

Sensitive intervention points: a strategic approach to climate action

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Abstract

While some countries are making progress reducing greenhouse gas emissions, few are progressing rapidly enough to be on track to reach net zero emissions by mid-century. The transition to net zero involves deep structural transformation of the global economy and its associated complex socio-technical systems. Here, we set out a conceptual framework to identify 'sensitive intervention points' (SIPs) in systems where a small or moderately-sized intervention could drive outsized impacts and transformational change. These points take three forms: (i) critical tipping points, such as a critical price threshold, (ii) critical nodes in networks, such as an influential actor in a social network, and (iii) critical points in time, where windows of opportunity for change open up. We also propose an assessment methodology for prioritizing interventions in terms of their potential impacts, risks, and ease of implementation. We apply our framework and assessment methodology to evaluate a list of proposed interventions for accelerating global decarbonization. Promising interventions include investing in key clean energy technologies with consistent cost declines, introducing central bank policies to reduce the value of polluting collateral, and enhancing climate-related financial risk disclosure.

Keywords: sensitive intervention points, climate policy, social tipping points, climate change

JEL classification: Q50, Q54, Q58

1. Introduction

Achieving net zero emissions by mid-century would require major changes to global energy, industrial, and agricultural systems, and associated socio-economic systems (IEA, 2021). While there have been some successes, few believe that the pace of current decarbonization efforts is currently on track. To meet the goals of the Paris Agreement and transition to a 1.5°C pathway, global annual emissions will need to drop 45 per cent by 2030 compared to the current trajectory underpinned by today's policies (UNEP, 2022). This challenge is enormous. And while these

policies currently commit us to 2.8°C of warming by the end of the century, updated country pledges since COP26 in 2021 are only likely to bring this down to 2.4°C at best.

With such a large scale of change required and such limited global appetite for policy implementation, sobering questions naturally arise around the attainability of the Paris goals. However, in recent years a more hopeful body of complex systems literature has emerged, offering novel insights into how to accelerate change or ‘tip’ systems towards more sustainable trajectories (Geels, 2002; Farmer *et al.*, 2019; Lenton, 2020; Otto *et al.*, 2020; Sharpe and Lenton, 2021; Lenton *et al.*, 2022). Building on this work, we argue that policy effort to drive system-wide change may not need to be quite so large if policy interventions can be strategically targeted at a socioeconomic system’s *sensitive intervention points*, i.e. where a small or moderate change is likely to have a large impact. This is not to suggest that reaching the Paris goals will be straightforward, or easy, but like Achilles’ heel, it points to the areas where there is the greatest chance of success.

In section II, we offer a taxonomy to identify which points in systems are sensitive. Drawing on the initial ideas outlined in Farmer *et al.* (2019), we set out a conceptual framework that sets out three categories of sensitive intervention points (SIPs). The first category, which has received significant attention in the literature, is critical tipping points or thresholds. These points arise when a system’s dampening forces holding a system in its present state are offset by positive reinforcing forces driving it into a different state or trajectory. An example is a critical price threshold whereby low-carbon technologies become cheaper than fossil fuels. The second category is critical points (or nodes) in networks, where, due to their position in the network, they can have an outsized impact on the system they are embedded in. These nodes could be critical firms in a supply chain network, or influential actors in a social, political, or institutional network, or even critical technologies or sectors in production networks. The third category is critical points in time, where windows of opportunity open up that make systems more ‘ripe’ or primed for change. Such windows can open up when exogenous shocks hit the system, such as the Covid-19 pandemic opening up the possibility for large green stimulus packages (Hepburn *et al.*, 2020). At these points in time, structural changes that would normally be very difficult to implement can become much easier. Based on these categories, we argue that systems are more likely to display points of sensitivity (i) where positive (or reinforcing) feedbacks are present), (ii) where actions of firms, people, technologies, or organizations are highly dependent on a few key players, and (iii) when shocks occur that destabilize the existing system.

In section III, we propose a general methodology for how to intervene in systems that have SIPs. Our approach involves four key steps. First, we identify whether an intervention will ‘kick’ the system, ‘shift’ the system, or some combination of the two. Kicking the system refers to taking the current system as given and using interventions to try to kick a key variable over a critical tipping point, or targeting critical nodes in key networks to drive outsized impacts. Shifting the system involves introducing institutional or regulatory shifts that fundamentally change the way the system operates. Second, we identify who can change the system—who are the key actors or entities that have the agency to be able to trigger a given intervention? Third, we identify potential barriers that could block or create resistance to a given policy intervention. Once identified, we look for ways these barriers can be mitigated. Fourth, we identify ways to ‘lock in’ a given change to reduce the likelihood that the change is easily reversed by others in the future.

In section IV, recognizing time and resources are in short supply, we also set out a simple approach for prioritizing interventions that are more likely to be successful and have an outsized impact. We consider specific characteristics of each intervention in terms of three key axioms: (i) trigger potential, which relates to the ease at which a given intervention can be implemented and whether it is likely to be difficult to reverse; (ii), impact potential, which relates to the likely size, scale, and speed of a given intervention; and (iii) risk potential, which relates to the degree of uncertainty, unintended consequences, and trade-offs associated with an intervention. High priority interventions are those that have high trigger and impact potential and low risk potential. A summary of our SIPs policy framework is illustrated in Figure 1.

Finally, in section V we demonstrate our framework by applying it to a list of 20 policy interventions that were proposed as having the potential to accelerate global decarbonization. These interventions were gathered from a group of leading experts from academia, industry, government, and civil society. For each intervention, we (i) identify whether it operates on key critical points in a system, (ii) assess how it intervenes and drives change in the system, and (iii) evaluate its trigger, impact, and risk potential. The three highest priority interventions identified through this process include investing in clean energy technologies with consistent cost declines, enacting central bank policies to reduce the value of brown collateral, and enhancing climate-related financial risk disclosure.

Our work is closely related to the recent literature on tipping ‘positive’ change in socio-economic systems (Milkoreit *et al.*, 2018; Lenton, 2020; Otto *et al.*, 2020; Sharpe and Lenton, 2021; Lenton *et al.*, 2022; Winkelmann *et al.*, 2022). In this work, tipping points and positive (or reinforcing) feedback loops are emphasized as the key characteristics that can make systems sensitive. Our work also has strong connections to the literature on

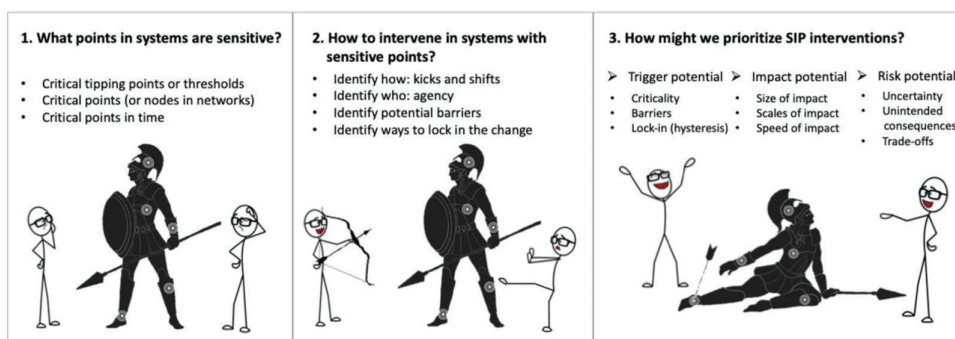


Figure 1: Diagram of the SIPs policy framework. *Note:* Elements of this figure were created with Storyboard That <https://www.storyboardthat.com/>

socio-technical transitions (Geels *et al.*, 2017; Sovacool and Hess, 2017) and the multi-level perspective for understanding sustainability transitions (Geels, 2002, 2004; Geels and Schot, 2007). Such theories and frameworks provide valuable ways to understand the process by which innovation in niches can break through to create larger system change when the broader socio-technical regime experiences sensitivities such as tensions or windows of opportunities.

Our work is similar in spirit to Meadows' (1999) conceptual framing of 'leverage points', which sets out a list of places to intervene in a system to drive large-scale transformative change. However, while many of Meadows' top-ranked leverage points relate to actions that are very difficult to achieve (e.g. changing the goals or paradigm of the system), our approach places greater primacy on pragmatic actions that target and exploit sensitive points in systems. Our approach is therefore somewhat distinct from mission-oriented policy frameworks aiming to shape system goals or objectives (Mazzucato, 2018; Robinson and Mazzucato, 2019), and can be seen as complementary to these frameworks. While large or outsized impacts are the ultimate outcome we seek, in this paper we aim to identify interventions which do not require commensurately large effort.

Our work is also related to the literature advocating for 'big push' style policies to help shift the economy from its current brown, unsustainable equilibrium to a greener and more sustainable equilibrium (van der Ploeg and Venables, 2022). Analogous to the literature on poverty traps (Rosenstein-Rodan, 1943; Murphy *et al.*, 1989; Collier, 2006; Sachs, 2006; Kraay and McKenzie, 2014; Ghatak, 2015; Barbier and Hochard, 2019), proponents of this research emphasize the presence of strong feedback mechanisms holding the economy in a brown, carbon-intensive trap. Identified forces include the underpricing of fossil fuels (through explicit and implicit subsidies (Barbier, 2010, 2020, 2023, this issue; Helm, 2015; Parry *et al.*, 2021; Black *et al.* 2022), institutional inertia (Geels, 2014), and powerful, well-resourced vested political interests that stand to lose from the transition (Moe, 2010; Ohlendorf, Jakob and Steckel, 2022). Hence, unless policies are effective in pushing the economy past a tipping point onto a green trajectory, the economy will keep sliding back into its brown equilibrium. The muted impact of green stimulus packages introduced in response to the 2009 financial crisis were highlighted as a possible example of policies that didn't go far enough to propel economies onto a self-reinforcing greener pathway (Barbier, 2010). Similar to van der Ploeg and Venables (2022), our paper therefore underscores the importance of policies that—due to their ability to leverage existing sensitivities in a socio-economic system—could be potent enough to overcome systemic inertia and make outsized gains towards a green equilibrium.

II. What points in systems are sensitive?

(i) Critical tipping points or thresholds

Tipping points are the most obvious points in systems where a small change or perturbation can have a big impact. Tipping points come in a variety of different forms, but generally involve a critical threshold in the value of a state variable or parameter where the system becomes unstable and can be tipped from one equilibrium to another, or onto an entirely different trajectory. At a tipping point, dampening (or negative feedback) forces keeping the system in its existing state are counterbalanced by reinforcing (or positive feedback) forces driving it into another state or trajectory (Lenton *et al.*, 2022).

A key example of a tipping point is a 'critical mass' threshold (Centola *et al.*, 2018). The benefits of adopting a behaviour, product, or technology often increases with the number of people adopting it, such that once a critical

mass of adopters is reached, the majority soon follows. For example, it generally becomes more advantageous to join international climate agreements as more countries participate, and studies have suggested that adoption by a critical number of countries (a ‘tipping set’) can make it in the interests of all countries to sign up (Heal and Kunreuther, 2011; Helm and Ruta, 2012; Hale, 2020). Similarly, peer-effects have been shown to play an important role in the adoption of rooftop-solar and other environmentally friendly behaviours (Bollinger and Gillingham, 2012). While the size of this critical mass will likely depend on the specific context and countries involved, experimental evidence has suggested that a committed minority of around 25 per cent of the group size can be enough to ‘tip’ opinions of the broader majority (Centola *et al.*, 2018). Somewhat counter-intuitively, Iacopini *et al.* (2022) have shown that when non-committed members of the population are less susceptible to social influence, committed minorities of much smaller sizes (0.3 per cent of the population) can be effective in flipping the majority’s consensus view.

The price point at which low-carbon technologies become cheaper than emissions-intensive technologies is another example of a critical threshold. Once passed, switching to cleaner technologies is likely to become much more rapid and widespread. Owing to the impressive cost-declines experienced in many renewable energy technologies in recent years, clean energy (and storage) is now close to price parity with fossil fuels in much of the world (Way *et al.*, 2022). In transport, the ownership cost of electric vehicles (EVs) is now also close to that of internal combustion engine vehicles in several leading car markets (Lam and Mercure, 2022). Relatively small interventions to make low-carbon technologies even more affordable could therefore have a large impact in driving mass switching away from emissions-intensive technologies (Sharpe and Lenton, 2021). While declines in technology costs are necessary, they are not by themselves always sufficient—achieving a net zero energy system or the electrification of personal transport also requires grid and charging infrastructure upgrades. However, lower costs of panels and EVs greatly increase the likelihood that governments and firms will provide the associated infrastructure.

(ii) Critical points in networks

In socio-economic systems, most interactions between people, firms, and organizations don’t happen at random. Whether it be the exchange of goods and services, or the flow of funds, information, or ideas, patterns of interaction tend to be relatively persistent and occur within distinct network structures. Many networks in socio-economic systems have several hubs where a few key nodes (or actors) are linked to many others. These network structures are generally robust to perturbations on random nodes, but highly vulnerable (or sensitive) to targeted interventions on key nodes.

Much of the literature on network fragility has focused on how the presence of critical nodes can allow comparably small negative shocks to cascade through networks and cause much larger system-wide impacts. Key examples include the possibility for cascading failures in power systems or communication or infrastructure networks (Korkali *et al.*, 2017; Schäfer *et al.*, 2018), and the potential for widespread economic disruption to be caused by localized shocks hitting critical firms in global supply chain networks (Inoue and Todo, 2019; Chakraborty *et al.*, 2021). Coupling between networks (such as production networks and transport networks) can also significantly increase the risk of catastrophic outcomes (Colon *et al.*, 2021).

However, insights about critical points in networks have also been exploited in various fields to improve the efficiency and efficacy of specific interventions. In epidemiology, targeting vaccines towards highly connected individuals (or ‘super-spreaders’) has been shown to be more effective in limiting virus outbreaks than vaccinating people at random (Pastor-Satorras and Vespignani, 2001; Dezső and Barabási, 2002; Chen *et al.*, 2008; Saunders and Schwartz, 2021). In financial systems, institutions that are recognized as being ‘systemically important’ (i.e. too-big- or too-critical-to-fail) have become subject to higher levels of regulation and increased capital requirements since the 2007/8 financial crisis (Bardoscia *et al.*, 2017; Poledna *et al.*, 2017; Battiston and Martinez-Jaramillo, 2018). And in studies of behaviour change in the context of sustainability, targeting highly connected ‘opinion leaders’ in social networks has been shown to be an effective strategy for accelerating the diffusion of information and actions (Barnes *et al.*, 2016; Matous and Todo, 2017; Mbaru and Barnes, 2017).

Leveraging information about critical points in networks can also improve the effectiveness of interventions aiming to accelerate decarbonization. For example, King *et al.* (2019) show that targeting incremental carbon taxes towards key sectors based on their position in the economy’s production (or input–output) network can result in greater emission reductions than directly targeting the most heavily emitting sectors. Such insights can be valuable in contexts where political opposition to an economy-wide carbon tax is too high. Several studies have also demonstrated how strategies to deploy and diffuse green technologies can be more effective if they account for information about social networks (Bale *et al.*, 2013; Chen and Shi, 2021). For example, Du *et al.* (2016) demonstrated that exploiting information about the number of connections and strength of links in households’ social networks when rolling out energy efficiency technologies can improve energy savings by 47 per cent in the first month.

(iii) Critical points in time

Small or moderate interventions at the right moment—when a system is ‘ripe for change’—can have large impacts. In the multi-level perspective on sustainability transitions, ‘windows of opportunity’ are emphasized as critical points in time when conditions become more favourable for destabilizing existing regimes and changing entrenched institutional landscapes (Geels, 2006; 2012).

An important example is the critical window of opportunity that opened up in the UK that allowed the introduction of the world’s first long-term, legally-binding emissions reduction framework—the 2008 UK Climate Change Act. The Act introduced national legislation requiring emission reductions of 80 per cent relative to 1990 levels by 2050, as well as a range of institutional bodies enforcing accountability. In addition to playing an important role in driving emission reductions in the UK over the last decade, it also inspired similar legislation globally (Fankhauser *et al.*, 2018; Averchenkova *et al.*, 2021). But what possessed the UK government to impose such binding obligations on itself—at a time when no other country had adopted a similar framework?

While causality is difficult to prove, the UK Climate Change Act’s introduction was preceded by a rare culmination of factors including (i) effective campaign and awareness raising efforts by numerous NGOs in the years leading up to the Act’s introduction, (ii) Conservative Party Leader David Cameron’s decision to make climate change a key issue to revamp and increase the appeal of the Tory brand, (iii) the publication of significant reports such as the IPCC’s 4th Assessment Report, and the Stern Review of the Economics of Climate Change, which stressed that early action was the cheapest policy option, and (iv) the appointment of Labour’s ambitious and energetic David Miliband as Secretary of State of the UK’s key government department for the environment (Defra). The combined alignment of these factors—awareness raising campaigns, political competition, the authoritative reframing of climate action in economic terms and an engaged actor within government—likely gave rise to a socio-economic system that was ‘ripe’ for institutional change. This was recognized by several bodies and the idea of an independent committee, by analogy to the independent monetary policy committee of the Bank of England, was introduced to political thinking during this critical window. Scholars had also called for, and *ex ante* recognized, the value of such an independent body to ensure long-term climate goals would not be subject to the vagaries of political short-termism (Helm *et al.*, 2003).

Windows of opportunity can also open up unexpectedly when exogenous shocks hit the system. The recent Covid-19 pandemic is a good example: with trillions of dollars currently being spent or earmarked for economic recovery measures, this was a unique, global window of opportunity for countries to make substantial investments in clean technology, climate-friendly infrastructure, and building the green industries of the future (Hepburn *et al.*, 2020). While green spending only accounted for a relatively small fraction of rescue and recovery packages (O’Callaghan *et al.*, 2022), the combined investment in major economies such as China, the US, Europe, and India could be enough to drive low-carbon technology costs and uptake past critical price and adoption tipping thresholds. A further example could be Russia’s war on Ukraine, which has drastically increased the cost of oil and gas and resulted in one of the most severe global energy crises in recent history. On the one hand, the war represents a unique opportunity for countries (particularly in Europe) to reduce their dependence on Russian oil and gas and rapidly switch to renewable energy sources. But on the other hand, some European countries have turned to coal in the short-term to bridge the energy shortfall.

(iv) A note on reinforcing feedbacks

Much of the recent literature on SIPs and tipping positive change in socio-economic systems has emphasized the importance of reinforcing or positive feedback mechanisms (Milkoreit *et al.*, 2018; Lenton, 2020; Otto *et al.*, 2020; Sharpe and Lenton, 2021; Lenton *et al.*, 2022; Winkelmann *et al.*, 2022). Positive feedback processes—where more begets more—are inherently destabilizing forces that can be leveraged to amplify the change triggered by an intervention. However, while the presence of a tipping point implies the existence of underlying positive feedback mechanisms, the converse is not necessarily true.¹ Many positive feedback mechanisms do not give rise to tipping points (Lamberson and Page, 2012), and their effectiveness for driving outsized impacts depends on their relative strength compared to negative (or dampening) feedback processes in the system (Meadows, 1999).

That said, interventions that exploit reinforcing feedback loops have important advantages over those that don’t. In the case of energy technologies, solar and wind have demonstrated strong learning-by-doing effects (a well-recognized positive feedback mechanism), while other technologies, such as carbon capture and storage and nuclear, have not (Way *et al.*, 2022). Policy interventions that encourage greater production and deployment of solar

¹ For example, many exponential growth processes arise due to positive feedback mechanisms (e.g. world population, number of Facebook users, or number of internet websites), but these do not involve a tipping point (Lamberson and Page, 2012).

and wind (such as subsidies or tax credits) have been much more effective at bringing down costs than those aimed at CCS or nuclear. Several reasons are hypothesized. One reason is that renewables' low operation costs enables them to easily win preference in a market-based electricity networks thanks to the 'merit order effect', and has led to average wholesale electricity price declines in many countries (Clò, Cataldi and Zoppoli, 2015; Woo *et al.*, 2013; Kyritsis, Andersson and Serletis, 2017; Mountain *et al.*, 2018). Another reason is that nuclear and CCS plants are major civil engineering projects, taking many years to complete. Because they are not modular, but have more bespoke features associated with 'one of a kind', or at least 'first of a kind' projects, the opportunity for learning, and hence the learning rates, are considerably lower (Wilson *et al.*, 2020; Ansar, 2022). A further advantage is that policies to support deployment and learning of modular technologies, such as wind and solar, are unlikely to be needed permanently; once technologies become cost competitive, market forces can take over (Aghion *et al.*, 2009; van der Ploeg and Venables, 2022).

III. How to intervene in systems with sensitive points?

(i) Identify how: kicks and shifts

Building on Farmer *et al.* (2019), we distinguish between two approaches for intervening in systems with sensitive points (see Figure 2). The first approach—a 'kick'—takes the existing system as given and targets the system's SIPs. For example, having identified that many countries are now very close to the critical price threshold at which renewable energy technologies become cheaper than fossil fuel technologies, a kick intervention would target specific policies (e.g. temporary subsidies or tax credits) to 'kick' renewable energy costs over the threshold.

The second approach—a 'shift'—aims to change the way the system operates. Shift interventions involve introducing institutional changes to bring systems closer to a tipping point, alter power dynamics in a given network, open up new avenues for positive feedback mechanisms, or weaken or remove key obstacles to change. As institutional shifts can often be politically challenging, they usually can only be introduced at critical points in time—such as the window of opportunity that opened up to allow the introduction of the UK Climate Change Act.

Another 'shift' would be to increase the regulatory hurdles before fossil fuel companies can expand or renew their operations. Fossil fuel permitting laws can be updated to account for the full-system costs of mining and combustion (Klenert *et al.*, 2018). Natural capital accounting can provide the evidentiary basis on whether such activities still meet the public interest by explicitly measuring and sizing negative societal impacts, such as mortality and morbidity from air pollution, displacement of communities, destruction of pastoral lands and native forests, and the reduction of ecosystem services (Rafaty *et al.*, 2020). Moreover, in many cases, the existing base of laws

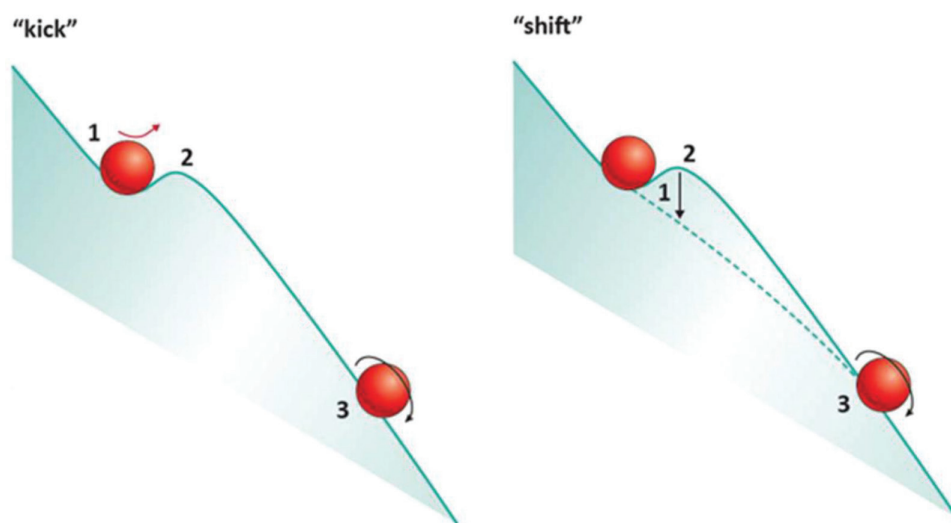


Figure 2: Kicks and shifts: two types of intervention for SIPs. A 'kick' takes the existing system as given (its rules, institutions, tendencies, etc.), and introduces interventions targeted at the system's sensitive intervention points. A 'shift' involves changing the way the system operates, usually through an institutional shift.

provides implicit subsidies for coal by providing fast-track pathways for development—simply aligning these with the processes for general infrastructure development would level the playing field (Srivastav and Singh, 2022).

Many interventions can involve both kicks and shifts. For example, strategies to accelerate the electrification of transport could deploy interventions to kick the cost of EVs below price parity with internal combustion engine vehicles, and shift the institutional (e.g. planning and regulatory standards) and infrastructure (e.g. charging stations) landscape to support the switch to EVs.

(ii) Identify who: agency

When designing SIP interventions, it is important to understand and identify the relevant sources of agency. Which individual, institutional body, or community of stakeholders are capable of implementing or orchestrating change in the system, and to what extent are they able or incentivized to carry out the necessary actions?

When the system and lines of influence are relatively well defined, actor mapping, which involves mapping out key organizations and/or individuals that both influence and are impacted by a system, can be a useful process to understand which actors could act as critical nodes in a social, political, or institutional network (Bryson, 2004). It can also be helpful for identifying how easily a ‘shift’ style intervention can be triggered. On the one hand, an energy and resources minister can end the permitting of fossil fuels exploration and extraction with a simple pen stroke, but on the other hand that minister’s capacity to act may be limited by a variety of obligations to other influential actors.

Platforms can also be powerful sources of agency. As the world has become more complex and digitally networked, power and influence have become more distributed across digitally mobilized masses. Social media and other digital platforms that engage the attention, participation, and collaboration of people all around the world, are now incredibly important vehicles for channelling what has been referred to as ‘new power’ (Heimans and Timms, 2018). While recent political events and disinformation campaigns have underscored the potential for these new forms of influence to be used for nefarious purposes, it has also highlighted how leveraging these platforms for driving pro-climate campaigns and positive, climate-friendly engagement has never been more important.

(iii) Identify potential barriers

Change rarely happens without encountering and overcoming significant resistance and pushback. In the context of addressing climate change, one of the most important sources of resistance is actors or entities that stand to incur losses as a result of policies promoting decarbonization. Fossil fuel companies are obvious candidates, and efforts of various companies to obstruct, dilute, or reverse climate policy have been well documented (Srivastav and Rafaty, 2022). Tactics such as aggressively lobbying politicians, funding misinformation campaigns, and supporting think-tanks that promote climate change denialism or which present climate policies as anti-growth, have proven to be particularly effective forms of resistance.

Other entities likely to be adversely impacted include people working in emissions-intensive activities (e.g. coal miners, fossil fuel power plant operators, oil and gas workers) who stand to lose employment opportunities (Carley and Konisky, 2020). Unexpected entities like railway companies may also stand to lose because of unique co-dependencies in the system. For example, coal accounts for 44 per cent of Indian Railways’ freight revenues and an even higher share of profits. The Indian Railways business model is based on coal freight cross-subsidizing passenger fares. This creates a unique source of resistance (Kamboj and Tongia, 2018).

While various modelling efforts (including computable general equilibrium, post-Keynesian, and input–output models) consistently show that well-planned climate policy is likely to create more jobs than it will cost (Garcia-Casals *et al.*, 2019; Vona, 2019), the possibility that job losses are geographically concentrated in certain communities with limited diversification possibilities can amplify the adverse local economic impacts and political pushback.

Srivastav and Rafaty (2022) articulate five strategies for overcoming these sources of resistance. The first—‘antagonism’—involves various types of activism that increase the economic and reputational costs of non-climate-friendly behaviour. These can include protests that build public awareness of the importance of addressing climate change, encouraging consumers to boycott products from companies that act irresponsibly towards the climate, and even filing lawsuits against companies for damages caused by emissions-intensive activities. A second strategy—termed ‘co-optation’—involves leveraging powerful elites to persuade obstructionists to reform their behaviour. For example, Pope Francis, a particularly influential ‘co-opter’, drew on his unique moral authority to call on oil and gas executives to change track. Similarly, majority shareholders, well-respected academics, celebrities, or high-profile advisors or thought leaders can often use their influence to co-opt businesses or public institutions towards a more climate-friendly stance. A third strategy, ‘appeasement’, relates to the provision of compensation to ‘losers’ of the transition. For owners of emissions-intensive assets, appeasement can involve payments

from the government for early closure. For adversely impacted workers, appeasement strategies are often framed in terms of a ‘just transition’, and can involve compensatory payments for job losses, worker retraining programmes, or the funding of regional development programmes to support economic diversification. The fourth strategy—‘countervailance’—can invigorate green lobbies that create a counterweight lobbying force to fossil fuel incumbents, and the fifth strategy, ‘institutionalism’, aims to change the rules of the game to make business-as-usual harder, for example by requiring companies to disclose climate-related risks.

It is important to consider how interventions can be best designed to minimize potential pushback, without compromising on the integrity of the intervention. Early identification and active engagement with sources of resistance throughout the policy development process is likely to ensure sticking points are appropriately diagnosed and efforts directed at overcoming them are well targeted.

Finally, not all obstacles stem from actors or entities who stand to lose out. Other barriers to change may arise due to the nature and complexity of the particular intervention. For example, if the intervention is particularly novel, the lack of precedent or know-how can sometimes be a stumbling block. In some cases, clean technologies represent a paradigmatic shift in technological terms from dirty counterparts, and consequently will require the cultivation of new skills, scientists, and knowledge (e.g. Dugoua, 2020; Jee and Srivastav, 2022). Similarly, if the proposed change requires the coordination of multiple parties or stakeholders or overly burdensome administration, the complexity of implementation can act as an obstacle.

(iv) Identify ways to lock in the change

Interventions that drive change—even large-scale system-wide change—are unlikely to be worthwhile if the change can be easily reversed at some point in the future. Hence, when designing and prioritizing interventions, it is important to consider elements that prevent the given change from being easily undone, such as lock-in effects, embeddedness, and high switching costs.

Interventions that drive down technology costs are advantageous in this regard as it is unlikely the associated innovation and learning that drove such cost reductions will be un-learned or forgotten. Technological ‘lock-in’ is also a widely recognized source of path-dependency, where once a particular technology or set of technologies is adopted, it tends to remain embedded, even when it is not the optimal or most efficient (like the QWERTY keyboard) (David, 1985; Arthur, 1989). Technological lock-in may mean that it is more difficult to displace emissions-intensive energy technologies, even when they become less economical than green technologies. However, once the switch does occur, the probability of switching back to dirty technologies is very minimal.

On the flip side, interventions that involve policy or institutional shifts can be more vulnerable to reversal if a non-climate-friendly political party comes into office. A good example of this is the Australian carbon pricing scheme, which was originally introduced by the Labour Party in 2011 but repealed by a coalition of the Liberal and National parties in 2014. Such policies can be made more difficult to repeal by directing the revenue raised from the tax towards purposes that have broad public appeal (e.g. salient lump sum transfers to citizens) (Klenert *et al.*, 2018), or if the costs of changing a policy are very high. Other interventions that could be less ‘sticky’ include those that rely on public awareness (e.g. eating less meat), which can wax and wane over time and can also be influenced by disinformation campaigns.

IV. How might we prioritize SIP interventions?

Having provided the conceptual background for identifying sensitive intervention points in systems and ways to intervene, we now set out a framework for systematically prioritizing different SIP interventions. Our framework is summarized in Table 1 and includes three key pillars by which interventions are assessed: trigger potential, impact potential, and risk potential. We discuss each of these elements in turn, before applying this framework to evaluate 20 expert-elicited SIP interventions for decarbonization.

Interventions with high *trigger potential* can be implemented relatively easily and are also difficult to reverse. To assess an intervention’s trigger potential, we consider whether it exploits a specific SIP, whether any possible barriers can be easily diffused, and whether there are mechanisms that can help lock-in the intervention’s desired impact.

Interventions with high *impact potential* are those that are likely to result in impacts that are large in terms of size, scales, and speed. We draw a careful distinction between size and scales. Size relates to the possible magnitude of the impact (e.g. in terms of emission reduction potential or other relevant outcome) compared to the likely cost of effort involved in implementing it. Scales refers to the possibility for an intervention to drive cascading

Table 1: Overview of framework for prioritizing SIP interventions

Prioritization pillar	Key assessment elements	Considerations
Trigger potential	Criticality: Does the intervention exploit a sensitive intervention point?	Is the system close to a critical tipping point? Does the intervention target a critical node in a network? Is this a critical point in time?
	Barriers: Are there barriers or resistance to the intervention, and can they be easily diffused?	Who stands to lose out from the intervention? Are there any other possible stumbling blocks or binding constraints?
	Lock-in and hysteresis: What prevents the change from being reversed?	Will a change in political leadership reverse the change? Does the intervention create path-dependency? Are actors in the system incentivized to keep the change in place?
Impact potential	Size of impact: Likely size of impact relative to cost of effort	Size of impacts relative to costs can be difficult to quantify without a model that is able to capture non-linear dynamics. However, rough estimates and expert opinion can also be useful (Lenton <i>et al.</i> , 2008).
	Scales of impact: Potential to generate compounding change at greater scales	Does the intervention lead to upward-scaling cascades across multiple system scales (e.g. sectors, geographies, or social spheres)? Does the intervention create synergies with other interventions, amplifying the overall effect of change?
	Speed of impact: Time scale in which the intervention can be triggered and impacts realized	Are the desired impacts likely to be realized at a time-scale relevant to address the problem (e.g. addressing climate change requires significant emissions reductions in the next few decades)
Risk potential	Uncertainty: What are the sources of uncertainty around the envisioned change process and associated impacts?	Are there examples where similar interventions have been tried in the past? Are there inherent sources of uncertainty that could put the viability of the intervention at risk?
	Unintended consequences: Could the intervention lead to impacts that are not intended or anticipated?	The risk of unintended consequences can be higher in complex systems that are sensitive to small changes in initial conditions or involve complex dynamics that are not well understood. Engaging with diverse groups of stakeholders can help bring to light unapparent unintended consequences
	Trade-offs: Could the intervention or desired impacts cause adverse outcomes in other areas?	Are there any possibilities where the intervention or its impacts may create tensions or adverse impacts in other areas? If so, are there ways in which these trade-offs can be mitigated?

or compounding impacts across multiple sectors, social spheres, geographies (e.g. local → national → global) (Bernstein and Hoffmann, 2019; Sharpe and Lenton, 2021; Tozer *et al.*, 2022). We also consider whether the intervention may have synergies with other existing interventions or change dynamics, such that they reinforce each other or drive ‘virtuous’ cycles towards desired outcomes. Speed relates to the timescale in which the intervention can be triggered and impacts realized. Given the urgency of the climate crisis, when considering SIP interventions for decarbonization we place a strong primacy on interventions that can realize impacts in the next decade.

Interventions with low *risk potential* are those that involve low levels of uncertainty, unintended consequences, and trade-offs. We consider an intervention’s uncertainty with respect to the envisioned change process and associated impacts. Interventions that have never been implemented before will generally have higher uncertainty than those with a greater track record. Interventions that depend on inherently uncertain processes (such as the election of a particular political party) will also have higher uncertainty. While all policies have the potential for unintended consequences, such risks are likely to be higher in complex systems that are sensitive to small changes in initial conditions, or that involve complex dynamics that are not well understood. Trade-offs in the form of adverse associated outcomes in other areas are also relevant. For instance, removing fossil fuel subsidies, extraction permits or otherwise restricting fossil supply could cause (temporary) higher energy costs, disproportionately affect low-income households, and lead to a political backlash.

V. Evaluating 20 SIPs for decarbonization

In this section, we demonstrate an application of the framework discussed above to a list of 20 potential SIP interventions based on qualitative data collected through a series of consultations with relevant experts from academia, industry, government, and civil society. Their expertise covered a wide range of topics including energy, agriculture, transport, economics, development, future studies, industrial relations, policy, environment, and climate. A full description of the data collection process (along with information about the interview questions and range of experts) can be found in the [Supplementary Materials](#).

Proposed interventions covered a variety of sectors (e.g. energy, transport, finance), and policy areas (e.g. governance, behaviour, technology, education, just transition) (see [Figure 3](#)). For each intervention, we assessed its key characteristics corresponding to its trigger, impact, and risk potential (summarized in [Table 1](#)) by drawing on literature, discussions with experts, and modelling where possible. Our detailed assessments for each element can

	Potential SIPs	Trigger potential			Impact potential			Risk potential		
		Criticality	Barriers	Hysteresis	Size of impact	Scale of impact	Speed of impact	Uncertainty of impacts	Unintended Consequences	Trade-offs
A	Invest in clean energy technologies with evidence of consistent cost declines									
B	Enhance climate-related financial risk disclosure by improving requirements for companies to report their exposure to climate risk									
C	Enact central bank policies that reduce the value of polluting collateral to incentivise clean investment									
D	Remove fossil fuel subsidies									
E	Electrify transport by investing and supporting deployment of EVs and associated infrastructure									
F	Invest in the development and deployment of zero-carbon hydrogen-based fuels									
G	Implement carbon border adjustments in large trading blocs									
H	Support strategic climate litigation against actors that irresponsibly contribute to GHG emissions									
I	Introduce a decarbonisation-based civilian jobs program									
J	Implement a climate change Act to legislate strict national emissions reduction targets									
K	Introduce decarbonised development loans that tie development lending to decarbonisation goals									
L	End fossil fuel exploration and extraction permitting									
M	Improve efficiency and emissions standards in government									
N	Appoint a national climate minister with strong political support									
O	Invest in smart grid technologies									
P	Support green behavioral change programs and pro-climate social mobilisation efforts									
Q	Improve climate risk education for vulnerable groups									
R	Develop better bicycle infrastructure									
S	Invest in negative emissions technologies (including CCS)									
T	Invest in new nuclear fission technologies									

Figure 3: Heatmap showing the breakdown of each SIP intervention's trigger, impact, and risk potential into its constituent elements. More details on each assessment and the associated analysis and supporting literature are provided in the [Supplementary Materials](#).

be found in Table SM1 in the [Supplementary Materials](#). Based on these assessments we assigned a rating for each element indicating whether they were unfavourable, favourable, or in-between. To aid visualization, we converted this into a traffic light system where green denotes favourable, red is unfavourable, and yellow is in-between (see [Figure 3](#)). Note that in the black-and-white version of this article, we have labelled these colours to make this clear. [Figure 3](#) also shows each SIP intervention ordered in terms of its total ranking over all assessed elements, such that most favourable interventions appear closer to the top.

It is important for readers to recognize that the ratings given to each SIP intervention reflect the authors’ subjective evaluations, informed by existing literature, expert consultations, and modelling. This qualitative approach is not intended as a means for providing accurate predictions but rather designed to bring visibility and discussion to bear on the likelihood that a potential SIP intervention could be effective in accelerating decarbonization.

[Figure 4](#) shows a scatter plot illustrating our evaluation of each intervention. Here, each bubble represents a potential SIP intervention which is coloured in terms of its assessed risk potential (darker grey corresponds to higher risk while lighter grey relates to lower risk). The x-axis plots each intervention’s assessed impact potential, while the y-axis plots its trigger potential.

Proposed SIP interventions with the highest trigger and impact potential include (A) *Invest in key energy technologies with consistent cost declines* and (C) *Enact central bank policies to reduce the value of polluting collateral*. Our assessment of (A) is based primarily on the modelling undertaken in [Way et al. \(2022\)](#), which is focused explicitly on the predictability of cost declines in clean energy technologies, and suggests that continuing current trends in the deployment of renewables and storage technologies could result in the global energy emissions being reduced by as much as 80 per cent by 2040. This SIP intervention was therefore rated highly in terms of its size, scale, and speed of impact. As solar PV has already achieved price parity with fossil fuels in a number of major economies such as India and China, and is now regarded as the ‘cheapest electricity in history’ ([IEA, 2020](#)), this intervention also exploits a critical price threshold, giving it a high rating in terms of its criticality. Moreover, as cost declines driven by technological learning are difficult to unlearn, the disruptive change driven by this intervention is considered difficult to reverse.

The idea behind (C) *Enact central bank policies to reduce the value of polluting collateral* is to reduce the recognized value of brown collateral held with central banks on behalf of commercial banks, incentivizing the latter to provide more financial support for green assets ([McConnell et al., 2022](#)). As the actions of central banks play a critical role in directing capital flows around the world, such an intervention could have a rapid impact on driving capital away from emissions-intensive assets and towards green assets. It was thus assessed as having high potential for size, scale, and speed of impact. Whether this intervention will scale will depend on the extent to which central banks mimic the actions of others, particularly those of influential central banks, such as the US Federal Reserve and the European Central Bank. In terms of trigger potential, this intervention targets critical nodes in the financial system (central banks). There is also some evidence to suggest that a window of opportunity is opening

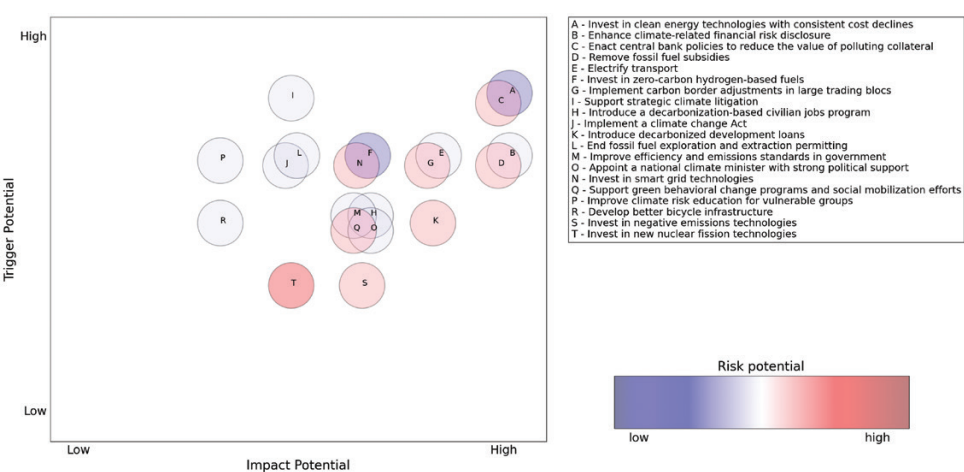


Figure 4: The 20 interventions ranked based on their impact potential (x-axis) and trigger potential (y-axis), with colour coding providing an appraisal of each intervention’s risk potential. A full version of the analysis of each characteristic for these SIPs that justifies their ranking from the authors perspective are provided in the [Supplementary Materials](#).

with the European Central Bank recently announcing that it will be applying such policies (Dikau and Volz, 2021; ECB, 2022).

While these interventions are promising, both involve potential barriers. The strength of fossil fuel lobbyists and workers with livelihoods dependent on the fossil fuel industries could act as a barrier to channelling greater investment towards renewables in certain national contexts. Interestingly, however, fossil fuel lobbies tend to react less vigorously against renewables support, and more vigorously against policies that directly harm their economic prospects (Srivastav and Rafaty, 2022). Required investment in grid infrastructure to support higher renewables penetration is also an important barrier that requires careful planning. Similarly, the implementation of central bank policies to reduce the value of brown collateral also faces some opposition from regulators concerned that such actions fall outside central banks' mandates.

Where the two interventions differ in terms of their assessment is risk potential. Investment in clean energy technologies with consistent cost declines was assessed by the authors as relatively favourable in terms of risk potential, as the uncertainty associated with cost declines is relatively low (particularly for solar and wind) and there appear to be limited trade-offs. While there is a potential risk of environmental impacts associated with mining for minerals critical for clean energy technologies, the risks overall with this SIP intervention were rated as much lower than central bank brown collateral revaluations. While collateral revaluations have been tried in other contexts, such interventions have greater uncertainty in terms of the expected outcome. There is also some risk of unintended consequences if central banks lose their credibility for managing systemic risk and instead gain a reputation for 'picking winners and losers'.

Another notable SIP intervention includes (B) *Enhancing climate-related financial risk disclosure*, which involves improving requirements for companies to report their exposure to climate risk (physical, transition, legal, reputation). This SIP was assessed to have high trigger potential given recent developments from the international Financial Stability Board and the Task Force on Climate-Related Financial Disclosures (TCFD). It was also rated reasonably high in terms of impact potential, as the intended impact (incentivizing companies to reduce exposure and decarbonize) is likely to be much greater than the associated cost of implementation (although Barbier and Burgess (2018) argue that impact is more likely if companies are required to go beyond climate risk disclosures to climate risk management measures). Once established in one country or jurisdiction, it also has strong potential to influence others (the US Securities and Exchange Commission is currently working on such disclosure rules). Risks were also assessed to be moderate, although efforts in this domain have triggered a backlash against 'woke capitalism'. There is some uncertainty around the likely impacts of a change in financial reporting requirements, and potential that such reporting could be difficult for some companies, particularly for those in the Global South that may lack the technical expertise to measure and disclose climate risks.

VI. Discussion and conclusion

This paper attempts to set out a more strategic approach for climate action. Building on the ideas in Farmer *et al.* (2019), we propose a conceptual framework for identifying and prioritizing interventions that are likely to have outsized or transformative impacts. High-priority interventions are those that exploit points in systems that are sensitive—where small or moderate changes are likely to have large impacts. These sensitive intervention points can take the form of critical tipping points, critical points (or nodes) in networks, and critical points in time where windows of opportunity open up to allow for institutional or system-wide change.

High-priority interventions are also those that are likely to have high impact potential and low risk potential. These interventions are likely to result in high impacts (such as emissions reductions) relative to the cost of effort required to implement them, and have high potential for cascading or compounding change into other areas, and, given the urgency of addressing climate change, high likelihood of achieving results relatively quickly. Interventions with low risk potential involve lower uncertainty around likely impacts, and less risk of unintended consequences or trade-offs.

By applying our framework to a list of 20 policies proposed to accelerate decarbonization, we seek to identify some of the most promising high-priority interventions. These include investing in key clean energy technologies with consistent cost declines, enacting central bank policies to reduce the value of polluting collateral, and enhancing climate-related financial risk disclosure. Each of these interventions received favourable ratings for the majority of their characteristics, and no unfavourable ratings. Within the five most highly rated interventions there is coverage of the full range of sensitive intervention points (tipping points/thresholds, critical nodes in networks, and critical points in time).

Progress on the first top two interventions is promising. Renewables are already past price parity with fossil fuel generation in many countries (IEA, 2020), and costs have potential to decline further. However, limited resources for investment and higher costs of capital in developing countries still pose a challenge for rapidly diffusing these technologies across the globe (World Bank, 2023). Similarly, the push from the Bank of England and the Financial Stability Board to establish climate risk disclosure reporting represents a promising step towards transforming the finance sector. However, obstacles still remain around preventing ‘greenwashing’ and ensuring the industry has sufficient information to accurately report climate risks.

A key limitation of our approach for prioritizing SIP interventions is that while our assessments were well researched, ratings were ultimately subjectively determined. Different assessors could no doubt arrive at different ratings, and ratings may differ in different countries or cultural contexts. We also note that the ideal way to assess each intervention’s trigger, impact, and risk potential would be with a well validated and calibrated model of the system one is seeking to change. However, detailed modelling was not available for all interventions on our list. Moreover, most standard modelling frameworks used to inform policy-makers about costs, benefits, and likely impacts of specific policies tend to be limited in their ability to incorporate non-linear dynamics such as positive feedbacks, tipping points, or multiple equilibria (Dietz and Hepburn, 2013, Pindyck, 2013, Farmer *et al.*, 2015, Stern, 2016, Mercure *et al.*, 2021, Xiao *et al.* 2021). Improving and expanding the set of policy models able to appropriately capture these elements is an important avenue for future work.

It is also important to emphasize that our list of SIP interventions and our resulting assessments were not designed to give a definitive or exhaustive set of interventions that would be sufficient to drive a successful transition to net-zero. Our goal has been to set out a conceptual framework that can identify and prioritize interventions that are more likely to generate outsized impacts. The assessment of interventions described in this paper are merely intended to provide an example of our framework in practice.

And indeed, although this paper has focused on the key challenge of accelerating progress towards net-zero, our framework is completely general and could be applied to various other socio-economic contexts and objectives. An obvious and important avenue would be economic development, where the goal of policy is sometimes viewed in terms of helping shift an economy from a low-income equilibrium to a high-income equilibrium. As noted in the Introduction, ‘big-push’ style policies have previously been proposed in the development literature, which aim to provide sufficient support to ‘push’ an economy out of its stagnant state and towards an industrialization pathway. However, a development strategy based on exploiting SIPs in low-income countries could potentially achieve greater levels of growth and development with considerably less effort.

Finally, for simplicity our framework has focused only on identifying and prioritizing individual interventions. However, we do not want to under-emphasize the importance of developing well-designed portfolios of policies and being mindful of the dynamic interactions between interventions. The introduction of one policy can make another more effective (Sharpe and Lenton, 2020; van den Bergh *et al.*, 2021), and strategic sequences of interventions can be an effective way to overcome political economy barriers and successively introduce more ambitious interventions over time (Meckling *et al.*, 2017; Pahle *et al.*, 2018). Future work could extend the SIP framework to consider multiple policies and identify policy packages that collectively could drive outsized impacts in a system. With more interventions and actions synergistically acting in concert, achieving the Paris goals might still be within our reach.

References

- Aghion, P., Hemous, D., and Veugelers, R. (2009), ‘No Green Growth Without Innovation’, Bruegel Policy Brief-2009/07.
- Ansar, A. (2022), ‘Old Challenges, New Solutions: Getting Major Projects Right in the Twenty-first Century’, *Oxford Review of Economic Policy*, 38(2), 217–23.
- Arthur, W. B. (1989), ‘Competing Technologies, Increasing Returns, and Lock-in by Historical Events’, *The Economic Journal*, 99(394), 116, <https://doi.org/10.2307/2234208>.
- Averchenkova, A., Fankhauser, S., and Finnegan, J. J. (2021), ‘The Impact of Strategic Climate Legislation: Evidence from Expert Interviews on the UK Climate Change Act’, *Climate Policy*, 21(2), 251–63, <https://doi.org/10.1080/14693062.2020.1819190>.
- Bale, C. S. E., McCullen, N. J., Foxon, T. J., Rucklidge, A. M., and Gale, W. F. (2013), ‘Harnessing Social Networks for Promoting Adoption of Energy Technologies in the Domestic Sector’, *Energy Policy*, 63, 833–44, <https://doi.org/10.1016/j.enpol.2013.09.033>.
- Barbier, E. (2010), *A Global Green New Deal: Rethinking the Economic Recovery*, Cambridge, Cambridge University Press.
- (2020), ‘A Green Post-Covid-19 Recovery’, in *United Nations Association-UK (UNA-UK), Climate 2020*, Painswick, Witan Media, 54–6.
- (2023), ‘Greening the G7 Economies’, *Oxford Review of Economic Policy*, 39(4), 731–51.

- Barbier, E., and Burgess, J. C. (2018), 'Innovative Corporate Initiatives to Reduce Climate Risk: Lessons from East Asia', *Sustainability*, special issue *Climate Change Adaptation, Mitigation and Development*, <https://doi.org/10.3390/su10010013>.
- Hochard, J. P. (2019), 'Poverty-Environment Traps', *Environmental and Resource Economics*, 74(3), 1239–71, <https://doi.org/10.1007/s10640-019-00366-3>.
- Bardoscia, M., Battiston, S., Caccioli, F., and Caldarelli, G. (2017), 'Pathways towards Instability in Financial Networks', *Nature Communications*, 8(1), 14416, <https://doi.org/10.1038/ncomms14416>.
- Barnes, M. L., Lynham, J., Kalberg, K., and Leung, P. (2016), 'Social Networks and Environmental Outcomes', *Proceedings of the National Academy of Sciences of the United States of America*, 113(23), 6466–71, <https://doi.org/10.1073/pnas.1523245113>.
- Battiston, S., and Martinez-Jaramillo, S. (2018), 'Financial Networks and Stress Testing: Challenges and New Research Avenues for Systemic Risk Analysis and Financial Stability Implications', *Journal of Financial Stability*, 35, 6–16, <https://doi.org/10.1016/j.jfs.2018.03.010>.
- Bernstein, S., and Hoffmann, M. (2019), 'Climate Politics, Metaphors and the Fractal Carbon Trap', *Nature Climate Change*, 9(12), 919–25, <https://doi.org/10.1038/s41558-019-0618-2>.
- Black, S., Chateau, J., Jaumotte, F., Parry, I. W. H., Schwerhoff, G., Thube, S. D., and Zhunussova, K. (2022), 'Getting on Track to Net Zero: Accelerating a Global Just Transition in This Decade', *IMF Staff Climate Notes*, 2022(010), A001, <https://doi.org/10.5089/9798400223877.066.A001>.
- Bollinger, B., and Gillingham, K. (2012), 'Peer Effects in the Diffusion of Solar Photovoltaic Panels', *Marketing Science*, 31(6), 900–12, <https://doi.org/10.1287/mksc.1120.0727>.
- Bryson, J. M. (2004), 'What to Do When Stakeholders Matter', *Public Management Review*, 6(1), 21–53, <https://doi.org/10.1080/14719030410001675722>.
- Carley, S., and Konisky, D. M. (2020), 'The Justice and Equity Implications of the Clean Energy Transition', *Nature Energy*, 5(8), 569–77, <https://doi.org/10.1038/s41560-020-0641-6>.
- Centola, D., Becker, J., Brackbill, D., and Baronchelli, A. (2018), 'Experimental Evidence for Tipping Points in Social Convention', *Science*, 360(6393), 1116–19, <https://doi.org/10.1126/science.aas8827>.
- Chakraborty, A., Reisch, T., Diem, C., and Thurner, S. (2021), 'Inequality in Economic Shock Exposures across the Global Firm-level Supply Network', *ArXiv:2112.00415*, 1–19.
- Chen, H., and Shi, H.-L. (2021), 'The Impact of Network Topological Structures on Systematic Technology Adoption and Carbon Emission Reduction', *Scientific Reports*, 11(1), 20380, <https://doi.org/10.1038/s41598-021-99835-3>.
- Chen, Y., Paul, G., Havlin, S., Liljeros, F., and Stanley, H. E. (2008), 'Finding a Better Immunization Strategy', *Physical Review Letters*, 101(5), 58701, <https://doi.org/10.1103/PhysRevLett.101.058701>.
- Clò, S., Cataldi, A., and Zoppoli, P. (2015), 'The Merit-order Effect in the Italian Power Market: The Impact of Solar and Wind Generation on National Wholesale Electricity Prices', *Energy Policy*, 77, 79–88, <https://doi.org/10.1016/j.enpol.2014.11.038>.
- Collier, P. (2006), 'African Growth: Why a "Big Push"?', *Journal of African Economies*, 15(suppl_2), 188–211, <https://doi.org/10.1093/jae/ejl031>.
- Colon, C., Hallegatte, S., and Rozenberg, J. (2021), 'Criticality Analysis of a Country's Transport Network via an Agent-based Supply Chain Model', *Nature Sustainability*, 4(3), 209–15, <https://doi.org/10.1038/s41893-020-00649-4>.
- David, P. A. (1985), 'Clio and the Economics of QWERTY', *The American Economic Review*, 75(2), 332–7.
- Dezső, Z., and Barabási, A.-L. (2002), 'Halting Viruses in Scale-free Networks', *Physical Review E*, 65(5), 55103, <https://doi.org/10.1103/PhysRevE.65.055103>.
- Dietz, S., and Hepburn, C. (2013), 'Benefit–Cost Analysis of Non-marginal Climate and Energy Projects', *Energy Economics*, 40, 61–71.
- Dikau, S., and Volz, U. (2021), 'Central Bank Mandates, Sustainability Objectives and the Promotion of Green Finance', *Ecological Economics*, 184, 107022, <https://doi.org/10.1016/j.ecolecon.2021.107022>.
- Du, F., Zhang, J., Li, H., Yan, J., Galloway, S., and Lo, K. L. (2016), 'Modelling the Impact of Social Network on Energy Savings', *Applied Energy*, 178, 56–65, <https://doi.org/10.1016/j.apenergy.2016.06.014>.
- Dugoua, E. (2020), 'Induced Innovation and International Environmental Agreements: Evidence from the Ozone Regime', Grantham Research Institute on Climate Change and the Environment Working Paper No. 363.
- ECB (2022), 'ECB Takes Further Steps to Incorporate Climate Change into its Monetary Policy Operations', European Central Bank, retrieved from <https://www.ecb.europa.eu/press/pr/date/2022/html/ecb.pr220704-4f48a72462.en.html>
- Fankhauser, S., Avertchenkova, A., and Finnegan, J. (2018), '10 years of the UK Climate Change Act', Policy Paper. London School of Economics and Political Science, Grantham Research Institute on Climate Change and the Environment, Centre for Climate Change Economics and Policy, <http://www.lse.ac.uk/GranthamInstitute/publication/10-yearsclimate-change-act>.
- Farmer, J. D., Hepburn, C., Mealy, P., and Teytelboym, A. (2015), 'A Third Wave in the Economics of Climate Change', *Environmental and Resource Economics*, 62(2), 329–57, <https://doi.org/10.1007/s10640-015-9965-2>.
- Ives, M. C., Hale, T., Wetzler, T., Mealy, P.,... Way, R. (2019), 'Sensitive Intervention Points in the Post-carbon Transition', *Science*, 364(6436), 132–4, <https://doi.org/10.1126/science.aaw7287>.
- Garcia-Casals, X., Ferroukhi, R., and Parajuli, B. (2019), 'Measuring the Socio-economic Footprint of the Energy Transition', *Energy Transitions*, 3(1), 105–18, <https://doi.org/10.1007/s41825-019-00018-6>.
- Geels, F. W. (2002), 'Technological Transitions as Evolutionary Reconfiguration Processes: A Multi-level Perspective and a Case-study', *Research Policy*, 31(8–9), 1257–74, [https://doi.org/10.1016/S0048-7333\(02\)00062-8](https://doi.org/10.1016/S0048-7333(02)00062-8).

- Geels, F. W. (2004), 'From Sectoral Systems of Innovation to Socio-technical Systems: Insights about Dynamics and Change from Sociology and Institutional Theory', *Research Policy*, 33(6–7), 897–920, <https://doi.org/10.1016/j.respol.2004.01.015>.
- (2006), 'Multi-level Perspective on System Innovation: Relevance for Industrial Transformation BT—Understanding Industrial Transformation: Views from Different Disciplines', in X. Olsthoorn and A. J. Wiecek (eds), *Understanding Industrial Transformation, Environment & Policy*, vol 44, Dordrecht, Springer Netherlands, 163–86, https://doi.org/10.1007/1-4020-4418-6_9.
- (2012), 'A Socio-technical Analysis of Low-carbon Transitions: Introducing the Multi-level Perspective into Transport Studies', *Journal of Transport Geography*, 24, 471–82, <https://doi.org/10.1016/j.jtrangeo.2012.01.021>.
- (2014), 'Regime Resistance Against Low-carbon Transitions: Introducing Politics and Power into the Multi-level Perspective', *Theory, Culture & Society*, 31(5), 21–40.
- Schot, J. (2007), 'Typology of Sociotechnical Transition Pathways', *Research Policy*, 36(3), 399–417, <https://doi.org/10.1016/j.respol.2007.01.003>.
- Sovacool, B. K., Schwanen, T., and Sorrell, S. (2017), 'The Socio-technical Dynamics of Low-carbon Transitions', *Joule*, 1(3), 463–79, <https://doi.org/10.1016/j.joule.2017.09.018>.
- Ghatak, M. (2015), 'Theories of Poverty Traps and Anti-poverty Policies', *The World Bank Economic Review*, 29(suppl_1), S77–S105, <https://doi.org/10.1093/wber/lhv021>
- Hale, T. (2020), 'Catalytic Cooperation', *Global Environmental Politics*, 20(4), 73–98, https://doi.org/10.1162/glep_a_00561.
- Heal, G., and Kunreuther, H. (2011), 'Tipping Climate Negotiations', National Bureau of Economic Research, retrieved from <http://www.nber.org/papers/w16954>
- Heimans, J., and Timms, H. (2018), *New Power: Why Outsiders are Winning, Institutions are Failing, and How the Rest of Us Can Keep Up in the Age of Mass Participation*, London, Pan Macmillan.
- Helm, D. (2015), *The Carbon Crunch*, New Haven, CT, Yale University Press.
- Hepburn, C., and Mash, R. (2003), 'Credible Carbon Policy', *Oxford Review of Economic Policy*, 19(3), 438–50.
- Ruta, G. (2012), 'Trade, Climate Change, and the Political Game Theory of Border Carbon Adjustments', *Oxford Review of Economic Policy*, 28(2), 368–94.
- Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., and Zenghelis, D. (2020), 'Will Covid-19 Fiscal Recovery Packages Accelerate or Retard Progress on Climate Change?', *Oxford Review of Economic Policy*, 36(Supplement_1), S359–S381.
- Iacopini, I., Petri, G., Baronchelli, A., and Barrat, A. (2022), 'Group Interactions Modulate Critical Mass Dynamics in Social Convention', *Communications Physics*, 5(1), <https://doi.org/10.1038/s42005-022-00845-y>.
- IEA (2020), *World Energy Outlook 2020*, Vol. 2050, Paris, International Energy Agency.
- (2021), *World Energy Outlook 2021*, Paris, International Energy Agency.
- Inoue, H., and Todo, Y. (2019), 'Firm-level Propagation of Shocks through Supply-chain Networks', *Nature Sustainability*, 2(9), 841–7, <https://doi.org/10.1038/s41893-019-0351-x>.
- Jee, S. J., and Srivastav, S. (2022), 'Knowledge Spillovers between Clean and Dirty Technologies', INET Working Paper No. 2021-22, retrieved from <https://www.inet.ox.ac.uk/publications/no-2021-22-knowledge-spillovers-between-clean-and-dirty-technologies/>
- Kamboj, P., and Tongia, R. (2018), 'Indian Railways and Coal: An Unsustainable Interdependency', Brookings India report, July, retrieved from <https://www.brookings.edu/research/indian-railways-and-coal/>
- King, M., Tarbush, B., and Teytelboym, A. (2019), 'Targeted Carbon Tax Reforms', *European Economic Review*, 119, 526–47, <https://doi.org/10.1016/j.eurocorev.2019.08.001>.
- Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., and Stern, N. (2018), 'Making Carbon Pricing Work for Citizens', *Nature Climate Change*, 8(8), 669–77, <https://doi.org/10.1038/s41558-018-0201-2>.
- Korkali, M., Veneman, J. G., Tivnan, B. F., Bagrow, J. P., and Hines, P. D. H. (2017), 'Reducing Cascading Failure Risk by Increasing Infrastructure Network Interdependence', *Scientific Reports*, 7(1), 1–3, <https://doi.org/10.1038/srep44499>.
- Kraay, A., and McKenzie, D. (2014), 'Do Poverty Traps Exist? Assessing the Evidence', *Journal of Economic Perspectives*, 28(3), 127–48, <https://doi.org/10.1257/jep.28.3.127>.
- Kyritsis, E., Andersson, J., and Serletis, A. (2017), 'Electricity Prices, Large-scale Renewable Integration, and Policy Implications', *Energy Policy*, 101, 550–60, <https://doi.org/10.1016/j.enpol.2016.11.014>
- Lam, A., and Mercure, J.-F. (2022), 'Evidence for a Global Electric Vehicle Tipping Point', Working Paper Series Number 2022/01, University of Exeter.
- Lamberson, P. J., and Page, S. E. (2012), 'Tipping Points', *Quarterly Journal of Political Science*, 7(2), 175–208.
- Lenton, T. M. (2020), 'Tipping Positive Change', *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, <https://doi.org/10.1098/rstb.2019.0123>
- Benson, S., Smith, T., Ewer, T., Lanel, V., Petykowski, E., ... Sharpe, S. (2022), 'Operationalising Positive Tipping Points towards Global Sustainability', *Global Sustainability*, 5, e1, <https://doi.org/10.1017/sus.2021.30>.
- Held, H., Krieger, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J. (2008), 'Tipping Elements in the Earth's Climate System', *Proceedings of the National Academy of Sciences of the United States of America*, 105(6), 1786–93, <https://doi.org/10.1073/pnas.0705414105>.
- Matous, P., and Todo, Y. (2017), 'Analyzing the Coevolution of Interorganizational Networks and Organizational Performance: Automakers' Production Networks in Japan', *Applied Network Science*, 2(1), 5, <https://doi.org/10.1007/s41109-017-0024-5>.
- Mazzucato, M. (2018), 'Mission-oriented Innovation Policies: Challenges and Opportunities', *Industrial and Corporate Change*, 27(5), 803–15, <https://doi.org/10.1093/icc/dty034>.

- Mbaru, E. K., and Barnes, M. L. (2017), 'Key Players in Conservation Diffusion: Using Social Network Analysis to Identify Critical Injection Points', *Biological Conservation*, 210, 222–32, <https://doi.org/10.1016/j.biocon.2017.03.031>.
- McConnell, A., Yanovski, B., and Lessmann, K. (2022), 'Central Bank Collateral as a Green Monetary Policy Instrument', *Climate Policy*, 22(3), 339–55, <https://doi.org/10.1080/14693062.2021.2012112>.
- Meadows, D. H. (1999), 'Leverage Points: Places to Intervene in a System', Sustainability Institute, 1–19, <https://doi.org/10.1080/02604020600912897>.
- Meckling, J., Sterner, T., and Wagner, G. (2017), 'Policy Sequencing toward Decarbonization', *Nature Energy*, 2(12), 918–22.
- Mercure, J.-F., Sharpe, S., Vinuales, J. E., Ives, M., Grubb, M., Lam, A., ... Nijssse, F. J. M. M. (2021), 'Risk-opportunity Analysis for Transformative Policy Design and Appraisal', *Global Environmental Change*, 70, 102359, <https://doi.org/10.1016/j.GLOENVCHA.2021.102359>.
- Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderón-Contreras, R., Donges, J. F., ... Werners, S. E. (2018), 'Defining Tipping Points for Social-ecological Systems Scholarship—An Interdisciplinary Literature Review', *Environmental Research Letters*, 1 March, Institute of Physics Publishing, <https://doi.org/10.1088/1748-9326/aaa75>.
- Moe, E. (2010), 'Energy, Industry and Politics: Energy, Vested Interests, and Long-term Economic Growth and Development', *Energy*, 35(4), 1730–40.
- Mountain, B., Percy, S., Kars, A., Saddler, H., and Billimoria, F. (2018), 'Does Renewable Electricity Generation Reduce Electricity Prices?', <https://doi.org/10.13140/RG.2.2.22213.81124>.
- Murphy, K. M., Shleifer, A., and Vishny, R. W. (1989), 'Industrialization and the Big Push', *Journal of Political Economy*, 97(5), 1003–26.
- O'Callaghan, B., Yau, N., and Hepburn, C. (2022), 'How Stimulating Is a Green Stimulus? The Economic Attributes of Green Fiscal Spending', *Annual Review of Environment and Resources*, 47(1), 697–723, <https://doi.org/10.1146/annurev-environ-112420-020640>.
- Ohlendorf, N., Jakob, M., and Steckel, J. C. (2022), 'The Political Economy of Coal Phase-out: Exploring the Actors, Objectives, and Contextual Factors Shaping Policies in Eight Major Coal Countries', *Energy Research & Social Science*, 90, 102590, <https://doi.org/10.1016/j.erss.2022.102590>.
- Otto, I. M., Donges, J. F., Cremades, R., Bhowmik, A., Hewitt, R. J., Lucht, W., ... Schellnhuber, H. J. (2020), 'Social Tipping Dynamics for Stabilizing Earth's Climate by 2050', *Proceedings of the National Academy of Sciences of the United States of America*, 117(5), 2354–65, <https://doi.org/10.1073/pnas.1900577117>.
- Pahle, M., Burtraw, D., Flachslund, C., Kelsey, N., Biber, E., Meckling, J., ... and Zysman, J. (2018), 'Sequencing to Ratchet Up Climate Policy Stringency', *Nature Climate Change*, 8(10), 861–7.
- Parry, I., Black, M. S., and Vernon, N. (2021), *Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies*, Washington, DC, International Monetary Fund.
- Pastor-Satorras, R., and Vespignani, A. (2001), 'Epidemic Spreading in Scale-free Networks', *Physical Review Letters*, 86(14), 3200–3, <https://doi.org/10.1103/PhysRevLett.86.3200>.
- Pindyck, R. S. (2013), 'Climate Change Policy: What Do the Models Tell Us?', *Journal of Economic Literature*, 51(3), 860–72, <https://doi.org/10.1257/jel.51.3.860>.
- Poledna, S., Bochmann, O., and Thurner, S. (2017), 'Basel III Capital Surcharges for G-SIBs are Far Less Effective in Managing Systemic Risk in Comparison to Network-based, Systemic Risk-dependent Financial Transaction Taxes', *Journal of Economic Dynamics and Control*, 77(C), 230–46, <https://doi.org/10.1016/j.jedc.2017.02.00>.
- Rafaty, R., Srivastav, S., and Hoops, B. (2020), 'Revoking Coal Mining Permits: An Economic and Legal Analysis', *Climate Policy*, 20(8), 980–96, <https://doi.org/10.1080/14693062.2020.1719809>.
- Robinson, D. K. R., and Mazzucato, M. (2019), 'The Evolution of Mission-oriented Policies: Exploring Changing Market Creating Policies in the US and European Space Sector', *Research Policy*, 48(4), 936–48, <https://doi.org/10.1016/j.respol.2018.10>.
- Rosenstein-Rodan, P. N. (1943), 'Problems of Industrialisation of Eastern and South-Eastern Europe', *The Economic Journal*, 53(210/211), 202–11, <https://doi.org/10.2307/2226317>.
- Sachs, J. D. (2006), *The End of Poverty: Economic Possibilities for Our Time*, London, Penguin Books.
- Saunders, H. A., and Schwartz, J.-M. (2021), 'COVID-19 Vaccination Strategies Depend on the Underlying Network of Social Interactions', *Scientific Reports*, 11(1), 24051, <https://doi.org/10.1038/s41598-021-03167-1>.
- Schäfer, B., Witthaut, D., Timme, M., and Latora, V. (2018), 'Dynamically Induced Cascading Failures in Power Grids', *Nature Communications*, 9(1), 1975, <https://doi.org/10.1038/s41467-018-04287-5>.
- Sharpe, S., and Lenton, T. M. (2021), 'Upward-scaling Tipping Cascades to Meet Climate Goals: Plausible Grounds for Hope', *Climate Policy*, 21(4), 421–33, <https://doi.org/10.1080/14693062.2020.1870097>.
- Sovacool, B. K., and Hess, D. J. (2017), 'Ordering Theories: Typologies and Conceptual Frameworks for Sociotechnical Change', *Social Studies of Science*, 47(5), 703–50, <https://doi.org/10.1177/0306312717709363>.
- Srivastav, S., and Rafaty, R. (2022), 'Political Strategies to Overcome Climate Policy Obstructionism', *Perspectives on Politics*, 1–11, <https://doi.org/10.1017/S1537592722002080>.
- Singh, T. (2022), 'Greening Our Laws: Revising Land Acquisition Law for Coal Mining in India', *SSRN Electronic Journal*, <https://doi.org/10.2139/ssrn.4218788>.
- Stern, N. (2016), 'Economics: Current Climate Models are Grossly Misleading', *Nature*, 530(7591), 407–9, <https://doi.org/10.1038/530407a>.

- Tozer, L., Bulkeley, H., van der Jagt, A., Toxopeus, H., Xie, L., and Runhaar, H. (2022), 'Catalyzing Sustainability Pathways: Navigating Urban Nature Based Solutions in Europe', *Global Environmental Change*, 74(March), 102521, <https://doi.org/10.1016/j.gloenvcha.2022.102521>.
- UNEP (2022), *Emissions Gap Report 2022: The Closing Window—Climate Crisis Calls for Rapid Transformation of Societies*, United Nations Environment Programme, Nairobi, <https://www.unep.org/emissions-gap-report-2022>.
- van den Bergh, J. C. J. M., Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F.,... and Savin, I. (2021), 'Designing an Effective Climate-policy Mix: Accounting for Instrument Synergy', *Climate Policy*, 21(6), 745–64.
- van der Ploeg, F., and Venables, A. J. (2022), 'Radical Climate Policies', Department of Economics Discussion Paper Series, University of Oxford, <https://openknowledge.worldbank.org/entities/publication/5f23bc3b-c83a-5b00-9371-323490fff8d0>.
- Vona, F. (2019), 'Job Losses and Political Acceptability of Climate Policies: Why the "Job-killing" Argument is so Persistent and How to Overturn It', *Climate Policy*, 19(4), 524–32, <https://doi.org/10.1080/14693062.2018.1532871>.
- Way, R., Ives, M. C., Mealy, P., and Farmer, J. D. (2022), 'Empirically Grounded Technology Forecasts and the Energy Transition', *Joule*, 6(9), 2057–82, retrieved from [https://www.cell.com/joule/fulltext/S2542-4351\(22\)00410-X](https://www.cell.com/joule/fulltext/S2542-4351(22)00410-X).
- Wilson, C., Grubler, A., Bento, N., Healey, S., De Stercke, S., and Zimm, C. (2020), 'Granular Technologies to Accelerate Decarbonization', *Science*, 368(6486), 36–9, <https://doi.org/10.1126/science.aaz8060>.
- Winkelmann, R., Donges, J. F., Smith, E. K., Milkoreit, M., Eder, C., Heitzig, J.,... Lenton, T. M. (2022), 'Social Tipping Processes towards Climate Action: A Conceptual Framework', *Ecological Economics*, 192(July), 107242, <https://doi.org/10.1016/j.ecolecon.2021.107242>.
- Woo, C. K., Zarnikau, J., Kadish, J., Horowitz, I., Wang, J., and Olson, A. (2013), 'The Impact of Wind Generation on Wholesale Electricity Prices in the Hydro-rich Pacific Northwest', *IEEE Transactions on Power Systems*, 28(4), 4245–53, <https://doi.org/10.1109/TPWRS.2013.2265238>.
- World Bank (2023), 'Scaling Up to Phase Down: Financing Energy Transitions in the Power Sector', Washington, DC, World Bank.
- Xiao, M., Junne, T., Haas, J., and Klein, M. (2021), 'Plummeting Costs of Renewables—Are Energy Scenarios Lagging?', *Energy Strategy Reviews*, 35, 100636, <https://doi.org/10.1016/j.esr.2021.100636>.