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Sunset and sunrise business strategies shaping national energy transitions

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ABSTRACT

Energy intensive processes are embedded in the socio-economic and political fabric of our societies; therefore a "green industrial revolution" entails major technical achievements and profound social transformations. In this uncertain landscape, businesses face a crucial but difficult position: they need to manage the decline of their legacy assets, are expected to provide stable employment, and must contribute to national energy resilience and security. As such, significant societal risks are associated to business positioning towards decarbonisation. This paper describes "sunset" versus "sunrise" corporate strategies and their interconnections with market developments, citizens, and government's support to low-carbon transitions. Using a qualitative System Dynamics approach, the paper highlights vicious and virtuous feedback mechanisms where accumulations and tipping points may arise. While defensive strategies to preserve fossil-based assets may appear rational in the short-term, they can have deleterious long-term effects for business and society. The main risks stem from the creation of stranded physical, financial, and human assets. On the contrary, incumbents can increase market certainty and generate industry-society co-benefits by engaging in skills transfers and sending clear innovation signals to investors. The findings, synthetised in a Causal Loop Diagram highlighting key variables and delays, constitute a building step towards improving the realism of energy systems modelling. The study also provides a discussion on centralisation and the political power dynamics of national energy transitions.

1. The criticality of socio-political perspectives in industrial decarbonisation

Industrial activities are part of the historical fabric of our societies [1]. This occurs through housing, heating, transportation, and the consumption of goods and services, but also via the provision of jobs, economic stability, and the underpinning national skill base. Therefore, transitioning to low-carbon energy processes entails important techno-economic innovations but also entire regime disruptions at socio-technical, socio-economic and political levels, a "co-evolution of systems and sub-systems" [2].

Industrial and business emissions together account for a quarter of emissions globally [3] and about 22% of total emissions in the UK [4]. In many countries, industrial decarbonisation must play a vital role towards the Paris agreements goal to mitigate greenhouse gas emissions and keep warming below 1.5 °C–2 °C above preindustrial levels [5]. 140 countries globally have either committed to or have announced they are considering net-zero targets [6]. Via the European Green Deal, the EU has announced updates to its Industrial emissions directive and Industrial Strategy to help industries navigate long term green transitions and support green and digital transformations [7,8]. The Industrial decarbonisation strategy commissioned by the UK sets out its support to innovations and the development of a low-carbon market [4]. Independent organisations such as the Climate Change Committee (CCC) for the UK and the "Advisory board" for the EU are advising governments on climate change mitigation strategies while keeping track of advancements or missed milestones on NDCs targets [9,10].

While early research on decline pictured industries as facing a limited number of external pressures, the sustainability transition literature defines low-carbon transitions as a broader set of socio-technical systems and sub-systems which are multi-level and co-evolutionary in nature [2]. This societal transformation is driven by landscape pressures -climate regulations, public concern, global threat - together with emerging technologies, and creates disruption not only for incumbents but for the whole supply, demand and distribution system [11,12]. For instance, as great a challenge as industrial decarbonisation would be in isolation, industries are facing growing public and shareholder scrutiny to operate in accordance with appropriate

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environmental, social and governance practices (ESGs) [13,14].

Seminal systems studies and frameworks of the sustainability transitions literature, such as the multi-level perspective (MLP), the three perspectives, and technological innovation systems (TIS) have called for more socio-political depth in transitions studies, especially pertaining to socio-technical and industrial energy transitions [2,15,16]. Geels and Turnheim reiterated these considerations and the need for a multidimensional view of actors and "reconfigurational" approaches to low-carbon transitions [17]. Kungl and Geels propose that research and policy should bring a broader inter-disciplinary exploration to the destabilisation of existing regimes [15,18], while Rosenbloom and Rinscheid argue research must intensify efforts to engage with the "deliberate decline" of both technologies and practices in carbon-intensive systems, including its pivotal mechanisms of phase-out (rooted in policy regulations) and divestment (rooted in civil movements seeking to erode the license to operate of fossil fuels by asking shareholders to divest their investments) [19]. There is growing interest from governments and academics alike for "whole-system approaches" to societal transformations studies [20]. Yet, strategic corporate management has rarely been researched in the full context of national and global energy transitions [11], and only a few contributions explored socio-technical transitions associated to energy systems with System Dynamics principles [21–23]. Walrave and Raven have initiated a SD simulation modelling focused on TIS dynamics [24] while Walz and all used SD for an integrated TIS and MLP study of wind turbines [25]. Systems thinking approaches, including System Dynamics modelling, are an emerging avenue to strengthen medium and long-term corporate strategic decision-making. Although uncertainty is unavoidable, systems thinking studies encompassing broader socio-technical trends including environmental concern, technological diffusion, and behavioural shifts, could contribute to inform long-term strategic decision making and smooth the oscillations of business lifecycles to sustain business performance [26]. We can think in this context of the transition examples of General Motors and the Danish energy company Orsted. GM was the first car manufacturer to introduce an electric vehicle to the market but chose to terminate production in 2003 due to unfavourable short-term profitability forecasts. Two decades later, they try to regain market shares and innovation opportunities lost mostly to Tesla [27]. Orsted was established to extract oil and gas from the North Sea to reduce Denmark's reliance on imported energy, but from the 2000s a mix of technology innovations, renewable subsidies, increased climate concern on the political agenda, and the 2008 financial crisis led to strategic innovation. A shift in capital expenditure investments and rapid transfers of infrastructures and human skills led the company to become the largest global producer of offshore wind [28].

Industrial sectors facing decline due to changing market conditions are sometimes referred to as "sunset" industries that must manage their "end-game" [29]. Indeed, a fundamental opposition can be drawn between "declining" incumbents and "emerging" new entrants. Large industries in a process of decline are often understood as well-established, highly consolidated entities dealing with large flows of financial, human and infrastructures assets which start to lose investors interest due to changing market and socio-economic conditions. Incumbent industries are also generally strongly linked to fossil fuels and dominated by "multinationals and large state actors", benefiting from high levels of political connections and stable flows of private and institutional investments for decades [30]. In contrast, new entrants are often understood as a business in the first stages of its development, with high levels of technical and societal innovations, but low levels of networking coalitions, coordination, or political influence. In the energy context, such businesses are often linked to renewable energies, which despite rapid growth are not yet seen as stable enough on the market to attract steady flows of finance [30]. Lowes et al. pinpoint the lack of rigorous definition of the concept of incumbency in the socio-technical transition literature and suggest that incumbents can be seen as entities that have likely been involved in unsustainable practices in the current system and have the "economic, social or technological capacity to affect system change" [31,32]. However, while incumbents have often been portrayed as struggling to manage the decline of their assets, structurally resistant ("locked-in"), or even likely to slow or inhibit change (especially in the power sector), they also engage in active business diversification and have strong potential to drive innovations [33]. The term "sunset" has sometimes been associated as a blanket term to declining sectors and pejoratively linked to the loss of jobs and inescapable impoverishment of whole areas and communities. We advocate in this study that declining industries can on the contrary leverage their expertise and experience to turn the challenge of "sunset" market conditions into opportunities for transformation that will sustain business models and support socio-economic stability.

2. Contribution and methods

The energy transition is a whole societal transition towards low-carbon energies. It is a society-wide, highly complex undertaking presenting uncertain systemic risks into the future, with heightened risks and unsolved challenges for companies and policy processes. This study focuses on energy intensive incumbents, but challenges the rigid difference often attributed to "sunset versus sunrise" *firms* by exploring evolving sunset and sunrise *strategies*. Exploring the interconnectedness between corporate decision-making, markets, policymaking, and social movements, it asks the question: can companies strategies contribute to sustain and support national socio-economic stability and society's resilience in the longer term? This original qualitative research is embedded in the sustainability transitions and socio-technical energy transitions scholarships. Results are inferred from a synthesis of the literature at the intersection of industrial decarbonisation, organisational decline and financial mechanisms of transitions, as well as energy democracy. The research engages most notably with the themes of Schumpeterian "creative destruction", the (MLP) [34], the "three perspectives" framework [2], and the mechanisms of "deliberate decline" [19]. The study provides a) an elicitation of interconnections between business strategies and societal transitions, b) a synthesis of causal loops (feedback mechanisms) using a System Dynamics approach, and c) a discussion on political power dynamics of energy transitions. Together with a particular attention given to key intangible variables to decision making, these provide a building step towards operationalising major systems frameworks of transition studies and improve the realism of quantified energy transition modelling, a gap highlighted unequivocally in the socio-technical energy transition literature [35].

Systems dynamics (SD) is a well-recognised systems thinking, problem-based modelling approach known for its use in world resources dynamics [36,37]. It has recently emerged as a novel approach to tackle socio-technical policy decision-making and business risks in the context of energy transitions [21–23]. SD can add dynamic emphasis to transitions frameworks by highlighting interconnected causal flows, reinforcing feedback loops, delays and non-linear relationships to understand the behavior of systems over time [38]. In "Business Dynamics", Sterman stresses the importance to consider qualitative, "intangible" and "soft" values to enrich strategic corporate decision-making [26]. The methodology is well suited to finding socio-technical and socio-political policy levers to add nuance to the techno-economic focus often given to energy systems. It allows to open the conversation to how socio-technical organisations can be expressed as practices of willingness, influence and power distribution, a gap clearly identified by Newell [39].

This study is part of research conducted for the industrial decarbonisation research and innovation centre (IDRIC) and builds on previously published policy briefs which proposed a set of definitions to emerging and declining industries strategies [40,41].

The next section draws on the literature to elicit causalities between industrial transitions, socio-economic stability and business viability and presents a taxonomy of "sunset" versus "sunrise" business strategies.

In section 4, the findings are synthetised into feedbacks loops and organised in a Causal Loop Diagram (CLD), before discussing implications for policy and industry decision making. Section 5 broadens the conversation to the distribution of political influence, or the "power dynamics" of national energy transitions. Concluding remarks acknowledge limitations and offers avenues for further research. Intended to decision makers and scholars in the fields of sustainable transitions, industrial decarbonisation, and corporate social responsibility, the study contributes to inform emerging whole systems and interdisciplinary approaches to energy transitions and highlights key variables to incorporate into socio-technical modelling efforts.

3. Industrial transitions and socio-economic stability

3.1. Business, financial, sectoral, and macro-economic risks

Evolutionary economists and technology management scholars locate crisis mechanisms primarily in disruptive technologies and sunrising agents [18], the most common risks being the destabilisation of established markets and the creation of financial bubbles. The Schumpeterian perspective places innovative agents at the heart of "creative destruction", a process by which clusters of more productive and efficient technologies are driving factors of economic and financial destabilisation by generating structural change [42]. However, the phenomenon can be reinforced by the tendency from incumbents to culturally favour incremental change; studies on "disruptive innovation" picture them as vulnerable to the rapid emergence of new entrant's solutions and likely to exacerbate wider financial destabilisation, except if growth opportunities for sunrise organisations are sustained [43–45]. The downfall of incumbents can come about as they respond too late because of routine inertia [46] linked to their large technical and strategic processes [47,48].

These considerations bridge management studies to the sustainability transition scholarship. The later places the most important societal risks on sunsetting organisations, whose depreciated assets can gradually become "stranded" as they lose value on markets, placing risks on communities and regional and national economies [49]. Assets can be technological and financial (investments), but also physical infrastructures, and human resources (skills). If the company's assets are tied to a particular industrial process or geographical location, their value will diminish even more rapidly, reinforcing cost barriers to transitions and resistance due to the impact on local jobs [18]. If they resist, delay or actively mobilise action to slow or inhibit change [50], incumbents can reinforce the risks coming from stranded assets [15]. Lowes demonstrated that the heat sector in the UK does promote a vision of "low-carbon gas", and questioned whether incumbents have the power to shape transitions [51] without necessarily providing benefits to the public [52–55]. While defensive strategies can sometimes appear to sustain the business in the short and medium term, reinforcing organisational and cultural resistance will close windows of opportunities for the business while cost and risks are rising, which can ripple through wider transitions "lock-ins" for national energy pathways [18]. The organisational decline literature also pinpoint that firms often do not adjust quickly enough because of an "initial denial or misinterpretation" of their position on the market, which eventually impact their business performance [18,56,57].

Improving transparency in the reporting of corporate investment strategies and sustainability risks has been promoted as a solution to transition smoothly towards a decarbonised economy by naturally pushing investors away from fossil fuels. However, this does not consider that fossils and renewables industries have distinctive characteristics and are treated differently by markets [30]. Incumbents are mature, consolidated industries dominated by well-known actors which are still attracting large funding, while the renewable industry remains fragmented and operating on a single market. The rapid growth of renewables is not enough to secure market capitalisation and meeting investor's criteria, in turn limiting steady investments and delaying transitions [30]. Incentives for development of renewables are enforced in most European countries but are not accompanied by large restrictions on fossil energies. The UK presented increased tax breaks for oil and gas exploration in recent years despite the country's lead in ambitious decarbonisation targets [1].

Additional financial barriers to the diffusion of low-carbon technologies come from the characteristics of energy intensive and high-capital expenditure (CAPEX) industries such as steel, chemical or cement, where new technologies struggle to enter the commercialisation stage since investments carry uncertainty, longer paybacks and operational shutdowns to upgrade existing process and assets [58,59]. Carbon pricing mechanisms can help increase demand for low-carbon steel if they are introduced In the same time as planned investments, to avoid further competitiveness risks [60]. Semieniuk et al. provide an analysis of energy transition risks for the financial sector [42]. Reconciling views from different strands of research, the authors describe financial destabilisation as jointly led by risks inherent to incumbents and by the economic expansion of new entrants, such as assets valuation, debts and the creation of bubbles. They argue that other drivers such as mitigation policies, technology and preferences can impact the wider macro-economy through a chain of feedback causations reinforcing a cycle of high costs propagated via mechanisms of inflation, wealth inequality, and exchange rates [42].

3.2. Harvesting business and society co-benefits

Some warn that stereotyping incumbents as locked-in comes with the risk of not leveraging their capacity to help accelerate the transformation of energy systems [11,29,33]. Engaging early in low-carbon transformations allows gradual levels of disruptions as firms shift from perceiving initial capital costs as barriers to seeing them as investment opportunities to avoid increasing costs and become resilient organisations aligned with evolving customer demand, public scrutiny and shareholder values [61]. Incumbent industries who recognise and seize the opening of these "windows of opportunities" can leverage their resources in "virtuous cycles" capturing value in niche sectors in domestic and international markets. They can both contribute to and benefit from transitions through a) technological innovation, b) knowledge and resources transfer, and c) enhancing the credibility of novel technologies, therefore offering market certainty and stability for investors while securing their position on new markets, improving their image and delaying the decline of their legacy assets [11].

3.3. Industry strategies

In the context of societal transformations, rather than assigning "sunset" characteristics to whole sectors in transformation, it is more appropriate to recognise the plurality of actors types and explore the diversity and temporality of industries strategies [33,62,63]. The transient nature of strategic positioning over time means firms can evolve into "sunsetting" and "sunrising" roles, from leading and supporting transitions, implement change imposed by regulations, through to mobilizing opposition to policies and new entrants, notably via lobbying practices [32,62]. This section presents a taxonomy of "sunset" and "sunrise" strategies that businesses may adopt when faced with changing landscapes and decarbonisation pressure. They take three main shapes: defensive, exploratory, and offensive (Fig. 1).

3.3.1. Sunset: defensive and resistive strategies

Firms can resist, delay, or reposition their contribution to transitions. Incumbents organisations tend to favour incremental change, which can render them vulnerable to the rapid emergence of new entrant's solutions [43]. They are further liable to technical and cultural lock-ins, or "business model inertia", with slow responses reinforced by "initial denial or misinterpretation" of their position on the market [46]. If the

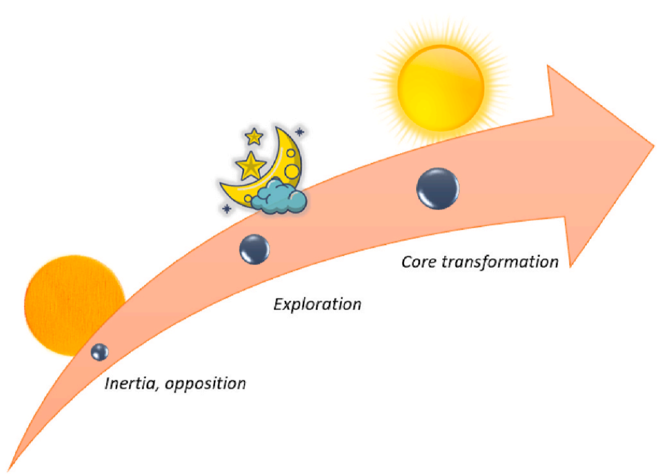

Fig. 1. Industry transition strategies.

need to re-organise is only recognised when risks and costs are too high, organisational and cultural resistance to change are reinforced. Short term strategies such as downsizing or cost-cutting, may appear rational in the short-term but can impact medium and long-term business performance if core business adaptation is delayed for too long [64]. Similarly, when inertia is too entrenched, it can take an external shock or crisis to shift strategies, which can arrive too late to sustain longer the industry [18]. Studies demonstrated that actors from the coal, gas and nuclear industries used active resistive strategies such as lobbying and opposition to renewable investments, instead repositioning themselves as heading towards carbon neutrality without fundamental transformation [15].

3.3.2. *Moonlight: exploratory strategies*

Many firms engage in exploratory decarbonisation strategies through business models and technologies. They represent an incremental re-orientation, experimentation, and potential re-invention of existing market players where the lines between sunrise and sunset firm's types and strategies can become more blurred [11,15]. Business models' experimentations such as interorganisational interactions and collaborations, even between competing firms (coined "coopetition"), have been highlighted to enhance business viability and innovation [65,66]. Incumbents may also initially pursue different experimentations models than start-ups, for instance, by focusing on environmental process innovation to save costs for consumers while new entrants may first favour green product innovation for niche eco-conscious consumers [67,68]. These activities can grow from individual incremental changes through to disruption and transformation [46,69], and firms can be part of unified or diversified types of strategies within industrial sectors and supply chains. As a specific example, while sunset and sunrise practices are often understood as an opposition between fossil fuels and renewables technologies, many energy incumbents are partnering with new entrants to develop tailored carbon capture and storage (CCS) infrastructures and hydrogen technologies associated to chemical optimisation towards circular, closed loops processes. The association of large industries to technologies such as CCS which are yet to become viable on a large scale is of particular interest to future energy pathways as it is both widely recognised as necessary to help society transition to a low carbon economy [3] and, a controversial solution liable to avoid structural changes and delay sustainable and emissions mitigation goals (see also section 4.2.2).

3.3.3. *Sunrise: offensive, supportive strategies*

Established actors can adopt strategies normally attributed to new entrants, and there is evidence of incumbents driving innovation and supporting transformative change [33,34,70]. The business position on future markets is recognised without major delays, which highlights the opening of windows of opportunities. As a result, they actively seek technical innovations and technology diversification towards renewables, but more importantly engage in core cultural transformations driven by a clear top-down vision enriched with bottom-up expertise. By linking fast-forward transition strategies to their already well established expertise and networks, incumbent actors are more likely to manage efficiently and objectively the decline of their legacy assets and sustain the long-term viability of their business [29], while harvesting technology deployment, sustainability practices and public image co-benefits [33].

Table 1 provides a synthesis of the "rational" and "intangible" techno-economic and socio-technical decision-impacting factors elicited in this section. They can affect incumbent's perceptions and strategic business choices and are presented with their associated potential medium and long-term risks.

4. Socio-technical feedback cycles of industrial energy transitions

4.1. *Causal loops*

In this section, systemic causalities inferred from the literature are synthetised into full feedback loops and illustrated with CLDs. A CLD illustrates "polarities" between systems components. They can be positive (+) (b goes in the same direction as a) or negative (−) (b goes in the opposite direction as a) and form reinforcing or balancing feedback loops (an odd number of (−) causal links creates a balancing loop). A reinforcing feedback drives variable a in the same direction, whatever the number of variables in the loop. A balancing feedback tends to drive a in the opposite direction or slows it down towards an equilibrium.

Two central reinforcing feedback loops are presented in Fig. 2. For illustration purposes we refer to them as "vicious" and "virtuous" patterns for business strategic viability, to pinpoint where lie the main risks and opportunities in driving the system in the desired direction. The first loop, which can be described as "business lock-in", illustrates that defensive strategies lead to less diversification and limited transfer of

Table 1
Summary of incumbent industries decision-impacting factors.

Techno-economic factors	Socio-technical factors	Risks
• Large manufacturing processes • Assets tied to sector-specific process or single geographical location • Investment limitations (e.g. high CAPEX, long paybacks, process shutdowns) • Differential treatment by markets towards incumbents (e.g. power sector) and new entrants (e.g. renewables) • Government incentives for renewables not accompanied by restrictions on fossils	• Large organisational processes • Entrenched cultural inertia • Short-term vision and/or incremental change • Misinterpretation and/or delay in perception of new market position • Uncertainty in future regulations • Incumbents already stereotyped as locked in	• Assets mismanagement/rapidly decreasing asset value • Rising costs • Delayed action and/or opposition • Business performance vulnerable to disruption • Missed investments and closed windows of opportunity for business and communities (tech innovation, transfer of skills) • Business values misaligned with evolving customer's demand • Market uncertainty • Wider national lock-in, delay to transitions

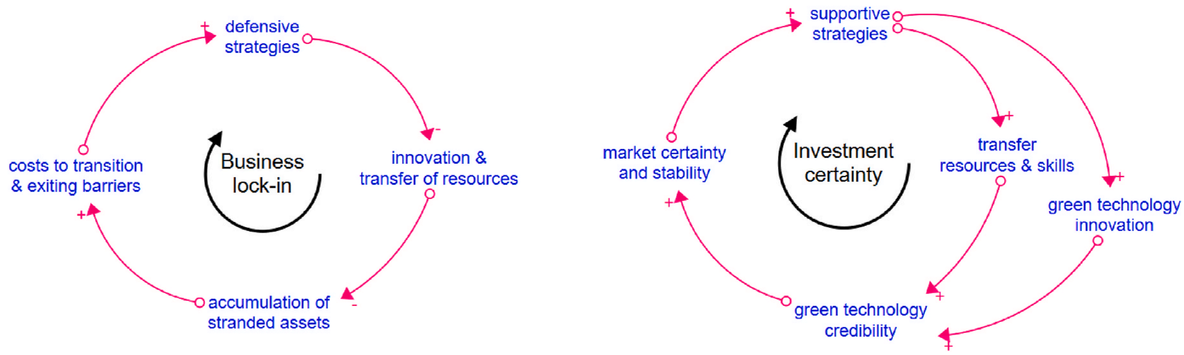

Fig. 2. Two central "vicious" and "virtuous" reinforcing strategic cycles.

physical and human resources, gradually increasing the amount of assets becoming stranded, costs and cultural barriers, encouraging further resistive actions. This loop is informed by links from inertia, resistance or denial to delays in action [46,50] gradually increasing stranded assets [15,49], leading to rising costs and risks to business performance [64], reinforcing initial resistance [18]. This loop can be particularly acute for heavy-process, large expenditure and high carbon industries inherently prone to further transformation risks (e.g steel, chemical, cement). By opposition, the right-hand side loop illustrates a pattern of "green investment certainty". It is a process of virtuous creative destruction driven by supportive industry strategies [42] allowing more gradual disruptions and co-benefits such as business diversification, technological innovation [33], green markets credibility [11], and business alignment with customers and shareholders values [61].

In Fig. 3, the two loops are connected by representing defensive and supportive strategies with different levels of the single variable "resistive business strategies". By increasing or decreasing, the variable illustrates shifts in strategic directions which can tip the system towards the dominance of either the *"business lock-in" or "investment certainty"* patterns. The causalities are updated accordingly, with two negative (−) polarities between investors scrutiny, resistive strategies, and sustainable innovations. "Investor scrutiny" is disaggregated from market certainty to account for rising investor's scrutiny in corporate sustainability and ESGs risks [13]. The reinforcing nature of each loop remains unchanged, as only an odd number of negative polarities (−) in a loop creates a balancing feedback. If "resistive business strategies" tend to decrease, lock-in effects are alleviated by less accumulation of stranded assets and costs, in turn lowering resistance [29]. Business lock-in is referred to as "R1" and investment certainty as "R2" in Fig. 4 and Table 2.

Additional causal connections reveal feedback patterns matching major socio-political themes of the sustainable transition literature. "Public commitment" provides political mandate to enact transition policies ("political commitment") [1,71], which we link positively (+) (in the same direction) to "green technology credibility and market certainty", and "investor's scrutiny". This corresponds to the mechanisms of divestment and phase-out, driven respectively by civil actions and policy regulations [19]. In Fig. 4/Table 2, this loop is disaggregated into R3 and R4. An inverse causality (−) between resistive strategies and public commitment is informed by the observed use of actions and narratives supporting the continuation of fossil-fuels [50,51] ("mobilisation of opposition" or R7). The loop "sustainable transitions" (R6) links rising costs to wider socio-economics via risks to jobs and regional economies [49], as well as, in the case of large industries, wider financial destabilisation [43–45]. Destabilisation and uncertainty can bring about wider lock-in effects including delaying the achievement of transition targets [18]. As many targets are both reliant on and acting as building steps to technology development and scale up, this variable is looped

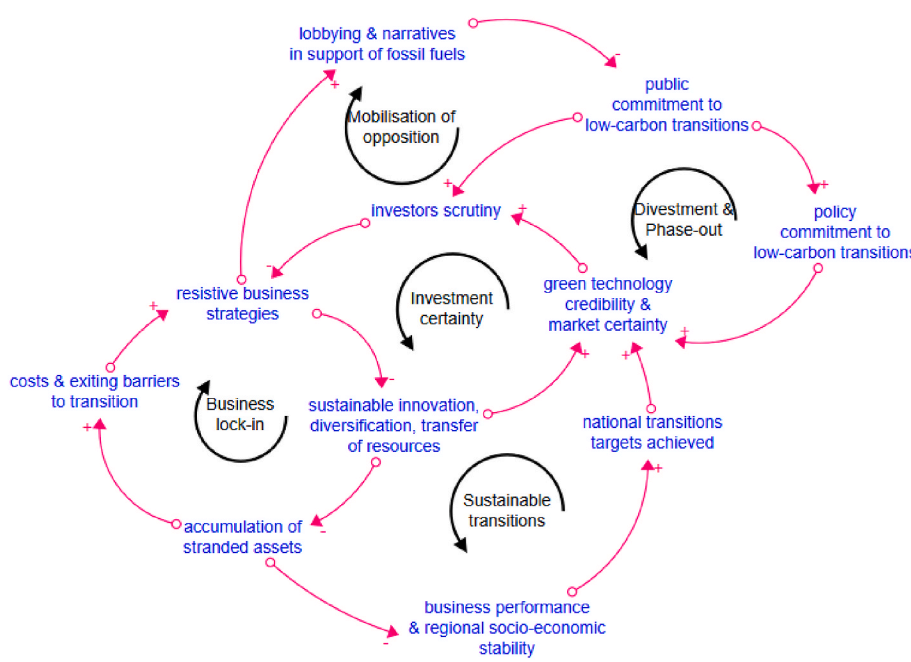

Fig. 3. Feedbacks driving sustainable transition mechanisms.

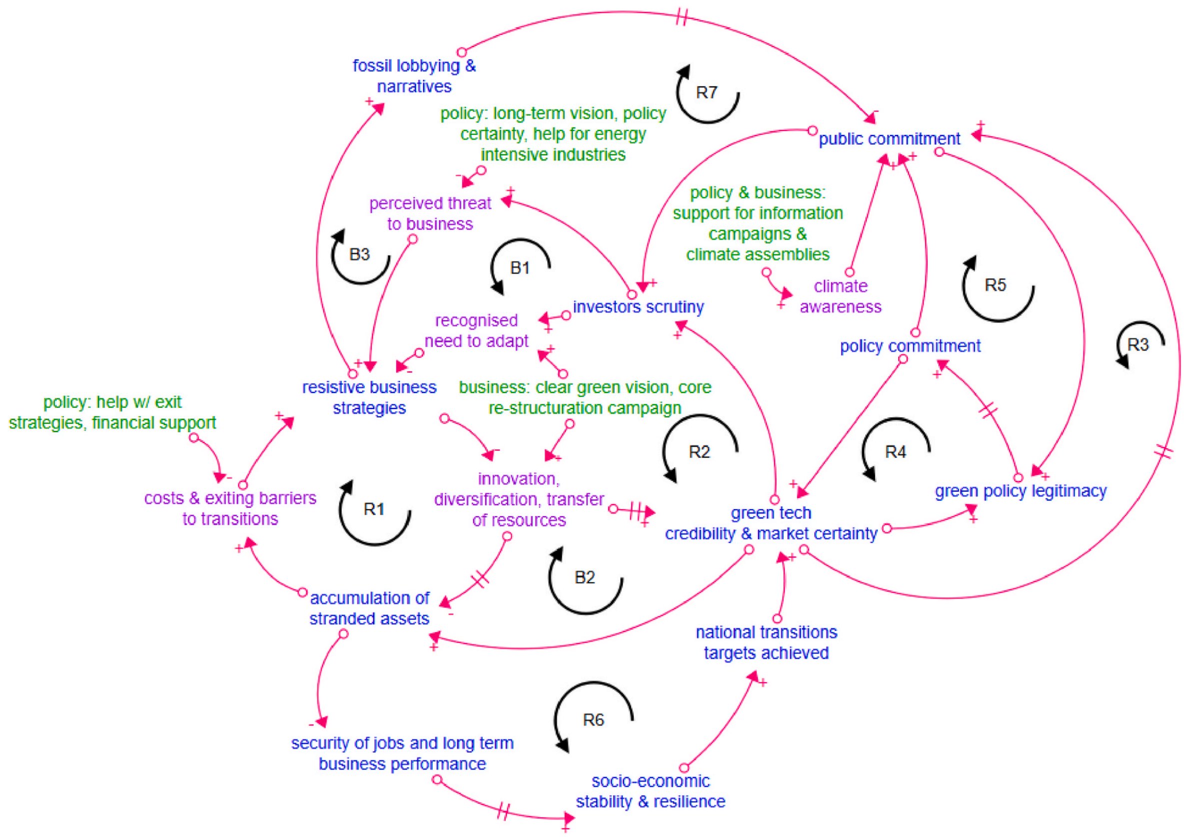

Fig. 4. Feedbacks and levers in socio-technical cycles of industrial transformations (legend: hash marks = delays; in purple = notable intangible variables of leveraging interest; in green = industry and policy levers).

back to the level of green market development and certainty.

Fig. 4 introduces balancing mechanisms, delays (hash marks), variables of interest to leverage the system towards the desired direction (in purple), and industry and policy levers (in green). It expands on causalities by disaggregating links between a) public and political commitment, market developments and "political legitimacy" (R3- R5); b) investor's scrutiny and resistive actions via strategic perceptions of threats or opportunities (R2, B1); and c) adds a positive causality between technology credibility, market certainty and public commitment to account for the diffusion of innovations theory [72] where environmental values spreading to different segments of citizens help drive technological change [23]. If growing market and investor's pressure to decarbonize is perceived primarily as a threat rather than a business adaptation necessity and opportunity, the investment certainty pattern (R2) is counterbalanced by loop B1. Another balancing effect to virtuous innovation cycles is the disruption that can be brought about by fast developing markets (creative destruction), which can also fasten the creation of stranded assets (loop B2) [42]. Lobbying actions (R7) balance themselves when a reduction of public and policy commitment lessens the perception of threat, in turn reducing the need to engage in resistive actions such as mobilizing opposition (B3). A detailed summary of feedback loops is presented in Table 2. To ensure consistency between single company and national scales, the variables representing business strategies and the creation of stranded assets are considered as national level aggregations. The quantification of this CLD into a simulation model with different company characteristics would require these variables to be populated as arrays or indexes, e.g., per industry sector or industrial cluster.

4.2. Application to industrial policies

4.2.1. Levers and implications

Although often neglected in cost-optimizing scenario modelling, intangible variables influencing human decision making are essential policy leverage points for assessing future transition pathways [26]. National green policies have failed in the past due to a lack of systems considerations including public engagement, skills and jobs, investments patterns and supply chains risks (e.g. the UK's Green Deal for energy efficient home improvement [75], taxes on fuel prices leading to the Yellow vests movement in France, or the recently watered-down Building Energy Act GEG in Germany). Policy and regulations for industrial energy transitions have so far mostly focused on carbon taxes, emissions reduction, market development incentives, large infrastructure developments as well as transparency requirements to drive green investment incentives [4].

Notable endogenous variables affecting the direction of the feedbacks over time are highlighted in purple. The level of climate awareness is directly linked to public commitment which has an important driving effect on political commitment, market development and shareholder scrutiny. The perception of scrutiny as either a threat or an opportunity drives in opposite directions market development outcomes, business performance and ultimately socio-economic stability. Finally, assets diversification and costs to transition, which are more easily quantifiable variables, are notable drivers of respectively market change and physical and cultural lock-ins. External industry and policy levers (in green) can be applied to influence these endogenous variables in the chosen direction. Perceptions of threat and business costs to transitions can both be alleviated by tailored policies offering "exiting" strategies to declining firms. These policies can involve increasing low-carbon financing in conjunction with more transparency and climate awareness to appeal to broader market participants and incorporate

Table 2
Summary of socio-technical feedbacks.

Feedback loop name	Denomination & type	Summary of causalities	Causes and References
Business lock-in	R1 (reinforcing)	Resistive strategies and delayed innovations increase stranded assets and transition costs, reinforcing barriers to business adaptation	*Incumbents are liable to delays, inertia, misinterpretation of new position on markets* [46] *or using short-term strategies* [64] *leading to a gradual stranding of assets* [49] *and increased barriers to transitions, cultural lock-ins and resistance* [18] *eventually impacting performance* [18,56,57]
Green investment certainty	R2	Innovation and resources transfers increase credibility and market certainty, securing the firm's position on new markets	*Early low-carbon transformations allow more gradual disruptions, effective management of declining assets* [29] *and secured alignment with evolving customer demand, public scrutiny and shareholder values* [33,61]. *Co-benefits include technological innovation, knowledge transfer, and market credibility and certainty for investors* [11,33].
Perception of threat	B1 (balancing)	The perception of pressure and scrutiny as a threat rather than adaptation opportunity encourages resistance	*Landscape pressure and scrutiny as well as decentralisation can be seen as threats to incumbents* [73]
Market disruption	B2	Fast market innovation can bring disruption by contributing to the creation of stranded assets	*Creative destruction brings about fast paced innovations which can also contribute to market disruption and threaten economic stability* [42]
Divestment	R3	Public movements trigger investors' scrutiny, helping drive market change	*A pillar of "deliberate decline", divestment is rooted in civil movements seeking to erode fossil fuels' license to operate, asking shareholders to divest their investments* [19]
Phase out	R4	Policy commitment to transitions drives low-carbon technologies in and fossil fuel technologies out	*Another pillar of deliberate decline, phase out is rooted in policy regulations* [19]. *Engaging citizens provides leaders with more political mandate to challenge business resistance to transition policies* [1,62,71].
Social values change	R5	Mutually reinforcing link between public and policy commitment expanding to market change	*The diffusion of environmental values drives market change* [23,72]. *Engaged citizens provide political legitimacy* [1,62,71], *and early transitions help policy makers manage business costs and market penetration* [42,49,74].
Sustainable transitions	R6	Business innovation, technology and skills transfer drives long-term security for jobs and business performance, increasing economic stability and likelihood to achieve national transition targets	*Large industries may exacerbate financial destabilisation by delaying action* [15,50], *placing risks on communities and regional and national economies while costs and risks are rising* [49]. *Closed windows of opportunities for businesses can ripple through wider transitions "lock-ins" for future national energy pathways* [18,42,74]. *Incumbents may have the "economic, social or technological capacity to affect system change"* [31,32].
Lobbying	R7	Mobilizing opposition reduces public and policy commitment to transitions, decreasing technological innovation and market certainty	*Incumbents may use well established networks to resist decarbonisation pressure* [15,51], *mobilise opposition to policies and new entrants via lobbying practices* [32,62] *to inhibit or affect transitions* [31,32,50,51] *sometimes leading policy makers to self-internalize industry interest as their own* [15]
Lobbying reduces perceived threat	B3	Lobbying reduces pressure and scrutiny to decarbonize, alleviating the perception of threat which drove resistance in the first place	*Feedback revealed in CLD by interconnections between lobbying (R7) and perception of threat (B1)*

investor's considerations in policy design [30]. Carbon pricing mechanisms introduced at the same time as planned investments could help energy and capital intensive industries such a steel to upgrade their processes [58–60]. Growth opportunities for new technologies must be sustained to avoid disruption from stranded assets [43,44]. Private and public information campaigns, as has been proven by successful climate assemblies [76] can greatly increase awareness and public and consumer commitment to low-carbon technologies, to help unlock entrenched inertia. Engaging citizens provides policy legitimacy and support to alleviate resistive actions (see also section 5). Clear, long-term, well-defined policies are needed, notably to leverage existing local awareness and capacity. For instance, the Black country industrial cluster in the UK has shown proactive engagement with decarbonisation but smaller companies (SMEs) face obstacles such as lack of access to appropriate information and investment/abatement options, policy support and certainty [77]. Policy action to support exiting strategies must be adaptable to the diversity of sectors and companies to incentivise and enable internal capacity building in the direction matching government long-term targets. Having more certainty in the future of the market is a sticking point for all industry decision makers [78]. However, the system illustrated here shows that incumbents in particular can greatly contribute to reducing uncertainty by sending their own signals to investors and policy decision makers. Coordinated top-down and bottom-up internal awareness campaigns to initiate restructuration may help perceive investor's and public scrutiny as opportunities to inform future business resilience.

Delays of interest (hash marks) represent both information and material delays which have the capacity to affect the dominance of certain feedbacks over time. In simulation modelling, delays are primordial in determining short-term versus long-term potential directions of the system's behaviour. Here, they highlight windows of opportunities for industry and policy decision makers to avoid wider societal lock-ins. Some of the most important delays are those related to the gradual accumulation of stranded assets, as these will determine "buffer" times and "tipping points", i.e. the reasonable range of delays and amount of stranded infrastructures before jobs, businesses and eventually wider socio-economic resilience may experience long-lasting impacts.

4.2.2. Carbon offset technologies and alternative fuels: support or hindrance for transitions?

The development of blue and green hydrogen and CCS technologies is now widely recognised as essential to reach UK national decarbonisation targets [3,9], and is currently attracting large research and investment efforts. Yet, if not developed as part of a comprehensive, "holistic" set of approaches, some of these technologies have the potential to restrain the diffusion of renewables and delay the phase-out of carbon intensive fuels [15], and hence operate as a predominantly sunset strategy. CCS technologies come with energy intensive functioning requirements, which can be at odds with other emerging whole system transitions solutions such as behaviours change and demand reduction [79,80]. It has been suggested that CCS can be used to justify the continuation of business as usual operations with narratives influencing public opinion such as "clean coal" produced with CCS [15,81]. In such cases, these technologies feed into reinforcing defensive cycles between lobbying and public commitment (loop R7). In the case of hydrogen, proponents argue that dual hydrogen-gas infrastructures are one of the best options for gradual transitions to clean energy (alleviating impacts of rapid system transformation, loop B2). Opponents criticize these narratives as leading to undue and economically un-viable competition (especially in the residential sector and heating) against already available low-carbon technologies such as renewables, heat pumps or heating networks [82,83]. This can impact the virtuous effect of "green credibility and market certainty" in R2. Yet, there are also important opportunities to seize to accelerate and support low-carbon transitions, in hard to abate sectors with CCS and in energy storage with hydrogen (e.g. extra energy produced from renewables stored as hydrogen), which would in this case support virtuous cycles of green market investment certainty (R2). Opposing views on hydrogen can find common ground in solutions adapted to the needs of each sector [83].

5. Discussion: towards a political economy of industrial energy transitions

The sustainability transition research gives growing attention to the political and coalitions conflicts dynamics of societal transitions [52]. Several authors and prominent transitions frameworks highlight the need for a more comprehensive inclusion and representation of socio-political aspects to enrich our understanding of future energy transition pathways [2,15,84,85]. For instance, the energy transition creates tensions and interconnections between physical power generation and the distribution of political power. Large-scale, centralised power production is often linked to fossil fuels as opposed to diversified, distributed systems often linked to renewables. Because of its centrality to national security and economic growth, energy strategies are highly political issues. The balances of forces shaping transition policies help explore possible future energy pathways and determine how much they can be aligned with broader social and development goals [39]. While sunrising industries can struggle to participate in networks of influence, incumbent regime actors in the UK have been observed to use several forms of power to resist climate related pressures [15,51]. Because of close relational networks between large businesses and senior policy-makers, many have denounced the potential lobbying influence of incumbents on governments, media and litigation to protect what is commonly termed "vested interests", as this can not only provide political power to firms but also subtly lead policy makers to self-internalize industry's ideas and interests over time as their own [15].

While the necessity to leave existing fossil fuel reserves underground to reach legally binding national decarbonisation targets has been demonstrated several times [86], and discussion as to how this can come about in practice have entered the scholar and policy making spheres, the feasibility and evaluation of potential approaches has not yet been comprehensively researched and all have been assessed as challenging because of complex institutional interests [87]. However, decentralised generation from households and community groups has recently grown as a developing niche market in the UK [88], and small sunrising actors such as renewable energy communities (RECs) have gained capacity in shifting political centralised power structures, though regime pressure limit their potential to exercise real influence on policy change [89]. In other cases, as was observed in Finland, the impact on policy of newly formed green political coalitions was weakened by a lack of internal unity and coordination [52].

In the UK, decarbonisation efforts are mostly driven through industrial "clusters", but almost half of the country's industrial emissions come from geographically dispersed sites and SMEs, making carbon capture networks meant for energy-intensive and concentrated industries less economically viable [77]. The policy focus on centralised sites may also lead to market distortions and uneven adaptability to transitions for some communities [77]. Decentralisation is often seen as a threat to incumbents [73], but firms including energy suppliers can use it as an opportunity to develop new businesses [43]. The government positioning on distribution and control of energy assets can determine the evolution of interconnections in energy system ownership and political power over time [89]. Power relations can limit long-term transitions [90] if energy pathways are shaped through tactics to reduce support for climate policies (e.g. "discourses of delay") [81]. On the contrary, shared long-term visions can guide and unite stakeholders [51, 91]. Brisbois argues that systems can be stretched then transformed despite resistances, highlighting strong potential for shifts in social norms as pressures to decarbonize, decreasing renewable prices and EU energy packages normalise the presence of smaller actors and new entrants in energy mixes [89]. Systems thinking methodologies also encourages the harmonisation of goals between stakeholders to alleviate the issue of "policy resistance", a common archetype of complex social systems, where every actor continues to pull into their own direction, which creates delays, an accumulation of risks, and tipping points beyond which the performance of companies and the eventual society resilience can no longer be sustained. Willis warns against other common decarbonisation policy "traps" where policy makers attempt to decarbonize the economy "without people noticing" through small incremental actions [1] which could help perpetuate "lock-in" vicious cycles (Fig. 4, loops R1; R7) and lower rather than increase climate awareness (an essential policy lever, see also section 4.2). Governments are sometimes seen as bearing the main responsibility for increasing consumer acceptance and set the direction for innovations and investments in a "socially beneficial way", which will help manage economic instabilities arising from structural change [92]. Politicians can lose their electorate in the medium and longer term because not enough action has been taken, whereas engaging citizens and including energy democracy perspectives in current energy politics may help easier governance, increasing stability and provide leaders with more political mandate to challenge resistance to transition policies [1,62,71]. Energy transitions and democracy can indeed be mutually reinforcing, as a distributed model can retain both local and shared broader economic benefits [12].

Pursuing the exploration of these mechanisms, it is possible to argue that governments can create vicious dynamic patterns of "self-fulfilling prophecy", where citizens are less likely to support appropriate climate action if they don't see their politicians "leading the way" [1] (see also loop R5). This links to the "windows of opportunity" highlighted for both industries and whole societal transitions, where missed opportunities can lock future scenarios pathways into reinforcing existing patterns [42,74].

6. Concluding remarks

Industries face increasing scrutiny on their assets and investments and increasing climate awareness from the public. Because large industries are historically tied to the well-being of society through their developments, services, infrastructures, and the provision of jobs and skills, the strategies they choose to mitigate disruptions have important implications for whole regions and their communities. Exploring the interconnections between "sunset" versus "sunrise" strategies risks and benefits for society (e.g. stranded assets versus market certainty), we show that under the right conditions of high business innovation, tailored government support, and continued public commitment, declining industries can leverage their expertise to turn difficult market conditions into opportunities to sustain business viability, socio-economic stability and support sustainable transitions. Defensive strategies may appear as a rational choice when considering short and medium-term techno-economic factors but can generate an accumulation of risks making business and society more vulnerable to disruptions. The main findings are illustrated with a System Dynamics' CLD, before discussing the political power dynamics of energy transitions. The study offers a building step towards the operationalisation of socio-technical system studies, providing key variables and causal flows for quantified simulation modelling, which can be enhanced with multi-stakeholder participatory approaches.

The study presents several limitations. First, we acknowledge that the study's scope means that some areas may be more detailed and feedback loops eventually added to be adaptable to solving a wider range of transitions-related problematics. A comprehensive differentiation of incumbent sectors and their existing services would allow to pinpoint specific relationships and policy interventions, as it can affect the stability of their position on a changing market, and lead to diverse constraints to adopting decarbonisation strategies [51,93]. Studying complex societal transitions with an industry-focused agenda could also further be brought about by linking corporate sustainability and environmental, social and governance (ESG) risks scrutiny. Further, there is important potential to explore the influence of global governance and international companies on national industry strategies and the decarbonisation of energy heavy industries [67,94]. Policies, corporate governance and societal movements including consumption patterns are increasingly "transnational"; and changes in global economy landscapes and investment patterns which affect national energy transition strategies must be studied further [39]. Another essential emerging area is the study of societal consequences of increasingly polarised political narratives affecting energy policies, including on net-zero targets, fair transitions, and the sourcing of raw materials.

CRediT authorship contribution statement

Brunilde Verrier: Conceptualization, Methodology, Investigation, Writing – original draft. **Neil Strachan:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

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.

Data availability

Data will be made available on request.

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