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Risk-opportunity analysis for transformative policy design and appraisal

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ABSTRACT

The climate crisis demands a strong response from policy-makers worldwide. The current global climate policy agenda requires technological change, innovation, labour markets and the financial system to be led towards an orderly and rapid low-carbon transition. Yet progress has been slow and incremental. Inadequacies of policy appraisal frameworks used worldwide may be significant contributors to the problem, as they frequently fail to adequately account for the dynamics of societal and technological change. Risks are underestimated, and the economic opportunities from innovation are generally not assessed in practice. Here, we identify root causes of those inadequacies and identify them to structural features of standard analysis frameworks. We use a review of theoretical principles of complexity science and the science of dynamical systems and formulate a generalisation of existing frameworks for policy analysis and the appraisal of outcomes of proposed policy strategies, to help better identify and frame situations of transformational change. We use the term “risk-opportunity analysis” to capture the generalised approach, in which conventional economic cost-benefit analysis is a special case. New guiding principles for policy-making during dynamic and transformational change are offered.

1. Introduction: The low-carbon innovation policy problem

The urgency of climate change and the inadequacy of the global response has led some to ask, ‘why are we waiting?’ (Stern, 2015). Part of the answer may lie in the inadequacy of the tools most commonly used to guide decision-making processes (Farmer et al., 2015; Mercure et al., 2016). The problem of reducing global emissions of greenhouse gases pose three challenges that standard and prevailing welfare economics policy assessment methods are generally not in an adequate analytical position to address (cost-benefit analysis, CBA (Stern, 2007; EPA, 2014; EC, 2015; Nordhaus, 2017; HM Treasury, 2020b), and partial/general economic equilibrium analysis (Château et al., 2014; Kriegler et al., 2015; Weng et al., 2018; Takeda and Arimura, 2021)). These include the pervasive and transformative nature of the necessary changes including non-marginal elements (Fouquet, 2016; IPCC, 2018); the highly heterogenous interests of different actors, stakeholders and decision-makers (Geels, Berkhout and van Vuuren, 2016); and the high uncertainty regarding costs, benefits and path-dependence in the outcomes of policy strategies (Hughes, Strachan and Gross, 2013). Conventional textbook welfare economic methods, as often applied in current policy appraisal worldwide, are designed to analyse changes of marginal nature with relatively uniform stakeholders. Change that is structurally transformative change may not, however, be successfully triggered by informing policy using a paradigm designed for managing marginal change (Dietz and Hepburn, 2013). Furthermore, as could be observed during both the 2008 financial crisis and the COVID-19 crisis, marginal analysis, by ignoring systemic risk, may also be leading policy-makers to design fragile systems with insufficient resilience to handle increasingly frequent extreme events (Schwarcz, 2019).

Climate change policy epitomises a need for change in approach felt

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in several domains of policy-making where substantial change is desired, as expressed in current policy objectives in various constituencies, but not materialising. Other areas include innovation policy, industrial strategy, finance, infrastructure, regional development, productivity growth, and the response to structurally disruptive events such as pandemics. Marginal analysis is useful to inform policy over the vast domain of economic scenarios where static efficiency is the focus. But in the areas of transformative policy-making, marginal analysis is not suitable to handle the complex dynamics involved. These problems of transformational change require a more general approach, expanded to include concerns for dynamic efficiency, with corresponding definitions and methods.

A more general set of social scientific methods (Kattel et al., 2018), both quantitative and qualitative, is necessary for these situations, and could serve as part of a general paradigm for policy appraisal. An appropriate approach would admit the limits to available knowledge to adaptively guide the approximate direction of change of a complex transition, rather than attempt to identify a highly uncertain distant end point with false precision. A practical scientific handling of deep uncertainty emerges more naturally from complexity science than it does from traditional welfare economics (Arthur, 1999).

In this paper, we identify the scientific basis to manage information flow in a policy appraisal framework theoretically compliant with structurally transformative situations, which we call 'Risk-Opportunity Analysis' (ROA). This paper is not a policy or political proposition; rather, it identifies suitable scientific methods, drawn from the sciences of complexity and dynamical systems, that are coherent with problems involving structurally transformative change. A number of methodologies exists (e.g. Robust-Decision-Making) for analysing decision-making options under deep uncertainty (Marchau et al., 2019), to which ROA is to some degree related. What these lack, however, is the broad philosophical pedigree that welfare economics possesses going back to 18th century, through which much of our present day understanding of legitimacy-building in the eyes of the public and public institutions during policy appraisal has been developed, as well as the mechanisms of the science-policy interface itself. ROA is a generalisation of widely used CBA, and therefore benefits from the same intuitive philosophical background, while avoiding the most important flaws of CBA when applied to problems of transformational change.

In Section 2, we consider the root causes of the inadequacy of marginal analysis in the appraisal of policy design for structurally transformative change, using climate change policy as the main testing ground. Section 3 sets out the scientific basis of ROA. Section 4 sets out the methodological framework of the analysis itself. Section 5 provides examples of application and section 6 concludes. The Supplementary Material provides further information on complexity science in the context of social systems and economics.

2. Challenges to be addressed by policy appraisal frameworks

2.1. Preamble

Basic welfare economics principles, as applied in finance ministries, are most useful when

(1) An intervention does not substantially change the background economic situation (e.g. prices of goods and services and GDP growth) nor the relationships between variables (Dietz and Hepburn, 2013);
(2) The heterogeneity of affected stakeholders, and of the dimensions of policy outcomes, is not highly relevant for decision-makers to consider the objectives achieved;
(3) All parameters and outcomes involved in policy analysis are known with sufficient confidence, with quantified uncertainty, such that expected values are considered robust.

For many situations, including notably policy that concerns innovation, these requirements do not hold, invalidating any conclusions based on the application of basic welfare economics, either as descriptions of reality, or as normative principles. Three useful definitions relate to the reliability of the knowledge that decision-makers use: heavy-tailed and fundamental uncertainty, and systemic risk.

Heavy-tailed uncertainty is characterised by a probability distribution where very large events are sufficiently likely that the variance fails to exist. This means that the estimated value of the variance becomes larger and larger and diverges to infinity as the sample size becomes large. In extreme cases the mean also fails to exist, but even if it does exist, the average converges very slowly with the addition of data, which makes it unreliable.

Fundamental uncertainty about the future involves unknown unknowns, arising when one cannot enumerate and rank all possible futures. We propose that fundamental uncertainty is generally related to heavy-tailed uncertainty.

Systemic risk is associated with complex interdependencies within a system and can precipitate systemic collapse based on the cumulative contribution of certain actions by the individual entities that collectively compose that system. It can arise when the actions of any individuals do not necessarily pose a risk to themselves directly but contribute to forming risks at the community level. Systemic risk is not the aggregation of individual risk but rather an emergent property of the system that arises as an amplification of any such aggregate risk (Cont and Schaanning, 2017).

We acknowledge the existence of a discrepancy between definition of 'risk' used in economics, as the impact of uncertainty on objectives quantifiable with probabilities (following Knight), and the definition used in most other spheres of society (such as public health, engineering, or national security, e.g. the ISO risk management standard), which does not require probability to be quantifiable in order for something to be considered a risk. For the sake of communicating with policy-makers, we adopt the latter definition, recognising that probabilities are rarely quantifiable in practice. Meanwhile, we use the term 'uncertainty' to refer to the range of possible variations in the accuracy of existing knowledge and predictions, and not in the sense used by economists meaning unquantifiable risk.

2.2. Understanding dynamically rapid pervasive change

According to the UK's Green Book for policy appraisal, itself an internationally recognised methodological set of guidelines for policy appraisal, marginal analysis is 'generally most appropriate where the broader environment (e.g. the price of goods and services in the economy) can be assumed to be unchanged by the intervention' (HM Treasury, 2020b). By contrast, it works 'less well where there are potential non-marginal effects or changes in underlying relationships'. Meanwhile, general equilibrium economic models are designed to handle marginal demand, supply and price changes, but do not handle deep structural changes in the economy, as they take the structure of the economy to be fixed. The 2021 Green Book version sees the inclusion of a definition for 'transformational change' (Appendix 7), but no methodological steps are recommended yet, a situation perhaps representative for many science-policy interfaces.

To understand the mismatch that occurs when a marginal analysis technique is applied to a problem of non-marginal change, it is necessary to identify the relevant system dynamics and their potential path-dependence.

2.2.1. Dynamics of economic systems

The economy is characterised by inertia against change, which implies understanding it as a dynamical system (Mokyr, 1992; Grübler et al., 1999). Inertia in the economy stems from two broad processes: the long-lived nature of productive capital assets required for generating return, and the interconnectedness of agents, firms, industrial systems and supply chains/trade networks (Mercure, 2015, 2018). Production requires building physical and human capital assets, and this takes time, and such investment occurs with the expectation they will be used for an even longer period of time. Rapidly changing economic circumstances can lead to a devaluation of capital before it has paid for itself. Thus, for problems that potentially involve transformative change, understanding dynamics is of primary concern, where the dynamic effectiveness of policies can be analysed instead of their static efficiency (Farmer et al., 2019). The static and dynamic efficiency of complex systems is only ever knowable *ex ante* for as long as change is marginal, beyond which it can be misleading.

2.2.2. Path dependence

Policy action in certain domains almost always has the outcome of changing to some degree the problem at hand, creating the need for further analysis and further policy action (Rittel and Webber, 1973). Playing the game may change the game. For example, research suggests that it has been the German introduction of feed-in tariffs that created a global market for grid-scale solar photovoltaics, which allowed Chinese manufacturers to justify expanding production at a large scale, which subsequently resulted in substantial cost reductions and the availability of low-cost solar energy to the rest of the world (Yu, Popiolek and Geoffron, 2016). A relatively benign climate policy decision transformed the whole low-carbon industry and climate change problem, affecting the policy strategy of all nations, by opening new opportunities and closing older ones.

Path-dependence is intrinsically difficult to represent in equilibrium-based economic analysis, because by definition, the notion of equilibrium erases the impact of history, the memory that is embedded in economic structure. Seen as an evolutionary metabolic system, as time passes, economic evolution identifies the range of what were past possibilities of what the economy will not become, while it expands the range of what it could become - but neither can be exhaustively enumerated with certainty (Day, 1992; Arthur et al., 1997; Kauffman, 2000). In the language of marginal analysis, the constraints of the allocation problem that must be solved in path-dependent systems keep changing according to the solution that was reached in previous time positions. This is a difficult to solve, infinitely recursive problem when framed using standard economic optimisation (Way et al., 2019).

2.3. Addressing normatively highly differentiated and heterogeneous interests

A common criticism levelled against methods embedded in current policy appraisal is that it requires normative valuation elements to be included in an otherwise descriptive quantitative analysis (e.g. the monetary value of risk to life or the willingness to pay for beauty or pollination services, see Bateman et al., 2002; Hanley and Barbier, 2009; HSS, 2016; HM Treasury, 2020b), valuation that is often ultimately interpreted as objective science (Baram, 1980; Ackerman and Heinzerling, 2002). 'Moral' values (or beliefs) are quantified in monetary terms using methods that have frequently been argued as an arbitrary choice of the analyst, since beliefs are, strictly speaking, not reliably measurable quantities (*ibid*). Aggregating the value of moral choices with real flows of economic quantities may be methodologically inconsistent as it can lead to internal philosophical contradictions and challenges. For example, the Stern Review (Stern, 2007) involved measuring the statistical value of life of affected people which generated different values according to ethnicity and social background (Aldred, 2009), inconsistent with other widely accepted human rights-related principles. Both the review's valuation and human rights are derived from normative principles, and they are inconsistent with each other.[1]

More importantly, welfare economic valuation methods ascribe value to multiple dimensions of policy impacts using only one monetary metric that combines all real and moral costs and benefits, with an often-unstated interpretation that the resulting quantity represents their normative value to society as a whole. Where that quantity remains constant, society is interpreted as being indifferent, but this can involve substantial underlying structural changes, with winners and losers. The normative weighting of different actors' interests is inevitably a political choice, and, where one takes a positivist view of science, this cannot be the outcome of any scientific assessment (Ackerman and Heinzerling, 2002; Pindyck, 2017). In other words, if analysts rely solely on discounted costs and benefits, by including normative elements into objective analysis, current appraisal methods are at risk of taking the value judgment, and thus agency, away from the policy-maker, and give it to the analyst. The former may meanwhile be in need of guidance for policy design on how to pursue a range of goals, while the latter could become at risk of coming under undue pressure (political or other) to shape the subjective component of the assessment in particular ways.

2.4. Working scientifically with uncertainty

The concept of Pareto-optimal policy-making, in a strict sense, may in some instances be scientifically tenuous, since the possible outcomes of policy action cannot usually be exhaustively enumerated and ranked (Baram, 1980; Ackerman and Heinzerling, 2002; Weitzman, 2009). The aim to deliver optimality may be too restrictive as it can involve unrealistically high demands on information availability and reliability, while in practice, it frequently leads to the use of some untestable proxies for inferring missing information. Meanwhile, the role and value of uncertainty as the generator of both risk and opportunity is generally missed. By alleviating requirements for optimality, uncertainty could in fact be seen as an ally rather than as an enemy.

2.4.1. Uncertainty is fundamental

Fundamental uncertainty is an essential characteristic of the economy (Keynes, 1921; Fontana, 2008) and is present in most policy decisions. Its sources include the development of new technologies; the intentions and investment decisions of economic agents; the outcomes of entrepreneurial ventures; the future costs and prices of all traded goods and services; and the behaviour of the economy as a whole. Possibilities are in general not exhaustively known, and therefore probability distributions around these possibilities are not knowable. Arbitrarily assigning probabilities to unknowable quantities can lead to scientific inconsistency.

That fundamental uncertainty cannot be represented using probability distributions is closely related to the degree of path-dependence inherent in the economy. For example, a range of possible values for auctioned connectivity broadcasting licences did not exist until the mobile phone was created. But moreover, many futures may either be distinctly advantageous or clearly disastrous. That probability distributions could be heavy-tailed implies that expected values – and therefore discounted costs and benefits – are generally unreliable quantities, as they involve adding up large uncertain values with small relatively well-known values.

[1] We note that in the UK case, many of these issues are recognised, and the current 2020 Green Book takes specific measures to avoid ascribing different values to different ethnicities. Furthermore, the Green Book also emphasises the importance of considering distributional impacts in decision-making and includes methodology to address such issues. Other appraisal guidelines elsewhere have their own approaches.

One crucial consequence of fundamental uncertainty is that knowledge about a system after a non-marginal transformation has taken place is inherently less robust than knowledge of the status quo. As a natural consequence, the valuation of the predominantly long-term direct and indirect benefits of policy action is more prone to uncertainty than the valuation of the predominantly short-term direct costs of the same policy action. Thus, mis-handling uncertainty may generate, in marginal analysis, a status quo bias if the tendency of analysts is to avoid including uncertain quantities, or a confidence bias if uncertainty is underestimated. This affects particularly innovation and regional development policy.

Experience tells us that the standard response of welfare economics analysts to fundamental uncertainty is to make proxies for missing knowledge, and impose short-tailed distributions to missing data, since marginal analysis requires users to quantify probabilistically all real and moral costs and benefits (e.g. measuring the statistics of rare events involves long waiting times and is not commonly done). Some of these quantities inevitably have heavy-tailed or unknown probabilities, such as the social cost of carbon, or the benefits of hypothetical technologies that do not yet exist. The pressure on analysts that results from the requirement to make proxies when data is unavailable in order to obtain results bears the risk of biasing the policy analysis process, and could ultimately undermine it.

2.4.2. *Uncertainty has value*

The economy naturally evolves through its attraction towards productivity increasing novelty (Schumpeter, 1939; Freeman and Louçã, 2001). Entrepreneurs and venture capitalists in fact make practical use of fundamental uncertainty, since business opportunity frequently arises through unpredictable events that allow for capturing competitive advantage, for instance through innovation. This notion contrasts with normative, probability-based standard portfolio optimisation (Markowitz, 1952), which requires fully quantified risks. Venture capital would likely not exist if probabilities of entrepreneurial success were equally known by everyone, as there would be less untapped opportunity for creating comparative advantage out of innovative industrial ventures.

Entrepreneurs do not typically focus on single sources of cash flow (excluding monopolies), as they strive to future-proof their enterprises by creating new products and capture new markets (Porter, 1996). Fig. 1A illustrates a typical business perception of returns on investment in research and development (R&D) at the firm level, drawing from empirical findings (Klingebiel and Rammer, 2014; Meifort, 2016). Investing insufficient resources into innovation leads an enterprise towards obsolescence and eventual failure. Meanwhile, too high an investment of available resources into too many risky ventures is a gamble that leads to a relatively high chance of successive strategic mistakes, unproductive investments, and failure. A middle-ground thus exists.

This behaviour is observed empirically in innovation portfolio analysis, where it is observed that a combination of breadth, selectiveness and innovative intent increases return on R&D investment, due to its generation of options (*ibid*). This can coincide with some types of normative portfolio analysis in the context of innovation (Way et al., 2019). It may be understood as the entrepreneur's adaptive response to strong path-dependence, where strategic re-adjustment takes place as time passes, information is gathered and expectations are recurrently reformed (Fig. 1B). A similar logic is known empirically to apply to public innovation policy-making (Mazzucato, 2012; Mazzucato and Penna, 2016): although pressure arises for policy-makers to identify 'optimal policies', in practice not all policies succeed, while objective value exists in trial and error, investing in both high and low risk ventures.

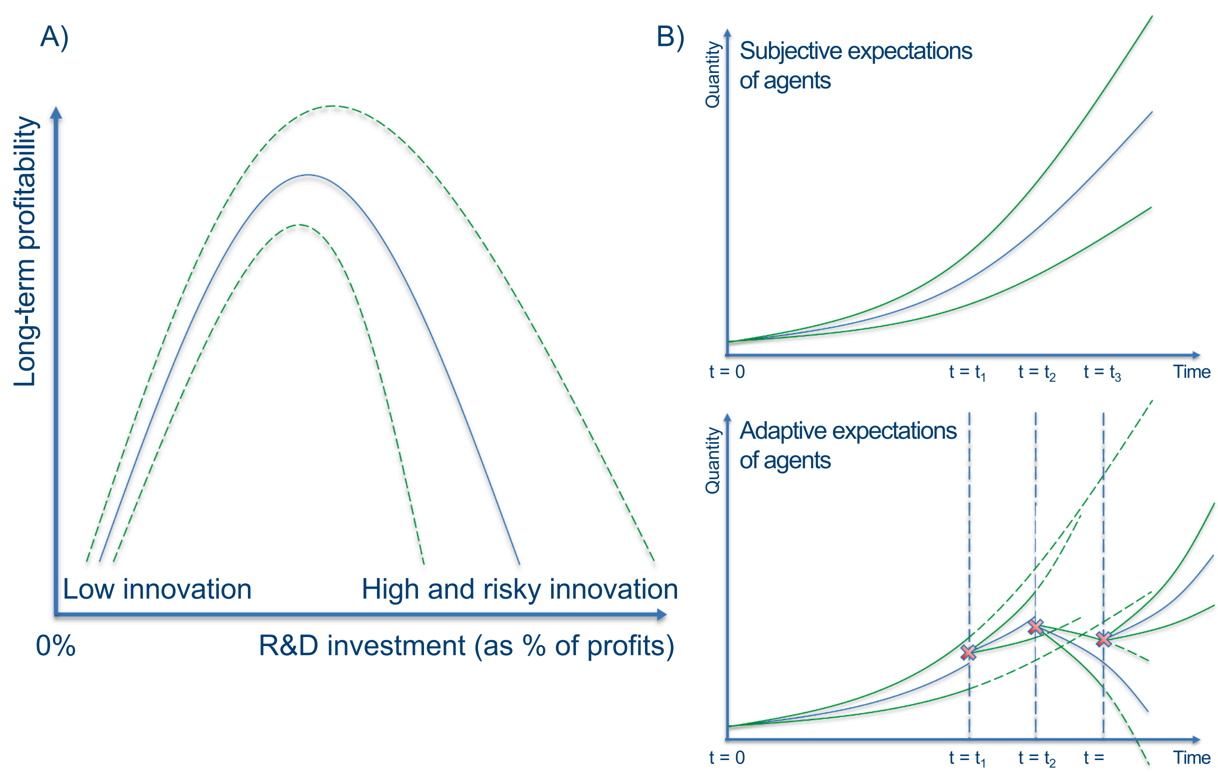

Fig. 1. Innovation and profitability. (A) Illustration of the profitability of companies in relation to their degree of commitment of resources to R&D investment for the development of new products, drawing from empirical studies of innovation systems (Klingebiel and Rammer, 2014; Meifort, 2016). Dashed lines illustrate degrees of uncertainty. (B) Illustration of the process of expectations creation and readjustment by agents to capture opportunities as time passes. (Top panel) Agents in practice form subjective expectations of the future, with central scenario and limit cases. (Bottom panel) As time passes, agents re-form their expectations adaptively according to new information. Red crosses are actual realisations, while curves delimit ranges of possibilities expected by agents. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Risk-opportunity analysis for informing policy-making

In this section, we define a risk-opportunity assessment (ROA) framework, based on complexity science (see the SM for definitions), designed to inform policy-making for problems involving non-marginal change, that can be used within existing science-policy interfaces. ROA is a generalisation, in fact possibly the only self-consistent generalisation one can make, of CBA when in the presence of dynamics and strong path-dependence in the economy, and of fundamental uncertainty and heterogeneity of stakeholders. When these are not present, CBA can be suitable. ROA requires abandoning the standard use of expected values on the basis that detailed probabilities are unknowable in general, and demands appropriate treatment of uncertainty in each domain of analysis.

3.1. Summary of methodological steps in Risk-Opportunity analysis

Building upon the standard guidelines of common policy appraisal frameworks including the Green Book and the European Commission guidelines for policy appraisal (EC, 2015; HM Treasury, 2020b), as well as on the above descriptive principles of dynamical systems, ROA involves the following steps:

(1) Identify the boundaries of the system considered and map out all relevant feedbacks between components, considering their magnitudes and directions. Choose or develop suitable dynamical quantitative and/or qualitative analysis models and datasets accordingly.
(2) Estimate median (not mean) outcomes and impacts on the process and direction of evolution and on the structure of the system itself, in a chosen relevant set of qualitatively or quantitatively measurable metrics, associated with each comprehensive policy portfolio proposed, under various plausible scenarios of economic evolution through time. Establish ranges of uncertainty or degrees confidence for each outcome metric.
(3) Carry out, using a stress test or other method, a risk assessment for each policy portfolio under study, to identify all possible extreme unintended detrimental consequences and worst-case scenarios, estimating their severity and likelihood, under each dimension considered. This should identify notably the possibility of reaching tipping points and rapid non-linear changes, and their dependence on known variables.
(4) Carry out, using scenario variation analysis or other methods, an opportunity assessment, identifying all possible option creation potentials for each policy portfolio under study, under each dimension considered. Option creation potentials are elements of scenarios and systems that expand the ranges of possible desirable futures.
(5) Report to decision-makers median impacts, direction of system change feedbacks, risks and opportunities, in all dimensions considered, along with uncertainty ranges and/or confidence levels. Report both qualitative and quantitative evidence, against current regulatory norms and risk tolerances. The normative weighting or valuation of outcomes is not considered part of ROA.

3.2. Taking a systems perspective

The intended and unintended impacts of policy-making are typically felt across several dimensions, such as income, inequality, access to stable services, environmental quality, financial stability, health and so on. To minimise the chance of missing important impact transmission mechanisms, establishing a holistic systems view and system boundaries is required, identifying feedbacks between system components using multiple outcome indicators that cover the main possible intended and unintended outcomes. Furthermore, system changes can include structural changes in which the system gradually changes its mode of operation. Given the structure of uncertainty, what can reliably be analysed is the direction of whole system change in multiple domains, with the understanding that the end point is uncertain. Lastly, important background changes may exist superimposed onto the outcomes of policy action, where the latter may exacerbate or synergise with existing background evolution trends.

For example, from this perspective, imposing a particular policy measure to achieve a certain objective (e.g. carbon price to reduce carbon emissions) should not be understood to lead to a new static equilibrium state of society, technology and the economy, but rather, to *a new state of change* of behaviour, technology and the economy. That direction of change may suit some stakeholders and groups thereof, while others not, depending on their individual circumstances, motives, and aspirations. Particularly, some social groups may have vulnerabilities or states of resilience in various domains, which may be created, exacerbated, or mitigated by the policy initiative.

By taking a holistic systems view, the methodology encompasses the broader direction of change induced by possible policy strategies, including unintended impacts on different groups of stakeholders, as well as the wider range of possible extreme events and vulnerabilities associated with newly created systems. Thus, the use of models of complex systems by definition generates ranges of path-dependent outcomes, feedbacks and structural changes useful to populate a risk-opportunity analysis by generating both median outcome projections and tail risk analyses.

In practice this means that policy options are to be assessed in combination, rather than individually, and assessed for a whole system, rather than limiting the analysis to a subset. Relationships between system components are to be mapped and reinforcing and balancing feedbacks identified. As opposed to assessing the expected outcome of a policy at a moment in time, these approaches can be used to assess whether a policy decision changes things in the direction sought by decision-makers (the direction of change), how much it changes things (the effectiveness), how quickly change happens, how confident one can be that this new direction would be taken, and what the risks and opportunities are, as defined below.

3.3. Costs and benefits generalized as risks and opportunities

Governments as well as other organisations generally find it to be part of their remit to consider tail risks, in various domains, generated by their actions, although the focus varies depending on the purpose of the policy or decision appraisal exercise. For example, central banks have recently begun to routinely carry out climate stress test to assess the vulnerability of the banking system to climate-related events (DNB, 2018; Banque de France, 2020; Bank of England, 2021; Dikau and Volz, 2021). Strategic, regulatory, and budget policy- and decision-making are interested in different aspects of uncertainty (Fig. 2). On the strategy side, the focus is on the most likely outcome and direction of change induced by a strategic decision. However, regulatory decision-making (for example with safety, regulatory norms, compliance, quality assurance and insurance), will typically focus on ensuring that the system evolves within certain bounds away from extremes, maintaining sufficient capacity to absorb the impacts of unexpected events (e.g. based on estimates of tail events such as the likelihood of electricity black-outs, financial crashes, flooding, pandemics). Yet another category of policy action will assess whether a strategy fits within existing budgets and priorities. For the purpose of the present text, the three classes of policy-making *functions* will be denoted, respectively, '*strategy*', '*regulation*' and '*accounting*'. All three functions and purposes of decision-making can make use of risk-opportunity analysis for different but related purposes.

Generalising welfare economics to complex dynamical systems, an accurate and comprehensive interpretation of non-linear dynamics and fundamental uncertainty suggests that comparing costs and benefits in fact implies a comparison of risks and opportunities. In that

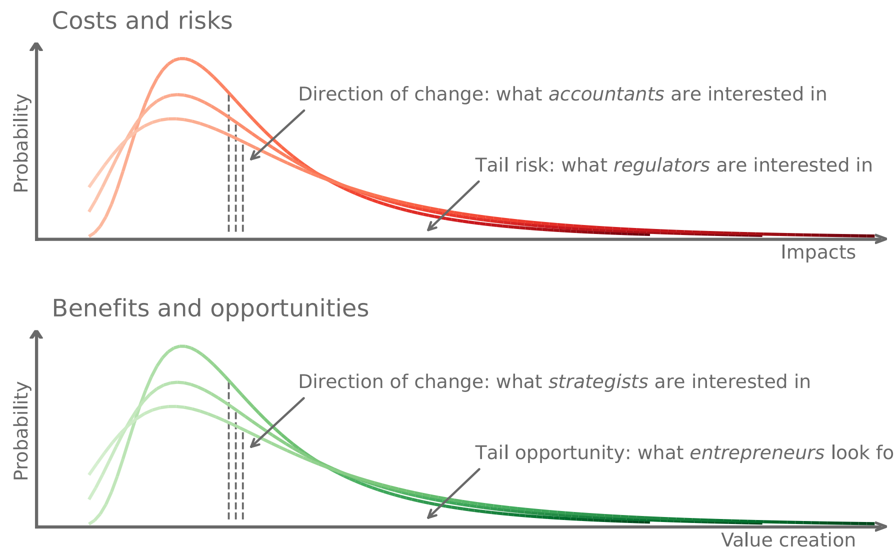

Fig. 2. Heavy-tailed risks and opportunities. Illustration of heavy-tailed probability distributions for risks and opportunities. In complex systems, one can rarely accurately determine probability distributions, and thus these are shown with truncated unknown heavy tails. This suggests that expected values either do not converge or cannot be reliably calculated, but risks and opportunities can nevertheless be critically appraised.

generalisation, the standard concept of 'externality' encompasses *systemic risk*, and the risk of reaching a tipping point due to collective action (and conversely for *systemic opportunity*). Probability distributions cannot be assumed to be fully known since due to emergence in complex systems, one cannot confidently enumerate and rank all possibilities and have comprehensive knowledge, even if one can be confident about what is likely and what is less likely. Since they cannot be assumed known, due to the possible emergence of extreme events, probability distributions for costs and benefits must therefore allow for the possibility of heavy tails for any systems with moderately high degrees of complexity. *Therefore, expected values do not always exist and are not reliably calculated, and thus risk is not reliably quantifiable* (Fig. 2). This is particularly important in the context of the common and standard imposition, in present methodologies, of arbitrary probability distributions onto existing data, especially short-tailed distributions since they potentially lead to wrong inferences and underestimation of real risks. Where multiple plausible scenarios are generated but expected values are not reliable, three useful elements can be informed:

(1) The confidence that the strategist can have over whether a policy adoption will reach a certain outcome and send the system in movement in a desired direction that fits current objectives;
(2) The confidence that the regulator can experience as to whether a system will avoid becoming prone to collapse in ways that exceed existing regulatory norms;
(3) The accountant can also assess whether costs, negative outcomes, and tail risks of unintended negative consequences overshadow benefits and opportunities, and whether outcomes fit within or contribute to current fiscal priorities.

System stress tests can be used to assess risk. Indeed, as is clear in the practice of stress-testing, tail risk can be estimated without probability distributions necessarily being fully known, notably using network models (Battiston, 2017). This complements the estimate of *costs* with an assessment of *risks*.

However, in addition to these standard practices, the strategist, taking the role of an entrepreneur, can also assess, using this methodology, whether policy action is likely to open *options* for further economic and innovation opportunities. That is, without this being the main focus, some innovation strategies may offer further potential for opportunity generation and economic spillovers than others. This complements the estimate of *benefits* with an assessment of *opportunity*.

For example, a particular low-carbon transition policy strategy could have, compared to an alternate approach, different simultaneous types of outcomes: (1) it increases/decreases the likelihood of meeting stated emissions target; (2) it is more profitable/costly; (3) it makes the financial system more/less resilient (systemic risk decreases/increases); (4) it decreases/increases energy poverty; (5) as side effects, it creates/destroys, industrial capabilities with more/less potential to generate new products, markets and jobs.

In practice this means that policy options are proposed to be assessed upon knowledge of their broader risks and opportunities, not just their costs and benefits, and avoid aggregating outcomes over arbitrary probability distributions. Specifically, the assessment encompasses 'tail' risks and opportunities (e.g. tipping points), which may include very high impact outcomes, positive and negative (Farmer et al., 2019). Reducing systemic risks generally implies increasing systemic resilience. The assessment also considers outcomes that can only be qualitatively assessed. The assessment is likely to rely on relevant expert knowledge and judgment; where this is the best available form of evidence it can be retained in its pure form, and not be converted to monetary values.

3.4. Defining risk and opportunity

Systemic risk is well defined and managed in risk assessment methodologies (HM Treasury, 2020c). Managing systemic risk is done in policy-making in order to design and shape systems in resilient ways, which allows them to withstand unexpected situations without leading to a likelihood of systemic failure. Systems typically need spare capacity to absorb such situations (e.g. during pandemics, or speculative bubbles). In many if not most systems, seeking to maximise performance is known to affect stability and increase systemic risks (Doyle and Carlson, 2000; Carlson and Doyle, 2002) (e.g. reducing capital requirements in finance accelerates investment and systemic risk). Underplaying heavy-tailed uncertainty, and optimising systems based on incomplete knowledge, can lead strategists to design brittle systems prone to failure. Regulators, if not involved in the design, can inherit a built-in fragility challenging to manage, at potentially high costs for accountants and society. Uniting risk and cost assessments in the same policy analysis framework, including unintended consequences of design, logically leads to focusing on improving the resilience of systems. It may help plan the direction of development of the economy in resilient ways. The risk-opportunity methodology therefore incentivises strategists, regulators and accountants to work coherently together.

Opportunity, however, is a more diffuse concept. Whereas 'risk', as normatively understood, concerns the likelihood of 'harm' to existing components of a well-understood system (i.e. the one prevailing at decision-making time), 'opportunity' concerns the likelihood of decisions resulting in a system which is considered 'better' (under certain normative criteria) by stakeholders, and/or features more option generation potential, than the prevailing one. Since a putative 'better/worse' system (as normatively understood in the relevant context), after transformation, is by definition less well known than the prevailing system, a 'better/worse' outcome is naturally surrounded by more fundamental uncertainty than the *status quo*. However, the economy and markets are systems in continuous change, and entrepreneurs generally embrace that dynamism in their search for opportunities (Klingebiel and Rammer, 2014; Meifort, 2016). Uncertainty is ultimately inseparable from innovation and productivity growth (Fontana, 2008; Klingebiel and Rammer, 2014).

In practice this means that, for example, policy choices with higher near-term costs and high near-term uncertainty (such as investing in innovation) are identified in ROA for their potential to generate options to capture future opportunities with economic returns, while in comparison, other policies that have low near-term costs with low uncertainty but characterised only by moderate long-term return can be identified as such in ROA. ROA can also caution against policies that generate high short-term return with high confidence (such as focusing on natural resource exports, or deregulating finance) but that are damaging to the economy in the long run as they concurrently lead to a systemic risk build-up. Such strategic insights resulting from ROA are not commonly obtained using marginal analysis. This information can allow relevant stakeholders to achieve stated normative objectives more effectively.

3.5. Complex dynamics

Fundamental uncertainty implies that distant outcomes are uncertain, success is not guaranteed, and decision-makers can at best reliably control the direction of change, rather than the endpoint, and adaptively adjust policy over time to achieve stated outcomes. Fig. 3 illustrates as an example the understanding of the effectiveness of a pricing policy for supporting the diffusion of low-carbon products (green) and the phase out of high carbon products (black), from the perspectives of both static equilibrium (top row) and a dynamic complexity policy (bottom row) assessment frameworks.

In the static framework, the driver is typically a tax that intends to 'internalise' a stated externality and is understood, in the parent theory, to change the relationship between supply and demand accordingly. The expected outcome, such as the level of adoption of low-carbon technologies, is understood to be a unique static outcome of the driver, as it settles in a new equilibrium.

In a scientific context of complex dynamics, a policy change shapes driver variables that are themselves dynamic (e.g. vehicle prices declining with learning-by-doing cost reductions, which reinforce dynamic diffusion processes, which reinforce learning-by-doing processes). Scenarios are generated in which uncertainty encompasses a range of directions of change rather than a range of static end points. Heavy-tailed uncertainty over outcomes exists due to the compounding effect of interactions between system components. Thus, a risk-opportunity assessment identifies central-, worst- and best-case scenarios, without generating a false sense of knowledge and certainty.

In practice this means that as opposed to identifying new theoretical equilibria reached by pricing policy signals, ROA identifies feedbacks that control the dynamics of evolution of a system, in order to identify a range of new trajectories that a system could take following the introduction of a policy portfolio. This makes use of scenario analysis: whether some or all of the scenarios achieve a stated objective; and whether opportunities can arise; and whether worst case scenarios fall within established accepted bounds of failure. Based on establishing system feedbacks and sensitive intervention points, policy space can be searched by policy-makers until all stated objectives and standards are met under all dimensions of analysis.

3.6. From one-dimensional to multi-dimensional assessment

Different stakeholders value different outcomes of policy decisions, measured using different metrics, differently (e.g. GDP, health, jobs, environment), leading to political debates. In complex systems, each dimension has different degrees of uncertainty and tail lengths. Combining all metrics into one would also lead to combining their uncertainties, which could obscure uncertainty analysis unnecessarily from

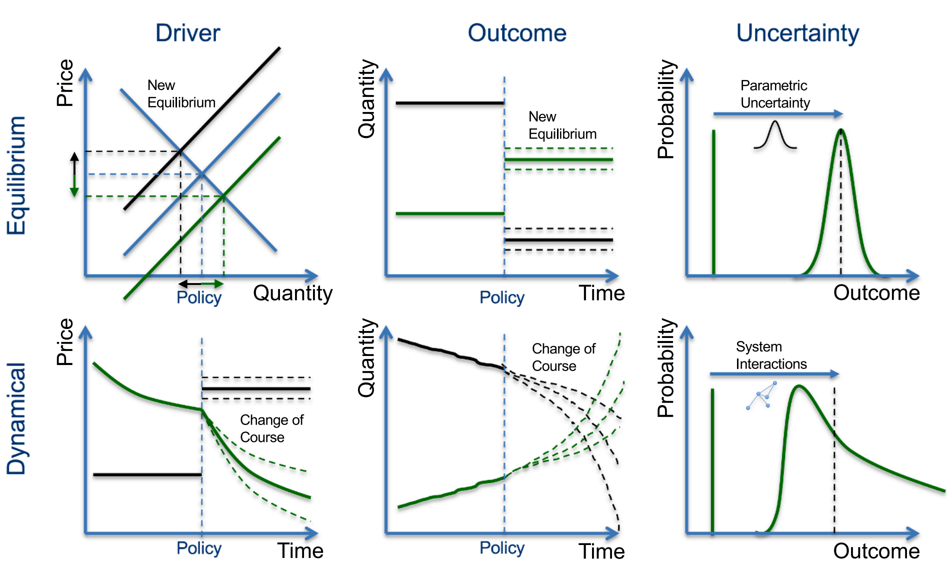

Fig. 3. Assessing change in policy assessment. Comparison of the process of assessing change in policy impact assessment, between the marginal analysis framing (top row), and the complexity science framing (bottom row), in terms of its drivers (left), outcomes (middle) and uncertainty (right). This illustrates a situation of impact assessment of hypothetical policies for the diffusion of low-carbon innovations. In marginal analysis, pricing policies are typically used, which change the position of the equilibrium between supply and demand of green and brown products. The outcome is a well-defined function of the driver, with assumed short-tailed probability distribution, giving a potentially false sense of knowledge and certainty. In complex systems analysis, the driver itself is dynamic, the outcome process can take a range of directions, and the true uncertainty, compounding system interactions, is frequently heavy-tailed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the perspective of users. For example, the health impacts of reducing vehicle pollution in cities and its uncertainty is increasingly well characterised, however the economic impacts of reducing petrol and diesel use in certain countries, due to job losses, may be substantially less well characterised. Aggregating highly uncertain outcomes with relatively well-known outcomes leads to a valuation that is overall highly uncertain, substantially undermining the analysis.

The assessment of impacts of a policy can be made individually on each metric chosen for the analysis, considering (1) intended and unintended outcomes, (2) alignment with the direction expected/desired, (3) its magnitude, (4) the degree of uncertainty or confidence in the outcome, (5) the likelihood of extreme events taking place, and (6) the option generation potential. In order to separate assessment from politics, a multidimensional analysis, estimated independently for each relevant dimension, is used. A relative normative valuation of policy outcomes can subsequently be carried out separately, with or without sophisticated quantitative methods, by independent actors who possess the political legitimacy to do so, but this lies outside of the ROA methodology (e.g. see the European Commission's impact assessment guidelines (EC, 2015)).

In practice this means that analysts report risks and opportunities in multiple dimensions relevant to the problem and leave the valuation of each of these dimensions to be done by policy-makers. The latter can evaluate the information and choices to be made in the context of stated multidimensional objectives and their knowledge of stakeholder needs and their diversity.

3.7. Normative principles for policymaking in a context of risk and opportunity

While this paper is methodological in focus and does not itself present policy recommendations, some normative principles can be derived from complexity science analysis that can usefully frame policy problems in the context of structurally transformative change.

3.7.1. Whether to act at all

The foundational normative principle for policy-making under the Coase Theorem and market failure framework is to develop one policy response per identified market failure (Coase, 1960; Hanley, Shogren and White, 2016; Lehmann et al., 2019). In a complex system with continuous endogenous change, or where the exogenous context changes faster than equilibrium can be reached, finding the optimal policy requires a search through an infinitely large set of possible futures branching out from one another. It therefore cannot be identified in practice, as the expected future dynamic efficiency of a complex system (Abel et al., 1989) can only be known under heavy-tailed unquantifiable uncertainty.

A foundational normative principle suitable for dynamical systems, inferred from the use of ROA, is to act to prepare for change that is likely to bring about options for change that is desirable, and to avoid change that is undesirable (Marchau et al., 2019). This is conceptually connected to the central normative principle of the 'market shaping' framework (Mazzucato and Penna, 2016) that has been used to support the development of so-called 'mission-oriented policies', including for example the 'Grand Challenges' in the UK government's Industrial Strategy (UK Government, 2017). It is applicable as a rationale for any policy that is intended to achieve structurally transformative change, or that takes place in a context of structurally transformative change.

3.7.2. How much effort to make

A basic normative principle of welfare economics is that effort to correct a market failure should be applied up to the level at which the marginal benefits of action are equal to the marginal costs of that action, thereby suggesting that this should be reliably identified. This is generally defended on the basis of an idealised normative utilitarian moral philosophy framework of social justice. However, given that real world agents are not necessarily utilitarians (Sahlins, 1972; Douglas and Isherwood, 1979; Wilk and Cliggett, 2007; Graeber, 2014), it is not an empirically validated description of human behaviour.

For non-marginal change, 'optimality' cannot reliably be identified because outcomes are heavy-tailed uncertain. A second normative principle inferred from ROA methodology is that sufficient policy effort may be applied to kick-start self-generating change over time (Farmer et al., 2019). This considers the observed effectiveness of policy in relation to the dynamic processes that it aims to influence in its stated objective. Notably, if a government invests in the development of a new low carbon technology but abandons support for it before it is successfully commercialised, self-generating increasing returns may never materialise, and the investment could be wasted. For example, UK offshore wind subsidies (see section 4; initially £100 /MWh, or over £200/tCO_2e abated) successfully helped drive the technology to market parity, while the current official value of emissions reductions in the UK was £14/tCO_2e for the power sector and £59/tCO_2e in other sectors. Had the official value been used to design the policy to support offshore wind following a market failure rationale, it would likely have failed.

3.7.3. Where to direct the effort

When a single marginal market failure is identified, standard economic theory contends that externality pricing or compensation mechanisms can be applied after which the market is expected to allocate resources optimally. In cases where structurally transformational change is possible (as for instance newly defined in the 2020 update to the UK's Green Book following an internal review, see HM Treasury, 2020b, 2020a), optimal states are not reliably identifiable, while some policies may be more effective in incentivising change towards stated objectives than others. A suitable normative principle is therefore not allocative efficiency, but dynamic effectiveness (Kattel et al., 2018). It may be most effective to act on known points of greatest known leverage (Farmer et al., 2019).

Applied to the pricing value of externalities, this principle suggests that the most effective approach may not necessarily be a uniform price across the whole economy, as would be inferred from welfare economics, but rather, prices targeted in specific sectors, set at specific levels that are estimated as likely to catalyse change (Kay, 2012; King et al., 2015). For example, in UK electricity, dramatic emissions reductions have been achieved with a total carbon price of around £35/tCO_2e, while the existing petrol fuel duty, corresponding to an implicit carbon price of £238/tCO_2e, and has had marginal impact. This principle also suggests that there is no reason to expect, *a priori*, pricing itself to be an effective policy, and that other forms of targeted policy may be equally or more effective (notably, regulation). That policy should be 'technology neutral' does not appear to be supported by the evidence; what appears to matter is to be effective at picking winners not losers (Mazzucato, 2012; Klingebiel and Rammer, 2014; Carreras, 2020).

3.7.4. Economic change, systems design and future-proofing

There exists a trade-off between optimising the performance of a dynamical system under constant observed conditions, and maintaining its resilience to unforeseen circumstances (Doyle and Carlson, 2000; Carlson and Doyle, 2002). Take for example technology choice in climate policy. Recent debate focused on the need for substantial negative emissions later this century to compensate for near-term emissions, a result from scenarios developed on the basis of systems optimisation, ultimately strongly influenced by discounting procedures (IPCC, 2018). This may be a risky and false narrative underplaying real systemic risk, where emissions today contribute to the accumulation of risk of possible future climate tipping points being triggered, a risk not fully mitigated by assuming future negative emissions. This suggests the principle that optimising excessively the short-term performance of policy strategies may affect the long term resilience of the system or program.

4. Policy domains where ROA could make a difference

In this section we describe two case studies, to explore both the limitations of cost-benefit analysis and equilibrium or optimisation-based appraisal, and the potential lessons from the use of a Risk-Opportunity Analysis approach. The first is historical, while the second is prospective. While space does not allow a detailed application of Risk-Opportunity Analysis in these case studies, they provide lessons that can help develop and shape Risk-Opportunity Analysis exercises.

4.1. Looking back: The success story of UK offshore wind policy and industry

In just over a decade offshore wind has evolved from an expensive, immature technology, to one that is competitive with fossil fuel generation. Costs fell from around £170/MWh in 2008, to around £40/MWh for projects coming online in the UK in 2023 (Farmer and Lafond, 2016; Rechsteiner, 2020; Jennings et al., 2020), cementing its economic attractiveness and future contribution to electricity generation, and producing the wider economic benefits that the growth of a substantial new industry with a global market brings. This outcome is largely the result of strong, well-targeted, and sustained policy support from the UK government.

To achieve its legally binding target of 10% of electricity generated from renewables by 2010, in 2002 the UK government introduced the Renewables Obligation (RO); a technology-neutral tradable green certificate mechanism providing subsidy to qualifying technologies in addition to the market price of electricity. In 2009, when the UK formally agreed to achieve 15% of final energy consumption from renewable sources under the EU's Renewable Energy Directive (to be achieved through, *inter alia*, 30% of electricity from renewables), the government introduced technology 'banding'; awarding more RO Certificates (ROCs) to less mature technologies to encourage their development, with offshore wind receiving two ROCs per unit of generation. The RO had no cap on budget or capacity, and the government held levers to ensure the price of ROCs remained stable. In 2008–09, three other key enabling policies and measures were introduced:

(1) In June 2008, the British Crown Estate auctioned rights for space for over 32 GW of wind capacity and invested £80 million of co-funding for developments.
(2) In October 2008, the Offshore Wind Accelerator (OWA) was launched jointly by the government and nine leading offshore wind developers to accelerate cost reductions and technology reliability via RD&D.
(3) With the EU's Third Energy Package requiring electricity transmission and generation assets to have separate ownership, the UK regulator began awarding transmission operator licences via competitive tendering, which allowed low-risk transmission infrastructure to receive reduced costs of capital.

The stability, long-term security, and relative generosity of the RO subsidy for offshore wind, coupled with these supporting measures, provided developers space to experiment, for the industry to form, core technical knowledge to grow, and 'learning-by-doing' to develop across the supply chain, including in the financial sector (Jennings et al., 2020).

In 2013, the RO was replaced by a Contracts-for-Difference (CfD) scheme, in which new renewable capacity is sought in 'rounds', to which eligible renewable generators applied to receive a fixed 'strike price' for 15 years of generation capacity. If the market price for electricity falls below the strike price, the government pays the difference. If the market price exceeds the strike price, the generator pays the government the difference. In 2014/15 the process became fully auction-based, with capacity allocated across 'Pot 1′ (more mature technologies, including onshore wind and solar PV), and 'Pot 2′ (less mature technologies, including offshore wind). For each pot, the lowest bids across technologies received contracts until the capacity available in each pot is satisfied. In Round 1 in 2015, 1.2 GW of offshore wind contracts were granted in Pot 2–54% of supported capacity (BEIS, 2019a). Shortly afterwards, support for solar PV and onshore wind (Pot 1 technologies) with the majority of new CfD support then focused on Pot 2 only, and particularly offshore wind. In Rounds 2 and 3 in 2017 and 2019, offshore wind represented around 95% of all newly contracted capacity (BEIS, 2019c, 2019b). In 2019, the government and offshore wind industry agreed the Offshore Wind Sector Deal (OWSD), guaranteeing CfD action rounds every two years to achieve at least 30 GW of deployment to 2030 (subsequently increased to 40 GW in late 2020, as the first aim of the Prime Minister's Ten Point Plan for a Green Industrial Revolution', see HM Government, 2020), along with measures such as local content requirements and an aim to treble the size of the UK offshore wind workforce (HM Government, 2019).

In contrast to the RO, the CfD mechanism held an explicit objective of reducing costs of the now-maturing technology through competition, encouraged by a target, set in 2012 by the government's Offshore Wind Cost Reduction Task Force (CRTF), of achieving costs of £100/MWh by 2020. The CfDs, with the long-term commitments made in the OWSD, provided the industry with sufficient confidence to build on the developments made under the RO regime and invest in future growth and innovation. This generated economies of scale in local manufacturing capacity, the size of the turbines, and the number of turbines in a single project; investment in developing specialist support technologies (such as bespoke installation and maintenance vessels) and workforces and skills (both of which were previously repurposed from the oil and gas industry); and other improvements and efficiencies produced by continued learning-by-doing. The stable long-term support regime, coupled with increasing project size and accumulating experience also attracted a wider range of investors, further reduced finance costs.

Broadly, the cost reductions achieved have been the result of a combination of well-designed and context-appropriate 'technology-push' and 'demand-pull' policies, dominated first by the RO to encourage commercialisation, and then by the CfD to introduce competition once the technology was near maturity. But, throughout, these instruments were supported by both high-level, long-term commitments to the technology, and by more granular enabling measures to address specific barriers to development and diffusion.

A key aspect of this success story is that decisions that led to the creation of this policy framework were made based on the need to meet overarching legal EU commitments, and strategic considerations on which sectors and technologies would be most appropriate to achieve these commitments, based on metrics other than static cost considerations. Even considering indirect and non-financial benefits, CBA would not likely have supported the policy strategy that emerged, for its lack of understanding of business opportunity. Through the initial RO subsidy mechanism, offshore wind benefited from £100 per MWh (DECC, 2013; Jennings et al., 2020), which corresponds to a subsidy exceeding £200/tCO_2e (at the prevailing carbon intensity of power), in comparison to the value of carbon emissions in UK policy appraisal of £14/tCO_2e in the power sector and £59/tCO_2e in other sectors, used in CBA exercises. Through a traditional CBA paradigm, this would have seemed disproportionately large and unsound value for money when introduced, as other emissions reductions options existed at much lower (but static) cost.

Instead, offshore wind cost reduction was an explicit objective of the policy framework, alongside the development of industrial and supply chain capabilities. In the 2019 CfD auction, Offshore Wind projects cleared below estimated wholesale prices, raising the prospect that Offshore Wind could be 'subsidy free' depending on future wholesale electricity prices. New projects are now more likely than ever to generate direct revenue to the public purse, with the UK well positioned to export offshore wind technology, knowledge and services, to ever-expanding international markets.

4.2. Going forwards: Transition policies in passenger road transportation

Technology changes continuously, with or without policy changes, as preferences and industrial processes co-evolve with new technologies diffusing in consumer and industry markets. Policy can alter and accelerate those trajectories. As technologies evolve, costs reduce, further increasing their attractiveness to users, creating self-reinforcing and path-dependent trajectories of technology evolution. This is particularly important in consumer-driven markets such as for vehicles.

The Future Technology Transformations (FTT) model is a simulation model looking at technology competition and diffusion in markets (Mercure et al., 2014; Mercure et al., 2018a; Mercure et al., 2018b; Vercoulen et al., 2018; Knobloch et al., 2019). The diffusion process is modelled through the principle that technology adoption is determined by both preferences and technology access or prevalence. However, preferences in turn depend on costs and other considerations, while technology prevalence determines its availability. In other words, costs influence levels of technology adoption while levels of technology adoption in turn affect costs. Costs decline through a standard learning curve function of the cumulative production of technology, where increasing scale of production induces lower costs. The combination of both cost reductions and diffusion generates a reinforcing feedback, in which expanding scale leads to lower costs which attract more consumers, while more consumers expand the diffusion scale further.

These co-evolutionary dynamics can lead to avalanche effects, or alternatively, failure in the marketplace, depending on a range of factors including prevalent infrastructure, policy and consumer preferences. As discussed with offshore wind power, sufficient policy support can overcome initial hurdles and trigger an avalanche, if it brings its cost below parity with competitors, while insufficient or inappropriate policy might fail to reach that stage. Furthermore, policy instruments can synergise with one another - especially combinations of technology-push

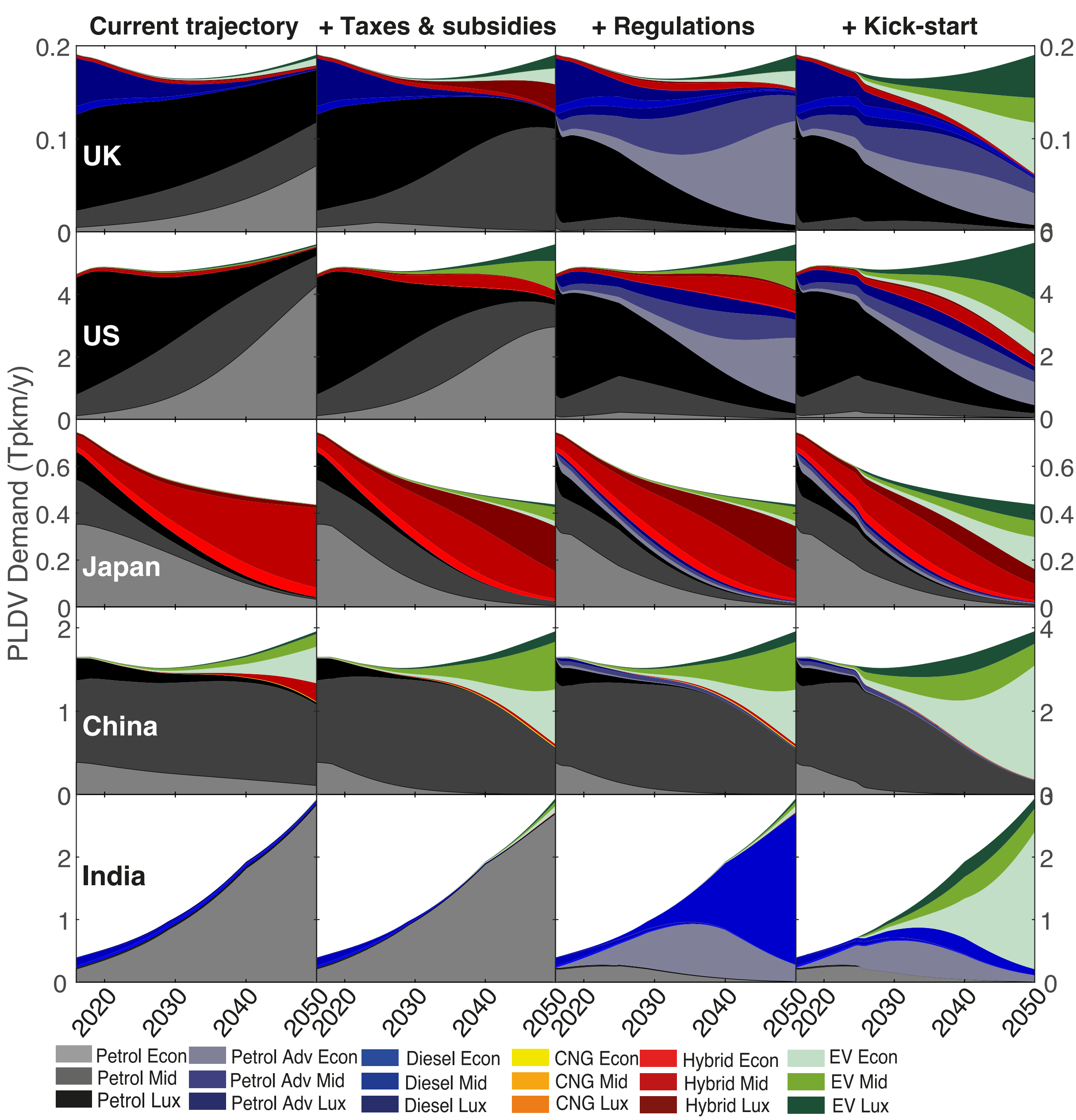

Fig. 4. Policy portfolios for road transport in five major economies. Derived from simulations performed in Lam & Mercure (Lam and Mercure, 2021).

and market-pull instruments, have greatest influence at two different points of the innovation and diffusion lifecycle – which can be harnessed to accelerate change. However, instruments can also conflict with each other, which may decelerate or even halt further diffusion and development.

Financial support can generate avalanches, but non-financial policy can also alter the way technologies win and lose market share, for instance with regulations, industry mandates and public procurement, or other programs that aim at shaping industry and markets. For a policy instrument such as a carbon tax to be effective, alternative low-carbon technologies or behaviours must be available to consumers. For example, if the purchase of petrol and diesel vehicles is taxed but electric vehicles or public and active transport options are prohibitively expensive, or otherwise unattractive or unavailable, then consumers must simply shoulder the cost with minimal benefit. Combining financial incentives with market-shaping action can synergise in unexpected ways.

Such a proposition is very different from the market failure narrative in which one expects to use just one policy instrument per market failure. With the FTT:Transport model, it was found that multiple financial incentives tend to interfere with one another, while taxes tend to synergise with industry mandates and fuel economy regulations; however, these effects are strongly market context and region-dependent (Lam and Mercure, 2021).

ROA can be carried out by searching through policy space, seeking to maximise synergies and minimise interference. Fig. 4 shows the impacts of different types of policies in FTT over time, as they are sequentially added, in five major vehicle markets starting from their present-day configuration. What can be seen is that, first, the diffusion of vehicles is path-dependent and never in an equilibrium, with or without directional policies, as different technologies of different competitiveness compete in markets with evolving contexts. Second, taxes and subsidies, on their own, have some impact at re-orienting the direction of diffusion, by re-scaling relative preferences. However, the addition of fuel economy or phase-out regulations clearly help shape emissions reductions further. Most interestingly, it is the so-called 'kick-start' EV industry mandate policy that really magnifies the effect of the taxes on EV uptake and overall emissions (Lam and Mercure, 2021).

Due to learning-by-doing, the diffusion of EVs eventually can become self-sustaining, such that the taxes and subsidies are no longer necessary, especially once the numbers of EVs become large, the availability of conventional vehicles goes into decline, and the surrounding socio-technical system becomes reconfigured. There may even exist a point of no return. At that stage, the situation reverses as it becomes increasingly difficult for consumers to acquire conventional vehicles as they are manufactured in ever smaller numbers, and for that reason, their costs increase as vehicle parts become increasingly scarce.

This path-dependent evolution of technology fleets, which incorporates learning, choice and diffusion, is highly non-linear, and therefore features important uncertainty. The FTT model could in principle be mis-specified, or incorrectly parameterised. Thus, the percentage of electrification of fleets that can be expected in 2050 is highly uncertain and could turn out substantially different from FTT projections. Indeed, that uncertainty increases exponentially with the time span of the projection, as slightly different storylines differ more and more to become entirely dissimilar by 2050. The non-linearity represented in FTT exists in the real world, and this indicates that there is an inherent limit to which technology diffusion can be accurately projected. This therefore requires to carry out detailed sensitivity analyses to provide policy-makers with reliable ranges of expected outcomes of policies.

Additional feedbacks with the economy should be modelled, to identify risks of further direct and indirect impacts on jobs, income and structural change in the economy, which may warrant the development of policies to mitigate wider socio-economic effects (Mercure et al., 2018a). The system can also be simulated in tandem with other low-carbon sectors such as power generation to ensure coherence and consistency and avoid moving risks to other sectors (Knobloch et al., 2020). Finally, the wider opportunities of investment in low-carbon mobility could be explored in relation with the opportunities generated by new technologies, notably batteries, in separate technological sectors.

An ROA exercise for informing EV policy therefore should take a shape similar to what led to the UK offshore wind success story: iterative and adaptive policy-making. At each step of the way, uncertainty is reduced by new market information, which allows to re-evaluate options on the basis of ever-better informed projections using non-linear vehicle adoption models. The models are used to evaluate what it takes to reach the target (from public budgets, consumers and companies, see (Lam and Mercure, 2021)), against the risks and opportunities generated by the induced market transformation. Further modelling exercises can be carried out to estimate dynamically the risks and opportunities arising, with uncertainty bounds, in separate sectors outside of transport and across the wider economy (Mercure et al., 2018b; Knobloch et al., 2020).

5. Conclusion

The next steps in developing a Risk-Opportunity Analysis framework to improve or replace welfare economics-based policy assessment lie in laying out a framework development roadmap. This roadmap should be co-created in close collaboration with stakeholders and users of the framework. Ideally, this should include actors involved in purposes such as *regulating, accounting* and *strategising.* Indeed, such a framework must respond to the needs of existing science-policy interfaces, which must be identified using an expansive engagement program between scientists and decision-makers.

A first part of the roadmap must involve an intensive dissemination program around the concepts of complexity science applied to decision-making (dynamics, heterogeneity, uncertainty). A second part should involve developing clear context-dependent guidelines on how to use this framework under diverse situations and problems. The risk-opportunity assessment framework proposed here is as defensible on grounds of social justice and legitimacy as are cost-benefit analyses, multi-criteria assessments and other welfare-economics based policy assessments. However, it makes more appropriate use of, and is more transparent of concerning, imperfect information and uncertainty inherent in processes of structural, non-marginal change.

It may be argued that welfare economics and equilibrium-based analysis and decision-making methods have not helped governments see clearly the best opportunities to drive the rapid, structural techno-economic change that is needed to meet climate change goals. As Stern writes, *'The economic response [to climate change] has to be very large, involve dynamic increasing returns, changed economic and urban organisation and design, and the avoidance of potential lock-ins'* but *'we have seen models predominate where these elements, the guts of the story, are essentially assumed away'* (Stern, 2018). When society faces great challenges, economic analysis that assumes away the most important considerations can lead to unease and distrust of economics and economists on the part of policy-makers and the public (Haldane and Turrell, 2018). A stronger science-based decision framework may be an important part of the solution.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Abel, A.B., Mankiw, N.G., Summers, L.H., Zeckhauser, R.J., 1989. Assessing Dynamic Efficiency: Theory and Evidence. Rev. Economic Stud. 56 (1), 1–19.
Ackerman, F., Heinzerling, L., 2002. Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection. University of Pennsylvania Law Review 150 (5), 1553. https://doi.org/10.2307/3312947.
Aldred, J., 2009. Ethics and Climate Change Cost-Benefit Analysis: Stern and After. New Political Economy 14 (4), 469–488.
Arthur, W.B., 1999. Complexity and the Economy. Science 284 (5411), 107–109.
Arthur, W.B., Durlauf, S.N., Lane, D.A., 1997. The economy as an evolving complex system II. Westview press (Santa Fe Institute studies in the sciences of complexity).
Bank of England, 2021. Stress testing the UK banking system: Key elements of the 2021 stress test. Available at: https://www.bankofengland.co.uk/stress-testing/2021/key-elements-of-the-2021-stress-test.
Banque de France, 2020. Scenarios and main assumptions of the ACPR pilot climate exercise. Available at: https://acpr.banque-france.fr/sites/default/files/medias/documents/20200717_main_assumptions_and_scenarios_of_the_acpr_climate_pilot_exercise.pdf.
Baram, M.S., 1980. 'Cost-benefit analysis: an inadequate basis for health, safety, and environmental regulatory decision-making.', Ecology Law Quarterly. doi: 10.15779/Z384V6C.
Bateman, I.J., et al., 2002. Economic valuation with stated preference techniques: a manual. Edward Elgar Publishing Ltd, Cheltenham.
BEIS, 2019a 'CFD Auction Allocation Round One'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/407465/Breakdown_information_on_CFD_auctions.pdf.
BEIS, 2019b. 'Contracts for Difference Allocation Round 3 Results'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/915678/cfd-ar3-results-corrected-111019.pdf.
BEIS, 2019c. 'Contracts for Difference Second Allocation Round Results'. Available at: source: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/643560/CFD_allocation_round_2_outcome_FINAL.pdf.
Battiston, S., et al., 2017. A climate stress-test of the financial system. Nat. Clim. Change. 7 (4), 283.
Carlson, J.M., Doyle, J., 2002. Complexity and robustness. Proc. Natl. Acad. Sci. 99 (Supplement 1), 2538–2545.
Carreras, M., 2020. 'Investigating the Role of BNDES as a Tool to Transmit Countercyclical Policy Decisions: Evidence from 2002-2016'. SPRU Working Paper Series 2020-02.
Château, J., Dellink, R.. Lanzi, E., 2014. 'An Overview of the OECD ENV-Linkages Model', (65). doi: 10.1787/5jz2qck2b2vd-en.
Coase, R.H., 1960. The Problem of Social Cost. The Journal of Law and Economics 56 (4), 837–877.
Cont, R., Schaanning, E., 2017. Fire sales, indirect contagion and systemic stress testing. SSRN. https://doi.org/10.2139/ssrn.2541114.
Day, R.H., 1992. Complex economic dynamics: obvious in history, generic in theory, elusive in data. J. Appl. Econometrics. Wiley Online Library 7 (S1), S9–S23.
DECC, 2013. Investing in renewable technologies – CfD contract terms and strike prices. London.
Dietz, S., Hepburn, C., 2013. Benefit–cost analysis of non-marginal climate and energy projects. Energy Econ. 40, 61–71.
Dikau, S., Volz, U., 2021. Central bank mandates, sustainability objectives and the promotion of green finance. Ecol. Econ. 184, 107022. https://doi.org/10.1016/j.ecolecon.2021.107022.
DNB, 2018. An energy transition risk stress test for the financial system of the Netherlands. Available at: https://www.dnb.nl/media/pdnpdalc/201810_nr-_7_-2018-_an_energy_transition_risk_stress_test_for_the_financial_system_of_the_netherlands.pdf.
Douglas, M., Isherwood, B., 1979. The world of goods: Towards an anthropology of consumption. Routledge.
Doyle, J., Carlson, J.M., 2000. Power laws, highly optimized tolerance, and generalized source coding. Phys. Rev. Lett.. APS 84 (24), 5656.
EC, 2015. Better Regulation Guidelines, European Commission Report. Available at: http://ec.europa.eu/smart-regulation/guidelines/docs/swd_br_guidelines_en.pdf.
EPA (2014) Guidelines for Preparing Economic Analyses. Available at: https://www.epa.gov/sites/production/files/2017-08/documents/ee-0568-50.pdf.
Farmer, J.D., Hepburn, C., Mealy, P., Teytelboym, A., 2015. A Third Wave in the Economics of Climate Change. Environ Resource Econ 62 (2), 329–357. https://doi.org/10.1007/s10640-015-9965-2.
Farmer, J.D., et al., 2019. Sensitive intervention points in the post-carbon transition. Science. https://doi.org/10.1126/science.aaw7287.
Farmer, J.D., Lafond, F., 2016. How predictable is technological progress? Res. Policy 45 (3), 647–665. https://doi.org/10.1016/j.respol.2015.11.001.
Fontana, G., 2008. Money, uncertainty and time. Routledge.
Fouquet, R., 2016. Historical energy transitions: Speed, prices and system transformation. Energy Res. Social Sci. 22, 7–12. https://doi.org/10.1016/j.erss.2016.08.014.
Freeman, C., Louçã, F.-L.-B.-F., 2001. As time goes by: from the industrial revolutions to the information revolution. Oxford University Press.
Geels, F.W., Berkhout, F., van Vuuren, D.P., 2016. Bridging analytical approaches for low-carbon transitions. Nature Clim Change 6 (6), 576–583. https://doi.org/10.1038/NCLIMATE2980.
Graeber, D., 2014. Debt: The first 5,000 years. Melville House.
Grübler, A., Nakićenović, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. Energy Policy 27 (5), 247–280.
Haldane, A.G., Turrell, A.E., 2018. 'An interdisciplinary model for macroeconomics', Oxford Review of Economic Policy, 34(1–2), pp. 219–251.
Hanley, N., Barbier, E.B., 2009. Pricing nature: cost-benefit analysis and environmental policy. Edward Elgar Publishing.
Hanley, N., Shogren, J.F., White, B., 2016. Environmental economics: in theory and practice. Macmillan International Higher Education.
HM Government, 2019. Industrial strategy: Offshore wind sector deal. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/790950/BEIS_Offshore_Wind_Single_Pages_web_optimised.pdf.
HM Government, 2020. Ten point plan for a green industrial revolution. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf.
HM Treasury, 2020a. Green Book Review 2020. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/937700/Green_Book_Review_final_report_241120v2.pdf.
HM Treasury, 2020b. The Green Book - Central Government Guidance on Appraisal and Evaluation.
HM Treasury, 2020c. Orange Book: Management of risk - Principles and Concepts.
HSS, 2016. Guidelines for Regulatory Impact Analysis.
Hughes, N., Strachan, N., Gross, R., 2013. The structure of uncertainty in future low carbon pathways. Energy Policy 52, 45–54.
IPCC, 2018. Global Warming of 1.5 °C: an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate chang. IPCC.
Jennings, T. et al., 2020. Policy, innovation and cost reduction in UK offshore wind. Report for the Carbon Trust. Available at: https://www.carbontrust.com/resources/policy-innovation-and-cost-reduction-in-uk-offshore-wind.
Kattel, R., et al., 2018. The economics of change: Policy and appraisal for missions, market shaping and public purpose Policy Report. Institute for Innovation and Public Purpose The.
Kauffman, S.A., 2000. Investigations. Oxford University Press.
Kay, J., et al., 2012. Complex New World: Translating new economic thinking into public policy. Institute for Public Policy Research, London. Available at: https://www.ippr.org/files/images/media/files/publication/2012/09/complex-new-world_Aug2012_web_9499.pdf.
Keynes, J.M., 1921. A treatise on probability. Macmillan & Co, London.
King, D. et al., 2015. Climate Change: A Risk Assessment. Report for the UK Foreign and Commonwealth Office. Available at: https://www.csap.cam.ac.uk/media/uploads/files/1/climate-change–a-risk-assessment-v11.pdf.
Klingebiel, R., Rammer, C., 2014. Resource allocation strategy for innovation portfolio management: Resource Allocation Strategy for Innovation Portfolio Management. Strat. Mgmt. J. 35 (2), 246–268.
Knobloch, F., et al., 2019. Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5 °C. Energ. Effi. 12 (2), 521–550. https://doi.org/10.1007/s12053-018-9710-0.
Knobloch, F., Hanssen, S.V., Lam, A., Pollitt, H., Salas, P., Chewpreecha, U., Huijbregts, M.A.J., Mercure, J.-F., 2020. Net emission reductions from electric cars and heat pumps in 59 world regions over time. Nat Sustain 3 (6), 437–447.
Kriegler, E., Petermann, N., Krey, V., Schwanitz, V.J., Luderer, G., Ashina, S., Bosetti, V., Eom, J., Kitous, A., Méjean, A., Paroussos, L., Sano, F., Turton, H., Wilson, C., Van Vuuren, D.P., 2015. Diagnostic indicators for integrated assessment models of climate policy. Technol. Forecast. Soc. Chang. 90, 45–61.
Lam, A., Mercure, J.-F., 2021. Which policy mixes are best for decarbonising passenger cars? Simulating interactions among taxes, subsidies and regulations for the United Kingdom, the United States, Japan, China, and India. Energy Res. Social Sci. 75, 101951. https://doi.org/10.1016/j.erss.2021.101951.
Lehmann, P., Sijm, J., Gawel, E., Strunz, S., Chewpreecha, U., Mercure, J.-F., Pollitt, H., 2019. Addressing multiple externalities from electricity generation: a case for EU renewable energy policy beyond 2020? Environ Econ Policy Stud 21 (2), 255–283.
Marchau, V.A.W.J., et al., 2019. Decision making under deep uncertainty: From theory to practice. Springer Nature.
Markowitz, H., 1952. Portfolio Selection. J. Finance 7 (1), 77–91.
Mazzucato, M., 2012. The entrepreneurial state. Soundings 49 (49), 131–142. https://doi.org/10.3898/136266211798411183.
Mazzucato, M., Penna, C.C.R., 2016. Beyond market failures: the market creating and shaping roles of state investment banks. Journal of Economic Policy Reform 19 (4), 305–326.
Meifort, A., 2016. Innovation Portfolio Management: A Synthesis and Research Agenda: Innovation Portfolio Management. Creativity Innovation Management 25 (2), 251–269.

Mercure, J.-F., 2015. An age structured demographic theory of technological change. J Evol Econ 25 (4), 787–820. https://doi.org/10.1007/s00191-015-0413-9.

Mercure, J.-F., et al., 2016. Modelling complex systems of heterogenous agents to better design sustainability transitions policy. Global Environ. Change 37, 102–115. https://doi.org/10.1016/j.gloenvcha.2016.02.003.

Mercure, J.-F., Pollitt, H., Chewpreecha, U., Salas, P., Foley, A.M., Holden, P.B., Edwards, N.R., 2014. The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector. Energy Policy 73, 686–700.

Mercure, J.-F., 2018. Fashion, fads and the popularity of choices: Micro-foundations for diffusion consumer theory. Struct. Change Economic Dyn. 46, 194–207. https://doi.org/10.1016/j.strueco.2018.06.001.

Mercure, J.-F., Lam, A., Billington, S., Pollitt, H., 2018a. Integrated assessment modelling as a positive science: private passenger road transport policies to meet a climate target well below 2 ∘C. Clim. Change 151 (2), 109–129. https://doi.org/10.1007/s10584-018-2262-7.

Mercure, J.-F., Pollitt, H., Viñuales, J.E., Edwards, N.R., Holden, P.B., Chewpreecha, U., Salas, P., Sognnaes, I., Lam, A., Knobloch, F., 2018b. Macroeconomic impact of stranded fossil fuel assets. Nature Clim Change 8 (7), 588–593. https://doi.org/10.1038/s41558-018-0182-1.

Mokyr, J., 1992. Technological Inertia in Economic History. J. Eco. History 52 (2), 325–338.

Nordhaus, W.D., 2017. Revisiting the social cost of carbon. Proc. Natl. Acad. Sci. 114 (7), 1518–1523.

Pindyck, R.S., 2017. The Use and Misuse of Models for Climate Policy. Review Environ. Economics Policy 11 (1), 100–114.

Porter, M.E., 1996. What is strategy? Harvard Bus. Rev. 74 (6), 61–78.

Rechsteiner, R., 2020. German energy transition (Energiewende) and what politicians can learn for environmental and climate policy. Clean Techn Environ Policy 23 (2), 305–342.

Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci 4 (2), 155–169.

Sahlins, M., 1972. Stone age economics. Taylor & Francis.

Schumpeter, J.A., 1939. Business Cycles. McGraw-Hill.

Schwarcz, S.L., 2019. Systematic Regulation of Systemic Risk. L. Rev. HeinOnline, Wis, p. 1.

Stern, N., 2007. The Economics of Climate Change. Cambridge University Press, Cambridge, UK.

Stern, N., 2018. Public economics as if time matters: Climate change and the dynamics of policy. J. Public Economics 162, 4–17.

Stern, N.-L.-B.-S., 2015. Why are we waiting?: The logic, urgency, and promise of tackling climate change. Mit Press.

Takeda, S., Arimura, T.H., 2021. A computable general equilibrium analysis of environmental tax reform in Japan with a forward-looking dynamic model. Sustain Sci 16 (2), 503–521. https://doi.org/10.1007/s11625-021-00903-4.

UK Government, 2017. Grand Challenges: Building a Britain fit for the future. Available at: https://www.gov.uk/government/publications/industrial-strategy-building-a-britain-fit-for-the-future.

Vercoulen, P. et al. (2018) 'Decarbonizing the East Asian steel industry in 2050'.

Way, R., Lafond, F., Lillo, F., Panchenko, V., Farmer, J.D., 2019. Wright meets Markowitz: How standard portfolio theory changes when assets are technologies following experience curves. J. Econ. Dyn. Control 101, 211–238. https://doi.org/10.1016/j.jedc.2018.10.006.

Weitzman, M.L., 2009. On Modeling and Interpreting the Economics of Catastrophic Climate Change. Rev. Econ. Stat. 91 (1), 1–19.

Weng, Y., Zhang, D., Lu, L., Zhang, X., 2018. A general equilibrium analysis of floor prices for China's national carbon emissions trading system. Climate Policy 18 (sup1), 60–70.

Wilk, R.R., Cliggett, L.C., 2007. Economies and cultures: foundations of economic anthropology. Westview press.

Yu, H.J.J., Popiolek, N., Geoffron, P., 2016. Solar photovoltaic energy policy and globalization: a multiperspective approach with case studies of Germany, Japan, and China: Globalization effects on photovoltaic policy mechanisms. Prog. Photovolt: Res. Appl. 24 (4), 458–476.