large-scale deployment, and maturation of the next generation of sustainable technologies, the ‘capital market’ frame focuses attention to the parts of the financial system, we should be the least concerned with from a sustainability transitions perspective. The financial system was shown to be a highly flexible system, not least empowered by the banks’ credit creation that both funded project financing, refinancing, and leveraged acquisitions (Appendix D: Figure 0.6). Moreover, the potential for using SIBs to finance deployment was held back by the mandated goal of ‘crowding in’ private investors as a quantitative rather than qualitative (i.e. learning) ambition.



While the original point that capital markets are ill suited for RE investments still stands, this dissertation has taken a broader approach to the financial system by examining the plethora of sources of finance potentially available for renewable energy. Instead of reasoning from the concept of capital markets, the ‘evolving complex system’ concept encompasses more modes of financing, incl. relationship and club banking, loan syndications, and de-risked ownership sales. By opening the conceptual space for these more relational modes of financing, we can better appreciate the importance of the endogenous learning processes in investor ecosystems based on the accumulation of investment know-how and network capital, i.e. network connectivity.

These two phenomena reveal key mechanisms behind the social process of investor system maturation. Investors learn about how to deploy OSW in patterns of co-investments, which produce new know-how from the deployment of new generations of technology under new market circumstances and diffuse the previously generated know-how through the system. The more explicit consideration of these social processes of organisational learning offers an advantageous position for understanding the role of investment in the cost reductions along learning curves and the observed non-linearities in the investment trajectory.

The complexity framework can also provide an improved explanation for why finance has not effectively been a constraining factor for the deployment of offshore wind. Hall et al. (2017) suggest investors will adapt and experiment to circumvent their cognitive deficiencies and constraints, and the analytical chapters in this dissertation have shown how this process has indeed occurred over time for OSW. While private investors have been important, especially regarding project finance, the history of how OSW matured could hardly be conceived without the path-shaping roles of entrepreneurial state investors. In other words, left to itself without the resolute investments by SIBs and SOEs, we should expect a quite different outcome for OSW. The path-shaping roles of entrepreneurial state investors also underline Gräbner's (2017) point that the complexity perspective should be combined with an understanding of institutional factors shaping the network's evolution.



To sum up, the first scholarly contribution of this dissertation is to have shown how a complexity perspective on RE finance can yield a better understanding of how finance and investments shape the development of emerging sustainable technologies. The regular policy approach of promoting RE investment through adjustments of the risks and returns is undoubtedly of crucial importance (Polzin et al., 2019). However, the analysis of OSW financing as an evolving complex system has displayed some of the underlying causal mechanisms that enable investors to respond effectively to the rewards offered by policymakers through the market design. Namely, the accumulation of investment know-how is a precondition for effective responses to price signals, as sufficient know-how can overcome the unavoidable uncertainties involved in scaling up the deployment of new technologies in unfamiliar market circumstances.

In addition, the large scale of these investments leads developers to depend on the willingness of financial institutions to take risk and – in their role as ‘ephors’ (Schumpeter, 1983) – allow new technology to be deployed, so more learning can occur. Since this dependency is not mediated through market exchange of tradable financial products, the networked reality of mobilising finance stands out as central to inquiries into the dynamics of RE finance.

The financial network of co-investments shapes which investors that achieve the most investment know-how from learning-by-doing and the know-how diffusion among investors. This leads to self-reinforcing and path-dependent evolution patterns where early movers benefit from the accumulation of investment know-how and network capital (Barabási and Albert, 1999). However, the way in which these self-perpetuating processes are initiated remains poorly understood. In the next section, we, therefore, move to consider some of the institutional factors that have shaped the evolution of the offshore wind investor network.

9.2. The complexity-institutional nexus and the raising of green animal spirits

While the previous section suggested that our understanding of renewable energy finance has been improved by adopting a complexity perspective, oftentimes complexity is difficult to combine with institutional factors – i.e. “integrated systems of rules that structure social interactions” (Hodgson, 2015, 57) – that impact how a network under consideration evolves.



Gräbner (2017) proposed that there is a complementary relationship between complexity and institutional economics. Institutional analysis can provide theoretically informed social mechanisms as explanations for how complex phenomena lead to particular outcomes, while complexity approaches offer a methodology for empirically assessing institutional theories. Bale et al. (2015, 152) similarly suggest social norms and institutional rules shape networked interactions which in turn may change the intuitions or create new ones “such as practices for energy use or particular market frameworks governing energy supply”.

One bridge between complexity and institutionalism is the focus within complexity studies on heterogeneous actors and the institutionalist perspective on organisations as one type of institution that can “enable, facilitate, and incentivize as well as constrain activity” (Hodgson, 2015, 58). The OSW analyses have shown how organisational diversity – and the resulting variety of investment behaviours over time – has been an important driver behind the maturation of OSW. This section considers one of the main categories of organisations that has shaped the evolution of OSW: The role of entrepreneurial state investors.

Keynes (1964 [1936]) emphasised how the state of effective demand in the economy depended on the state of confidence in private businesses, which in turn would shape their investment plans. He used the concept of ‘animal spirits’ to characterise the socio-psychological dynamics that – in the absence of rationalistic calculus – could either lead to multiple equilibria with either persistent optimism and investment or reluctance and unemployment. Based on this image, Chapter 7 considered how *green animal spirits* arose in the OSW investor community to advance the deployment and cost reductions of OSW. Given the vast uncertainties related to deploying new capital-intensive technologies, we should not expect such green animal spirits to automatically appear and set off virtuous cycles (Schmidt, 2014). Rather, the private sector may be fundamentally ill-equipped to invest early in this type of assets.

Mazzucato (2013, 30) criticised the common image of “a roaring business sector and purring bureaucratic State”. Rather, in the realm of innovation, the animal spirits of the private business sector are prone to act:



not as tigers and lions, but as pussycats [which] means that the State is not only important for the usual Keynesian countercyclical reasons – stepping in when demand and investment is too low – but also at any time in the business cycle to play the role of real tigers ... even in the boom (when in theory there is full capacity utilization), there are in practice many parts of the risk landscape where private business fears treading and government leads the way (Mazzucato, 2013, 30).

This conception of government as a chief investor in the face of the uncertainties of innovation focuses attention on “what the State can do to raise the ‘animal spirits’ of business – to get it to stop hoarding cash and to spend it in new path-breaking areas” (ibid.). This study of OSW investment has provided a micro- and meso-level account of how entrepreneurial state investors can summon green animal spirits in the private and non-profit business sectors. They can do so by advancing new sustainable technologies across their ‘valleys of death’ (Figure 5.8) through public investments in deployment and because of their central role in the accumulation and diffusion of investment know-how.

The success of bringing down the cost of OSW deployment suggests the investor diversity and dynamic changes in the network composition provided the needed resilience to overcome the hurdles both from the technology itself (e.g. technological breakdowns and deployment in more difficult conditions) and the market environment (GFC, more expensive materials, competition for installation vessels, currency swings). In a discussion of know-how management in financial organisations, Clark (2018, 288) posited that “what counts as knowledge can be highly contingent and subject to unexpected failure”, why markets where expectations are stabilised may attract more investment activity. One key to achieving more stable outcomes may be organisational diversity: “The coexistence of different types of investment organisations designed to deal with much the same challenges suggests that the ever-present conditions of market risk and uncertainty provide both opportunities for institutional innovation as well as a rationale for the persistence of organisational differences up until the point certain types of organisations fail” (Ibid.).



In the OSW case, we can see how different types of organisations have displayed strengths and weaknesses as investors at different stages of technological maturity. This could be considered a *division of financial labour*⁵⁴. This division materialised by some investors being more responsible for investing large volumes of capital and taking on construction risk, mostly public and private utilities, while others, predominantly commercial banks, were connecting the investor ecosystem both within and across phases. The SIBs contributed markedly to both of these roles in the three middle phases. So far, the system impact of having SOEs and SIBs adding to the organisational diversity of investor ecosystems is underappreciated in the green finance literature (Geddes and Schmidt, 2020).

While the analytical chapters displayed a considerable heterogeneity among investors – both in terms of organisation types and endogenous differences in know-how – a group of SOEs and SIBs stood out as trajectory-shaping investors. We saw how SOEs, especially Ørsted, were important in the first two phases, and they were reinforced in the ensuing growth phase by SIBs, especially by EKF, EIB, and KfW. We can refer collectively to such state-owned enterprises and state investment banks who seek to deploy novel technologies at scale as *entrepreneurial state investors*.

Gradually, the private financial sector matured to take over most of the financing of OSW in recent years. A core of experienced banks formed the crucial links between the growth phase, which was underpinned by SIBs, and the orderly fifth phase, organised around private banks and capital funds. The ambition for the next sections is to advance towards a theory of how entrepreneurial state investors can promote the adoption of new sustainable technologies both through direct investments and their co-investment relations to the wider network.

9.2.1. State-owned enterprises – learning curve initiators?

In recent years, SOEs have been considered an organisational form for promoting innovation and learning in the economy with under-explored potential (Benassi and Landoni, 2019; Jerneck,

⁵⁴ Similarly, Arora et al. (2015, 4) observed a growing “division of innovative labor” where R&D is increasingly undertaken by smaller firms, while larger firms focus on commercialisation.



2020; Tõnurist and Karo, 2016). According to these contributions, SOEs can serve both as independent innovation actors and coordinating change agents in the innovation system. The SOEs' 'softer budget constraints' and more patient corporate governance models provide an institutional setting for marrying financial incentives that gets accounted for in their annual financial statements, with a long-term orientation towards wider public purposes. Benassi and Landoni, (2019) suggest SOEs could to a greater extent be used as 'knowledge explorer agents' in the economy.

So far, most attention in the entrepreneurial state literature (Block and Keller, 2011; Mazzucato, 2013, 2021) has been given to grant-giving innovation agencies in tandem with public procurement, especially within the defence and airspace sectors, and more rarely to public enterprises that deploy technologies to service citizens or customers. However, as recognised in the mission-oriented innovation literature (Foray et al., 2012; Mazzucato, 2018), the 'NASA model' with a comprehensive efforts towards a single goal is not well-suited to the current generation of 'grand challenges' that require ongoing rounds of incremental, radical, and complementary innovations by numerous competing solutions. Also, grand challenges aim to achieve far-distant goals, such as global net zero emissions, rather than a specific outcome, such as a man on the moon or the invention of a nuclear bomb.

In this regard, SOEs could more actively be used as deployment institutions for new technologies in the early stage of their learning curves. Ørsted's success in OSW stands out as a clear example of how states can shape technological trajectories by directing capable organisations into new technological niches (Voldsgaard and Rüdiger, 2021). While the first push required the visible hand of the government, Ørsted's later strategic pivot towards OSW arose more endogenously within the company as it recognised its unique position as a front-runner in this sector, which dovetailed the tendencies towards strengthening climate policy ambitions (Ibid.).

If the Danish government had not required Ørsted's predecessors to construct the two first utility-scale OSW farms in the early 2000s, it is unlikely that the ensuing decades would turn out to be the same growth phase for OSW as they did. These path-shaping investments by energy company SOEs concur with a broader pattern of low R&D expenditure among energy companies (Grubb



et al., 2017), suggesting many opportunities for energy innovation are not pursued as soon as economically warranted.

9.2.1.1. *Rethinking the governance of state-owned enterprises*

For society to benefit from this possibly impactful role of SOEs, renewed attention must be directed at the corporate governance of SOEs. One literature review finds that we generally know little empirically about SOE governance since most studies use regression analysis on “secondary database data [that reduces] SOE performance to financial figures, which hinders a broader perspective” (Daiser et al., 2017, 457). The researchers call for more qualitative studies since “the primary goal of SOEs is not to make profit, but to fulfil its public service and to create public value”. This lacking attention to qualitative impacts is particularly pertinent to the ability of SOEs to move the technological frontier. However, such considerations have been neglected because “SOE-oriented corporate governance methodologies are not available” (ibid.).

One case study of Swedish SOE governance finds “a clear hierarchization of values, prioritizing financial values [and] the few chosen non-financial targets are financialized when translated into an economic performance language and presented in economic figures aiming for a commensuration of the different missions that all get price tags for their fulfilment” (Alexius and Örnberg, 2015, 301). If SOEs are not governed to pursue qualitative impacts such as innovation, the potential is likely severely underutilised.

The results of this dissertation’s analysis can be used to reflect critically on the OECD’s (2015) official *Guidelines on Corporate Governance of State-Owned Enterprises*. The guidelines take departure in the maxim that “market-led development is the most effective model for efficient allocation of resources” (Ibid., 11). Consequently, the guidelines are primarily concerned with making “SOEs operate with similar efficiency, transparency and accountability as good practice private enterprises” and to ensure that “competition between SOEs and private enterprises, where such occurs, is conducted on a level playing field”, which has been a part of the New Public Management trend in the governance of the public sector (Florio, 2014). Moreover, the resulting ‘good corporate governance’ is also “an important prerequisite for economically effective

privatisation” (OECD, 2015, 11). The role of SOEs as vehicles for delivering public policy objectives is more of an afterthought, with most attention directed at avoiding disturbance of the market opportunities for private companies. For instance, SOEs should be required to earn the same rates of return as private enterprises (ibid., 21). Notwithstanding, there is a recognised role for “public policy objectives”, incl. industrial policy (Ibid., 45). Still, OECD research has found that “state ownership itself has a positive effect on investment in the renewable electricity generation sector in OECD and G20 countries” (Prag et al., 2018, p. 9). In 2020, two thirds of 28 surveyed countries had made progress on integrating sustainability-related values into the governance of SOEs (OECD, 2020b). The OECD (2022, p. 2, 14) recently reported on the potential for SOEs to “lead by example”. However, this role is largely limited to reducing the firm’s own environmental footprint, e.g. through investments in RE, while neglecting the potential for SOEs to act as agents of system change through innovation partnerships and early large-scale deployment of new technologies.⁵⁵

One possibility for benefiting from the innovation potential of SOE investments could be to confer relevant SOEs with a *Technological Frontier Investment Mandate* (TFIM). The TFIM would obligate the SOEs to dedicate some of their investment spending on deploying new technologies according to their own analysis of technological trends in their field. For instance, Ørsted pushed the technological frontier in offshore wind by strategically supporting the industrialisation of the supplier ecosystem (Voldsgaard and Rüdiger, 2021). Before Ørsted, DONG and the civic utilities were required by the Danish Minister of Energy to deploy OSW to be allowed to expand coal production. This was successful in hindsight. However, to better utilise the SOEs’ monitoring of technological and market tendencies and associated emerging opportunities, it would be preferable to allow SOEs more freedom in selecting technologies. The importance from a policy perspective is to ensure sufficient experimentation.

This conclusion is informed by the industrial policy scholars who have advocated *reflexive* and *experimentalist governance* as a precondition for maturing technologies and raising political

⁵⁵ The report’s (p. 32) mention of the Swedish Hybrit project, aiming to produce steel with green hydrogen, is a notable exception in line with this section’s argument.



ambitions through iterations based on learning rather than perfect foresight (Charles Sabel, 2021; Cullenward and Victor, 2020; Hanna and Victor, 2021; Loorbach, 2010; Sabel and Zeitlin, 2012; Voß et al., 2006). When uncertainty is pervasive and change is rapid, “fixed rules written by a hierarchical authority become obsolete too fast to be effectively enforced on the ground” (Sabel and Zeitlin, 2012, p. 172). Experimentalist governance deals with this condition through iterative steps of, first, setting broad, shared targets without clear conclusions regarding the best solutions. Then “local units [such as private firms or territorial authorities] are given broad discretion to pursue these goals in their own way” (ibid., p. 170). Third, to deserve this autonomy the ‘local units’ must report regularly on their performance and participate in peer review processes. If their own progress is inadequate, they must adopt knowhow and practices from more successful units engaging in experimentation. Lastly, the goals, metrics and decision-making processes are under periodic review in light of revealed problems and opportunities.

Placing a TFIM on SOEs would more firmly integrate SOEs in the experimentalist processes of climate change policy, such as the EU’s climate targets. More specifically, in relation to mitigation of safety failures, experimentalist governance advocates “to build on and monitor firms’ own error detection and correction mechanisms by requiring them to develop systematic, verifiable plans for identifying and mitigating possible hazards in their operations” (ibid., p. 172). TFIMs likewise require SOEs to undertake more deployment of innovative technologies guided by their own detection and monitoring mechanisms. The public owner scrutinises the decisions taken and results and, if necessary, challenges the fulfilment of the investment mandate by the company’s leadership.

TFIMs should therefore be placed upon SOEs active in the relevant sectors such as electricity, heating, steelmaking, and aviation. They would be obliged to take experimental action scaling up technologies with underexplored and radical innovative potential, to avoid promoting only incremental innovations. Still, the innovation mandate should be articulated in broad enough terms to allow the SOEs freedom to experiment and take advantage of their particular strengths and organisational capabilities. Systematic adoption of TFIMs should be considered a *tactical* type of transition management that targets the change of institutions over a 5-15 year horizon



(Loorbach, 2010), i.e. the role of SOEs in the economy. Each concrete TFIM would be an *operational* form of transition management aiming to spur new concrete projects (ibid.).

In terms of accountability, a TFIM would oblige the SOE to account for its technological frontier investments in its annual reports. The reporting should account for the SOEs demonstration and utility-scale use of new technologies and the progress made underway. It should not necessarily result in cost reductions, but tangible lessons learned underway should be identifiable. The SOE should work with its suppliers to provide these insights. The reporting on technology deployment and development should enable the public owner(s) to demand a technological re-orientation or diversification if the SOE's activities are not inducing desired results. However, from a public value perspective, SOE failures on particular frontier technologies may still be valuable by providing novel information on their limitations based on experimentation.

In relation to using SOEs as delivery vehicles for industrial policy, the OECD (Ibid., 45) suggests separating ownership and industrial policy formulation. With regard to TFIMs, arm's length between politics and SOE operations is still warranted, so the technological decisions are not based on overtly politicised reasoning. However, an absolute detachment could lead to misaligned SOE investments compared to the opportunities opened by other industrial policy levers, incl. grants for research and demonstration or new companies financed by SIBs that are looking for early opportunities to deploy technologies in politically desired areas. The mandates could therefore provide guiding suggestions informed by the government's transition strategies, such as an identified need for more flexible energy production and storage technologies, or an aim to develop low-carbon steel.

9.2.2. *State investment banks – public value ephors?*

As mentioned in the introduction, Schumpeter (1983 [1934], 41) valorised the banker as “essentially a phenomenon of development” who enables the visionary entrepreneur to acquire inputs from the rest of the economy through the creation of new purchasing power. However, he was critical of public banking as he believed this entrepreneurial function of finance – akin to the ephors overseeing the kings of Sparta – could only be served “when no central authority directs

the social process”. Nonetheless, this dissertation has observed how SIBs have been integral to the deployment of OSW by committing vast amounts of risk-embracing capital. They were also important for the learning processes within the investor community by building up technical expertise in-house that allowed them to become trusted partners in co-financing arrangements and network hubs (Geddes et al., 2018). Indeed, the need for financing deployment of renewables has been one occasion for the return of national development banking (D’Orazio and Löwenstein, 2020; Griffith-Jones and Ocampo, 2018; Marois, 2021a; Mertens, 2021; Mertens et al., 2021a; Mertens and Thiemann, 2019; Steffen et al., 2020a). This financing has enabled OSW technology to be deployed and mature along its learning curve until the current point where it has the potential to supply more than 2,000 GW of generation capacity in 2050 in 1.5 degree scenarios (IRENA, 2021d).

9.2.2.1. The four roles of state investment banks in OSW

Mazzucato and Penna (2016) developed a typology of the four roles of SIBs: they can be *countercyclical*; *capital developmental*; *venture capitalist*; and *challenge-led investors* – and take on multiple roles at a time. The analyses of OSW financing display several of these aspects whereby SIBs can have a market-shaping role in the economy and affect technological trajectories.

In phase 3, the SIBs assumed a classical Keynesian countercyclical role following the GFC, where they scaled up their investments in OSW as a channel for improving demand in the European economies. As Mazzucato and Penna (2016) note, the SIBs’ role as an investor when the financial sector is reluctant is not only relevant in macro downturns because of pervasive financialisation, short-termism, and risk aversion in finance. We saw this in the actions of EKF in the early project financings before the GFC, where the Danish export credit agency assumed a considerable part of the risk. EIB provided much of the capital at risk for the first project financing deal after the GFC for the Belwind project. Since SIBs are also learning organisations, these early engagements were also important enablers for their subsequent substantial financial commitments in OSW.

Secondly, the SIBs contributed to the capital development of Europe by enabling large-scale deployment of OSW during the third phase, where deployment rates increased further (Figure 5.1). This directed push for scaling up OSW contributed to the technical change of the European energy sector, where OSW has since become a major strategic priority (EU Commission, 2020). In addition to the direct effect of providing large volumes of capital, their presence lessened the need for bringing unexperienced investors on board, which would have delayed the falling cost of capital due to their unfamiliarity – because it is commonly the least confident debt provider that sets the terms in a club financing arrangement (Guillet, 2021).

The capital development was, in a sense, underpinned by the educational role of the SIBs (Geddes et al., 2018; Geddes and Schmidt, 2020; Steffen et al., 2020a). Although they lessened the need to include more commercial banks without the expertise to invest in OSW, their recognition as expert investors meant that more inexperienced investors became confident enough to invest in OSW. This improved the financial system's potential for gradually learning-by-doing. Economic geographers have emphasised the existence of barriers to knowledge transfers across space and time, which means “the effectiveness of learning-by-doing is mediated by geography-specific institutional formations and social relationships” (Clark, 2018, p. 287). Chapter 7 showed how the SIBs were an important kind of ‘institutional formation’ that ameliorated the fragility of know-how accumulation in the investor network by being trusted partners for private banks based on their evolving in-house expertise in in-depth risk assessment (Geddes et al., 2018).

The technical and financial in-house expertise of SIBs was used to conduct parallel due diligence exercises, which project financiers also obtained from external advisors. This practice provided less-experienced investors with increased trust in the soundness of the projects. KfW was a notable example of this practice (Geddes et al., 2018). EIB (2022) offers their borrowers access to their technical and financial knowledge, development of skills and expertise, sharing of best practices, and access to the bank's network of experts. This dissertation's interviews indicate that EIB had a know-how-based impact like KfW's of attracting less-confident banks (interview 2). Less-experienced bankers could avoid blame internally in case of mishaps and losses since the SIBs were regarded as sophisticated investors (interview 2). From a more networked perspective,



the high inclusion rate of SIBs in OSW financing meant that they were in a privileged position to know the sector and the lessons learned from handling various construction and contractual issues. Guillet (interview 2) also indicated that some investors used the involvement of SIBs for diplomatic reasons vis-à-vis the government.

Finally, the EIB provided a structural link in the network between the balance-sheet financing utilities, who possessed much know-how from their early investments in OSW during phases 1 and 2, and the more densely connected project finance-based cluster of the network (Figure 6.6). In addition, the main SIBs in OSW in this way assumed a network-integrating role, as the EIB, KfW and EKF took part in most project financing of OSW until the fifth phase where private financiers became more self-reliant (interview 1).

The venture capital role was less pronounced for SIBs. They did not exactly target potential high-growth ‘gazelle’ firms, although they were an early investment partner of Ørsted, who managed a remarkable growth path in the sector. On the other hand, their presence in project finance did enable smaller developers and their co-sponsors to become independent power producers, which led to increased competition in the auctions for price agreements in the 2010s.

Lastly, some SIBs displayed a pronounced grand challenge role while articulating a central role for OSW in structural transformations of energy systems: KfW’s dedicated offshore wind programme in the context of the wider *energiewende* programme, UK GIB’s mandate to support OSW, and EIB’s sustained presence as a large-scale investor in OSW with reference to supporting the EU’s 2020 climate and energy targets.

9.2.2.2. *Governing the state investment banks*

Similarly to SOEs, there is no automaticity in the impact of SIBs (Marois, 2021b). SIBs have to be governed with particular strategic goals in mind to realise their market-shaping potential (Mazzucato and Penna, 2016). SIBs have for example been identified as organisational tools in the state-led promotion of market-based finance, where loans are pooled and sold in tranches on capital markets (i.e. securitisation) (Mertens and Thiemann, 2018) and active promoters of



public-private partnerships for privatising ownership of infrastructure (Liebe and Howarth, 2020).

In this dissertation's analysis of OSW, the SIBs do not appear to have been occupied with the development of a market for securitisation, although this should be studied further. And while the debt provided for offshore wind deployment has contributed to private ownership of energy assets, the SIBs have likewise supported SOEs in funding their projects, incl. Ørsted and EnBW. Rather, the SIBs were governed to promote lending by banks and strengthen their familiarity with the characteristics of the technology. This was a design feature of KfW's lending policy under the German government's green transition programme, the *energiewende*, to involve private investors to take part in green investments by capping the KfW's participation at 50% of any investment deal (Moslener et al., 2018).

Yet, there has been notable variation in SIB governance for OSW financing. It was noted in chapters 6 and 7 that the UK's Green Investment Bank (GIB) failed to deliver a comparable impact to EIB, KfW, and EKF since it was more focused on acquiring and refinancing existing assets with few connections to other investors. This role was intended to recycle capital to developers so they could continue to construct new parks, but it was not clear that the GIB was filling a gap since there was ample interest in owning operational parks with fixed-price contracts once the right model for structuring the ownership was developed, as evidenced by Ørsted's success with its farm-down practice (interview 1).

The GIB could instead have offered to fund new construction if that was indeed the essential issue rather than buying existing assets to deliver capital gains after construction was finished. If instead, the motivation was for the government to own energy infrastructure in the long-term it would make more sense to provide equity for construction and maintain its stake afterwards. In contrast, KfW, EIB and EKF appeared more successful in contributing both to the deployment of OSW and developing a vibrant ecosystem of OSW investors through their direct investments and high network reach across periods. Yet, they did not make equity investments to pursue public ownership of new energy infrastructure.

Turning to more recent trends in SIB governance, the central role of SIB investments in maturing sustainable technologies has been acknowledged in policy-making circles. In Europe, the EIB has published a roadmap to become a ‘climate bank’ (EIB, 2020), while in the US, the Biden administration has revived the Department of Energy’s Loan Programs Office after almost a decade of lying dormant since it supported Tesla’s growth. Most recently, the Inflation Reduction Act has increased the DoE’s loan authority by \$350bn (DoE, 2022a, 2022b) in addition to appropriating ca. \$20bn for the capitalisation of the first national green bank in the US (Greve, 2022). The conservative UK government has also recognised its lack of strategic investment capacity following the privatisation of the GIB, why it has launched a new UK Infrastructure Bank (UKIB) focused on clean energy and promoting growth outside the most prosperous areas of the UK (FT, 2022b).

Both the EIB and UKIB seek to ‘mobilise’ private capital for the projects they fund. The blending of public and private financing is commonly motivated by a desire to “leverage scarce public resources” (EIB, 2020, 23) as if the public’s currency was an inherently scarce resource rather than a social technology created by expanding public balance sheets (Wray, 1998). Moreover, there is less strategic attention to the role of SIBs in greening the financial sector by changing the capabilities to assess new technologies. According to this dissertation, this has been a more substantial impact from SIB investments than the quantitative attraction of private investments. While the EIB does offer valuable advisory services to project developers (EIB, 2022a), this educational role is not considered a part of its efforts to “Greening the financial system” (EIB, 2020, 20).

In relation to the creation and diffusion of know-how, the SIBs should be more concerned with the *asset side* of investor balance sheets, i.e. their abilities for creating new climate-friendly assets by detecting and investing in worthwhile, sustainable investment opportunities. However, the ambition of ‘greening financial systems’ is commonly more focused on the *liability side* of balance sheets. For instance, with reference to know-how transfer, the EIB (Ibid., 20) states it will “actively seek to transfer its knowledge to other potential green issuers, to help them develop

and market products that meet the EU Taxonomy and so contribute to broadening and deepening the market for green finance.”

The knowledge diffusion goal of EIB’s promotion of the EU’s Green Bond Standard and the Green Taxonomy is that more financial institutions and corporations will issue financial liabilities, such as bonds, with green labels that may or may not attract preferential terms of finance compared to non-labelled investments. The EIB, therefore, appears more focused on changing the labels on the liabilities in the financial system and make credit provisioning more market-based (with traded instruments like bonds) in line with the Capital Markets Union project (Braun et al., 2018; Mertens and Thiemann, 2018) than changing the capability base of the financial sector.

More issuance of bonds with green labels may incentivise investors to create more climate-friendly assets, but insofar as a favourable credit spread – a ‘greenium’ – does exist, it is unlikely to sway investors to invest in a markedly different manner. One study finds that “the greenium is essentially zero” (Larcker and Watts, 2020), while another finds a 0.15-0.20% interest rate reduction for green bonds (Löffler et al., 2021). Such minor differentials are unlikely to sway investors to take the chance on a technology with an unproven track record. They will likely be overwhelmed by the animal spirit effects stemming from urges to take advantage of newly identified profit opportunities – or the paralysing effect of uncertainty (Mazzucato, 2013). According to this dissertation, green animal spirits are unlikely to arise in the investment community in the absence of investment capabilities and know-how with respect to burgeoning clean technologies. This should be the kind of learning that SIBs target to advance.

9.2.3. The systemic impacts of entrepreneurial state investors

These findings from the OSW case add new empirical substance to theorised ‘catalytic’ effects of how public investments spur new private energy investment (Deleidi et al., 2020; D’Orazio and Löwenstein, 2020; Geddes et al., 2018). Ørsted and Vattenfall were notable first-moving SOEs who acted as ‘knowledge explorer agents’ (Benassi and Landoni, 2019), but their ability to finance investments on their own balance sheets also limited their interactions with other



investors since they did not lack capital. They did, however, co-invest with other utilities, especially in phase 2, to pool their know-how, lower the chance of mishaps, and share the risk of the projects.

In addition to utility co-investments, SIBs served as important know-how bridges that diffused the early experiences to the wider investor community through their high rate of participation in project financing with commercial banks and smaller developers. They generally did not do project financing with the utilities in which they would be directly exposed to construction risks⁵⁶ (interview 2). It was rather a sort of ‘earmarked’ corporate financing with reference to specific projects, such as the Nordic Investment Bank’s lending for Ørsted’s Anholt project (chapter 6). Nonetheless, the SIBs did have a more active role as investment partner with the utilities compared to buyers in regular corporate bond markets and could therefore gain access to the know-how of the utilities which banks and their financial advisors could not.

9.2.3.1. Integrating entrepreneurial state investors in a sustainability policy mix

Sustainability transitions researchers have emphasised that successful transitioning requires a policy mix that both downscales the polluting sectors and actively promotes the development of sustainable niche technologies (Kivimaa and Kern, 2016). Mobilisation of financial resources is recognised as one goal of a policy mix, which can be pursued through: “R&D funding, deployment subsidies, low-interest loans, venture capital” (p. 208). However, this financial aspect of policy mixes remains underdeveloped (Bergek, 2019; Geddes and Schmidt, 2020; Naidoo, 2020). The major policy focus has been to de-risk revenue streams for generators (Schmidt, 2014), while little policy attention has been directed to how investors learn to assess the risks of new technologies (Egli et al., 2018) and the role of public investment in this process (Deleidi et al., 2020; Mazzucato and Semieniuk, 2018).

⁵⁶ Except for cases where utilities did set up project financing, which was more common in Germany than the UK and Denmark.



Somewhat surprisingly, the approach of using price incentives by taxing carbon or offering revenue subsidies to promote OSW investments has, to a large extent, been responded to by state-owned investors (Figure 5.8). Public investors should in theory be less responsive than private investors to simple price incentives due to their various, more or less formalised, social objectives. One reason behind the contradictory observation may be the self-reinforcing effect of early-moving SOEs accumulating a know-how advantage. It may also be the case that entrepreneurial state investors use energy policies as a signalling and coordination device for aligning their operations and investments with the public value objectives held by their ultimate political owners.

The large role of entrepreneurial state investors in phases 1-3 suggests that they have had a significant impact on the emergence of green animal spirits among private financial investors. Without the early learning by doing – with costly lessons – by SOEs and later network integrating functions of the SIBs, private financiers would unlikely have co-evolved with the technical supply chain as quickly to provide the amount of financing at low cost of capital that was available in the latest phases of the study.

Considering hypothetical alternative trajectories for OSW, one should be concerned whether there would even have been the same opportunities for private investment in OSW in recent years if the investor ecosystem had not contained SOEs and SIBs ready to invest at scale in the first three phases.

That is not to say that there would never be any OSW in a counterfactual scenario without these organisations. Yet, a slower trajectory could have led onshore wind and solar PV to get so cheaper that it would be less appealing to scale up the OSW market until land availability became a more binding constraint. Moreover, less familiarity with the risks of OSW in the investor community would also have increased the cost of inducing private deployment (Hirth and Steckel, 2016). In other words, active public investments have advanced the technological learning curve more rapidly and at lower cost to the treasury and electricity consumers.

Schumpeter's argument that banking only supports innovation "when no central authority directs the social process", i.e. a misgiving of central planning, is partly addressed by the decentralised



character of SOEs and SIBs, which makes them useful components in a ‘developmental network state’ (Block, 2008). In other words, they are not part of the centralised planning of the economy, but rather autonomous actors with public policy mandates.

SIBs can ‘open windows’ in new technology spaces by providing targeted resourcing in terms of capital and investment know-how to multiple private actors with high potential for making technological advances. SOEs can fill the gap if few such private actors exist (Block, 2008). Block (2008, 173) also argues that state-owned organisations can work as brokers by bringing “different groups together so they can take advantage of each other’s knowledge”. These public organisations need ‘embedded autonomy’ (Evans, 1995) to deliver effective impacts by being rooted in, yet not captured by, the technological and business communities they aim to advance.

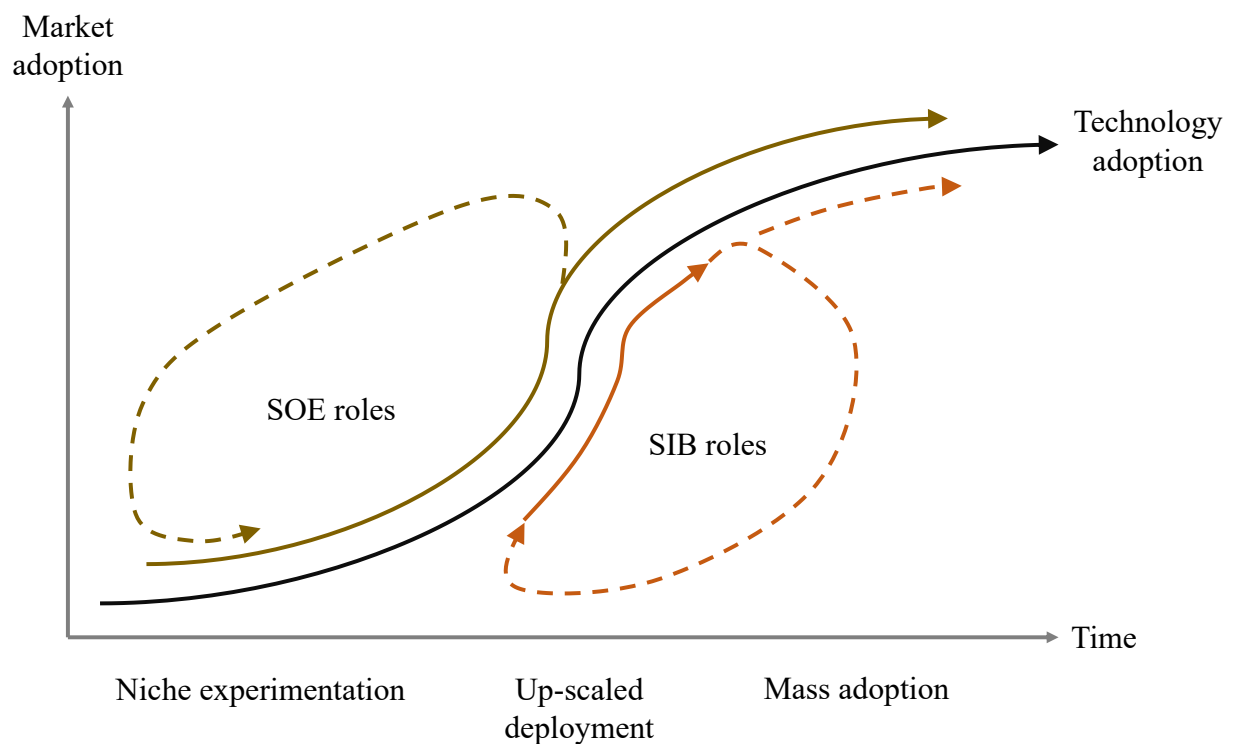
However, green industrial policy research has focused on policy-formulating bureaucratic agencies rather than public investors (Rodrik, 2014). The entrepreneurial state literature has focused on grant- and procurement contract-giving agencies (Mazzucato, 2013)⁵⁷ that aim to increase the ‘technology push’ to turn scientific discoveries into applied technological breakthroughs (Grubb et al., 2017). Lastly, a broad understanding has emerged that demand-pull policies have been important for maturing sustainable technologies, such as renewable energy, batteries, and electrolyzers, through the learning effects of cumulative deployment (Mercure et al., 2021a; Way et al., 2022). The results from this dissertation suggest that entrepreneurial state investors can be impactful policy levers to help technologies traverse the technological and financial ‘valleys of death’ where technology-push and demand-pull policies both have weak effects because of hesitation among investors (Grubb et al., 2017; Karltorp, 2016).

This suggests we need a dynamic theory of entrepreneurial state investors that ascribes shifting roles and changing behaviours according to the degree of technological maturity. In other words, a theory of how industrial policy can be conducted by way of influencing evolving complex systems through public investments. Figure 9.1 illustrates how SOEs can be used in the

⁵⁷ Such as the Defense Advanced Research Projects Agency (DARPA), the US National Institutes of Health (NIH), or the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs.

technological ‘niche experimentation’ phase to initiate learning curves through early deployment and investments into the ‘up-scaled deployment’ phase with early commercialisation.

Figure 9.1: The roles of SOEs and SIBs in the adoption of new sustainable technologies



Note: Own illustration. Dashed loops indicate ongoing repurposing of organisations to promote new technologies. The SOE roles are primarily involved in the creation of fixed investment know-how, while SIBs are more focused on creation and diffusion of financial know-how.

In the case of OSW, this would correspond to Ørsted’s⁵⁸ role as lead investor in phase 1 and 2. As the OSW case showed, endogenous processes can lead the public enterprises to be in a superior position based on its accumulated know-how to remain prominent investors during the phases of up-scaled deployment and mass adoption (Voldsgaard and Rüdiger, 2021). The mass adoption role could also be the result of a more explicit political strategy to collectively deploy

⁵⁸ And the pre-merger civic utilities.



and own energy infrastructure (Gabor, 2021; Nersisyan and Wray, 2021). The dashed loop suggests a role for SOEs to reorienting their business and target the deployment of new technologies within their sectors. This is where we may find a potential for stimulating innovation by introducing *Technological Frontier Investment Mandates* in SOE corporate governance to ensure more investment activity in the niche experimentation phases of emerging technologies.

The SIB curve in Figure 9.1 illustrates that their main role is located later on the adoption curve. In this phase, new technologies need much more financial capital to scale up deployment, however often without a sufficient track record to attract private finance on attractive terms to be competitive with incumbent technologies. The analyses have shown how SIBs can improve this phase by providing capital in larger portions, by taking de-risking loan tranches and providing guarantees, and by signalling trust in projects and having educational impacts on their less-experienced co-investors. This function requires a governance focus on developing dynamic capabilities such as technical and financial expertise (Kattel and Mazzucato, 2018).

Like for SOEs, the dashed loop signifies how SIBs continually have to reorient themselves to target new technologies as they become ready to be deployed at scale. This ability to monitor their technological environment is a core characteristic of dynamic capabilities (Teece and Pisano, 2003; Teece, 2019). The straight dashed curve that continues into the mass adoption phase suggests that the more state-led models for green transitioning (often with reference to a ‘Green New Deal’ (Gabor, 2021; Nersisyan and Wray, 2021)) could use SIBs in a more lasting role as financier and owner of mature technologies to ensure the sufficient pace of deployment and retention of the value created by the investments.

The policy implication of this discussion is that more efforts should be dedicated to creating and accumulating investment expertise in risk-embracing state-owned organisations that can subsequently be diffused through investment partnerships with private investors. Governments with existing well-performing SOEs in e.g. energy, aviation or steel manufacturing are in a better position to use entrepreneurial state investors, compared to governments that have to start from a small business portfolio. On the other hand, sustainability transitions are marathons rather than



sprints, so it could still be worthwhile to build up capabilities through learning-by-doing in new SOEs and SIBs.

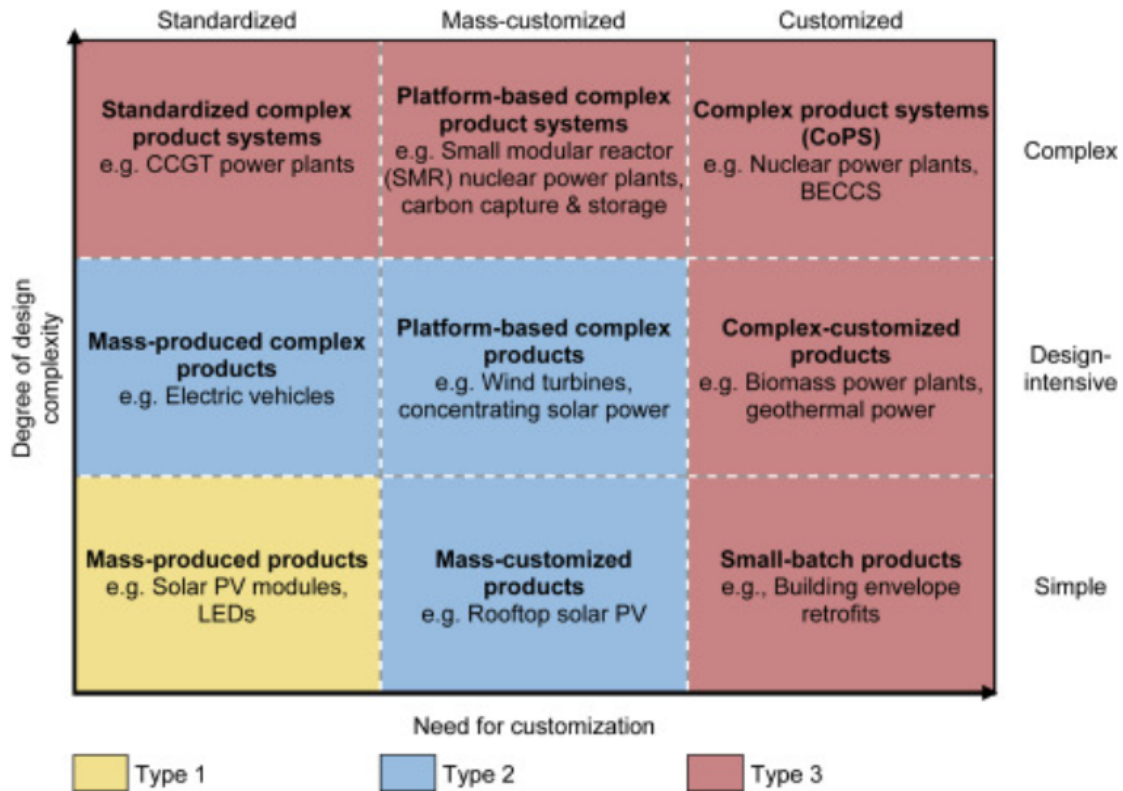
Still, the potential for using SOEs and SIBs in a more directed manner depends on the technological and product characteristics. It is not a universal fit for solving the technological challenges in sustainability transitions. Energy production and storage technology is arguably the area where the approach is best suited, since the products, electrons and hot water, are highly homogenous goods. In markets where the product must be continually adjusted in response to user demands, entrepreneurial state investors may be less advantaged when it comes to driving learning curves for the most promising technologies. For example, carbon capture and storage (CSS) must be customised to fit particular point-sources. It may therefore be more suitable for private companies to both procure and install than an SOE (although SIBs could co-finance), while direct air carbon capture (DAC) on the other hand would be a more standardised activity for which an SOE could procure capacity and drive learning.

In addition, entrepreneurial state investors should be used to target technologies with higher learning curve potential. Malhotra and Schmidt (2020) developed a technology typology based on design complexity and customisation of energy-related technologies (see Figure 9.2). They find that for technologies with either high design complexity⁵⁹ or a high degree of customisation⁶⁰ it is inherently difficult to lower the cost because of limitations to mass production and installation. For simple, mass-produced products like solar PV modules, the learning potential is sizeable, and SOEs can potentially make an important difference in the early phase of the learning curve. For instance, KfW financed a large share of the solar PV deployment in Germany during the *energiewende* (D’Orazio and Löwenstein, 2020), which rapidly brought down the cost.

⁵⁹ e.g. CCGT power plants, regular and small modular nuclear power plants, and CCS.

⁶⁰ e.g. regular new nuclear and biomass power plants, geothermal power, and building retrofits.

Figure 9.2: Design complexity and customisation determining cost-reduction potential



Source: Malhotra and Schmidt (2020)

In between, with medium degrees of design complexity and/or customisation, there are technologies with considerable but less steep learning curve potential. With both traits, this thesis has considered OSW that can be categorised as a ‘platform-based complex product’ – with OSW arguably being more customised than onshore wind or concentrating solar power because of the marine installation aspect. DAC and green hydrogen production possibly belong to this category, and could be potential areas for SOEs to target. As mentioned in chapter 8, these products are often deployed in a centralised manner, such as wind farms, which in addition to the homogenous output renders the operations and maintenance tasks more manageable for SOEs.

Products that are mass-produced yet more complex, such as electric vehicles, are probably less suited for SOE investments, since it requires management of advanced manufacturing, ongoing



product-development, customer analysis and marketing. Mass-customised products, such as rooftop solar, is likewise less well-suited since the SOE would have to organise numerous arrangements with small- and medium-scale rooftop owners. In both cases, SIB lending could advance the scale-up of manufacturing capacity and deployment at a lower financial cost.

This discussion has also, implicitly, revealed that SOEs and SIBs have a limited potential for driving the most decentralised technologies such as LED lights, rooftop solar, and electric vehicles. This category could also include smart grid technologies that enable flexible demand responses to energy price fluctuations. In these cases, entrepreneurial state organisations should probably be largely bypassed. However, other large-scale public sector organisations, such as hospitals, elderly care, schools, and public administration, could have considerable impact if their procurement was used more strategically to advance learning curves by creating larger niche markets rather than primarily lowering the organisations' carbon footprint (Edler and Boon, 2018; Edler and Georghiou, 2007).

9.2.3.2. *A long-term ownership role?*

However, these are only the initial steps towards a complexity-informed theory of a 'division of financial labour' between public and private sources. One question for further consideration is whether large-scale energy infrastructure that requires public consent and planning is well-suited to rely on private financing or whether this is an unnecessary source of volatility and value extraction where the returns could otherwise have been used to lower the cost of clean electricity and the cost of demand-side policies.

In other words, whether the catalysing effect of SIBs on private finance is better suited for other sectors than infrastructure, such as the development of new components and production facilities by innovative firms. This would require a new public value rationale for SIB and SOE investment that would be more focused on value retention of the gains from societal infrastructure in collective ownership forms, which also appears to be the reasoning behind China's approach to OSW investments via its SOEs (for an analysis see Appendix J: China's place in the investor network).



In the regular business sector, private finance serves a social purpose by halting activities that do not produce sufficient benefits as judged by the consumers in the market, so the productive resources can be redeployed elsewhere, e.g. the commercial space and staff used by an unprofitable restaurant. On the other hand, if the holding company of an offshore wind park goes bankrupt, the resources would not be redeployed elsewhere in the economy. On the contrary, the ownership will be restructured, and the OSW farm will simply continue to generate electricity for the grid. It can therefore be useful to distinguish more explicitly between the usefulness of private finance in different sectors. This could be done based on a continuum of ‘infrastructure-ness’ of the assets, signifying the degree to which the assets require public planning before their creation and whether the physical and human resources can be redeployed elsewhere if the investment is less profitable than expected. Such a perspective could form the basis of a public value-based approach to equity investments by SIBs in long-lasting infrastructure.

To sum up, the second scholarly contribution of this dissertation has been to identify and examine the central roles played by entrepreneurial state investors in the maturation process of a low-carbon energy technology. The insights from the OSW case provided a foundation for discussing how the entrepreneurial potential of SOEs and SIBs could be harnessed by reconsidering their dynamic roles in relation to technology adoption curves and changing their governance models.

9.3. The future of offshore wind investment – a brewing storm?

Based on this complexity perspective on OSW financing, we can attempt to consider how the financial sector, market institutions, and business strategies may plausibly evolve over the medium term and if there is a reason for caution regarding the future deployment of OSW. One of several helpful insights from [Hall et al. \(2017\)](#) is their articulation of how investments, energy investment conditions, and actor compositions co-evolve over time.



At the time of their writing, UK policy makers were implementing the Electricity Market Reform (2013), which provided de-risked revenues for the winners of auctions of contracts for difference, i.e. with fixed-price contracts. In effect, the price risk was socialised by the energy consumers via the government's contracting agency. This led to the falling cost of capital and enabled further deployment, which contributed to reducing the costs from learning by doing and economies of scale in the supply chains (Jennings et al., 2020; Mercure et al., 2021b). While the sector appeared to have reached a state of orderly expansion in phase 5 (Figure 6.7), this is not the end of the co-evolutionary process.

Most notably, there has been a tendency towards auctions with lower or even zero-bids. On the one hand, it is promising for the future of OSW that several projects in Germany and Netherlands, where the transmission system operator pays for transmission to the grid, have won auctions with zero-bids, and that the recent auction for the Thor project in Denmark resulted in the winner, RWE, both paying for the transmission and a fee to the government (Danish Energy Agency, 2021a). Also, more projects are being submitted to 'open door' procedures for building offshore parks in Denmark beyond the scheduled project auctions (Danish Energy Agency, 2021b). These tendencies are the clearest signs that the OSW technology and industry have matured and become competitive with fossil fuels and other RE alternatives.

One major concern should be whether this is a stable honeymoon phase where the mastering of a now-proven technology coincides with benevolent electricity market conditions that will not last. Reasoning based on rational, representative investors would suggest that investors will identify the emerging risks and gradually adjust to a new equilibrium. However, the complexity perspective reminds us that complex systems have historically displayed tranquillity before sudden disruptions (Beinhocker, 2007).

9.3.1. Four disequilibrating processes

Four factors suggest that the OSW investor system may be heading for a disruption on the mid-term horizon. These factors contain feedback effects that make OSW investments attractive in the short run, although more unviable in the longer run: fossil fuel domination of wholesale



markets and eventual cannibalisation of capture prices for RE generators, a small market for power purchase agreements, aggressive bidding by inexperienced investors, and reinforcing policy co-evolution.

First, if the market frameworks with fixed-price contracts with the government, which have become common in Europe, are phased out, investors will have to rely on the prices they can obtain from private consumers (Christophers, 2022a). The default option is to sell on the spot market to power providers who sell it to their retail customers. In the spot market, the price for all traded power is set by the asking price of the marginal producer. All power producers submit their prices, and the power exchange creates a ‘merit order’ that ranks producers from cheapest to most expensive, which is, in effect, the supply curve facing the buyers. The price is set by the least expensive producer in this ranking, which enables the power demand to be met.

Since renewable energy producers have very low operational costs, this marginal price is often set by fossil fuel producers when renewables cannot meet the entire demand. As long as the share of renewables in the electricity mix is too low to meet all of the demand, new OSW parks can expect to be remunerated by the cost of producing power from coal or gas, which is generally above the LCOE of OSW (IRENA, 2022a). OSW can therefore generate considerable, so-called infra-marginal rents by producing power from renewable energy sources in this market framework. It creates a positive feedback effect on the current investment trajectory in the sense that increased deployment leads to lower cost of OSW and hence higher profitability *as long as fossil-fuel sources predominantly set the price*.

Expectations of continued fossil fuel dominance are likely one of the reasons behind the OSW investors’ acceptance of merchant risk in recent auctions. However, this market dynamic is bound to co-evolve with the deployment of more variable and synchronised renewables. As more renewables get deployed, one likely emergent property is that spot prices in electricity markets become more volatile and lower on average because of the low prices at times of windy and sunny weather.

The volatility in prices will stem from more changes between conditions where renewables can meet all demand and thus press marginal prices close to zero and periods of scarcity where

flexible sources of power will have to step in to meet demand (and which have to recover their fixed costs on shorter operational time). This volatility will likely become an issue since banks do not like to take on merchant risk, as it is notoriously hard to forecast (Christophers, 2022a).

One initial effect of exposure to merchant risk will, therefore, likely be higher cost of debt and lower debt-to-equity, which will lead to higher WACC for OSW projects. Banks and other financial investors have largely been able to avoid market risk and only considered construction and operational risks (Guillet, 2021). So, merchant risk is likely to make banks take a more sceptical stance. While the financial conditions for OSW have eased in multiple ways during the 2010s (Figure 5.6), the financial OSW advisor Green Giraffe estimates the LCOE from a fully ‘merchant’ wind farm would rise by 50-80% due to higher interest rates compared to the two-way contracts for difference currently used in the UK (WindEurope, 2021). As a knock-on effect, this would render electrification technologies aimed at substituting for fossil-based technologies in heavy industries and heavy transport less attractive since their competitiveness relies on the availability of cheap electricity.

A more detrimental long-run effect than price volatility may be the ‘cannibalisation’ effect. It refers to the situation where the ‘capture prices’ that renewable energy generators obtain will be depressed below average wholesale prices, since they will tend to produce synchronously with zero marginal cost and cause the spot prices to fall exactly when they produce (Blyth et al., 2021; Halttunen et al., 2020; Jones and Rothenberg, 2019). This can create a market where renewables are dependent on comprehensive demand flexibility, e.g. from large battery storage facilities, to use the excess power. However, this could turn out to be a chicken-and-egg issue where OSW will only be deployed if flexible offtake technologies, incl. storage and electro-fuel production, are already widely available. On the other hand, these technologies may only be deployed at scale if RE, to some extent, becomes overbuilt, so the opportunities for profiting from demand flexibility become more visible.

One could hope for a smooth co-evolution of renewables and flexibility options as they respond to price signals, but the complexity literature suggests the sector may be facing several trajectories (‘basins of attraction’) that can become self-reinforcing rather than a single optimal



equilibrium based on economic ‘fundamentals’ (Arthur, 2014; Beinhocker, 2007; Dosi, 2013). One path could see rapid decarbonisation in which a major push to deploy utility-scale energy storage, flexibly charging electric vehicles and electro-fuel production will pull forward increased renewable energy investment. A more unfavourable scenario is one where cascading concerns over price volatility and cannibalisation lead to a potentially abrupt deceleration in OSW investment, which again decreases the pull for complementary energy technologies that depend on cheap and volatile electricity prices.

The second positive feedback that could lead markets towards more merchant risk in the long run than what investors can bear is the current availability of power purchase agreements (PPAs) with large corporate electricity consumers, such as industrial corporations and tech firms with large data centres. For instance, Ørsted has signed PPAs with five corporations for its Borkum Riffgrund 3 project, which was among the first large-scale parks winning auctions with a zero-bid, covering 786 MW of the project’s 900MW capacity⁶¹ (Recharge News, 2021), which enabled it to use its farm-down practice with a sale of 50% of the ownership to a US pension fund. Christophers (2022a) argues that the expansion of renewables can only be temporarily supported by the possibility of signing fixed-price PPAs because of the small PPA market relative to the scale of investments needed (see also Jones and Rothenberg, 2019).

The main issue is that credit-worthy corporates are in short supply, which limits the potential for basing net zero-scale deployment of renewables on contracts with such firms. A long-term PPA is only as good as the solvency of the buyer. In a microeconomic sense, the need for developers to find fixed price arrangements to obtain finance confers large rents on these large corporations that can bid down their cost of electricity through auctions with RE developers that smaller firms cannot achieve (Christophers, 2022a). Nonetheless, it may be a viable way of funding large RE projects so long as PPAs from credit-worthy corporates are available.

One concern is whether a larger number of parks will be planned for that cannot obtain PPAs to make their projects bankable, which could change the sentiment in the investor community. Since

⁶¹ PPAs signed with Covestro (100MW), Amazon (350MW), REWE Group (100MW), BASF (186MW), and Google (50MW).



the investor network in the last two phases has contained a densely connected core (Figure 6.5) and financial knowledge of the future is inherently fragile and contingent (Clark, 2018), there is a possibility that a change of sentiment could cascade rapidly through the network and reduce the appetite for OSW financing.

Third, the resolute strategies by major oil companies to become large developers of OSW may not blend well with the re-risking trend in electricity markets. Jérôme Guillet warned that their experience with construction and operations and sea could be deceptive since there are markedly different economic and technological conditions in OSW that require experience with cost-efficient serial installations: “one 40,000 tonne platform is not the same as installing 100 times 400 tons. (...) There hasn't been a successful oil and gas contractor in offshore wind yet” (interview 2). Efficient offshore wind installation requires experience and discipline, but this is generally not present “because cost discipline is much less important in oil and gas” (Ibid.).

Guillet expressed concerns that the parallel trends of more cost-inefficient investors and the re-risking of electricity markets will lead to financial losses if electricity prices become too low. He warns the possible exit from the market by oil companies (if done noisily and with critical commentary about the economics of the sector) could damage the reputation of offshore wind: “*we could lose time in the deployment of more renewables as a result*” (Ibid.). This scenario effectively describes a dynamic process gone wrong because of the time lag between investment decisions and market validation. In evolutionary terms, this scenario can be described as a novel type of actor entering the ecosystem while pursuing an aggressive investment strategy. At first, the strategy drives out competitors from the market, but if the strategy is not well-suited to the investors’ investment know-how and the changing market environment, the new investors may be forced to exit again. This process could leave a lasting mark on the investor ecosystem.

There are already some signs of oil companies jeopardising their returns in an attempt to dominate the OSW sector. One academic study has found that Equinor’s stake in the world’s largest wind farm, Dogger Bank, is unlikely to reach the company’s required rate of return between 4-8% (Helgesen et al., 2021). Shell, Total, and BP have made aggressive bids for seabed licences in recent auctions in England, Wales, and Scotland (FT, 2022c, 2021), where the “global

leader in offshore wind, Ørsted, was squeezed out altogether” (M. Lewis, 2021). These higher seabed costs lower their eventual returns, and one market analyst concluded that “In signalling its willingness to pay to play, Big Oil seems to be risking returns for itself and the market leaders” (Ibid.). The oil companies’ resolute entrance has also led Danish pension funds to move funds out of OSW because of too high valuations (Frandsen, 2021). While competition and lower rates of return may be beneficial to consumers, it also risks the general profitability of OSW if oil companies turn out to be ill-disciplined developers while the prices in electricity markets become more volatile and structurally ‘cannibalised’.

Finally, policymaking is likely to co-evolve to reinforce the economic pull towards merchant risk, which for the moment, is underpinned by high spot market prices and the still non-exhausted PPA market. The move towards spot market-based remuneration of renewables is a natural iteration of the liberalisation of energy markets that have been promoted in Europe since the 1990s and accelerated in the 2000s (Kern et al., 2014a). Since markets are believed to provide the right informational signals to achieve more efficient use of resources instead of governmental planning, the zero-bids are generally considered a positive development. And in addition, a development that can even bring in funds to the notoriously subsidy-sceptical public treasuries, as seen with the 1GW Thor auction in Denmark. Regulators and policymakers are, therefore, less likely to consider critically if the market design will be supportive of the rapid and large-scale deployment beyond the short term.

9.4. *Summary*

This analytical synthesis has discussed to what extent OSW finance could be considered an evolving complex system and what could be gained analytically by emphasising the associated characteristics. The history of OSW financing displayed the five key aspects of complex systems, including heterogeneous actors, networked interaction, evolutionary processes, emergent properties, and non-linear dynamics in the system’s evolution. The complexity perspective provided a richer understanding of the reasons behind the oscillating investment patterns, the changing investor composition, the non-linear technological cost curve, and the cost of capital.



These aggregate phenomena were understood as emergent properties stemming from the networked interactions of heterogeneous investors under a continuous process of innovation and adaptation to the changing market circumstances.

This provided a more empirically grounded contribution which advances Hall et al.'s (2017) concept of energy finance as an adaptive market. However, the concept of an evolving complex system was found to better illuminate how financing is a considerably networked phenomenon rather than occurring through market exchange. The emphasis on evolutionary processes and the development and diffusion of investment know-how provided a clearer understanding of how the structural barrier of an immature investment community can be circumvented over time.

The complexity perspective also generated the second contribution of the dissertation by highlighting the important roles of entrepreneurial state investors who shaped the trajectory of the investor network and hence the technological development. This occurred both through the capital volumes invested, which created learning by doing throughout the industry, and via the central network roles of the SIBs, which connected the various parts of the investor ecosystem.

The OSW case, therefore, suggests that sustainability transitions can benefit from more strategic use of entrepreneurial state investors. This may require a reconsideration of their governance models. Especially SOEs appear constrained in their investment activities, which is why innovation systems could achieve better outcomes by placing *Technological Frontier Investment Mandates* on selected SOEs to increase the demand-pull around technological valleys of death (Grubb et al., 2017).

Finally, the complexity perspective provided a sceptical hypothesis regarding the future of OSW deployment in re-risked electricity markets, as financial investors are likely to respond adversely to price uncertainty in the context of an increasing share of RE in the electricity mix. Moreover, the emerging dominance of oil companies injects an element of unpredictability in the investor network because of their unproven investment know-how in OSW. It is, therefore, plausible that the current orderly phase in the investor network can be disrupted during the medium-term horizon.

Chapter 10

Theoretical synthesis: Lessons for sustainability transitions research

This chapter attempts to synthesise the analytical insights from OSW and RE finance with the sustainability transitions literature, motivated by research question 4 (RQ4): *What is the role of finance and investment in sustainability transitions?*

While offshore wind is distinct from other sustainable technologies by being extraordinarily capital-intensive and being deployed in fewer large-scale projects, its history may contain lessons for the maturation of other technologies needed to scale from small niches to mainstream technologies to achieve deep decarbonisation (Geels et al., 2017). As reviewed in chapter 3, sustainability transitions research aims to “conceptualize and explain how radical changes can occur in the way societal functions are fulfilled”. This is done with the ambition of solving environmental grand challenges by examining socio-technical systems (Köhler et al., 2019). Socio-technical systems are defined as “the interlinked mix of technologies, infrastructures, organizations, markets, regulations, and user practices that together deliver societal functions” (Geels et al., 2017). This socio-technical perspective suggests that conventional least-cost modelling exercises are inadequate for understanding the social processes that shape and settle future technological trajectories (Geels and Schot, 2007). A more comprehensive understanding requires consideration of “innovation processes, business strategies, social acceptance, cultural discourses, and political struggles, which are difficult to model but crucial in real-world transitions” (Geels et al., 2017, 1244).

The sustainability transitions research programme has developed various analytical frameworks (Köhler et al., 2019), counting the Multi-Level Perspective (MLP) (Geels, 2011, 2002), the Technological Innovation System (TIS) approach (Hekkert et al., 2007; Reichardt et al., 2016), Strategic Niche Management (Kivimaa and Kern, 2016; Schot and Geels, 2008) and Transition Management (Loorbach, 2010). Yet, the socio-technical approach has been criticized for giving “relatively little emphasis to economic factors, such as investment and relative prices” (Foxon, 2011). More specifically, the role of finance has been “largely marginalised by the transitions

literature” (Geddes and Schmidt, 2020, p. 1). By insufficiently examining the role of finance, researchers inadvertently have adopted a neoclassical theory of efficient financial markets that ensure optimal investments are undertaken insofar as the price signals in product markets are appropriate (Hall et al., 2017; Naidoo, 2020).

Köhler et al. (2019, 12) have called for further research on the role of financial capital “in restricting or promoting change in a certain direction”. Steffen and Schmidt (2021, 77-78) have argued that more research should be targeted at the “middle-range between specific case studies of individual financing challenges and broad analyses of the financial system as a whole”. They call for better conceptualisation of finance in the main theoretical models, such as the MLP and TIS, to improve generalised understanding of the role of finance and move “beyond the resource mobilization for individual new technologies”. An improved conceptualisation of finance in theoretical frameworks could improve the causal understanding of how sustainability transitions unfold, which has been identified as a weakness of the MLP (Sorrell, 2018; Svensson and Nikoleris, 2018). In other words, inductive knowledge regarding the role of finance in socio-technical systems and financial systems in general should be combined to develop more general theories of the role of finance in sustainability transitions.

A recent contribution has conceptualised finance as a ‘regime’ in the Multi-Level Perspective that constrains the potential for sustainable niche technologies to develop and get deployed at scale (Geddes and Schmidt, 2020). The authors argue that either the financial sector needs to change to be able to finance niche technologies, which can occur through learning, or else technologies will have to adapt to the constraining financial conditions. Based on case analyses (Geddes et al., 2018), they suggest that SIBs can play an important educational role in changing the financial sector to provide better conditions for niche technologies.

This perspective on finance as a regime provided inspiration for the dissertation’ theoretical framework regarding finance as an enabling or constraining factor in RE deployment. Moreover, Geddes and Schmidt (2020) elaborated on how SIBs can have a system-shaping impact on finance, which inspired the dissertation’ hypotheses. Still, the theory could benefit from more



explicit consideration of the complexity within the financial regime and hence the processes through which finance evolves over time (as discussed in chapter 9).

Moreover, the financial regime is also considered to be “overlapping and interacting with all other socio-technical regimes” (ibid., 4), yet this interaction among the regime elements remains unclear. There is a general focus on how finance affects technological niches, and it is mentioned how SIBs could help to promote “industry co-ordination” (ibid., 10). However, more explicit consideration of the co-evolutionary role of finance would be beneficial, incl. effects on institutions and business strategies. The following sections consider how the complexity of OSW finance contributed to the financial system’s co-evolution with other transition elements.

Naidoo (2020) argues that sustainability transitions place five demands on financial systems. The financial system and its participants must 1) orient themselves toward achieving a sustainable economic system, 2) respond reasonably to transition needs across short-, medium-, and long-term timeframes, 3) generate positive environmental and social system-level impacts while simultaneously destabilising the existing non-sustainable systems, 4) engage with a broad base of stakeholders to develop their responses to the transition process, and 5) use experimentation and adaptive approaches to address the contextual needs of the sustainability transitions. From these five demands, Naidoo deduces six design features for developing “appropriate solutions” and responses in the financial sector:

- 1) **Political:** The political aspects of the behaviours, institutions and values of financiers must be highlighted and called into question, including how the financial system frames the sustainability and climate breakdown.
- 2) **Relational:** Financial responses should be informed by how the financial system relates to itself and drivers of change in the economy.
- 3) **Structural:** Responses should also consider the structure of domestic financial systems and their relations to international financial markets, since this shapes the financial sectors institutional fit with the demands of each country’s sustainability transitions.
- 4) **Temporal:** Responses should instil a sense of urgent action.



- 5) **Qualitative:** Responses should promote qualities of finance, such as long-termism and patience, which enables the experimentation and learning-by-doing that are vital to sustainability transitions.
- 6) **Theoretical:** The responses should update the theories of finance that the investors and policymakers of the future will learn through education, which have historically neglected sustainability issues (Diaz-Rainey et al., 2017; Lagoarde-Segot, 2019).

The next two sections address the call by Steffen and Schmidt (2021) to use the knowledge of the role of finance in specific sustainability transitions to induce better conceptualisations of finance in general transition frameworks. The OSW case study was used to develop a general theory of finance as an evolving complex system with implications for sustainability transitions in chapter 9. Below, this complexity proposition is integrated with Foxon's (2011) co-evolutionary framework. In section 10.3, the outcomes of this approach are discussed in light of Naidoo's (2020) suggested design features.

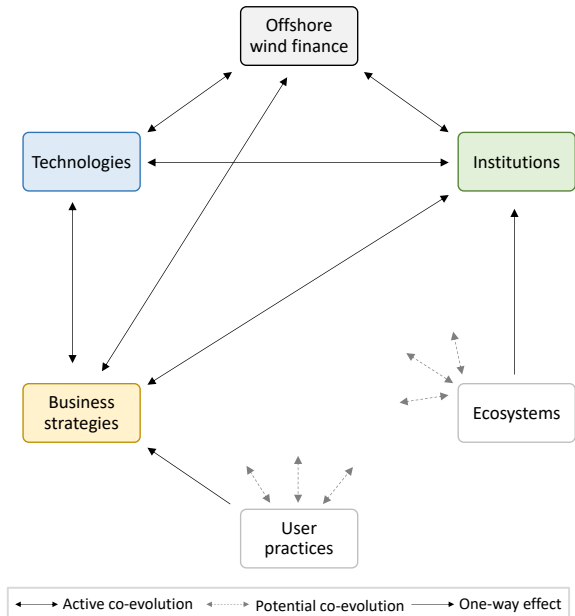
10.1. Finance and investment as a co-evolutionary element

The analytical results in this dissertation offer several contributions to the sustainability transitions literature regarding the still under-developed role of finance in the literature. First, in line with the literature's emphasis on sustainability transitions being long-duration co-evolutionary processes, it has been useful to consider the entire history of financing of a new low-carbon technology. This made it possible to observe how financial phenomena at micro, meso, and macro levels are influenced by and affect other elements of large transitions.

Chapter 3 showed Foxon's (2011) proposed co-evolutionary framework for sustainability transitions where technologies, institutions, business strategies, user practices, and ecosystems continually adapt to and influence each other in ways that tend to produce lock-ins in the transition trajectory (Seto et al., 2016; Unruh, 2000). Figure 10.1 adapts this model to the case of OSW by adding OSW finance as a separate transition element. The analyses suggested that OSW finance has been an important transition element in its own right and that it primarily co-evolved with technologies, institutions, and business strategies.

So far, ecosystems have had a mostly contextual role in climate change and the limiting factor of marine environmental concerns that have primarily had a one-way effect on the system via institutional regulations and policies. On a longer horizon, RE deployment will have an important effect by mitigating the impact of climate change. On a shorter horizon, the framework could be helpful for showing the impact of developing ‘nature as an asset class’ (Paulson, 2020) by using financial logics and commodification to preserve biodiversity and create carbon offsets (Newell and Paterson, 2010), while accounting for the side-effects on users and local institutions.

Figure 10.1: A co-evolutionary framework with offshore wind finance



Note: Own illustration based on Foxon (2011) with OSW finance added to the framework.

User practices only had an initial impact by way of the civic investments in some of the earliest parks, most notably Middelgrunden (2000), which was eight times larger (40W) than the largest operational parks at the time. User practices may become more important as the increasing share of renewables in the electricity mix makes prices more volatile, offering both opportunities for the flexible and digitally capable consumers and frustration for the rest.

There was co-evolution between finance and investment the other three transition elements in the framework. The financial conditions in OSW shaped the conditions for viable business strategies, while the existing business strategies in the industry created demands for particular forms of financial innovations. For instance, the institutional investors searching for returns in a low interest rate environment opened opportunities for selling stakes in projects, and the smaller developers with project licenses created a demand for figuring out how OSW could be made creditworthy for commercial banks, which was solved with project financing.

Technologies and OSW financing have co-evolved, where investments have led to cheaper costs through learning curve development and financially by the establishment of a track record.



Technological maturation has increased performance and reliability, which has contributed to lowering the cost of capital.

Lastly, the financial system and the institutional frameworks have co-evolved over time as the lack of price certainty first hindered cheap financing. De-risking frameworks later led to lower cost of capital and technological improvements through deployment, which in turn have recently enabled a re-risking of electricity markets. The analysis of the changing investment patterns in chapter 6 also suggested that the creation and shifting creditor relationships of the OSW assets affected the political economy of climate change. The increasing financialisation has contributed to increasing the support from the financial sector to accelerate the green transition through de-risking energy investments.

The complexity analysis suggested that there were evolutionary processes connecting the micro-level behaviours with meso-level network structures and macro-level emergent properties. In the next section, the co-evolution with institutions, technologies, and business strategies are therefore considered across these three levels.

10.2. Co-evolution of finance and investment at multiple levels

This co-evolution between finance and investment, technology, institutions, and business strategies can be further detailed and analysed by considering the three levels within finance (micro, meso, and macro), as illustrated in Figure 10.2. The ‘levels’ concept is not used in the same way as in the multi-level framework, where niche technologies are found at the micro-level, and the macro-level contains more immutable circumstances. The three levels are used here to distinguish between the character of the various elements, processes, and outcomes *within* the finance and investment domain.

10.2.1. The three levels of finance and investment

The pillar in the middle of Figure 10.2 lists the main developments in the OSW investor system that were found in the analyses, stratified by occurrences on the micro, meso, and macro levels.



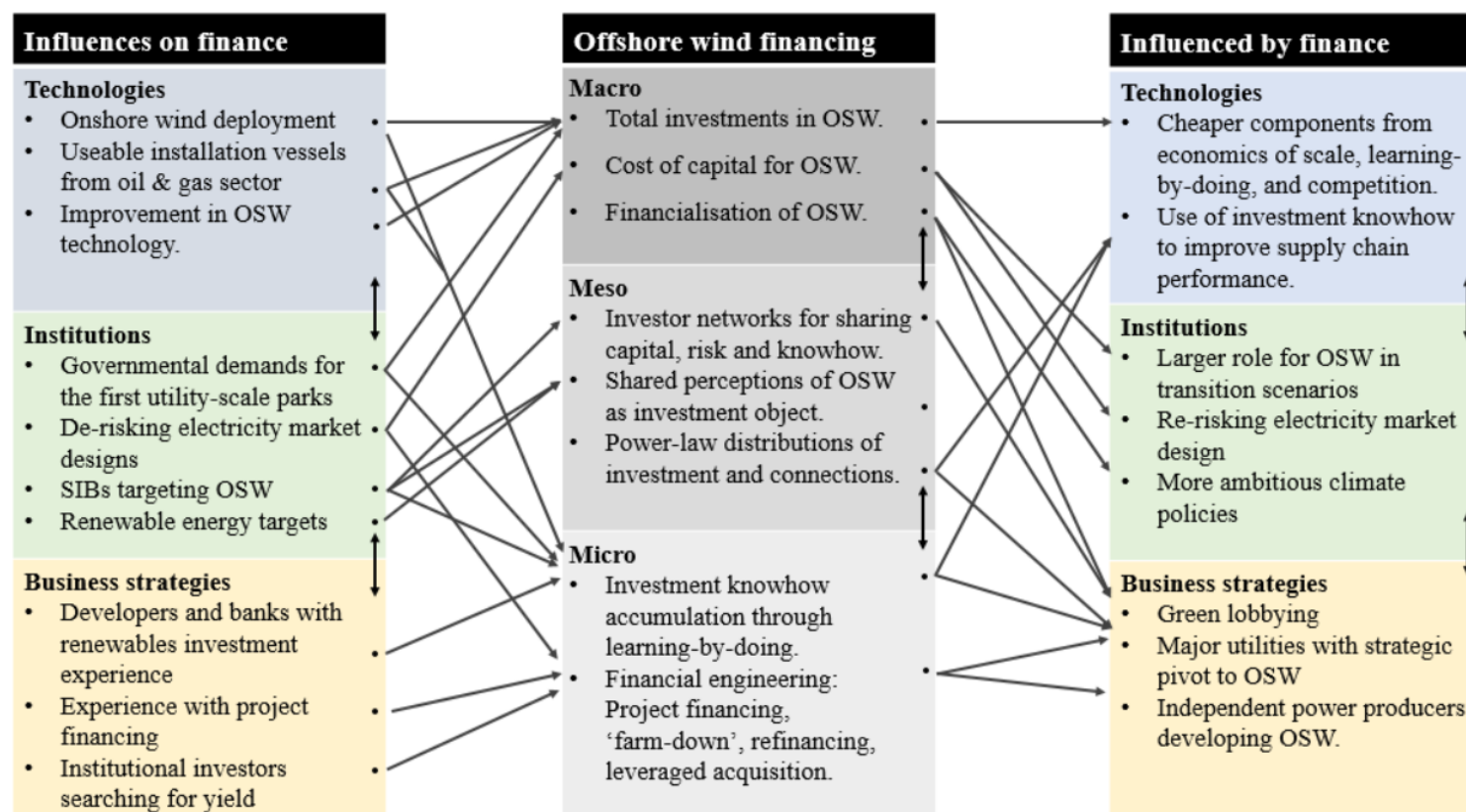
The vertical arrows across the levels reflect how lower-level phenomena, such as single actors and practices, both co-create and respond to higher-level properties of the system, such as the network structure or the cost trend of OSW. The accumulation of know-how and adoption of new financial innovations (micro), such as project financing and the farm-down model, led to new investor relations. The formation of ties was subject to network effects such as preferential attachment that led to highly skewed distributions of ties and investments, as well as shared perceptions of risks in OSW among core banks (meso), as well as more investment at a lower cost of capital (macro).

The macro properties in turn lead to new, unequally distributed investment opportunities through the structure of network relations (meso) and heterogeneous investment capabilities from histories of learning-by-doing (micro). In short, the dissertation has identified OSW financing as a complex system with self-reinforcing feedback effects that generated know-how and lower cost of investment while shaping who gets to reap the rewards from the increasing role of OSW in the green transition.

The following two sections first consider the effects upon OSW financing and investment (left-to-middle in Figure 10.2) and then the influences of finance and investment on the three other co-evolutionary elements (middle-to-right).



Figure 10.2: The co-evolution of offshore wind financing, technologies, institutions, and business strategies in a three-level perspective



Note: Own illustration with inspiration from Foxon (2011). The non-financial elements could also be considered in three levels, but this is not done here to focus on the financial element.

10.2.2. The influences upon financing and investment

There were three technological factors that influenced the finance and investment element in relation to OSW. Investment in OSW was fundamentally enabled by the existence of the onshore wind industry and the basic cable and foundation technologies with which onshore wind could be adapted to deployment near-shore (Backwell, 2018). Second, the early industry did not have to invent entirely new types of installation vessels as it could make use of oil & gas vessels when they were not in use. However, this was not sustainable due to the limited availability and the increasing scale of towers and turbines, which led to new niche firms, some of which were strategically acquired by utility developers (Voldsgaard and Rüdiger, 2021). The deployment in the demonstration phase enabled new learning among investors and technology suppliers with a particular focus on the risks and conditions in a marine environment. Third, the ongoing improvements in OSW technology led to increased durability and better performance (such as higher capacity factors), which stimulated the investment demand.

In the institutional domain, much focus has rightfully been on the de-risking of electricity markets through feed-in-tariffs, RE portfolio standards, and auctioning of fixed-price contracts (Butler and Neuhoff, 2008; Jennings et al., 2020; Mercure et al., 2021b; Mitchell et al., 2006; Polzin et al., 2019), which have – to a varying degree – attracted new sources of capital at a lower cost and provided dependable demand for further deployment of OSW.

Moreover, these risk-return-adjusting market reforms operated in a political context of increasing commitments to expanding the share of renewable energy, e.g. with the EU's 20% target for 2020 from 2008, which provided a shared vision towards which businesses could act strategically (Chang, 1994; Voldsgaard and Rüdiger, 2021). In the context of EU RE and climate targets, several countries specified OSW targets. Together this helped to coordinate investor perceptions of the future of OSW as an asset class to prioritise.

Yet, the historical analysis in this dissertation and a case study of Ørsted's strategic pivot to OSW (Ibid.) revealed that more coercive tools of statecraft were also critical. The Danish government's decision to require the initial large-scale deployment of two +100MW parks demonstrated the viability of large-scale OSW and created the initial know-how base on which the industrial



ecosystem could develop (Ibid.). Later on, the activation of SIBs as strategic investors in OSW provided the sector with the necessary amounts of capital and investors willing to de-risk the debt of other debt providers. Moreover, the SIBs became hubs in the network because of their technical and financial expertise in combination with large volumes of risk-embracing capital. This turned the SIBs into network integrators because they were so often participating in the OSW deals.

In terms of business strategies, OSW investment was advanced by utilities and banks with positive experiences from investing in onshore renewable energy, such as Dexia that went on to pioneer project financing for OSW (interview 2). In terms of financial techniques, the strong presence of French commercial banks in the investor network can be explained by their experience with project financing in other types of infrastructure assets, incl. oil and gas, which provided transferable organisational skills (interview 2).

10.2.3. Influences by finance and investment

The co-evolutionary consequences of OSW investment on the other three transition elements are listed in the right-side pillar in Figure 10.2. Most outgoing effects from finance emanate from the emergent properties at the macro level: total investments, lower cost of capital, and the growing financialisation of OSW deployment, which were created by the internal evolutionary processes at the micro and meso levels under the wider co-evolutionary influences.

In relation to technologies, there was a positive feedback loop between investment in deployment and learning in the supply chain, which translated into components with higher performance, most notably turbines with higher capacity, although some of these technological advances were overwhelmed in the 2000s by other cost factors, incl. materials, currency fluctuations, and deployment difficulties (J. A. Voormolen et al., 2016). Moreover, in the industrializing phases (phases 2 and 3) where a more specialised supply chain and industrial ecosystem was formed, Ørsted had a role as an industry “orchestrator” through its partnership with Siemens, which enabled coordination in the supply chain to keep innovations compatible (Ørsted, 2009; Voldsgaard and Rüdiger, 2021). The power law distribution of investments (Figure 6.8) had



turned Ørsted into the lead investor, which gave it a strategic interest in collaborating to mature the supply chain rather than merely purchasing services and equipment. In a sense, this was a user-driven innovation element within the supply chain (Jensen et al., 2007).

OSW finance has been affecting institutions by contributing to a changing the role of OSW in climate scenarios, changes in electricity market regulation, and by enabling more ambitious climate policies. First, the falling cost of capital has contributed to the general reduction in LCOE from OSW (Figure 5.7), which has increased the technology's role in transition pathways (IEA, 2021a; IRENA, 2021a) and political strategies for decarbonisation, exemplified with EU's 300 GW plan for the region (EU Commission, 2020).

Second, the falling cost of capital has also enabled the trend towards re-risking electricity markets for OSW deployment, evidenced by the first zero-bids both with and without transmission assets included. As discussed in chapter 9, this will produce a feedback effect to increase the cost of capital, especially when PPA markets run dry and RE generates a larger share of the electricity mix.

Third, it was argued in chapter 6 that the financialisation of OSW (and parallel tendencies in other sustainable technologies) contributed to realising more ambitious climate policies by changing the asset foundation of the green transition (Colgan et al., 2021; Newell, 2019). The way OSW financing and ownership developed to create de-risked, large-scale assets to be owned by large capital funds and with debt financing from international banks provided encouraging signs for financial capital managers and bankers that the transition would be profitable rather than disruptive. The main financial association for supporting net zero policies, GFANZ, recently broke with the UN's Race to Zero initiative that was about to effectively limit their profit opportunities from fossil fuel investments (Financial Times, 2022d). This suggests that the way emerging sustainable technologies become financed and owned also influences the way climate politics plays out. This was the 'green asset channel' considered in chapter 6.

Lastly, the evolution of the investor network has contributed to a series of changes to business strategies. From the micro level of finance, the early accumulation of investment know-how in OSW enabled a number of utility companies to pivot into OSW as a technology that better suited



their centralised business strategies than more decentralised technologies such as onshore wind and solar PV (Helms et al., 2020). Ørsted made the most decisive pivot with its 2008 strategy shift (Voldsgaard and Rüdiger, 2021).

Also, the use of various forms of financial engineering enabled new business strategies. Most notably, the use of project finance opened OSW to commercial banks, which enabled investments by smaller developers, while Ørsted's 'farm down' practice of selling ownership stakes to institutional investors contributed to fund its strategic pivot to OSW.

At the meso-level of finance, Ørsted's leading position in the investor network (distributed by a power law) also positioned it to educate institutional investors on investing in OSW (Ameli et al., 2019), similar to its orchestrating role in the supply chain. Moreover, the networking among the utilities may have had a positive influence on tipping the European lobby organisation for power producers, Eurelectric, towards a more ambitious climate policy stance (Eurelectric, 2020; Meckling et al., 2015), although it has historically been dominated by fossil fuel-based interests (Corporate Europe Observatory, 2016; Greenpeace, 2014). As mentioned above, the emergent property of financialisation of OSW has likewise contributed to a more supportive stance towards climate policies by financial capital interests.

10.3. A generalised complexity approach to finance in sustainability transitions research?

This section reflects on the value added of integrating a complexity view of finance in theoretical sustainability transitions research frameworks. Steffen and Schmidt (2021) called for improved generalised conceptualisations of the role of finance and this chapter has suggested that the complexity lens provides a useful framework for identifying how the financial system relates to itself over time through interactions and endogenous responses to new issues and opportunities in the sectors undergoing transitions. Moreover, it enables more causal interpretations of events during sustainability transitions with its emphasis on causal mechanisms (Sorrell, 2018; Naidoo, 2020) and through the proposed integration with Foxon's (2011) co-evolutionary framework.



As mentioned in chapter 3, Geddes and Schmidt (2020) considered if niche technologies will have to adapt to the financial regime to be deployed, or whether the ‘financial regime’ can be “stretched” to accommodate the particularities and uncertainties of the niche technologies. To a large extent, this depends on if the financial system can and/or will respond according to Naidoo’s (2020) six design features: Political, relational, structural, temporal, qualitative, and theoretical.

First, the complexity view of finance proposed in chapter 9 addresses the theoretical design feature head on. There is a need for improved theories of finance in transitions, which more clearly conceptualise what the financial system is made up of, how the actors behave interdependently and how the system influences transitions causally (Hall et al., 2017). The proposed complexity hypothesis builds on general scholarship on complex systems (Johnson, 2011), economic complexity (Beinhocker, 2007), the role of finance in complex economic systems (Kirman, 2011; Minsky, 2008) and in relation to sustainability transitions (Hall et al., 2017). Steffen and Schmidt (2021) make the observation that changes in finance are not dependent on external shocks from ‘landscape’ factors, such as the climate or the state of capitalism. The complexity perspective covers this fact by considering the endogenous processes of change operating within finance across the sector’s micro-, meso- and macro levels (Figure 10.2) that are generated by interactions and self-organisation among heterogeneous actors in response to changing macro outcomes arising out the system’s historical trajectory and external circumstances.

From this dissertation’s application of the complexity view, it is suggested that the role of finance is contingent upon the historical state of the investor network. In earlier periods of a technology’s lifetime financial investors shy away from investing. It requires creation of investment know-how through learning-by-investing and diffusion through learning-by-co-investing before the investor network matures sufficiently to become a more forceful driver of sustainability transitions. Moreover, it identified the institutional composition of active investors as a crucial variable having causal influence on the trajectory of the maturation process, since the presence of entrepreneurial state investors can speed up financial and technological learning curves (Mazzucato and Semieniuk, 2018).

In this chapter, the complexity perspective on finance has been integrated with Foxon's (2011) co-evolutionary framework. This framework was selected because of its larger concern for economic factors, incl. investments, and the conceptual focus on causal relations among the selected co-evolutionary transition elements. However, the complexity view would likely also improve other transitions frameworks such as the MLP or TIS that have historically focused more narrowly on finance as a resource and function that must be mobilised (Naidoo, 2020). For example, Geddes and Schmidt (2020b) mention that finance is a regime that 'overlaps' with other regimes. A more explicit complexity view would enable closer examination of how finance relates to other regimes (e.g. Figure 10.2) and potential for 'stretching' the financial regime to advance deployment of niche technologies (Geddes and Schmidt, 2020).

The potential for improving other frameworks by integrating a complexity theory of finance can be further elaborated by considering the complexity framework in light of the other five design features (Naidoo, 2020). The *relational* design feature requires consideration of how the financial system relates to itself and other social drivers of change. This is at the core of the complexity approach which requires explicit consideration of interactions among heterogeneous actors. The network structures and the qualitative data in the analysis supported that the interactions have been a crucial learning mechanism in OSW. The perspective hence supports efforts to improve the contribution of finance by leveraging the potential on improved relational patterns.

The *structural* design feature considers the structure of national financial systems in their international contexts. The complexity perspective enabled inclusion of such factors, e.g. the unwillingness of UK banks to provide project finance or, conversely, the willingness of Danish pension funds to take gradually more risk with OSW ownership. However, comparative studies would complement these initial insights to strengthen this aspect. On the other hand, the complexity perspective also offers a warning against taking a too compartmentalised view (i.e. of national systems), since the relational perspective showed how international investment patterns are in OSW – and possibly other areas sustainability transitions. The national view may be especially relevant in the earliest parts of the life of niche technologies – as the OSW case also showed with the early demonstration market in Denmark, although it relied on non-financial



investors. The complexity perspective suggests that the structural influence is contingent over time because of endogenous processes that can be triggered under the right conditions.

This relates to the *temporal* design feature, namely by requiring a historical view of how finance has evolved into what current state and its future trajectory. The complexity perspective enables a focus on how the maturation of investor ecosystems can be sped up through the right market frameworks and interaction patterns.

These conditions and patterns relate to the *qualitative* aspects of the financial sectors response to transitions. OSW showed how SOEs could take more patient and uncertainty-embracing investment strategies and how SIBs could promote learning-by-doing and know-how diffusion even when the market was challenged by common transition challenges such as elevated costs and inertial cost improvements. In more general terms, the complexity perspective elaborates on the role of public investors and large firms making strategic investments (Grubb et al., 2014) by adding the importance of iterative learning over time and diffusion to second-movers. Also, it stresses the importance of having experienced actors with high degree centrality in the network that can act as trusted partners for new-comers (Geddes and Schmidt, 2020). Lastly, a diversity of financial sources can improve competition and thus intensify cost reductions and activate learning across more financial and non-financial actors. In OSW, we saw the emergence of bank finance enable independent power producers as developers.

Lastly, the *political* design feature concerns the question of who finances what on what conditions and for what purpose, as these aspects shape transition trajectories. First, the complexity perspective takes an explicit interest in the actors who finance investments and their investor characteristics. Based on the case analysis, financial investors are generally timid in providing finance to emerging technologies and the early entrance is a fragile process that is vulnerable to external shocks or failures. Perhaps a more novel insight was the emergent property of financialisation of deployment. Rather than remaining a diversely financed technology, OSW became primarily funded by capital funds and international banks in the fifth phase (2019-2021). It was argued that sustainability transitions that successfully mature new technologies open up new spaces for low-risk accumulation. This affects the political economy of climate change

through a feedback effect by changing the attitude and organisation of powerful financial actors that in turn shape the politically envisioned transition pathways to promote the new accumulation opportunities, such as through the GFANZ association. If this is a systemic tendency across sustainability transitions, scholars and policymakers should be aware of it and critically examine other models for who captures the value generated by the transitions.

10.4. Summary and further perspectives

This theoretical synthesis has provided an answer to research question 4 (RQ4): *What is the role of finance and investment in sustainability transitions?* by including finance as a separate transition element in Foxon's (2011) co-evolutionary model and applying it to the case of OSW. The co-evolutionary model provided a structured way to consider how OSW finance and investment has been influenced by and exercised influence upon technologies, institutions, and business strategies. This co-evolutionary perspective on finance in sustainability transitions has been the third contribution of this dissertation.

In this regard, the complexity framework has been useful for disentangling how the financial element of transitions is itself undergoing evolutionary processes that link its micro- and meso-level interactions with its macro-level outcomes. This three-level perspective helped to systematically analyse how the financial system interacts with the other transition elements. One particular outcome was to clarify that much of finance's influence operated through emergent properties at the macro level, including the cost of capital, the investment level, and the degree of financialisation of OSW deployment. This supports the calls for systemic approaches to improving the role of finance in sustainability transitions since these properties depend on the interactions and learning processes at the micro and meso levels.

This contribution is compatible with Geddes and Schmidt's (2020) theory of finance as a regime in the Multi-Level Perspective model. The co-evolutionary framework integrated their points regarding the financial sector's role in enabling and constraining technological development and the role of SIBs in shaping the financial sector through educational and trust signalling effects in their networked interaction. Still, Foxon's (2011) co-evolutionary framework was preferred to



emphasise the co-evolution with other ‘regime elements’ as well as within the three levels of finance, which could otherwise get confused with the socio-technical niche, regime, and landscape levels of the Multi-Level Perspective.

Moreover, the theoretical discussion concludes that incorporating a complexity view of finance in transition frameworks provides an improved framework for identifying if and how the financial system can be “stretched” to advance deployment of novel technologies (Geddes and Schmidt, 2020). It is argued that the adapted co-evolutionary framework provides a better framework than the MLP for identifying causal processes and opportunities for instigating change. For example, the analysis and discussion showed how de-risking electricity market frameworks and entrepreneurial state investors in combination were crucial for spurring a mature OSW investor network dominated by private financiers. Nonetheless, the complexity perspective should be integrated into other transition frameworks to obtain a better conceptualisation of when how and if finance prevents or promotes transitions (Steffen and Schmidt, 2021). The potential for deliberately ‘stretching’ the financial sector through political initiatives is considered more in chapter 11.

While the findings also support Geddes and Schmidt’s (2020) results that SIBs can have a system-shaping impact on the financial system, the complexity perspective widens the scope of actors because of the emphasis on heterogeneity, networks, and self-organisation. For instance, it revealed the importance of the introduction of project financing before the GFC to enable banks and smaller developers to invest. This was an adaptive response where the financial system used innovation to enable the deployment of a niche technology – however, an innovation that was dependent on the institutional presence of risk-embracing SIBs.

Moreover, the complexity perspective more explicitly highlights the importance of evolutionary learning processes. For instance, the ability of SIBs to have a positive impact on the wider financial network is also a consequence of their own learning-by-doing through earlier investments. Like private investors, entrepreneurial state investors also require dynamic capabilities to attain the ability to have a trust signalling or educational effect on private investors (Kattel and Mazzucato, 2018; Teece, 2019). Their expertise is not exogenous to their investments



and strategies. We thereby get a clearer idea of how entrepreneurial state investors are also endogenous to the investor network and how their embedded roles can be used to strengthen the maturation of niche technologies (Figure 9.1).

Finally, I return to the connection between the financing and ownership of renewables and the political economy of climate change. The OSW case shows that the current industrial policy-based model for using technology push and demand-pull policies – as well as public investments – to develop new sustainable technologies (Breetz et al., 2018) can overcome the inertia of industrial incumbency, despite previous concerns (Geels, 2014; Johnstone et al., 2017), and build new powerful coalitions (Meckling et al., 2015; Pahle et al., 2022).

However, the political-economic analysis in chapter 6 and the co-evolutionary perspective in this chapter suggest that the current model for deep decarbonisation (Geels et al., 2017) may rest on conforming to the current financialised form of capitalism. The anglo-saxon model of capitalism that has been gaining influence in more coordinated ‘varieties of capitalism’ (Amable, 2003; Hall and Soskice, 2001) since the 1990s has, with different emphases, been referred to as ‘climate capitalism’ (Newell and Paterson, 2010), ‘rentier capitalism’ (Christophers, 2020), the ‘Wall Street Consensus’ (Gabor, 2021), ‘money manager capitalism’ (Minsky, 1989), or ‘asset manager capitalism’ (Braun, 2022b). According to this hypothesis, the financial sector and its modes of investing may not just be a constraint on the development of niche technologies (Geddes and Schmidt, 2020) but also a constraint on the way climate politics is conducted and translated into policies (Newell, 2019).

One hypothetical to consider is whether OSW would have received the patient support it needed to mature if it was developed to be held in non-profit ownership by SOEs, SIBs, and local civic associations, i.e. a public- or civic-led transition pathway (Foxon, 2013; Geels and Schot, 2007). For instance, the UK’s GIB acquired ownership in domestic OSW parks but was privatised after just five years of accumulating OSW ownership. Amassing public ownership was unsustainable given the logic of politics and/or the form of capitalism in the UK. The GIB ended up having neither a catalytical effect on the deployment of OSW nor a long-term value retention role. Ørsted’s dominance was also structured to benefit private and institutional financials through its



direct asset sales and the Danish government's partial privatisation in a sale to Goldman Sachs and two pension funds in 2014 because the government would not finance its growth plans (Voldsgaard and Rüdiger, 2021). Goldman Sachs oversaw the introduction of Ørsted's shares to the stock exchange. When the US investment bank sold its last Ørsted shares in 2017 it had made a 150% return in three years (Sommer, 2017). The main SOE was, hence, also governed to benefit the financial sector.

Under the current transition model, privatisation and financialisation stand out as an emergent property of the way sustainability transitions are institutionally shaped. Nonetheless, alternative forms of financial arrangements have been identified as conducive to civic ownership in the local communities where the assets are installed (Hall et al., 2016) or with more centralised ownership in the form of a 'Green New Deal State' (Gabor, 2021), which socialises both risks and rewards. Sustainability researchers should therefore reflect on the social equity impacts – and hence the long-term viability – of the current transition pathway and consider alternative institutional and financial arrangements that could change the ownership and financing patterns resulting from the investor network.



Chapter 11

Policy synthesis: Governing green finance as an evolving complex system

The potential for changing how and what the financial system finances is crucial for affecting transition trajectories (Geddes and Schmidt, 2020; Steffen and Schmidt, 2021). Based on the importance of financing investments in a low-carbon structural transformation, policymakers, academics, and financial industry professionals have allocated significant efforts to the question of how to ‘green’ the financial system through new governance initiatives. This is a burgeoning policy literature, and so far, the literature on policy mixes for sustainability (Kivimaa and Kern, 2016; Reichardt and Rogge, 2016) has not considered green financial policy in depth (Steffen, 2021). The complexity view of finance developed in this dissertation offers new analytical (ch. 9) and theoretical (ch. 10) insights that can be used to inform new policy initiatives and modes of governance that can “stretch” financial systems to better accommodate the needs of niche technologies.

11.1. *A green finance governance typology*

Governance is a characteristically vague term in political economy (Dixit, 2016). It is generically defined as “the act or process of controlling, directing, or strongly influencing the actions and conduct of something” (from the Merriam-Webster dictionary). However, to emphasise the inability of a single actor to control the complexity of modern economies, my governance conception also relies on the definition of governance as “the interactive processes through which society and the economy are steered towards collectively negotiated objectives” (Ansell and Torfing, 2016, 4). Green finance governance is therefore defined as *the interactive processes through which the financial sector is steered to be aligned with the Paris Agreement*.⁶²

⁶² Green finance can also refer to avoiding biodiversity loss, but here it is used with reference to mitigation of climate change.



The ongoing governance processes can be dominated by different philosophies regarding which policy methods are preferable for steering the financial sector and what specific problems to target in relation to climate change. Following initial policy advocacy by the data organisation New Energy Finance (BNEF, 2013) and the UN Environmental Programme (UNEP) in 2013-2015 that highlighted the need for green finance governance, the governance modalities and problem definitions were relatively unsettled. Some of the issues raised were post-financial crisis financial regulation that incentivised liquidity and safe assets over long-term illiquid investments, insufficient climate risk disclosure requirements, and state aid rules that prevented public banks from promoting new sustainable technology (BNEF, 2013). The UNEP (2015, 2014) launched a comprehensive policy research agenda for system transformation and concluded that “deeper changes and disruption are needed” (UNEP, 2016, p. 58).

However, these ambitions have not come to fruition. Since the Paris Agreement, the sixty largest banks have provided USD 4.6tn in financing for fossil fuel companies, out of which USD 742bn was invested in 2021, which was above the 2015 figure (Banking on Climate Chaos, 2022). Annual low-carbon investments need to more than double compared to the current trajectory (IRENA, 2021a, p. 37).

The mode of governance that has emerged since the 2016 UNEP report has been dominated by a mode of governance that I refer to as *governance by market efficiency*. This mode of governance is characterised by governments keeping out of capital allocation and by defining the primary problem as the safeguarding of financial stability from climate-related financial risk. The primary policy lever is to increase the amount of information on carbon exposure for financial market actors, so they can easier take the long-term risks into account (Carney, 2015). This is pursued through various accounting standards, taxonomies, and stress tests by central banks. It has been a hopeful side-effect to increase the allocation of capital to low-carbon investments by increasing the attention of investors to climate-related risk (Ameli et al., 2019).

Steffen (2021) analysed 136 green financial policies in 29 OECD countries and the EU. He finds that the most common single policy instruments were “carbon disclosure requirements, low-carbon investment policies for public funds, and green state investment banks” (p. 1). From 2015

to 2019, the number of policies increased from 47 to 136, led by the two categories: information provisioning by governments, such as official labels for green finance products or voluntary guidelines, and authoritative frameworks for disclosure of climate-related information, risk management practices, and regulation of green financial products (ibid., 4-5). UNEP (2020) also surveyed green finance policies and similarly found an emphasis on reporting and disclosure measures to improve the level of information regarding climate-related risks.

The third largest policy category was organisational policies regarding the use of public financial institutions. In this category, adjusting routine financial activities of the public sector towards climate goals is a more prevalent type of policy than engaging in new financial activities dedicated to low-carbon goals. The most common organisational policy has been the issuance of sovereign bonds with green labels. Additionally, some countries have implemented dedicated low-carbon financing programmes in their investment banks, while others have established new green investment banks (Steffen, 2021, 6).

Steffen (2021) usefully suggested a research programme for understanding green financial policy *inputs, outputs, and outcomes*. On the input side, he lists party politics, interest group activities and institutional settings, while the output refers to the more bureaucratic process of policy design, integration in policy mixes, and mechanisms of international policy diffusion, which result in the policy outcomes. As argued by Hall et al. (2017), another important input factor that shapes policy design is the prevailing ideas and theories of finance, i.e. the workings of the system targeted by the policies, and consequently also what problems the political process will find it most urgent to address (Blyth, 2002).

Neoclassical theories of finance perceive finance to be a system for moving loanable funds between savers and investors, which is generally efficient (Fama, 1970) although subject to market failures such as asymmetrical information to the disadvantage of lenders, which may lead to credit rationing (Hall et al., 2017; Mazzucato and Penna, 2016; Stiglitz and Weiss, 1981). Post-Keynesian theories see the financial system as an endogenous source of purchasing power (or liquidity) where banks and governments create money to finance investments and spending (Keen, 1995; Lavoie, 2014; Tymoigne, 2014). However, it is also a system that is subject to

fundamental uncertainty and fluctuating states of efficient demand, which leads to the prevalence of sub-optimal credit provisioning (Mason, 2022; Minsky, 2008). Complexity-informed theories of finance emphasise how the interactions of heterogeneous actors under uncertainty can produce unstable patterns of investment and asset valuations and why regulations may need to be continually updated to counteract the tendencies to booms and stagnation (Hall et al., 2017; Kirman, 2011; Minsky, 2008).

To make systematic sense of these policy interventions, I propose a categorisation of three modes of green finance governance resting on varying theories of finance and problem definitions that shape what green financial policies get adopted. The underlying policy rationales and theories of finance for each of the three modes of governance – *governance by market efficiency*, *governance by credit guidance*, and *governance by investing* – are summarised in Table 11.1, while their preferred policy instruments are summarised at the end of the chapter in Table 11.2, grouped by the problem definitions they target.

Table 11.1: A green finance governance typology

Mode of governance	Problem definition	Policy rationale	Complementary climate policies	Theory of finance
<i>Governance by market efficiency</i>	Climate-related financial risk	Financial investors are discounting future risks of climate change too strongly in part due to a lack of information on exposures, which could lead to a financial crisis when physical risks materialise, or politicians accelerate the transition. With more information and carbon taxation, markets can deliver efficient investment decisions.	<i>Academically:</i> Uniform CO2 taxation or emission quotas and CO2 offsets. <i>Lobbying:</i> De-risking policies	Neoclassical economics: Generally efficient markets with some market failures.
<i>Governance by credit guidance</i>	Capital allocation	Because of radical uncertainty regarding the impacts of climate change and conflicting interests in the financial sector, private finance needs quantitative credit guidance rather than merely information and price adjustments to support green industrial policies and rapid structural change.	Green industrial policy & strong financial regulatory framework	Post-Keynesian economics and critical macro-finance.
<i>Governance by investing</i>	Know-how development and innovation	The financial sector is prone to finance assets and technologies that it is already familiar with, which is why the state should promote learning among private and non-profit investors by investing through SOEs and SIBs to generate and share investment know-how.	Mission-oriented innovation policy & green industrial policy	Complexity, evolutionary, & institutional economics.

Note: Author's own development with inspiration from Kedward et al. (2022).

11.2. Governance by market efficiency to mitigate climate-related financial risk

As evidenced in the policy studies cited above, the currently dominant mode of green finance governance is *Governance by market efficiency*. It relies on a fundamental trust in the efficiency of financial markets in allocating capital to the most productive purposes and hence avoiding wasted resources and welfare losses for society. However, the recognition of short-termism among financial investors (Carney, 2015) means that the financial allocative mechanism is



exposed to financial risk stemming from the physical risks from climate change or from climate policies and climate-related shifts in technological innovation and consumption patterns that can make carbon-based assets stranded (Mercure et al., 2018). Policymaking is therefore based on the principle of using ‘market neutral’, non-coercive policy measures that improve the financial system’s ability to account for climate-related risks and avoid direct influences of policymakers on the allocation of capital (Christophers, 2017). The coercive element of climate policies should be implemented via carbon taxes or cap-and-trade quota schemes, so prices in product markets internalise the pollution externalities, which enables a perceivedly efficient mechanism for determining which activities should be discontinued and in what order during the transition and provide an incentive to innovate (Economists’ Statement on Carbon Dividends, 2019; Rosenbloom et al., 2020).

The strand of academic green finance literature that has most clearly shaped this mode of governance is the literature on climate-related financial risk, which incorporates the role of finance in the macroeconomics of climate change (Monasterolo, 2020). The literature has grown quickly since the Paris Agreement with seminal contributions by Battiston et al. (2017), Campiglio et al. (2018), Dafermos et al. (2018), and Monasterolo et al. (2018) among others. While the climate risk-focused literature has proposed unorthodox policy suggestions, such as green quantitative easing, green collateral requirements in monetary policy, and financial regulations to either penalise fossil assets or incentivise green assets via capital requirements (D’Orazio and Popoyan, 2019; van’t Klooster and van Tilburg, 2020), policymakers and financial industry initiatives are not moving in this direction, as they have, so far, aimed to uphold the principle of ‘market neutrality’ in financial regulation and monetary policy (Krogstrup and Omar, 2019).

As noted, the primary solution to mitigate this short-termism has been to provision market actors with more information about climate change exposure by introducing disclosure requirements on companies (Christophers, 2017). This policy agenda has most notably been advanced with the formation in 2015 of the *Task Force on Climate-related Financial Disclosures* (TCFD) by the Financial Stability Board (FSB), which is affiliated with the G20 and the Bank for International



Settlements. In 2017 they submitted their first recommendations, which were updated in 2021, on how corporations should disclose climate change exposure so the financial sector could act upon it (TCFD, 2021, 2017).

The agenda was extended to central bank and financial supervisors in 2017 with the *Network for Greening the Financial System* (NGFS, 2019), which works “to enhance the role of the financial system to manage risks and to mobilize capital for green and low-carbon investments”, including through the promotion of a “robust and internationally consistent climate and environment-related disclosure” regulatory framework for financial risks. In addition, financial authorities conduct climate financial stress tests to assess systemic resilience to climate risks.

Moreover, the EU has adopted a green finance taxonomy regulation that aims to advance the work towards a standardised disclosure methodology (EU, 2020). Meanwhile, the UK Government (2021, 2019) has been at the forefront of formulating a national green finance strategy to seize the sector-wide business opportunity to become the hub for climate-related financial services. However, so far efforts have been directed more at ‘greening finance’ (i.e. changing information flows and asset classifications) than actually ‘financing green’ – i.e. financing new low-carbon fixed investments (UK Government, 2022).

Lastly, a growing number of voluntary initiatives among financial institutions make pledges about their commitment to decarbonising their portfolios towards 2050 (UNEP, 2020). The aforementioned GFANZ (2022) has been the most notable association, and it has recently confirmed the dominance of governance by market efficiency by detaching itself from the UN’s Race to Zero initiative because of its attempt to impose quantitative carbon restrictions on the members (Financial Times, 2022d). In sum, the field of green finance is already subject to an increasingly polycentric governance regime (Ostrom, 2014) as numerous public and private initiatives in various sub-sectors of the financial system, including banking, accounting, insurance, and asset management, seek to establish reporting standards and valid targets for the carbon profile of financial portfolios (Liebreich, 2021).

Under governance by market efficiency, avoiding a financial crisis from deflating carbon assets is the key motivation for policymakers and industry actors. In other words, to protect finance



from climate change (referred to as single materiality) rather than protecting climate change from finance (together known as double materiality) (Kedward et al., 2022). To also have a boosting effect on the green transition, increased concerns regarding climate-related risk would have to lead to new investment in projects that contribute to decarbonisation: “The hope is that fear of carbon bubble risks would drive institutional investors to move money out of these assets and into clean energy investments that would insulate them from this risk” (Ameli et al., 2019, 20). However, the challenge is likely less a lack of climate-risk disclosure or inability to identify green assets, but rather for private financiers to find additional decarbonising investments attractive to finance at a low cost of capital compared to alternative assets (ibid.). In the OSW case, the resolute strategies by major oil companies in recent years to quickly win market shares in OSW crowded out pension funds from OSW. However, this led the pension funds to reallocate their portfolios towards real estate and stocks rather than other decarbonising investments (Frandsen, 2021).

Besides the barriers to decarbonising investment, the sustainable finance industry reverberates from ongoing charges of greenwashing (Bloomberg, 2021; Gabor, 2020; Urban and Wójcik, 2019), which makes the transmission mechanisms from more well-informed capital market investors to additionality in green investment tenuous. By relying on market discipline on the liability side of balance sheets (i.e. funding conditions) rather than more constraining regulation of financial institutions’ assets, the mainstream approach has consequently been described as a “neoliberal modality of governance” (Christophers, 2017). These reasons for scepticism towards governance by market efficiency have led to calls for a more state-directed mode of governance, also targeting the asset side of balance sheets.

11.3. Governance by credit guidance to accelerate the reallocation of capital

While governance by market efficiency has taken over mainstream policy discourse, some social scientists have advocated more stringent approaches that more actively shift the playing field in favour of low-carbon investment as well as hinders the expansion of the fossil fuel sector. In combination, I refer to this mode of governance as *governance by credit guidance*. In short,



governance by credit guidance focuses on re-directing the financial behaviour of private actors through financial incentives and more directional, or even coercive, regulations compared to the ‘market efficiency’ approach.

In terms of problem definition, governance by credit guidance provides more attention to the issue of *capital allocation from polluting to sustainable activities* as it maintains scepticism towards the financial sector’s willingness to do so without clearer incentives or directions. The approach is secondarily motivated by the prospects of climate-related financial risk and suggests green macroprudential financial and green monetary policies should be applied to incentivise a shift out of fossil-based assets, such as penalising capital requirements or larger haircuts in collateral frameworks (D’Orazio and Popoyan, 2019). This is seen as a more effective way to limit climate-related financial risk as financial institutions will be more able to withstand unforeseen losses (Kedward et al., 2022, 5).

In order to ensure that more sustainable financing takes place through fixed investments rather than mere portfolio reallocation into assets reclassified according to green taxonomies (that are liable to greenwashing), governance by credit guidance advocates more targeted approaches such as preferential refinancing rates for new green bank loans, green screening of central bank QE portfolios, and steering of credit via binding or non-binding guidance on banks for undertaking investment in selected industries and/or technologies (Kedward et al., 2022; Mikheeva and Ryan-Collins, 2022; van’t Klooster and van Tilburg, 2020).

This approach draws on developmental state practices that have been used during industrialisation programmes in Western and East Asian countries (Bezemer et al., 2021; Mikheeva and Ryan-Collins, 2022; Monnet, 2018). Given the more recent success of developmentalist industrial policies in East Asia and policy emulation in other developing countries, it is perhaps unsurprising that we see wider use of governance by credit guidance in developing countries. India has, for instance, included renewable energy as one of the priority lending sectors to which 40% of commercial bank net credit creation must go (Ryan-Collins and Dikau, 2017). China’s central bank has used green targets in its informal window guidance for



banks from 2006-2019 but recently moved towards a more formalised and market-based approach to green finance (Dikau and Volz, 2021).

Kedward et al. (2022) propose a comprehensive “allocative green credit policy” regime, which is presently the most coherent articulation of governance by credit guidance, based on both quantitative and price-based interventions in the operations of private financial institutions. A key difference from governance by market efficiency is that finance is considered as mainly quantity- rather than price rationed. This means that financial markets are not governed by a price equilibrium that allocates a pool of loanable funds, but by financial business decisions on whether to expand liquidity endogenously or not. With a Keynesian perspective grounded in fundamental uncertainty and insufficient effective demand as a normal condition, they do not expect investments to be initiated in neither the right direction nor quantity.

In contrast to the pairing of governance by market efficiency with carbon pricing as preferred climate policy, the credit guidance regime is considered a complementary policy set to Keynesian fiscal dominance in macroeconomic management and a state-led green industrial strategy (Gabor, 2021; Mason, 2022; Nersisyan and Wray, 2021), which is antithetical to relying on market efficiency. A key role of financial policy is promoting financing in support of the industrial policy’s goals. Central banks and regulators should therefore assume a promotional rather than prudential role.

Governance by credit guidance is less concerned about stimulating innovation or know-how development in the economy in general or the financial sector in particular. The perspective implicitly expects technologies and investor communities to mature insofar as the credit guidance succeeds in stimulating additional deployment of sustainable technologies. Yet, this mode of governance maintains a more quantitative focus on technology deployment and the restriction of polluting investments, rather than a qualitative focus on innovation and evolutionary processes within the financial sector.

In the same vein, the role articulated for SIBs is to steer credit to “where the private sector will not” by providing credit directly and indirectly by attracting private investors to the projects (Kedward et al., 2022, p. 21). The authors do implicitly recognise the need for moving the



technological frontier, since the efforts to wind down fossil fuel production may cause “inflationary consequences *if new green sectors are not readily able to absorb excess labour and capital*” (ibid., 23; emphasis added).

11.4. Governance by investing to advance the maturation of low-carbon technologies and spread the requisite investment know-how

As a third general type of green finance governance, I propose *governance by investing*. It is a mode of governance that is motivated by the need to move the technological frontier and improve the investor community’s know-how regarding investing in frontier technologies. It uses an understanding of the investor community as an evolving complex system to propose interventions that steer how the actors interact and change over time. It hence perceives the ‘stretching’ of financial systems (Geddes and Schmidt, 2020) as an emergent property arising from micro-interaction and learning-by-doing. In this formulation, it proposes to use state-owned investors as a primary tool for changing how private and civic financial institutions assess and invest in sustainable technologies.

Grubb et al. (2017) suggest that the technology frontier is moved by strategic investments in R&D, innovation, and infrastructure that can both be undertaken by large corporations and the state. Nonetheless, the potential for moving the frontier has received less attention in relation to public investment, although the renewable energy finance literature suggests that state-owned actors invest closer to the frontier of sustainable technologies (Mazzucato and Semieniuk, 2018; Steffen et al., 2020b) and diffuse new investment know-how among private financiers via co-investment (Geddes et al., 2018; Geddes and Schmidt, 2020).

Governance by investing uses state-owned investors such as SIBs and SOEs to make investments in the sectors and technologies that need to move down the initial parts of their learning curve. These investments can reveal the technologies’ learning gradients, i.e. their potential for cost reductions as a consequence of deployment, and lead co-investors to obtain the necessary experience to make well-informed risk assessments of emerging technologies (Figure 9.1).



This governance approach utilises the strengths of SOEs and SIBs that were identified in the case analyses (chapter 9). Mainly, their characteristic as decentralised economic actors makes them useful elements in a ‘developmental network state’ (Keller et al., 2017). They are more able than public bureaucracies to monitor the technological and commercial tendencies and opportunities in markets. With the right governance, they can be uniquely positioned to make strategic investments that push the technological frontier, and SIBs can have a special role in educating and encouraging private financiers to take on risks in new technologies. For SOEs, the analytical synthesis proposed to use Technological Frontier Investment Mandates to steer their investments towards more risky technologies that the rest of the economy will eventually benefit from.

While avoidance of climate-related financial risk from stranded assets is a core motivation behind governance by market efficiency and governance by credit guidance, governance by investing is more focused on rapidly deploying and maturing new technologies rather than hindering the deployment of fossil fuel assets. Indeed, more creative destruction from low-carbon technologies may increase the risk of stranding carbon-based operational assets. This suggests that it may be advisable to combine governance by investing with elements from guidance by credit guidance, including the use of green macroprudential policies that ensure carbon financiers have more equity to absorb losses on their balance sheets (Campiglio, 2016; Campiglio et al., 2018).

On the other hand, the USD 1.4tn in expected losses on oil and gas assets in a 2 °C scenario (Semieniuk et al., 2022) are relatively minor compared to the USD 110tn of assets under management by institutional investors and the additional USD 50tn value of publicly listed companies that institutional investors do not own (PwC, 2021, p. 2). These proportions should make financial stability attainable since it concerns a decades-long transition process, rather than the abrupt bursting of a bubble as with the USD 1.4tn of exposure to subprime loans in 2008 (Adrian and Shin, 2010).

The governance by investing approach is adjacent to two other state-led approaches that involve public investments. First, a ‘de-risking approach’ is commonly proposed in academic work and multilateral financial organisations whereby public investments are used to ‘target scarce government dollars’ at ‘crowding in’ or ‘mobilising’ private capital into low-carbon technologies



by de-risking particular projects (Deleidi et al., 2020; Krupa and Harvey, 2020, p. 128-130). The OSW case study supported that this mechanism is present and important for maturing low-carbon technologies, but governance by investing is not focused on ‘leveraging scarce public capital’ with private capital to be able to fund more projects.

Although interaction with private financiers is a core mechanism in the governance by investing framework, it is considered a means to the end: innovation and development of investment know-how. In other words, it is concerned with enhancing the dynamic efficiency of the investor system over time (Mazzucato et al., 2020) rather than economising with public funds at a particular point in time. One implication is that SIBs should not be limited by maximum loan amounts or maximum debt shares (e.g. KfW (2015, p. 2)) that could hinder important but riskier projects from being realised. It remains a priority to include private financiers, but participation with smaller amounts of capital provisioning can have a similar learning impact⁶³.

Second, there are state-led approaches to sustainability transitions where public investments are used more comprehensively and at the expense of private finance. They are commonly labelled as a Green New Deal approach (Gabor, 2021; Mason and Bossie, 2020; Nersisyan and Wray, 2021). In contrast to governance by investing, these approaches are less concerned with innovation and know-how development in private finance and more about ensuring a sufficient pace of investments and public value retention from the assets.

11.4.1. Considerations for implementing governance by investing

Several questions remain unsolved by this initial formulation of governance by investing. First of all, it is likely possible to combine governance by investing in the two alternative governance modes, which are more mutually exclusive. As mentioned above, if it were to be combined with governance by market efficiency, it would require an argument based on the identification of market failure. This could be the positive spill-over effect of generating new innovation and

⁶³ Although more capital at risk undoubtedly raises the efforts by the banks to understand the risk they take. Nonetheless, stringent loan limits can get in the way of deploying technologies closer to the frontier, which could make banks more willing to lend.

investment know-how. However, the neoclassical approach is generally ill-equipped to analyse differences in organisational capabilities (Loasby, 2002; Teece and Pisano, 2003) rather than information asymmetries (Stiglitz and Weiss, 1981). The result would likely be more SIBs taking a de-risking role, while the option to use SOEs likely goes too far against the grain of the principle of market efficiency.

Sustainability transitions researchers have stressed that policy mixes should both promote niche technologies and phase out unsustainable incumbent technologies (Kivimaa and Kern, 2016). In this respect, governance by investing may be more compatible with governance by credit guidance since the former contains no policies for hindering harmful, carbon-based investments. Likewise, the latter contains little attention to accelerating the development of substitution options, which is offered by governance by investing. Moreover, the green macroprudential elements can help to absorb financial losses that may result from speeding up the transition and hence the risk of stranded carbon assets. Finally, green credit guidance may also make it easier for entrepreneurial state investors to find willing co-investors in the network by tilting the playing field towards low-carbon investments.

Another question relates to the applicability to other technologies. As discussed in chapter 8, OSW is a technology with particular techno-economic characteristics, including its vast capital volume per project, its centralised nature, and the various sources of risk in the marine environment. On the other hand, several emerging sustainable technologies are also capital intensive with large up-front capital costs, exposed to electricity markets, and with unproven track records, such as long-duration storage, 2nd generation geothermal, and electro-fuel production (Table 8.1).

Third, it is uncertain whether politicians are willing to derogate responsibility for delivering on their political missions to investment organisations at arm's length without politicising the operations of the institutions. In other words, if they are willing to trust the process. Politicians need to substantiate how they will achieve their targets, such as emission reduction targets. This underlines why governance by investing can only be a component in a policy mix and not the entire strategy.

This leads to a fourth issue concerning how entrepreneurial state investors are governed. As discussed in chapter 9, governance by investing likely requires corporate governance reforms, especially for SOEs, to fully exploit the potential for advancing technological change and lowering the financial cost of the transition. SOEs are currently governed not to interfere with the business opportunities of private competitors while structuring them to be easier to privatise (OECD, 2015).

11.5. Summary

This chapter has developed a green finance governance typology containing three modes of governance, which are summarised in Table 11.2 based on their preferred policy instruments and what climate-related issues they aim to solve. *Governance by market efficiency* is the currently dominant policy paradigm focused on preventing climate-related financial risk through better disclosure of carbon exposures. *Governance by credit guidance* has been developed to counter the insufficient level of low-carbon investment with more coercive regulations while quantitatively limiting the expansion of fossil fuel extraction (Kedward et al., 2022). Based on the insights from the OSW case, *governance by investing* was proposed as a policy approach for harnessing the potential of entrepreneurial state investors for advancing the learning curves of emerging low-carbon technologies while transforming the wider financial system's propensity to finance them – thereby designing policy with an intention to create self-reinforcing feedbacks. Further studies should consider to what extent governance by investing has also been successful for other technologies, how the three forms of green finance governance can be combined, and how entrepreneurial state investors should be governed to set in motion transformative changes in technology development and investor communities.

Table 11.2: Policy instruments of green finance governance

Mode of governance	Instruments by problem definitions		
	Main concern	Secondary concern	General indifference
<i>Governance by market efficiency</i>	Financial stability - Financial transparency and disclosure of carbon exposure to enable financial market discipline and efficiency. - Internal and systemwide carbon stress testing by financial institutions and central banks.	Capital allocation Attention to climate risk may reallocate capital to sustainable activities. Other mechanisms: - Green taxonomies. - Voluntary pledges by associations.	Know-how and innovation - Partnership initiatives. - State organisations as mainstreamers of green taxonomy usage.
<i>Governance by credit guidance</i>	Capital allocation Incentivising (indirect) measures: - Capital requirements. - Credit guarantees. - Sectoral refinancing lines. - Collateral haircuts. - Tilting of asset purchase programmes. Coercive (direct) measures: - Interest rate floors and ceilings - Promotional credit for prioritised borrowers (e.g. through SIBs) - Portfolio restrictions: Bans financing certain sectors/assets, credit quotas, and lending ratios - Large-scale public investment (e.g. through SIBs) Other: Informal state-banking coordination.	Financial stability Increased capital allocation to green sectors at the expense of dirty sectors will lower financial instability risks as a by-product. Additional policies: Forced sale of dirty assets to state ‘bad bank’	Know-how and innovation Implicit potential for learning-by-doing insofar as credit guidance incentivises and/or coerces financiers to investment in either unfamiliar technologies or niche technologies.
<i>Governance by investing</i>	Know-how and innovation - Investment targeted at the technological frontier by entrepreneurial state investors - Organisational investments in in-house expertise to perform due diligence. - Development of credit assessment tools in niche sectors. - Co-investment between public and private actors to diffuse investment know-how. - On-lending via non-state financiers to improve familiarity with new tech.	Capital allocation - Direct investment via state entrepreneurial state investors. - Green export credit to increase deployment in new markets abroad.	Financial stability Accelerated innovation and technology deployment could lead to more rapid stranding of carbon-based assets. Maintenance of dynamic capabilities of state-owned investors provides better options for countercyclical investments in a crisis.

Note: For each mode of governance, the columns rank the priorities of financial stability, capital allocation, and know-how and innovation in their problem definitions. The colours correspond to the three problem categories.

Chapter 12

Conclusion

12.1. The general conclusion

The lack of clarity regarding the role of finance and investment in the development of competitive, low-carbon energy technologies led me to pursue the main research question (RQ1) of this dissertation: *What can be learned about how finance and investment influence sustainability transitions by analysing renewable energy finance as an evolving complex system?* Complex systems theory was applied to the case of investments in offshore wind (OSW) to advance Hall et al.'s (2017) theory of energy finance as an ‘adaptive market’. OSW investment offered a unique opportunity for a longitudinal case analysis of a maturing energy technology because the compiled database covered all investments in OSW parks from the first park that was commissioned in 1991 to 2021.

A combination of complexity theory and research on the entrepreneurial state’s role in innovation led to the formulation of the main hypothesis (H1). It was expected that the analyses would show that *finance and investment are not neutral to the way sustainability transitions develop*. The complexity perspective was expected to provide a clearer understanding of the diversity of investors and the importance of their learning and interactions in driving technical change through the deployment of renewable energy. Moreover, it was expected that entrepreneurial state investors would have a disproportionate influence on evolutionary processes in the network compared to other investor types. More specifically, the theoretical framework (chapter 3) hypothesised three causal mechanisms that would influence the impact of finance on technology deployment: bounded rationality, evolutionary processes, and actor heterogeneity – both exogenous heterogeneity associated with the various investor types and endogenous heterogeneity as a result of the differentiating evolutionary processes.



The synthesis of the analytical chapters supported the hypothesis that the domain of finance and investment decisions is not neutral to the outcome of sustainability transitions. The common reasoning based on a representative, rational investor that objectively weighs risks and returns is not adequate for understanding the deployment of new sustainable technologies that are disadvantaged by pervasive uncertainties and a lack of familiarity among investors (Bolton et al., 2016; Hall et al., 2017; Kay and King, 2020). The analyses showed that for OSW the impact of technology-push and demand-pull policies (Grubb et al., 2017) was contingent upon how the investor network evolves since the network shapes the crucial and strategic decisions to deploy new technologies. From this perspective, the oscillating investment patterns, the technology cost trajectory, the cost of capital, and the changing financing and ownership patterns during the history of OSW were emergent properties of interactions and learning processes in the network. The properties emerged under the co-evolutionary influences of available technologies, institutions and market frameworks, and active business strategies.

The social network analytical methods displayed how energy policies have an effect not by influencing a representative rational investor but by influencing an adaptive and learning network of investors. Finance is not neutral to technological development since the outcomes of the network depend on the evolutionary and interactive processes among the investors. Analyses of the role of finance in sustainability transitions must therefore analyse finance as a system of investors with heterogeneous investment know-how and hence different abilities to assume the risks of investing in emerging sustainable technologies. The deployment of new technologies, therefore, depends on the presence of organisations with dynamic capabilities (Katkalo et al., 2010; Kattel and Mazzucato, 2018; Teece and Pisano, 2003) to develop new investment know-how through learning-by-doing or absorbing it through co-investments with experienced partners.

The need for dynamic capabilities applies to private-, civic-, and state-owned companies alike, but the OSW analyses showed that entrepreneurial state investors have been more decisive for the deployment of OSW by creating and accumulating investment know-how as lead investors in the first 25 years of deployment, while SIBs have had a distinctively important role for



diffusing investment know-how in the financial system through their de-risking, educational, and capital-provisioning activities. These impacts were important for bringing OSW over, first, the technological valley of death and later the financial valley of death (Karlton, 2016, Figure 5.8). In parallel, a core of highly capable banks formed in the network, but until the last phase, they were dependent on the nearly ubiquitous presence of SIBs in project-financed OSW investment deals. In addition, Ørsted had an important role in integrating institutional investors in the financial network. Through their initial de-risked acquisitions, pension funds became familiar with the risks and returns of OSW and eventually gained the confidence to take on construction risks.

Although OSW has become competitive with fossil fuel technologies, the history of OSW was also a tale of caution regarding the fragility of know-how creation under uncertainty (Bolton et al., 2016; Hughes et al., 2013). There were three periods of historical contingency in the first three phases that could have changed the trajectory of OSW markedly: The first deployment of utility-scale OSW, the first use of project financing before the GFC, and the difficulties of sourcing enough finance to keep deploying OSW at large-scale at the high-cost level after the GFC. However, all these contingencies turned out favourably because of the investments undertaken by a few entrepreneurial state investors. These crucial investments and central roles in the investor network were used to discuss how SOEs and SIBs could be used more proactively to accelerate the maturation of other sustainable technologies (chapter 9).

The complexity-based analyses thereby showed how the “structural barrier” to renewable energy investment in the lack of expertise among private investors (Hall et al., 2017, 291) was overcome through evolutionary processes in the OSW investor network, most importantly through learning-by-doing and learning-by-co-investing. The distribution of investment volumes and network ties furthermore showed that these processes were highly skewed towards a few lead investors that had disproportionate impacts on the network’s trajectory (Figure 6.8). This was particularly the case for entrepreneurial state investors in the first three phases, while the fourth phase was a transition towards financing being dominated by private financial investors. Moreover, the evolutionary processes created path dependencies whereby the earliest banks in OSW became



dominant in the mature phase (Figure 6.9). The study of OSW financing thereby provides empirical support to Gräbner's (2017) argument that institutional perspectives can be helpful in understanding how complex systems evolve by offering a clearer focus on causal mechanisms.

As discussed in sections 8.3 and 9.2.3, the conclusions regarding the usefulness of complexity theory for understanding RE finance and the system-shaping impacts of entrepreneurial state investors cannot necessarily be generalised to other technologies that evolved simultaneously or the next generation of sustainable energy technologies currently under development. OSW is characterised as technology by being capital intensive and deployed in a centralised fashion in risky, maritime conditions. Onshore wind and Solar PV also matured rapidly during the same period, but their decentralised pattern of deployment possibly meant that there was less need for entrepreneurial state investors to move down the learning curve. The large share of german energiewende investments in RE financed by KfW (D'Orazio and Löwenstein, 2020) suggests that SIBs may be more relevant for maturing decentralised technologies than SOEs. For decentralised technologies, a crucial financial challenge is spreading sufficient investment know-how to numerous smaller financiers, such as local banks, while for centralised technologies it is more important to reach a critical mass of investors with high investment expertise and potential for large debt or equity investments. The complexity perspective is less likely to yield useful insights regarding decentralised less-capital intensive technologies, since they are regularly internal business decisions to acquire auxillary technologies to improve rather than perform the core business activity.

The next generation of sustainable energy technologies contains more centralised technologies that could share the dynamics observed in OSW. Some of them will have lower capital intensity because of the procurement of electricity, e.g. for eletrolysers or utility-scale energy storage, but the initial investments are still demanding from a financing perspective. However, as a consequence of the co-evolution of the financial sector during the maturation of the first generation RE technologies, the next generation will be deployed in considerably different – and more accommodating – financial environment compared to OSW (BNEF, 2022d). While this is in accordance with an evolutionary perspective (Hall et al., 2017d), this development could limit



the usefulness of entrepreneurial state investors. On the other hand, energy transitions have historically been characterised by financial “frenzies” that alternated between booms and busts (Perez, 2002), why retaining investment capabilities in public financial and non-financial companies could offer technology-specific counter-cyclical policy levers.’

Despite the yet-to-be ascertained external validity of the complexity theory of OSW finance with regard to other technologies and periods, the dissertation developed provisional theoretical and policy implications for sustainability transitions research and financial governance. Sustainability transitions research has recently prioritised moving beyond case analyses to develop general theories of how finance influences the possibility of rapid transitions of economic provisioning systems (Geddes and Schmidt, 2020; Köhler et al., 2019b; Naidoo, 2020; Steffen and Schmidt, 2021). One strength of this dissertation was the application of a general theory of finance from a complexity perspective to a sustainability transitions case, which could inform general theorising in relation to existing frameworks. The theoretical synthesis in chapter 10 developed the notion of finance and investment as a complex evolving system that could be integrated as a co-evolutionary element that develops under the mutual influence of technologies, institutions, and business strategies (Foxon, 2011; Figure 10.2).

Lastly, the analytical and theoretical synthesis suggested that the financial system can be governed towards greater support for the green transition by taking advantage of its complexity features (Colander and Kupers, 2014; Lenton, 2020; Otto et al., 2020; Sharpe and Lenton, 2021). *Governance by investing* was conceptualised as the use of entrepreneurial state investors to advance the financial system’s latent potential for learning about new technologies. As seen in the case of OSW, this can lower the cost of capital and increase volumes of capital made available, and hence advances technologies along their learning curves (Grubb et al., 2021a; Way et al., 2022)

12.2. Research methodology and dissertation overview

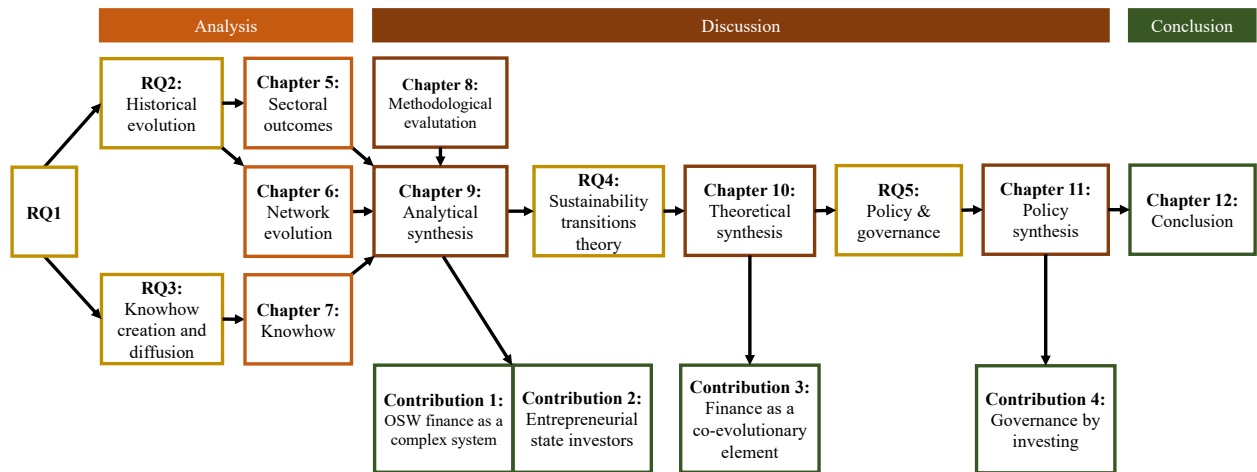
The main research question was operationalised into four sub-research questions designed to use the history of OSW investment as a case for analysing renewable energy finance as an evolving

complex system and discussing the theoretical and policy implications of the analysis. The case analysis examined all investments in OSW parks from the very first project that was commissioned in 1991 up to and including investments in 2021. The exhaustive data on how investors have co-invested in all projects up to this point provided a unique case for studying the financial influences on a sustainable technology's journey *from cradle to a mainstream asset class*.

Visual and statistical social network analysis were the main methods used because of their compatibility with the properties of complex systems (Bale et al., 2015; Foxon et al., 2013). In a mixed methods approach, I integrated the network analytical methods with qualitative data sources to establish a valid micro-foundation for interpreting the results of the network analysis.

Figure 12.1 shows how the main research question (RQ1) was first operationalised into two analytical sub-research questions that instigated three analytical chapters examining: 1) the investor network's aggregate outcomes, 2) the network's historical evolution, and 3) how investment know-how has been created and diffused in the network. The analytical insights led to the theoretical synthesis and its contribution of proposing finance and investment as a co-evolutionary element in sustainability transitions research (Foxon, 2011). Finally, in the policy synthesis, *governance by investing* was proposed as a new framework for green finance governance.

Figure 12.1: Research questions, chapters, and contributions



Note: Own illustration. Contributions are added to a condensed version of Figure 1.3 in chapter 1.

12.3. Analytical outcomes

12.3.1. The history of offshore wind investment

The first sub-research question (RQ2) was: *How has offshore wind investment co-evolved with the technology over time and how are these changes shaping the political economy of climate change?* The dissertation answered this question through the analyses in chapter 5, where I examined aggregate sectoral trends, and in chapter 6, where I used social network analysis to understand the causal mechanisms at the investor level and how these changes could affect the political economy of climate change.

Chapter 5 showed the central aggregate trends in the OSW sector, which provided both useful background knowledge of the sector's history and macro-level outcomes that could be examined as emergent properties of the evolving investor system at the micro- and meso-levels. The descriptive analysis found an increasing investment trend with considerable oscillations following a slow beginning, large shifts in the composition of investor types, two cycles of



technological costs reductions with a large intermediate period of increasing and stagnant costs, and a falling trend in the cost of capital following a deterioration during the GFC.

Considering these outcomes jointly, I interpreted that OSW had moved through the technological and financial valleys of death (Figure 5.8, see also Karltorp, 2016). First, state-owned utilities and state-led civic utilities were crucial for bringing OSW technology to the phase of early commercialisation in the early 2000s, when first private utilities and later banks entered the market. Secondly, state-owned investors increased their investments from 2008-2017, which helped OSW reach the last phase, where costs rapidly came down and private financiers would finance most new projects.

Chapter 6 used visual and statistical network analysis to examine the investors and interaction patterns among them that had brought about the identified emergent properties at the macro-level. Five distinct phases were delineated along OSW's maturation from *cradle to a mainstream asset class* (Table 4.1) based on the shifts in outcome variables, noticeable investment events and trends in the OSW sector, and external events influencing OSW investment.

The first phase was *SOE exploration* (1989-2001). In this phase, Ørsted's antecedent utility and energy companies (that were merged into the SOE in 2005) and the Swedish SOE Vattenfall were responsible for the deployment of most of the projects that made OSW cross the first technological valley of death (Karltorp, 2016). The success of one of the first two utility-scale projects set off the second phase, called *utility-led upscaling* (2002-2009), which led to increased network growth and fundamental product and process innovations (Jennings et al., 2020).

The ensuing financial valley of death was countered by patient investments in the third phase, named *state-led maturation* (2010-2015). Ørsted became the unparalleled lead investor, while the three SIBs, the EIB, KfW, and EKF, became large investors with central roles in the network's core. Following the Paris Agreement's signal of global willingness to decarbonise, the third phase was called *post-Paris learning and diffusion* (2016-2018). The majority of primary finance was still provided by state-owned investors, but private investors became more familiar with OSW through their refinancing and acquisitions of stakes in operational parks. In the fifth phase, *offshore wind as a mainstream asset class* (2019-2021), state-owned investors had a



noticeably smaller role, while private banks and capital funds now provided a majority of primary financing together with major oil companies.

The network's development through the five phases matched the punctuated equilibrium model used in complexity science for understanding how systems often go through three phases of experimentation, disorganised growth, and an orderly final state (Figure 6.7) (Beinhocker, 2007). The investments in the first large-scale parks in the early 2000s moved the system from its experimental phase to its growth phase. The growth phase was challenged by rising costs and worsening financial conditions, but SIB investments undergirded the growth and learning processes. Eventually, the costs came down through industrialisation, larger turbines, and falling cost of capital, which enabled private financiers to dominate what appears to be an orderly phase in recent years. However, the resolute entry of major oil companies and the institutional trend towards re-risking of electricity markets may provide new challenges that could disrupt the build-out of OSW in the medium term.

The analysis also found that the evolution of the investment patterns behind the deployment of OSW also had an impact on the political economy of climate change. Financialisation of the investment in the mature phase stood out as an emergent property of the self-organising behaviour in the investor network. Insofar as similar trends occurred in other sustainable technologies, this would have changed the material, or asset-based, foundation for the politics of climate change (Colgan et al., 2021). In OSW, private investors saw how the green transition would create vast new capital-intensive and de-risked assets under private ownership, which provides a framework for understanding the financial sector's embrace of net zero emissions targets, e.g. in the GFANZ (2022) association, despite considerable financial interests in the fossil fuel economy (Semieniuk et al., 2022).

On this basis, the analysis supported the theoretical expectations in hypothesis 2, that state investors had a decisive early role in maturing OSW technology, which attracted private investors. Ørsted was a lead investor in the first four phases, while the SIBs had an important impact on maturing the financial investor landscape in phases 2 and 3 through their near-ubiquitous presence as lenders to project-financed parks. Finally, the system's tendency in recent



years to promote financing and ownership by private and institutional investors has likely had a positive feedback effect on the level of ambition in climate politics since the sustainability transition of energy was being configured to fit the current form of capitalism.

12.3.2. The creation and diffusion of investment know-how

The second sub-research question (RQ3) was: *Which investors and interactions have been important for investment know-how creation and diffusion in the offshore wind sector?* The motivation was to understand how the structural barrier to renewable energy investment in the insufficient know-how in investor communities (Hall et al., 2017, 292) was overcome in the case of OSW. It was answered in chapter 7 by using network reachability analysis to measure each investor's exposure to the know-how generated in recent OSW projects and their potential for influencing the network's investors in the subsequent phase.

The analysis showed that Ørsted and the company's antecedent civic utility companies were disproportionately responsible for creating and absorbing know-how in the first experimental phase and for diffusing it to the investors in the second phase through co-investments with other utilities and the EIB. In the second phase, banks started using project finance to make OSW 'bankable' with support from SIBs. This enabled the formation of a financial core in phase 3, which increasingly became central to the transfer of investment know-how from past projects to future investors. Ørsted and the SIBs remained prominent investors both in terms of learning-by-doing and diffusing know-how into the third and fourth phases, but investment and commercial banks became more important know-how creators and diffusers in the fifth phase.

The qualitative research methods provided micro-level insights into how the core of banks became the lead financiers based on their accumulation of investment know-how. While the core banks gradually developed sophisticated financial know-how, they were still constrained by the lack of other capable banks which could contribute to supplying the capital volumes required by the projects that were increasing in size to exploit economies of scale. EIB, KfW, and EKF were important for attracting more private investors. They provided large sums of capital and instilled confidence in private banks, and had an educational effect because of their thorough due



diligence with in-house technical experts who had superior network connections to source experience from past projects (Geddes et al., 2018; Geddes and Schmidt, 2020). In addition, institutional investors with experience from owning stakes in operational parks became confident enough to also take construction risk.

The analysis thereby supported the hypothesis (H3) that entrepreneurial state investors were important for the development of OSW through the creation and diffusion of investment know-how, rather than simply as providers of capital in quantitative terms. The qualitative aspects of the SIBs investing with many co-investors, providing de-risking loans and guarantees, educating inexperienced investors on the characteristics of OSW investment, and signalling trust in an emerging low-carbon technology appeared more important for the maturation of the investor network than the simple quantitative provisioning of loans.

This interactive learning process stood out as an important causal mechanism that helped lower the cost of capital for OSW projects through the 2010s and deploy OSW at an increasing scale. The investment know-how perspective on OSW investment thereby contributed towards a capability-based theory of how green animal spirits arise in investor communities to support the deployment and cost reduction of sustainable technologies.

12.4. Research contributions

This section considers the four contributions of the dissertation. The first two contributions resulted from the analytical synthesis of the answers to RQ2 and RQ3, while the latter two contributions responded to RQ4 and RQ5 (see Figure 12.1 for an overview).

12.4.1. Contribution 1: Renewable energy finance as an evolving complex system

The first research contribution from the analytical part of the dissertation was the analysis of how RE finance operates as an evolving complex system through a longitudinal case analysis of OSW investment. The complexity perspective brought to the foreground how new technologies are deployed by a changing web of heterogeneous actors. It showed how the network evolved

through distinct phases driven by technological breakthroughs, strategic investments, financial innovations, the entrance of new types of investors, self-organised patterns of cooperation, and external changes in the financial and political environment. This contributed towards a capability-based theory of how *green animal spirits* arise in investor networks around new technologies.

12.4.2. Contribution 2: The system-shaping role of entrepreneurial state investors

The second analytical contribution was to address the neglect of the state as “an entrepreneur or direct investor” in RE finance literature (Elie et al., 2021, 10). Statistical studies have identified a tendency for public investors to invest in less mature energy technologies, attract private financiers, and hence promote technological development along their learning curves (Deleidi et al., 2020; Mazzucato and Semieniuk, 2018; Steffen et al., 2020b). This dissertation showed some of the causal mechanisms through which entrepreneurial state investors have had disproportionate impacts on both technological development and the maturation of the wider investor community. They most notably did so by investing confidently through OSW’s technological and financial ‘valleys of death’, and by integrating institutional and less experienced private financiers in the financial network.

More specifically, the impact of the entrepreneurial state investors stemmed from risk-embracing and large-scale investments, their in-house technical expertise, and their wide-ranging network reach, which positioned them as trustworthy and capable investors. This supports the theory that decarbonisation is, to a large extent, occurring through strategic investments that move the technology frontier, rather than by rational firms that optimise their technology use on the margin (Grubb et al., 2017, 2014), why entrepreneurial state investments should to a greater extent be integrated into mission-oriented innovation policy (Kattel and Mazzucato, 2018; Mazzucato and Penna, 2016) and policy mixes for sustainability transitions (Kivimaa and Kern, 2016).

12.4.3. Contribution 3: The role of finance and investment in sustainability transitions research

The third contribution was the theoretical synthesis prompted by the third sub-research question (RQ4): *What is the role of finance and investment in sustainability transitions?* In the theoretical synthesis in chapter 10, it was discussed how the finance and investment dynamics discovered in the analysis of OSW could be integrated into sustainability transitions research which has repeatedly recognised the need for a better account of how these economic factors interact with other main elements in deep decarbonisation transitions (Foxon, 2011; Foxon et al., 2013; Köhler et al., 2019; Naidoo, 2020). The complexity analysis further advanced Hall et al.'s (2017) theory of energy finance as an adaptive market and showcased how finance, in accordance with Geddes and Schmidt's (2020) theory of finance as a technology-constraining regime, operated and evolved along the lifetime of OSW.

In line with hypothesis 4 (H4), I concluded that finance and investment should be integrated as a co-evolutionary element in Foxon's (2011) co-evolutionary framework for explaining how institutions, technologies, and business strategies influence and adapt to each other (Figure 10.1). OSW investment was influenced by previous wind technologies, de-risking electricity frameworks and climate policy targets, and previous financial business strategies that were compatible with OSW. OSW investment, in turn, led to technological innovation, changed transition scenarios, re-risking of electricity markets, green lobbying, and strategic pivots by large businesses into OSW.

The insights from the co-evolutionary perspective were enhanced by considering the finance and investment domain as an evolving complex system with separate events and dynamics at the micro-, meso-, and macro-levels. This framework was helpful for understanding at what levels of finance the co-evolutionary influences occur. The analyses supported Geddes and Schmidt's (2020) policy proposition that SIBs could be used to change the financial sector through learning processes. It also added a complementary perspective on how SOEs can be a main source of early investment know-how that can diffuse through the network.

Finally, at a more structural level, the analysis showed how financialisation of the financing and ownership of sustainable technologies was an emergent property of the current form of industrial

policy-based decarbonisation. This tendency simultaneously changed the political economy of climate change by enhancing the political support from financial investors for a de-risked and financialised transition pathway (Gabor, 2021; Newell, 2019). This reinforcing feedback between financialisation of technology deployment and climate politics is positive news for more rapid deployment of sustainable technologies, but sustainability researchers should reflect on the equity impacts of this pathway and alternative institutional arrangements that could change who captures the value of the green transition.

12.4.4. *Contribution 4: Governance by investing*

The fourth sub-research question (RQ5) inquired about the policy implications of the analytical and theoretical conclusions: *How can insights from the complexity analysis motivate new ways of governing financial systems to support sustainable innovation and transition of economic provisioning systems?* The policy synthesis in chapter 11 devised a taxonomy of three modes of green finance governance. *Governance by market efficiency* focuses on improving corporate disclosure of carbon information to financial markets and is currently dominant in the policy domain. *Governance by credit guidance* contains more coercive regulations on the purposes of private credit creation and has been advocated by academic researchers and think tanks. Based on the complexity framework in the dissertation, I propose a third mode: *governance by investing*. In line with hypothesis 5 (H5), governance by investing addresses the lack of attention to investor capabilities in both of the alternative frameworks. It proposes to strategically use SOEs and SIBs to advance investment know-how and early technology learning curves while seeking to diffuse the new capabilities to private and civic investors through co-investment networks.

Governance by investing raises new demands on the governance of SOEs and SIBs so they can better contribute to public policy goals but also benefits from their arm-length distance from policymakers. For SOEs, the OECD's 'best practice' governance manual promotes a non-interventionist existence of SOEs that prepares them for privatisation. Instead, selected SOEs could be given *technology frontier investment mandates* that require them to undertake

investments in the deployment of technologies at the technological frontier in their field (Grubb et al., 2014). The governance of SIBs presently appears more promising, but there is much attention to the mobilisation of private capital – as if credit was a physically scarce resource rather than balance sheet entries – and to promote knowledge of green taxonomies (liabilities) rather than of green technologies (assets). SIB governance should focus more on developing dynamic capabilities through investments in their in-house technical expertise and the use of their investment networks to function as know-how diffusing hubs for private investors with less experience.

12.5. Implications for further research

12.5.1. The complexities of renewable energy finance

To advance the complexity approach to RE finance, the internal and external validity of the analytical results should be studied further. To get a clearer sense of the causal mechanisms, more qualitative research should be undertaken, including interviews with private bankers and SIB officers with experience from OSW investment. Besides the Danish government's exogenous initiation of the growth phase characterised by utility-scale parks, it was not possible in my research to evaluate to what extent the investment behaviour of the SOEs and SIBs was exogenous, i.e. determined by politics, or endogenous, i.e. adaptive responses to opportunities in their business environment based on initial know-how advantages. For instance, KfW's official programme to support OSW in 2012 came after KfW was already a core financier of OSW and remained a secondary instrument for funding OSW (interview 2). This proactive role suggests that the right governance mandates can be more impactful than specific policy programmes.

Moreover, comparative research designs that better account for how electricity market frameworks enabled particular projects could improve our understanding of how price incentives interact with the evolution of investor capabilities. In addition, quantitative studies using statistical network models could contribute to quantifying the causal dynamics identified in this

dissertation. Preliminary research for this dissertation used a ‘relational hyperevent model’ (Lerner et al., 2021; Lerner and Hâncean, 2021; Lerner and Lomi, 2022) to examine network effects, such as preferential attachment, and the institutional effect of SIB participation on the formation of investment partnerships, but was left out because of the space limitation.

The external validity of the results should be further examined by considering whether the complexity approach and the role of entrepreneurial state investors have similar explanatory power for other RE technologies. A technology typology was used to group sustainable technologies, which suggested that the conclusion may be more relevant for the next generation of sustainable technologies. But such a comparison should also account for the changes in the political economy of climate change that, in part, were caused by the development of the first generation of renewable energy technologies.

12.5.2. Theorising the role of finance and investment in sustainability transitions

The theoretical synthesis has opened new space for sustainability transitions researchers to examine the role of finance and investment in co-evolution with other elements. The co-evolutionary three-level framework proposed in this dissertation (Figure 10.2) could be applied to the development of other technologies and for analysing how the financial sector constrains and enables change in the other transition elements. Empirical research could analyse in greater detail how finance co-evolves with technology, policy frameworks, and business outcomes, for instance, in a ‘multiplex’ network model with different layers of interactions among the actors. More qualitative studies could use process tracing to examine how the creation and financialisation of sustainable energy assets have changed the political behaviour of large companies and financial institutions in relation to climate change policy.

12.5.3. Towards a public investment approach to green finance governance

Finally, the proposition to use *governance by investing* in advancing sustainability transitions calls for further studies regarding the capability- and network-based causal mechanisms and how



to integrate financial governance in a wider policy mix (Grubb et al., 2017; Kivimaa and Kern, 2016; Rogge and Reichardt, 2016). It remains unanswered how governance by investing can be combined with governance by market efficiency and by credit guidance. It appears more compatible with credit guidance policies (Kedward et al., 2022) because of the common problem recognition that disclosure of carbon exposure and carbon price adjustments are insufficient to make the financial sector sufficiently supportive of the green transition. While governance by investing seems less compatible with the concept of market efficiency, the efficiency concept's associated market-fixing framework is amenable to more interventionist actions than merely information provisioning if it is framed accordingly (Mazzucato and Penna, 2016), e.g. as seen with the creation of the UK GIB that was framed as a fix to a market failure in financial markets (Geddes et al., 2018).

Empirically, it would be beneficial to expand the existing research on national development banks (Griffith-Jones and Ocampo, 2018; Mazzucato and Penna, 2016; Mertens et al., 2021b) by examining the systemic impact on the investor networks around the targeted technologies. The potential for SOEs to act as “knowledge-explorer agents” also remains underexamined (Benassi and Landoni, 2019; Tönurist and Karo, 2016).

Lastly, the analysis of the governance constraints on the entrepreneurial functions of SOEs and SIBs warranted a critical examination of the governance standards promoted by the OECD and other multilateral organisations. Too high a priority is assigned to not disturbing markets, and too little attention is given to the potential for advancing technological change. The OSW case displayed the potential of SOEs and SIBs for advancing sustainable technologies across the technological and financial valleys of death. This history may inspire future technological trajectories from cradle to a mainstream asset class – or beyond.

* * *

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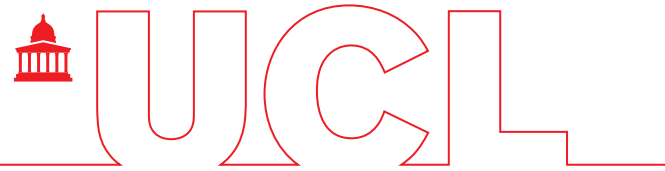


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Appendices

Appendix A: The cost of electricity and the role of finance

The cost of electricity and finance as an input

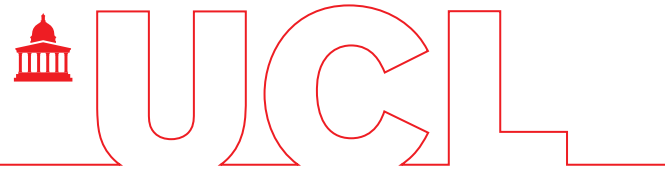
This section provides an introduction to analysing the cost of producing electricity. A common measure for comparison of the cost of providing electricity with different technologies is the levelised cost of electricity (LCOE), where the cost of capital is an important component. LCOE refers to the cost “that would recoup all costs, including return on investment but excluding transmission, distribution, and grid services” (Krupa and Harvey, 2017). It is the sum of costs, including the required return on equity, over the lifetime of a project divided by the sum of electricity produced over the lifetime of the project. It thus reflects the price where the project generates the required return on investment used as discount rate.

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (1)$$

where:

- I_t = Investment in year t (\$/kW/year)
- $O\&M_t$ = Operations and maintenance (\$/kW/year)
- F_t = Fuel cost (\$/kW/year)
- E = Electricity output (kWh/kW/year)
- r = discount rate
- t = lifespan (years of the project)

The cost of capital is the applied discount rate r in the formula. It is used to discount future costs and electricity production to account for the fact that earlier costs need to be financed in the meantime before future revenues can service the return on debt and equity.



To obtain a clearer sight on the importance of the cost of capital, the investment cost can be annualised to show how much must be paid each year to pay off the principal and interest on the diminishing stock of debt. This is also known as the *cost recovery factor* (CRF).

$$CRF = \frac{i}{1 - (1+i)^{-N}} \quad (2)$$

where:

N = lifespan of the project (years)

i = rate of interest

By assuming no annual variation in O&M cost and electricity generation and adding insurance cost component (INS), LCOE can be stated on an annual basis:

$$LCOE = \frac{(CRF + INS) * I_0 + O\&M}{E} \quad (3)$$

Since the principal must be paid off, the CRF can be significantly larger than the rate of interest for shorter project life spans. For instance, at a three percent interest rate, the CRF of a 20-year project is 6,7 percent (Krupa and Harvey, 2017). At longer maturities, the CRF remains larger than the cost of financing, but the difference is smaller since the repayment schedule is stretched over longer time. However, projects with longer lifespans may face a higher interest rate due to uncertainty and liquidity premium. At higher rates of interest, the spread to the CRF diminishes since interest cost becomes a larger part of the project's total capital expenditure.



WACC: The weighted average cost of capital

A given investment project requires external finance if the developer cannot or does not want to finance the project out of retained earnings. In that case, the external finance adds a cost of capital to the project⁶⁴. Following Krupa and Harvey (2017), the *weighted average cost of capital* (WACC) for an energy project consists of combination the cost of the equity and debt mix used to finance the project. Equity entails direct external co-ownership of the project while debt is a fixed cost liability, the servicing of which is prioritized over payments to equity holders. The specified rate of interest on debt will therefore often imply a lower cost of capital due to the higher certainty of being repaid. Furthermore, in many jurisdictions the cost of debt service is deductible against taxable income, leading to a lower effective cost of debt finance. The WACC therefore is defined as the cost and share of equity finance plus the cost and share of tax-adjusted debt finance:

$$WACC = (C_E * P_E) + (C_D * P_D * (1 - t)) \quad (4)$$

where:

C_E = Cost of equity (% per year)

P_E = Percentage of equity finance (0-100)

C_D = Cost of debt finance (% per year)

P_D = Percentage of debt finance (0-100)

t = tax rate

The cost of finance reflects the prevailing risk-free rate and a component reflecting the risk of the project. While the interest rates on debt instruments are generally fixed and have low risk, the return on equity is less certain since the equity holders is paid out of the residual the residual

⁶⁴ If the funds for investment are sourced from sales, the proceeds could also alternatively have been invested elsewhere and thus add an opportunity cost.



income not paid to debt providers. Therefore, a higher debt-to-equity ratio lowers a project's WACC.

Financial models for valuing assets

Investors can use various techniques to gauge the value of owning a potential asset. The *capital asset pricing model* (CAPM) is a prevalent model used to assess the fundamental value of an asset by comparing expected future cash flows with the risks involved with owning the asset. It formalises a distinction between asset-specific risk and market risk stemming from general economic conditions. Market risk cannot be escaped while specific risks are diversifiable and insurable. Investors seek to be compensated with the risk-free rate (often described as the time value of money) and a risk premium depending on the particular investment. Krupa and Harvey (2017) define CAPM as:

$$C_E = R_f + B_a(R_m - R_f) \quad (5)$$

where:

C_E = Cost of equity

R_f = risk-free rate of return in the market (%)

B_a = Beta, a risk weighting factor of the volatility of the investment's return relative to the market. (1 = same risk as market. 1,1 = 10% more risk than market)

R_m = Market rate of return of the investment in question

$(R_m - R_f)$ = The expected risk premium attached to the equity (above the risk-free rate).

Consequently, the cost of capital is determined based on perceptions of risk and future returns. A poor or missing track record is therefore likely to result in an elevated cost of capital when risk premiums are determined. In theory, the resulting cost of capital should be project-specific, yet



it has been shown that cost of capital for the same type of project is often investor-specific (Helms et al., 2020).

WACC gives a perspective on the liability side of a firm or project's balance sheet stating what it costs to fund the existing or planned assets. Turning to the asset side of the firm, investors predominantly determine whether to invest and under what conditions with two related valuation techniques (following Helms et al., 2020). By calculating either the net present value (NPV) or internal rate of return (IRR) metric to discount future cash flows, a firm can apply either a discount rate or a hurdle rate, respectively, in the process of deciding whether to undertake a specific investment. The firm's WACC would be a background variable determining whether an investment is worth undertaking.

When estimating a project's net present value, anticipated future cash flows are discounted with a selected discount factor and subtracted the upfront investment cost. If the result is an expected surplus, the implied decision rule calls for the project to be undertaken.

$$NPV = \sum_{t=1}^N \frac{PFCF}{(1+i)^t} - Investment_{t0} \quad (6)$$

where

PFCF = Project free cash flow to be distributed to creditors and equity holders.

The second valuation method is to calculate the internal rate of return (IRR), which is a measure of profitability that can be compared across potential investments. The IRR is the interest rate needed in equation 4 to return a NPV of 0. The IRR is the rate of interest, which equates the discounted cash flow with the initial investment outlay.

$$Investment_{t0} = \sum_{t=1}^N \frac{PFCF}{(1+IRR)^t} \quad (7)$$

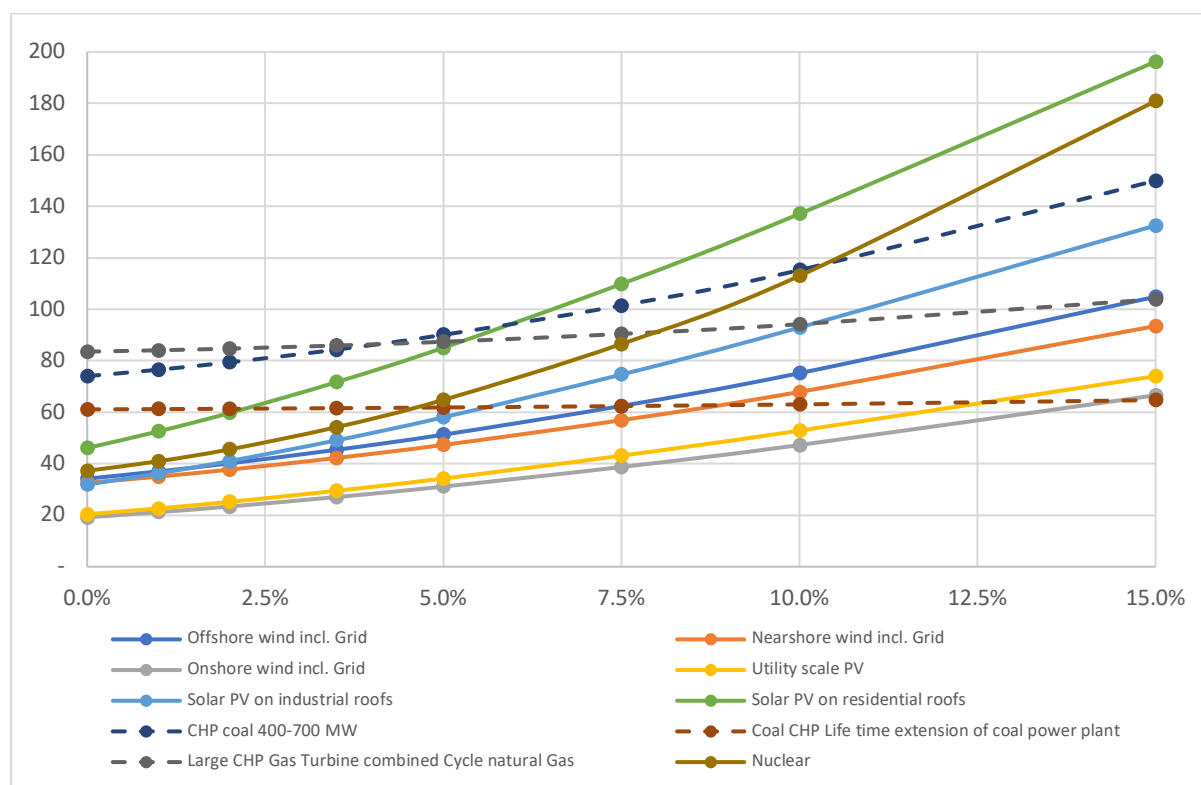
IRR indicates how large a rate of return the asset can be expected to generate. Consequently, IRR can be used in combination with a 'hurdle rate' for investment decisions. If the $IRR > \text{hurdle rate}$, the investment would normally be deemed worthwhile. The hurdle rate can be based on the investor's WACC, as the return on the assets would then generate profits (depending on administrative costs).

The impact of the cost of capital on the cost of different electricity technologies

Taking a cross-technological perspective, we can see the interest rate-sensitivity of renewable energy technologies compared to fossil-based technologies. The Danish Energy Agency provides a levelized cost of electricity calculator backed by a continually updated technology database. By inputting various interest rates, we can get a cost of electricity-curve for the energy-generation technologies that vie to dominate the future energy mix. Figure 0.1 shows how the price of electricity needed to pay for the cost of generation is much more sensitive to the cost of capital for renewable technologies. A utility scale PV installation has a levelised cost of electricity of 25€ per MWh at 2% cost of capital, 34€ at 5%, 53€ at 10%, and 74€ at 15%. In other words: higher interest rates, higher cost of electricity. While cost of solar electricity would triple, power cost from a new gas-fired power plant would only increase by 24% due to the lower CAPEX-OPEX ratio. We therefore see why renewable technologies have a clear edge at low cost of capital, while their competitiveness deteriorates at higher interest rates⁶⁵.

⁶⁵ The paragraphs accompanying Figure 0.1 and Figure 0.2 have already been published as a blog where I was the lead author (Voldsgaard et al., 2022).

Figure 0.1: Cost of electricity production at different interest rates (2020-EUR/MWh)



Source: Own calculation based on Danish Energy Agency's (2022) LCOE tool.

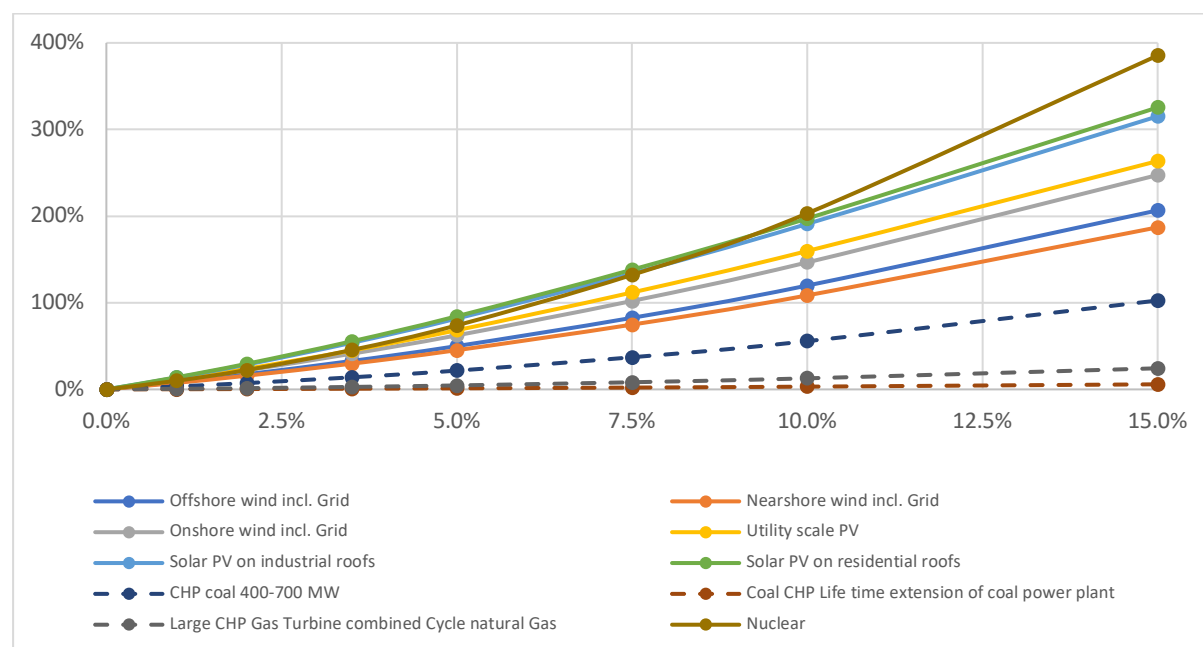
Note: Levelised cost of electricity (2020-EUR/MWh). Fossil-based technologies have dashed lines.

In Figure 0.2, we see how the LCOE for each technology evolves relative to a hypothetical situation with no cost of capital, that is with only the cost for installation, operation and maintenance etc.

Moving from 0-5% increases the cost of electricity from offshore wind by 50%, 62% for onshore wind, 68% for utility scale solar PV, 82-84% for solar PV on industrial and commercial roofs – while only becoming 5% more expensive for building new gas-fired power plants. Again – most of the lifetime expenditure lies in sourcing gas inputs. Moving from 5% to 10% in cost of capital would increase the cost of electricity from offshore wind by another 47% (compared to producing with 5% cost of capital, or 120% above the cost at 0% cost of capital).

The cost of onshore wind and utility scale solar PV would rise another 52-54%, 60% extra for solar PV on industrial and commercial roofs – *while only becoming 8% more expensive for building new gas-fired power plants*. Solar on residential roofs is especially disadvantaged due to higher base costs, which could limit the civic engagement in the transition.

Figure 0.2: Change in LCOE (%) from changing interest rates



Source: Danish Energy Agency (2022)

Note: Levelised cost of electricity (2020-EUR/MWh). Fossil-based technologies have dashed lines.

While a lower lifetime cost is a strong competitive advantage, renewable technologies are also challenged by their inflexibility to produce at times of high electricity prices like gas-fired power plants. Indeed, the synchronised production patterns of each renewable technology lowers the capture price of renewable generators – which is good for energy users but problematic for producers with a high cost of capital. The intermittency challenge can be ameliorated by integrating flexible technologies into the energy and production systems, but the economic viability of these solutions rely on low cost of electricity and capital.

LCOE and WACC in offshore wind

Table 0.1 shows the results from chapter 5 from analysing the impacts of different WACC assumptions in IRENA's reports on the LCOE of different RE technologies.

Table 0.1: LCOE differentials for offshore wind under different WACC assumptions

2020 USD/kWh	Constant WACC (IRENA, 2020)	Downward WACC-trend from 2010 (IRENA, 2021)	Country-specific WACC (IRENA, 2022)
Max. LCOE (year)	0.185 (2014)	0.180 (2007)	0.209 (2007)
Min. LCOE (year)	0.104 (2003)	0.084 (2020)	0.074 (2021)
LCOE in 2019	0.116	0.093	0.085
Change in cost from max. to 2019	-37%	-48%	-60%
Change in cost from max. to min.	-37%*	-53%	-65%

Note: *Lowest cost achieved after the maximum cost. Source: Own calculations based on IRENA (2022a, 2021c, 2020b).

Appendix B: Theoretical impacts of public sector investment in renewable energy

Table 0.2: The theoretical impacts of public sector investment in renewable energy

Functionality	Description	Source
Investor system impact		
Education of the financial sector	Private investors learn by co-investing. Expertise generated by public sector investors get diffused in the investor community via co-investments. Public sector investors can develop new standardised risk assessment tools and codified knowledge to by-pass lack of knowledge. On-lending via private banks or technical assistance schemes can be diffusion channels.	Geddes and Schmidt (2020) Geddes et al. (2018) Stiglitz and Greenwald (2014)
Building track-record	Sustainable energy technologies get more chances to mature through learning-by-doing. The investor community get novel insights into the risk-return conditions at the technological frontier. Both effects lead to crowding in of private investors over time.	Geddes and Schmidt (2020) Geddes et al. (2018) Mazzucato and Semieniuk (2018) Griffith-Jones et al. (2018) Deleidi et al. (2020) Benassi and Landoni (2019) Steffen et al. (2020)
Trust signalling	Public entities that develop investment expertise at the technological frontier can attract private co-investors to concrete projects by virtue of the know-how-based trust in the project they signal to less capable private investors. Insofar as the financial sector adapts to a ‘follow the SIB’ heuristic, trust signalling can also be said to have a system impact. Furthermore, targeted investment programmed can also be part of implementing a long-term vision for industrial policy, which acts as focal point for private investors.	Geddes and Schmidt (2020) Geddes et al. (2018) Mazzucato and Penna (2016). (Chang, 1994)
Industry coordination	By approaching projects and firms as a potential co-investor, public entities can get a better view of the barriers or missing parts in the innovation system, e.g. product guarantees and insurance products, and at the same time act to change this based on a public purpose mandate.	Geddes and Schmidt (2020)
Perception change	Mainstreaming of climate change considerations and associated principles, such as ‘do no harm’, in financial industry.	Griffith-Jones et al. (2018)



Market size impact	By investing, the public entities contribute to the downstream demand for new renewables technology, thus advancing the movement down the learning curve in component, installation and finance industries.	Egli et al., (2018); Lafond et al. (2018)
Project impact		
Crowding in by de-risking	Reduce the investment risk for private parties, by absorbing earlier losses in 'junior tranches' of a project's debt structure.	Ameli et al. (2019) Griffith-Jones et al. (2018)
Due diligence	Reduce transaction costs by decreasing the need for project and risk assessment for the private party. Relies on trust in public capabilities.	Ameli et al. (2019) Geddes et al. (2018)
Project pooling	Structures RE projects in pools that receive financing from the same fund. This can deliver 'size transformation' that circumvents the mismatch of project sizes with the desired transaction sizes of private. It provides both transaction cost reduction and risk diversification. It can also allow capital to be aggregated from numerous smaller sources.	Ameli et al. (2019) Geddes and Schmidt (2020)
Technical assistance	To meet due diligence requirements and attract required finance.	Geddes and Schmidt (2020)

Note: Own categorisation with inspiration from the causal model by Geddes and Schmidt (2020, 9)

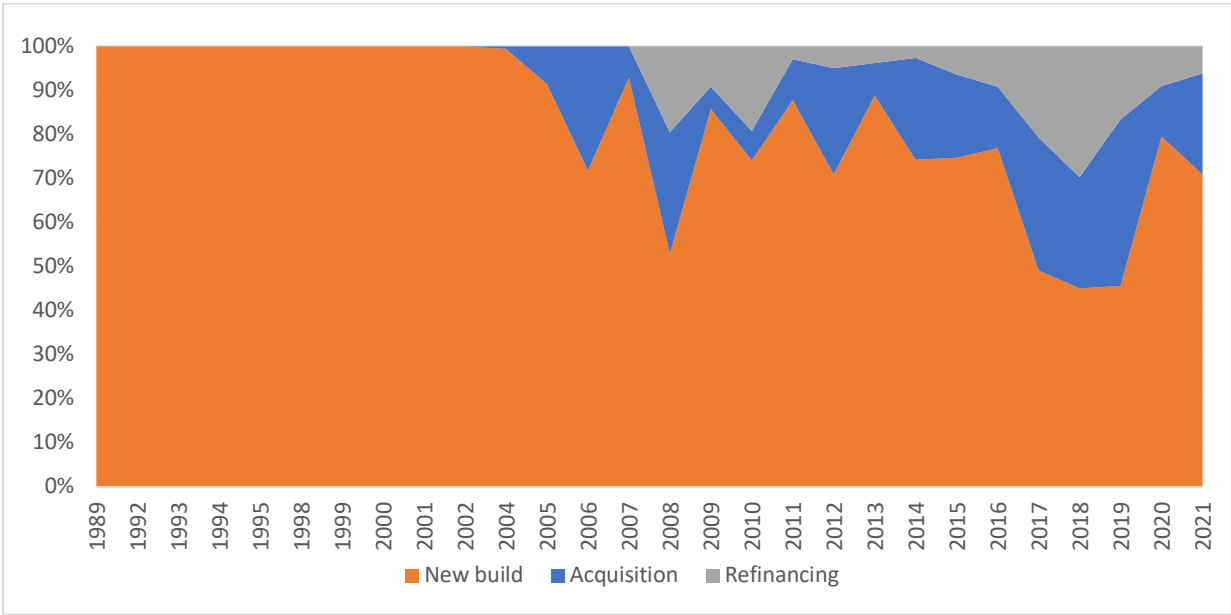
Appendix C: Semi-structured interview guide

Table 0.3: Semi-structured interview guide

Subject	Questions
Intra-organisational learning	
	What learning processes have been most decisive for your success as renewables financier?
	What internal investments in capabilities have you undertaken?
	What are the most important skills and abilities for an RE investor?
	What are the most important risk factors?
	How do you handle technology risk? (prefer proven tech? Intel?)
Learning from others	
	What have you learned from others when co-investing?
	How did that learning take place?
	What is the importance of networks in this business?
	What has been the role of state-owned actors? (SIBs, SOEs)
	Can learning take place via acquisitions? (or refinancing?)
Others learning from you	
	What did others learn from you?
	How did that learning occur?
The renewable finance market	
	Past and present: Adaptation, learning, uncertainty
	What is your role in the financial ecosystem in RE?
	How has the system evolved since you started?
	Future: Liberalisation and cannibalisation of electricity markets.
	How will renewable energy financing change when policy price subsidies disappear while RE comes to dominate electricity production?

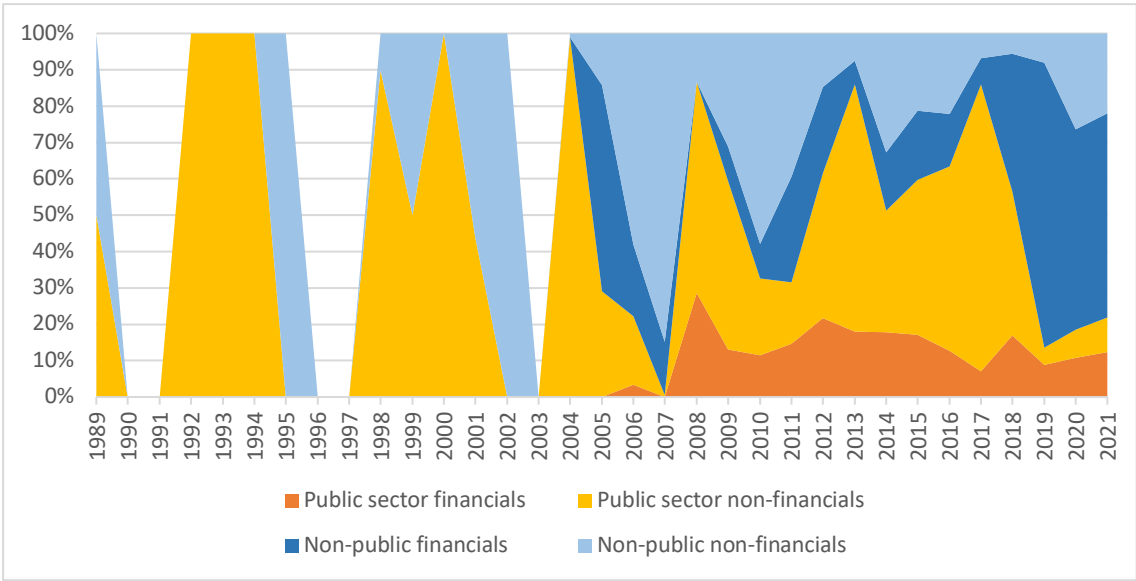
Appendix D: Offshore wind finance statistics

Figure 0.3: The composition of the types of financing



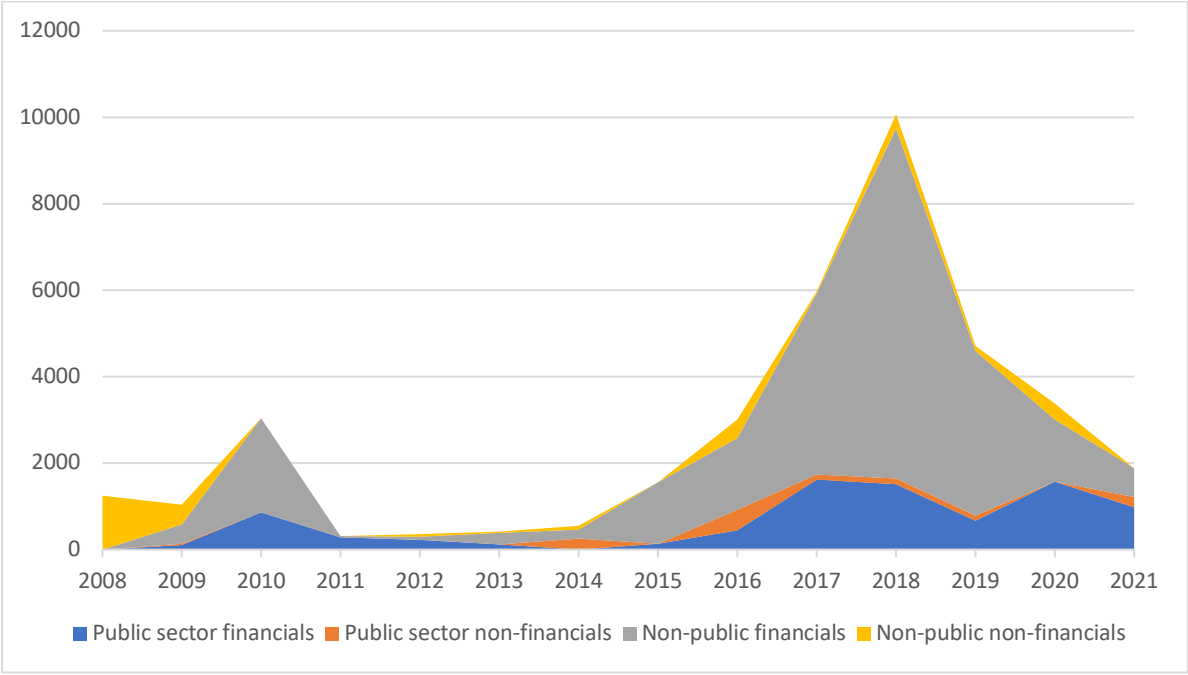
Source: Dissertation database

Figure 0.4: The distribution by sources of annual primary financing



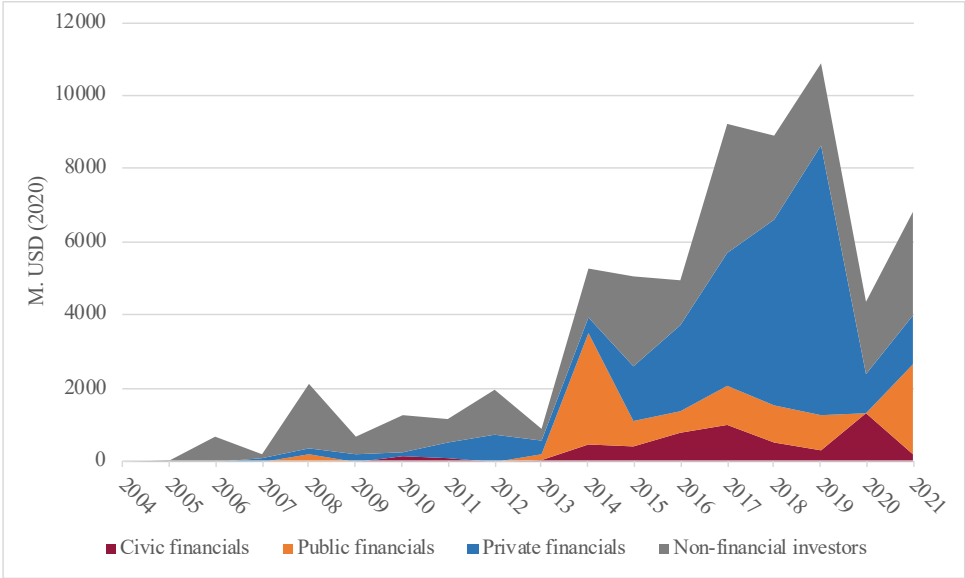
Source: Dissertation database

Figure 0.5: The sources of finance for refinancing offshore wind projects



Source: Dissertation database

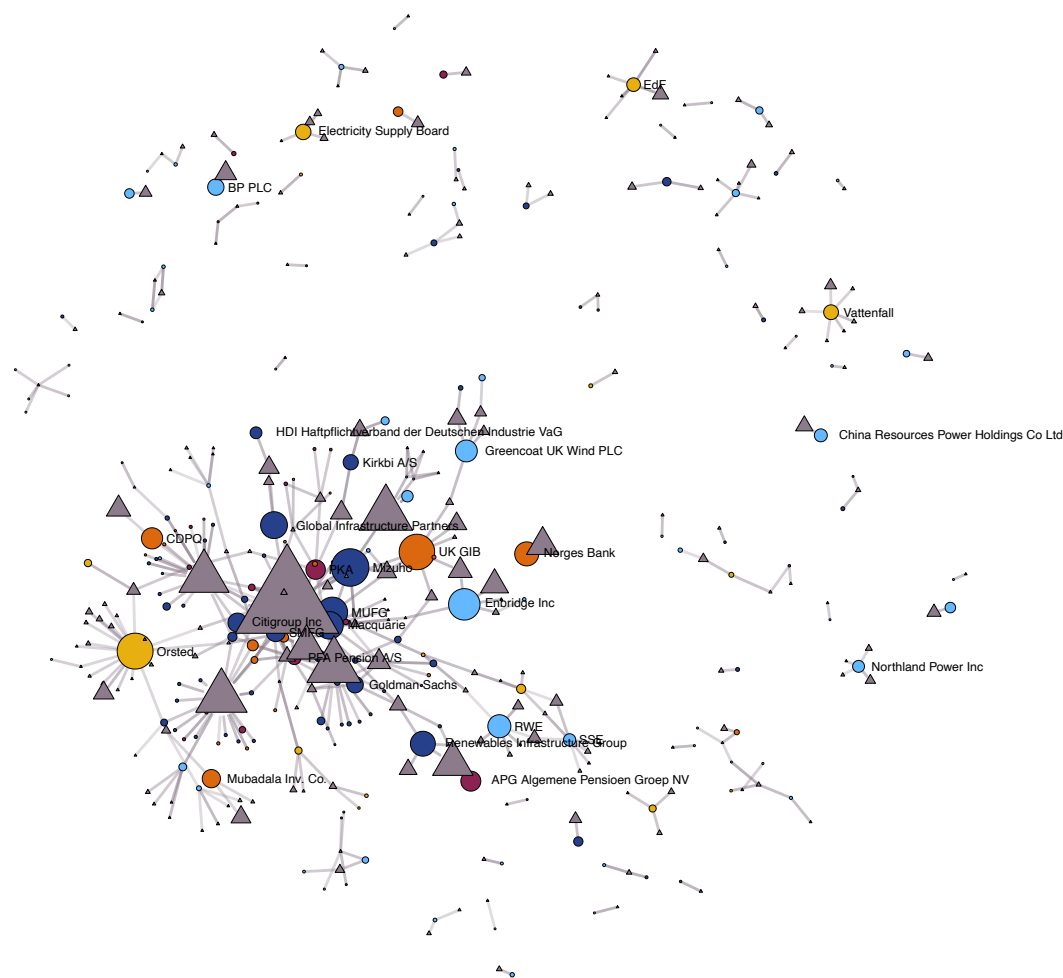
Figure 0.6: Acquisition finance by source



Source: Dissertation database

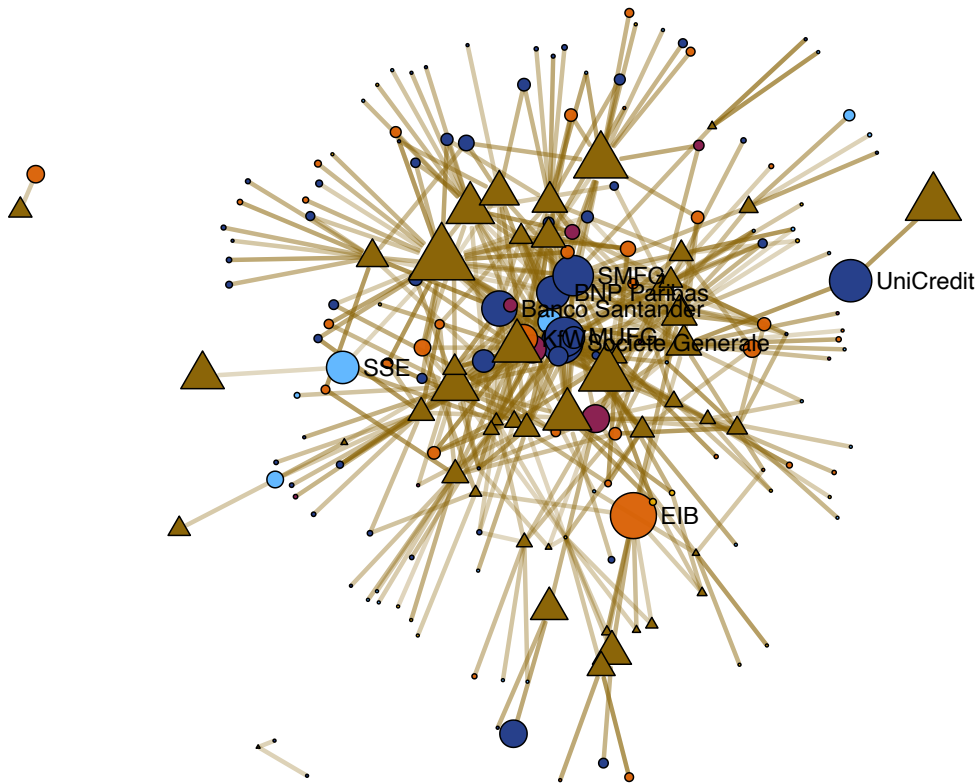
Appendix E: Offshore wind finance networks

Figure 0.7: The full-period network of acquisition finance



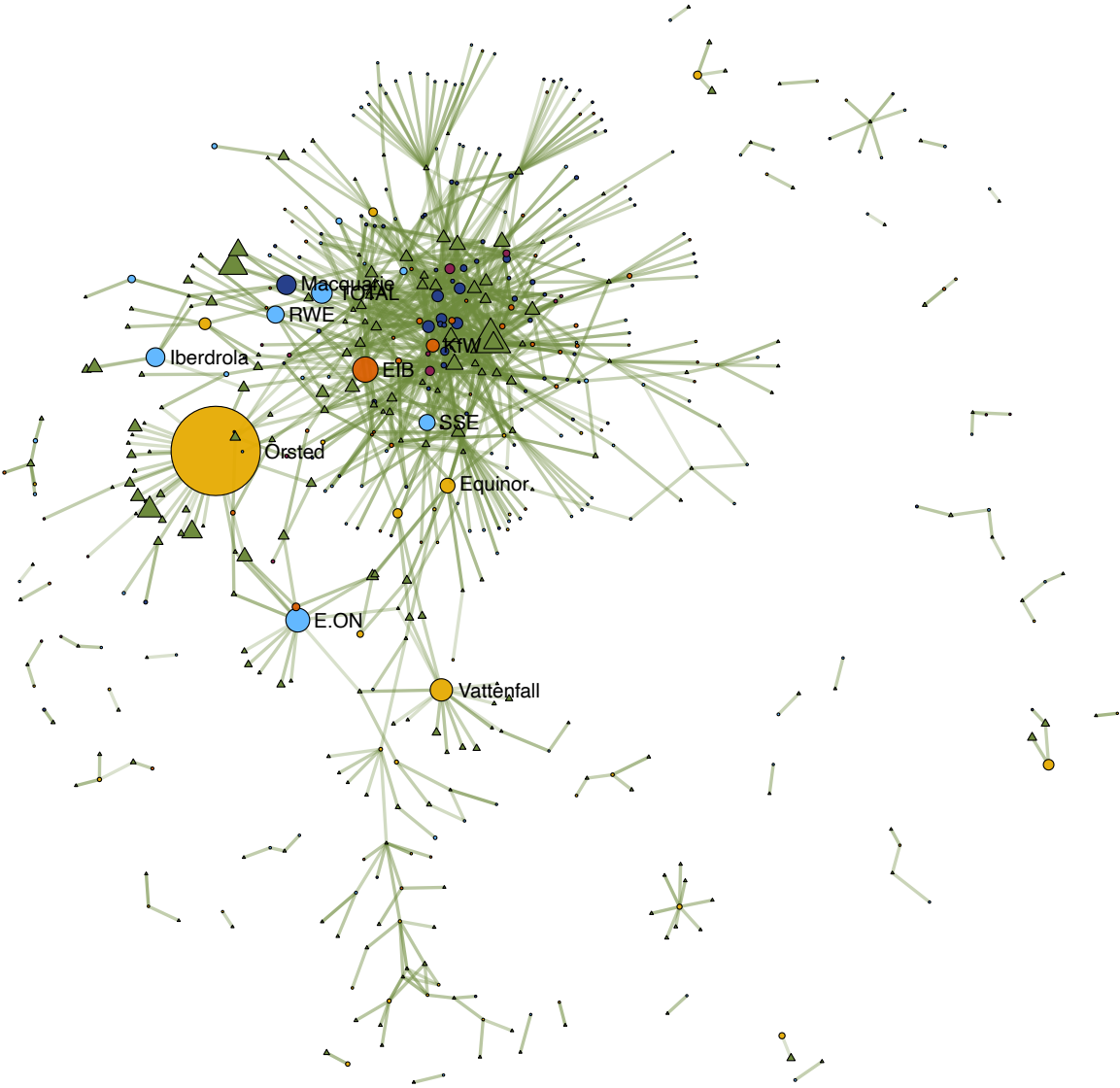
Source: Dissertation database

Figure 0.8: The full-period network of refinancing



Source: Dissertation database

Figure 0.9: The full-period network of primary financing



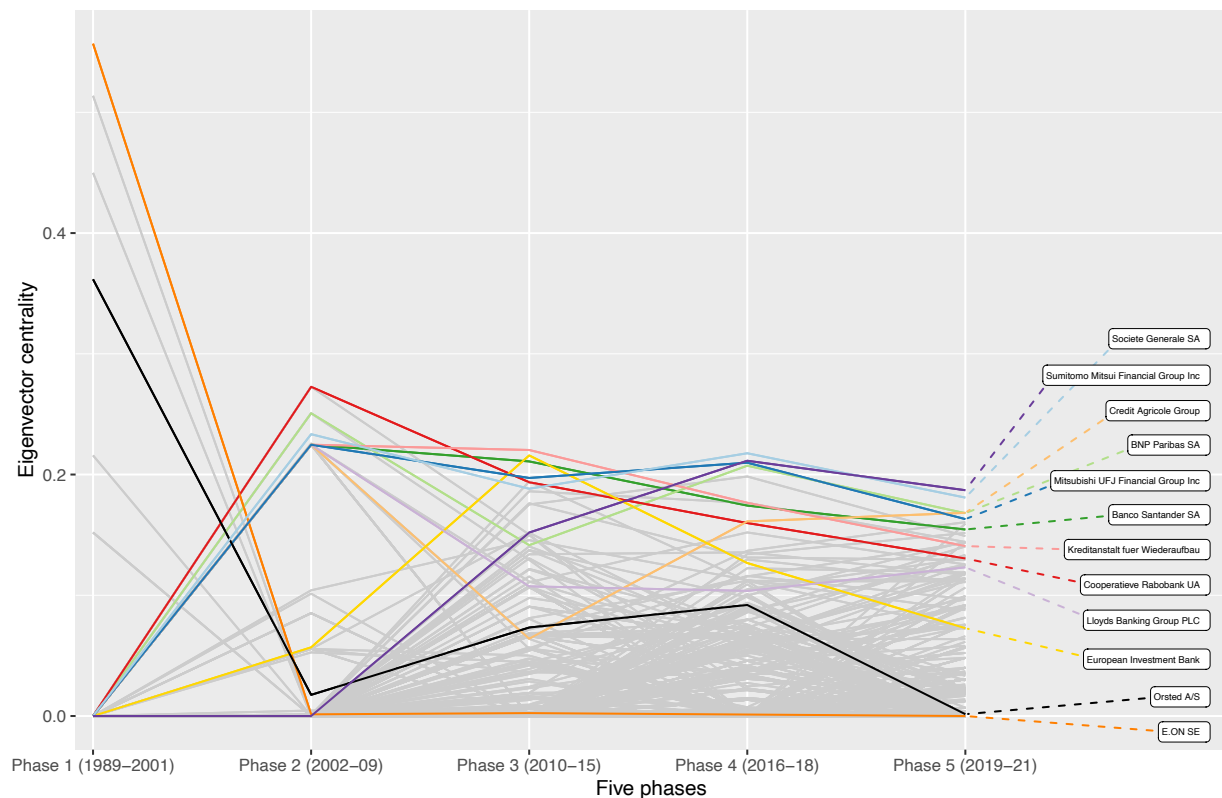
Source: Dissertation database



Appendix F: Offshore wind network statistics

The eigenvector node centrality scores in Figure 0.10 indicate which investors that are connected via OSW investments to other investors with many investment ties. It answers who are most connected to the most well-connected influential investors in the five phases of the network. The ten investors with highest average scores are highlighted with colours and Ørsted and EIB are added in black and yellow. It is notable from the upper coloured lines how a large share of the most well-connected investors in the last two phases were also well-connected in phase 2 and 3. In a world of rational calculus of risks and rewards of offshore investments we would expect this pattern to be much more volatile as different investors take advantage of the opportunities for financing OSW. The most well-connected investors in phase 2 were the financials who participated in Rabobank and Dexia's project financing. Besides the two utilities in phase 1, Ørsted and E.ON., the most volatile investors in terms of connectivity were the EIB (2nd in phase 3) and Sumitomo Mitsui who had top-two eigenvector centralities in phase 4 and 5, but none in phase 1 and 2. The GFC is reflected by the fact that Credit Agricole, Lloyd's and BNP Paribas fall markedly in phase 3, while EIB and KfW countercyclically become the two most central actors.

Figure 0.10: Eigenvector centrality of offshore wind investors 1989-2021

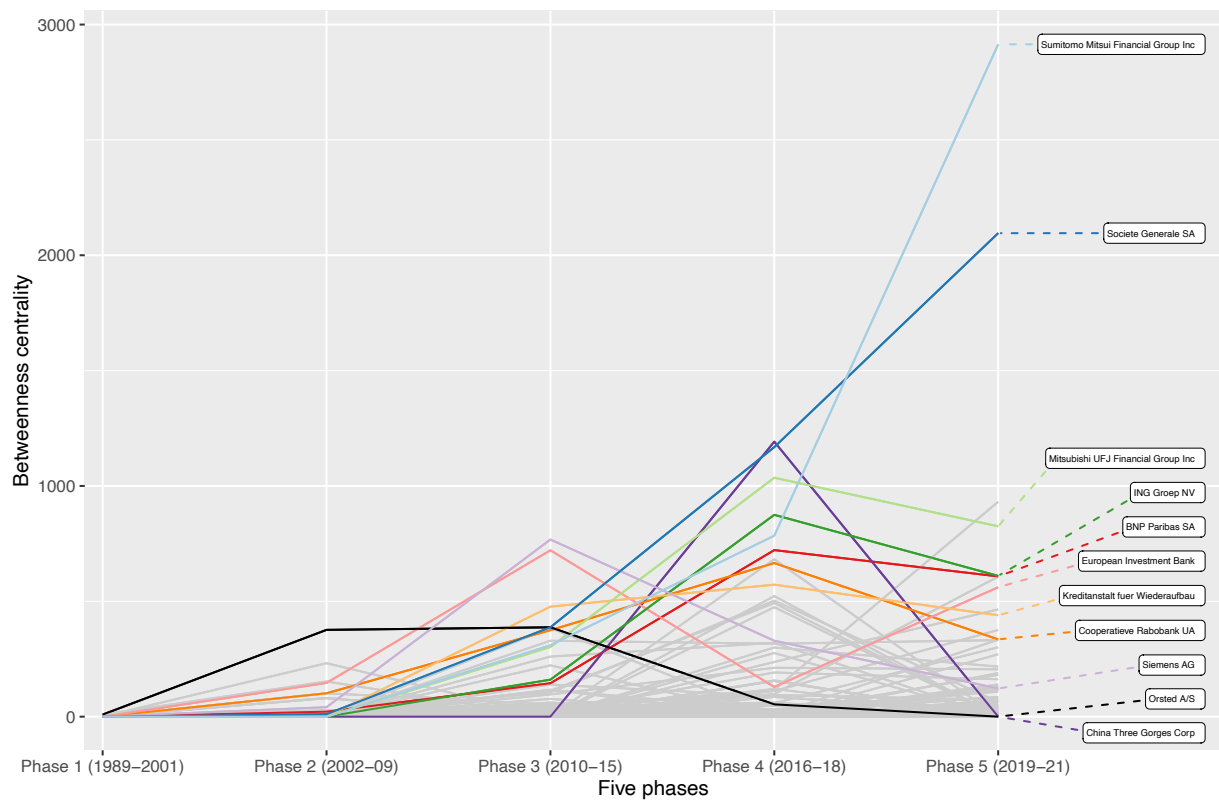


Note: Eigenvector centrality expresses the importance of each investor's connected investors normalised by the size of the network. Investors who are connected to investors with many investor-relationships relative to the network size display higher centrality values. The lines are coloured for the ten investors with highest average eigenvector centrality. In addition to the top ten, Ørsted A/S is highlighted with black, and the European Investment Bank is highlighted with yellow due to their roles as important investors.

Figure 0.11 displays the betweenness centrality of the investors in the network and tells a different story with some similarities. The betweenness centrality of a particular node counts the number of shortest paths between all pairs of investors that must cross the node. While the eigenvector centrality measures if a node is connected to the more attractive actors in the network, betweenness centrality better reflects the node's position in the structure of the network and thereby is relative potential for receiving more information flowing through the network (Freeman, 1978). An investor could have few connections, but bridge two densely connected sub-networks with few connections across and thus have informational superiority. Unlike with eigenvector centrality, we see how Ørsted and the EIB were among the most central early

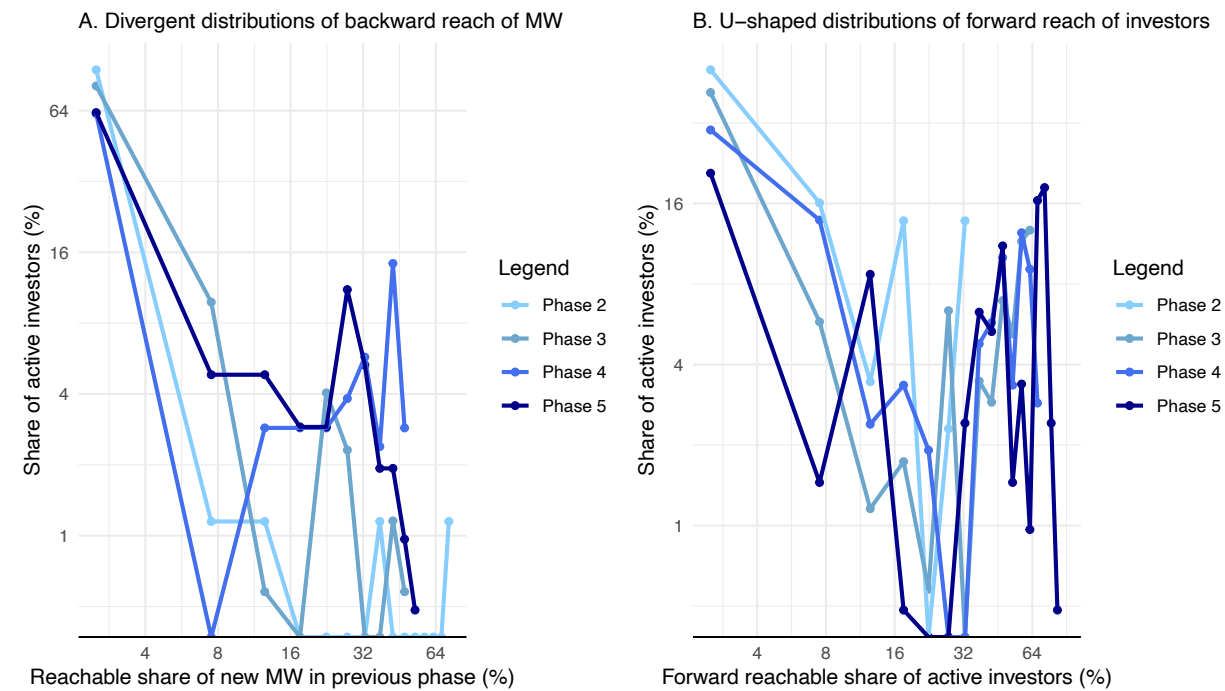
investors. This measure corroborates the observation that the EIB and KfW were among the most central investors in phase 3, albeit with Siemens most centrally positioned.

Figure 0.11: Betweenness centrality of offshore wind investors 1989-2021



Note: Betweenness centrality calculates the number shortest paths between all investors that pass through a particular investor in the network. The lines are coloured for the ten investors with highest average betweenness centrality. In addition to the top ten, Ørsted A/S is highlighted with black.

Figure 0.12: Distributions and forward and backward reach



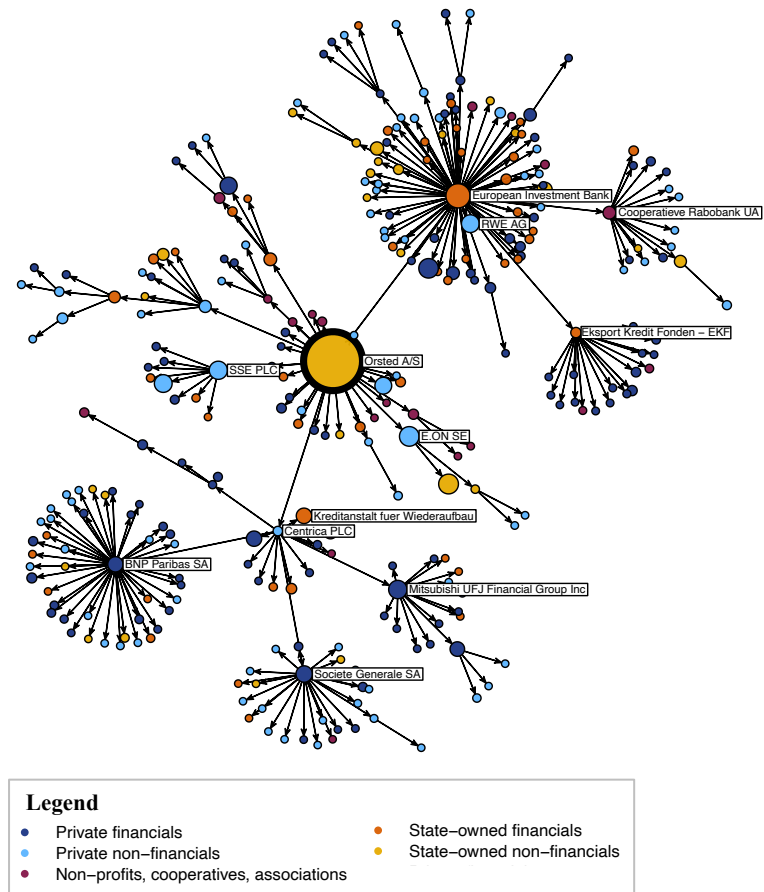
Appendix G: Lead investor analysis of Ørsted's forward network reach

In chapter 5, Ørsted stood out as the largest investor in phases 1, 2, and 4 and among the largest investors in phase 2. By involving other investors in the financing or development of these projects, Ørsted's unique experience from learning-by-doing and as a shaper of the supplier ecosystem (Voldsgaard and Rüdiger, 2021) could be transferred and shared in the investor network. Figure 0.13 shows Ørsted in the middle of a network consisting of the earliest forward path of arrival to all nodes that it

can potentially reach via co-investments in parks⁶⁶. This means that while Ørsted could potentially reach another investor in a myriad of possible paths and at different times, only the path that reaches the other node at the earliest possible time is shown. Given Ørsted's role as an early pioneer in offshore investment, the earliest paths are particularly useful for showing Ørsted's impact. However, it does not express well how Ørsted's know-how generated in the later phases has been diffused.

Ørsted's earliest paths contain direct connections to a variety

Figure 0.13: Ørsted's forward reachable set via paths of earliest arrival



Note: The graph displays the path of earliest time of arrival from Ørsted to all other nodes within its reach, while respecting the timing of interactions. The graph does not necessarily show the shortest paths between the nodes, e.g. if Ørsted interacts directly with a distant node at a later point in time. The nodes

⁶⁶ The arrows are therefore projects where the two connected investors have co-invested.



of investors, including private financials (dark blue), non-profit financials (burgundy), private non-financials (light blue) state-owned financials (orange), and a few state-owned non-financials (yellow).

To the left and right side of Ørsted, there are seven narrow branches with investment partnerships: four with private utilities, including large investors like E.ON and SSE, two with non-profits, and one with a state-owned financial institution. As we know from chapter 5, the collaborations with private utilities stemmed from the experimental and early growth phases 1 and 2 where deployment was scaled-up and various new technologies, incl. turbines, foundations, and installation vessels, were tried out (Jennings et al., 2020).

The two investors acting as the most important hubs for spreading Ørsted's early know-how were the European Investment Bank (EIB), and the UK utility company Centrica, who was also an early investor in the British offshore wind market. The numerous investors encircling the EIB shows how the EU's supranational SIB's early co-investments with Ørsted (and other market pioneers) gave it a unique position to spread the know-how to other investors in the ecosystem, incl. through the co-investments with Rabobank who pioneered project financing with Dexia Bank (Guillet, 2021) and EKF, the Danish export credit agency. This contrasts with the German SIB Kreditanstalt für Wiederaufbau (KfW), which was more focused on the German market and hence later involved.

As we in the following sections consider the network reach more quantitatively, the special role for EIB in connecting Ørsted to the wider system of investors suggests that we should remain attentive to the qualitative aspects as well. A large forward reachable set is likely more impactful for an investor with larger know-how. The backwards exposure to installed MW in the previous period provides a quantitative metric than can assist making such more qualitative considerations.

While EIB provides a bridge to a diverse set of investors in terms of ownership form and sectors, Centrica provides early links to a few dominant private banks. Centrica's co-investments with the two French universal banks BNP Paribas and Societe Generale and the Japanese investment bank Mitsubishi UFJ Financial Group (MUFG) established the earliest bridges between Ørsted's know-how base and the numerous financial and non-financial investors linked to the three banks.



We saw in chapter 5 how these banks were among the dominant banks throughout the growth phase of the network. Their early accumulation of experience and involvement with knowledgeable investors has made them attractive partners to include in financing arrangements, since it is commonly the most reluctant debt provider among a group of banks that sets the terms for the entire club of banks (EWEA, 2013).

In summary, a closer look at Ørsted's earliest forward paths in the network shows the complementary role played by the EIB as an important diffuser of Ørsted's unique investment know-how, since utilities are less inclined to co-invest. It also indicated an important diffusion role played by the early-moving international banks. With these insights from a key investor as an illustrative case of forward path analysis, the analysis turns to the entire population of OSW investors and examines the diffusion process phase-by-phase.

Appendix H: UK offshore wind industrial funding schemes

Table 0.4: UK Offshore wind industrial funding schemes

Initiative (Funder)	Years	Funding	Aims & Activities
Offshore Wind Accelerator (Carbon Trust)	2008–2010 (stage I)	Stage I: £1.5 m	Joint industry RD&D programme involving nine offshore wind developers that aims to reduce the cost of offshore wind by 10% by 2015 through innovation; often using international competitions.
	2011–2014 (stage II)	Stage II: £10 m for R&D; £30 m demo projects	
Offshore wind manufacturing funding (DECC/BIS); similar scheme in Scotland	2011–2015	£60 m from DECC/BIS; £70 from Scotland	Business investment grant funding for the development of wind manufacturing facilities at ports to exploit supply chain opportunities (turbine and component manufacturing).
Offshore Wind Component Technologies Development and Demonstration Scheme (DECC, TSB)	2011	£15 m	Provides competitive calls for funding aimed at helping companies to test and demonstrate devices and develop component technologies that can cut the costs of offshore wind energy in the run up to 2020 and beyond.
Offshore Renewable Energy Catapult (TSB)	2012–2017	£50 (across all offshore renewables, incl. tidal and wave power)	The Catapult aims to bring together knowledge, expertise and state of the art facilities to help UK businesses innovate and find new ways to capture and use the power from offshore renewable energy sources. One focus area is establishing a sustainable supply chain for the offshore wind sector in the UK.
SUPERGEN Wind Energy Technologies Consortium (RCUK Energy programme)	2006–2010 (phase I)	Phase I: £2.55 m	Consortium of 7 research partners led by the Universities of Strathclyde and Durham with active support from 18 industrial partners; its mission is to undertake research to achieve an integrated, cost-effective, reliable and available offshore wind power station.
	2010–2014 (phase II)	Phase II: £4.83 m	
UK Wind Energy Research – Doctoral Training Centre at University of Strathclyde (EPSRC)	2009–2014	£5.8 m	Funding scheme for developing highly skilled doctoral students working in multi-disciplinary research teams and with industry collaborators to gain competencies in wind energy systems engineering and understand the socio economic impact of wind energy systems in order to meet the needs of the wind energy industry.
Industrial Doctorate Centre in Offshore Renewable Energy at University of	2012	£6.5 m	Funding for doctoral training in offshore renewable engineering as well as developing commercial and entrepreneurial skills; training provided by leading Universities in collaboration with business partners

Initiative (Funder)	Years	Funding	Aims & Activities
Edinburgh (IDCORE) (ETI, EPSRC)			such as EDF Energy, E.ON, BP, Shell, Caterpillar and Rolls-Royce.
Offshore Wind Programme (ETI)	2009	£40.23 m (excluding funding for IDCORE)	Programme provides competitive funding for projects which have promise of achieving significant cost reductions, enhancing reliability and reducing technical uncertainties. Funding for an indoor test rig capable of testing complete drive trains and nacelles up to 15MW at NAREC.
Environmental Transformation Fund Offshore wind capital grant scheme (DECC)	2009–2011	£26 m	Under this programme three calls for capital grant funding for offshore wind were undertaken. The programme was launched to encourage the development of OSWF and to understand wind farm equipment and technology and develop the supply chain.
Crown Estate	2009	£70 m co-investment; £30 m ‘enabling actions’	The Crown Estate co-invests alongside project developers up to the award of consent and also has a programme of enabling actions including work on health and safety, supply chain and skills, project economics and finance, grid and technology and planning and consenting.
Funding for offshore wind cost reduction (DECC)	2011–2015	£30 m	DECC announced in its 2011 Renewable Energy Roadmap to provide up to 30m of direct government support for offshore wind cost reduction. The funding is aimed at fostering collaboration between technology developers and support innovation.
		Total: £452 m	

Source: Kern et al. (2014b, 641)



Appendix I: Risks in offshore wind investment

The methodology chapter developed the concept of investment know-how. I distinguished between fixed investment know-how regarding the ability to develop and construct projects with the right technologies on budget and time and financial know-how, denoting the ability to assess the risks and returns of a long-lived renewable energy asset. Here, I will briefly review the risks that an investor must be able to apprehend to be able to finance OSW without a large precautionary risk premium (Guillet, 2022; IRENA, 2021, 109). Following Guillet (2022), I list the risks by general infrastructure risks, wind power risks, and offshore risks. These risks will vary across the lifetime of an OSW project, from the planning and development phase with permitting and contracting, the financing phase, the construction phase, the operational phase, and the final decommissioning (Green Giraffe, 2019, 11).

Infrastructure risks

The general infrastructure risks are shared by most large construction projects and investors, therefore, generally know how to monitor and assess them. *Political risk* consists of possible changes to the institutional frameworks that the projects rely on to go through the construction process and achieve the predicted revenues. This could be changes to the revenue framework or in more extreme cases nationalisations. *Commodity price risk* is a key risk because of the vast volumes of materials used in physical infrastructure projects. For international investors, *currency risks* also add to the risk of the resulting profits. Lastly, *counterparty risk* refers to the risk of contractor bankruptcies. A risk never disappears but it can be converted to a counterparty risk if it is reallocated through a contract (interview 1). Counterpart risk has been larger in OSW because of the many small suppliers, e.g. owners of installation vessels, which were not financially robust. In complicated and coordinated construction processes, bankrupt contractors can have costly knock-on effects (Guillet, 2022).

Wind power risks

With regard to investments in wind energy, the *resource risk* of uncertain wind speeds jeopardises the accuracy of revenue projections. Over time and through digital innovations and geographical research, this has become a low risk factor. The wind turbines create a *technology risk* because of mechanical defects, which can require expensive reparations, especially offshore and in case of serial defects. However, over time this has become a low risk factor given the standardisation of turbine warranties. *Grid and transmission risk* relates to the connection to the grid and grid management, including curtailment from the grid.

Lastly, the wind project is subject to market risk from the electricity market. Demand-side policies have historically reduced this risk, and more recently power purchase agreements (PPAs) with large corporations have also provided price certainty. However, the market for PPAs is not on par with the deployment scenarios (Christophers, 2022a), and there is a re-risking trend towards exposing OSW to the market risk in the day-ahead spot market (Pahle and Schweizerhof, 2016). However, there is a feedback effect as the low marginal cost of RE depresses prices at the time of production. For the decarbonisation of the UK, Blyth et al. (2021, 9-10) find that “in all the scenarios tested, the capture price is below the levelised cost of wind, meaning that wholesale prices on their own are insufficient to recoup investment costs”. This is therefore an emerging risk on the mid-term horizon.

Offshore risks

Finally, there are specific risks when constructing wind power infrastructure *at sea*. This is mainly increased *construction risk* as OSW projects are undertaken in a harsher and changing environment that can cause delays and by a large number of contractors and sub-contractors. As the cost profile suggested (Figure 5.4), there is no major contracting party that is well-positioned to assume the responsibility of the other because of their equal size and different technologies. This creates contracting risks for the developer, as the allocation of risk and interfaces between contractors must be controlled in detail. These risks have been reduced through a reduction in the number of contracts, now usually divided between turbine, foundation, cables, and substation



contractors. Moreover, debt providers have developed abilities to assess the skills, track records, and experience of project management teams, which must be able to monitor the contractors' cooperation with sub-contractors and devise backup plans. Thirdly, banks require “maximum transparency” to assess contracts, subcontractors, and the risk-interfaces (Guillet, 2022). Contingency planning and insurance policies increase the cost but reduce the construction risk. Finally, there is the *operational risk* stemming from possible less production output or more maintenance than anticipated.

These are the risks investors must feel confident about before investing in OSW at a low cost of capital. Handling of these risks requires fixed investment know-how and financial know-how, as described in chapters 6 and 7.

Appendix J: China's place in the investor network

A final tendency was the increasing role of Chinese SOEs for OSW deployment, which has been inadequately examined by the network methodology because of their isolation from the main investor network. Figure 5.2 in chapter 5 showed

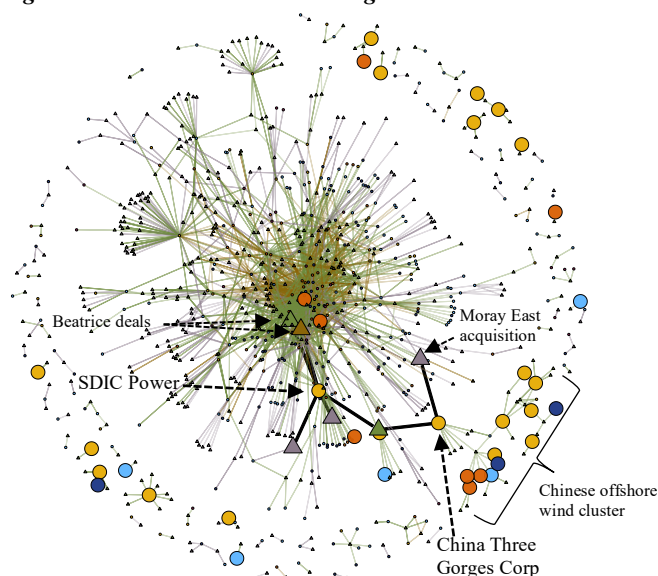
that the Chinese deployment grew at an extraordinary pace in phases 4 and 5, yet in this analysis, Chinese investors have generally displayed low backwards and forward reaches. However, there were exceptions that are worth exploring to see how the Chinese investor network has linked up with the main OSW financial network dominated by European banks and utilities.

One particularly interesting connection between European and East Asian OSW markets was in 2016 when the Chinese state-owned power generation company SDIC Power acquired stakes in two Scottish wind projects from the Spanish oil and gas company Repsol who left the OSW market (Wind Power Monthly, 2016).

It gained full ownership of the Inch Cape project during its early development and a 25% stake in the 588MW Beatrice project, owned together with CIP and SSE, which was under construction (Figure 0.14). This was particularly interesting for know-how flows since this partnership gave SDIC access to the know-how of the former Ørsted executives that had formed CIP. Indeed, with reference to the Beatrice project, SDIC boasts on its website that "SDIC Power has become China's first enterprise that has the capabilities of independent development-investment and acquisitions in large offshore wind farm projects abroad" (SDIC, 2022).

It is beyond the scope of this chapter to analyse how the Chinese SOEs cooperate and coordinate in practice. Still, SDIC Power can have contributed to the later remarkable market expansion in

Figure 0.14: China's know-how bridges to the investor network



Source: BNEF, IJGlobal, and own data collection.

Note: Chinese investors and their key European deals are highlighted by their size on this rendering of the full period network in Figure 6.6 while all other investors are decreased.



China through subsequent co-investments and collaborations with other Chinese energy companies, including a 200MW project in 2017 with China Three Gorges Corporation. The latter investor was more connected to the main Chinese OSW investor cluster (Figure 0.14), and also acquired a stake in the Scottish Moray East project in 2018 from Energias de Portugal⁶⁷ (Offshorewind.biz, 2019).

Figure 0.14 shows how these deals connected the Chinese cluster of mostly state-owned OSW investors with the main network based in Europe. These deals also led the China Three Gorges Corporation to have the highest betweenness centrality in phase 4 since it was the only bridge (Appendix F: Figure 0.11). In later years, more Chinese debt investments were undertaken abroad in Belgium, Netherlands, Germany, Vietnam, and Taiwan by a variety of state-owned investors⁶⁸ while also acquiring ownership in a project in Taiwan. In 2020, the French SOE EDF became the only foreign corporation to have acquired a stake in a park in China (IJGlobal, 2020).

Overall, China's model for achieving remarkable deployment in recent years (Figure 5.2) has been unmistakably state-led in an attempt to promote domestic know-how accumulation. This corresponds to China's approach to green transformation with the state in the Schumpeterian roles of "ephor of finance, creative destruction manager, and entrepreneur-in-chief" (Burlamaqui, 2019) commonly ascribed to private finance and enterprises in the West.

Somewhat surprisingly and at odds with its common business development model of absorbing know-how through joint ventures with foreign firms (Studwell, 2014), Chinese companies have largely been going it alone, with a few investments abroad to source experience from the know-how frontier. One reason may be that China strategically avoids foreign ownership of energy infrastructure. Another - not mutually exclusive - reason may be that China's status as an international creditor means that its growth model and strategy for know-how transfer is undergoing a change from one relying on know-how transfers through in-going foreign direct

⁶⁷ Where the China Three Gorges Corporation was already a major shareholder (21.35%) following the Portuguese government's sale of its SOE).

⁶⁸ Incl. the commercial banks Bank of China, Industrial and Commercial Bank of China, and the SOE Power Construction Corp of China.



investment in China to a strategy based on Chinese acquisitions and investments abroad (Liang, 2020). One Chinese SOE's investment in three smaller offshore wind parks in Vietnam indicates that OSW could also become a combined geopolitical, developmental, and export policy tool in place of China's now-abandoned plans for USD 50bn investments in coal power plants in developing countries (Stanway and Brock, 2021).

To sum up, in the transition from phase 4 to 5, private financials became central to the development and flow of know-how in the investor community. These tendencies have reduced the importance of state-owned enterprises and investment banks. In that sense, the network became more homogenous, but there were also diversifying trends as major oil companies, Chinese SOEs, Taiwanese financials, and US financials gained more prominent roles during the globalisation of OSW deployment.

Appendix K: Database descriptions

Table 0.5: Ties between investors and projects from the three data sources

Data source	Total ties	By type of finance		By purpose of finance		
		Debt	Equity	Primary	Acquisition	Refinancing
Manual (1989-2003)	34	15%	85%	82%	0%	18%
BNEF (2004-2017)	858	41%	59%	58%	24%	18%
IJGlobal (2018-2021)	923	70%	30%	50%	21%	29%
Total	1815	55%	45%	54%	22%	24%

Table 0.6: Investors and projects in the database

Nodes by type	Count	Share of investor and deal counts	Share of total investment value (2020-\$m.)
Total investors	423	47%	
<i>By ownership form:</i>			
Quoted company, partnership, or privately owned	249	59%	50%
State-owned commercial entity or governmental	118	28%	42%
Charity / Non-profit / Association	26	6%	6%
Other	30	7%	1%
<i>By sector:</i>			
Financials	213	50%	53%
Energy and utilities	120	28%	41%
Industrials	29	7%	0%
Government	18	4%	2%
Other	43	10%	3%
Total project deals	481	53%	
New projects	223	46%	68%
Acquisitions	205	43%	20%
Refinancing	53	11%	12%
Total nodes	904	100%	

Note: Percentages do not sum to 100 because of rounding.

Appendix L: Comparison of neoclassical and complexity economics

Table 0.7: Comparison of neoclassical and complexity economics

Aspects	Neoclassical economics	Complexity economics
Actors	Representative actors with 1, 2, or N distribution of types.	Diverse actors who can enter and exit the market over time.
Organising principle and dynamics	Equilibrium: Actor behaviours are consistent with aggregate outcomes where there are no reasons for further change. Market failures can cause an equilibrium to be sub-optimal.	Non-equilibrium: Agents act to aggregate outcomes and patterns, which enable emergent system properties not deducible to the sum of the parts.
Dominant theme	Allocation of scarce resources.	Formation of economic structures.
Behaviour	Agents optimise their utility in the context of a well-defined problem.	Agents face fundamental uncertainty as they try to make sense of and explore an often ill-defined situation.
Interaction	Homogenous interaction, commonly via market prices.	Explicit interaction in networks, which propagates changes.
Rationality	Rational expectations, implying all actors know the most accurate model of the economy. This baseline can be adjusted with informational market failure frictions.	Rationality is often not well-defined. Actors must continually adapt strategies to changing circumstances.
Structural change	The equilibrium shifts based on fundamental changes to supply and demand.	Endogenous restructuring because of novel outcomes, actors, strategies, capabilities and patterns of interaction.
Feedbacks	Mainly negative feedbacks.	Positive and negative feedbacks.
Time	Equilibrium is a timeless concept since nothing changes.	The path taken through history matters for the future trajectory.
Prominent approaches to finance	Efficient market hypothesis, financial frictions theory.	Adaptive market hypothesis, financial instability hypothesis.
Methodology	Methodological individualism.	Methodological combination of individualism and holism.
Prominent modelling approach	Solvable models with equilibrium solutions.	Computational models with simulations, such as agent-based models.

Sources: Based on Arthur (2022), Beinhocker (2007), Kirman (2021), Lawson (2013), and Tirole (2017).