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OUTLOOK ARTICLE

Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope

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ABSTRACT

Limiting global warming to well below 2°C requires a dramatic acceleration of decarbonization to reduce net anthropogenic greenhouse gas emissions to zero around mid-century. In complex systems – including human societies – tipping points can occur, in which a small perturbation transforms a system. Crucially, activating one tipping point can increase the likelihood of triggering another at a larger scale, and so on. Here, we show how such upward-scaling tipping cascades could accelerate progress in tackling climate change. We focus on two sectors – light road transport and power – where tipping points have already been triggered by policy interventions at individual nation scales. We show how positive-sum cooperation, between small coalitions of jurisdictions and their policymakers, could lead to global changes in the economy and emissions. The aim of activating tipping points and tipping cascades is a particular application of systems thinking. It represents a different starting point for policy to the theory of welfare economics, one that can be useful when the priority is to achieve dynamic rather than allocative efficiency.

Key policy insights:

- Pricing policies and targeted investments that bring clean technologies below the threshold of cost-parity with fossil fuel technologies can trigger reinforcing feedbacks that cascade up scales to propel disproportionately rapid decarbonization.
- Traditional approaches to climate policy based on welfare economics principles of minimizing marginal abatement costs, and pricing externalities, are likely to miss these opportunities. Systems thinking can help identify ways for policy to drive effective change.
- Positive-sum cooperation between small groups of countries can accelerate the activation of tipping points in the global economy, facilitating decarbonization in all countries. Early opportunities for this are in the power and light road transport sectors, where clean technologies are increasingly competitive with fossil fuels.
- The value of decarbonization policies should be judged not just on their immediate effects on emissions within the implementing jurisdiction, but also for their potential to contribute to upward-scaling tipping cascades in the global economy.

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Introduction

We have left it too late to tackle climate change incrementally. Limiting global warming to well below 2°C now requires transformational change, and a dramatic acceleration of progress (Farmer et al., 2019; Geels et al., 2017; Otto et al., 2020). The power sector needs to decarbonize four times faster than now (IEA, 2019a). The pace of

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the transition to zero emission vehicles needs to double. Improvements in energy efficiency need to proceed two to three times as fast (IEA, 2019b). Global zero carbon steel production needs to grow ten thousand-fold over the next two decades (Victor et al., 2019). Economy-wide decarbonization needs to happen at a rate only previously seen in the collapse of the Soviet Union. The achievability of all this is increasingly questioned. But plausible grounds for hope lie in the way that tipping points can be activated to propagate rapid change through complex systems (Farmer et al., 2019; Lenton, 2020; Otto et al., 2020).

This paper argues that the identification and activation of tipping points and tipping cascades can be a new focus for climate change policy and diplomacy. We begin by outlining the concepts of tipping points and tipping cascades. We then give two examples of decarbonization tipping points that have been crossed at a national level, where there is potential for international cooperation to trigger tipping cascades up to the global level. We end with discussion of how this implies different approaches to climate change policy and diplomacy from those that are currently dominant.

Upward-scaling tipping cascades

The economy is increasingly recognized as a complex adaptive system (Beinhocker, 2006). The behaviour of complex systems depends on the interaction of feedbacks: reinforcing (positive) feedbacks that tend to accelerate change; and balancing (negative) feedbacks that tend to oppose change.

In complex systems, change is often non-linear. Cause and effect need not be proportionate. Highly disproportionate change can be caused when a tipping point is crossed; that is, when a small perturbation triggers a large response from a system, sending it into a qualitatively different future state (Lenton, 2020; Lenton et al., 2008). At a tipping point, reinforcing (positive) feedbacks dominate the dynamics, propelling change. Tipping points have been observed in the climate, ecosystems, social, political, and economic systems, and in individual and collective behaviour (Lenton, 2020; Scheffer, 2009).

To bring a system to a tipping point typically requires some 'forcing' – i.e. a change in boundary conditions – in a direction that weakens balancing (negative) feedbacks maintaining the initial state and/or strengthens reinforcing (positive) feedbacks that amplify change. The change of state at a tipping point may be reversible or irreversible, depending on the strength of reinforcing feedbacks in the system, and whether the forcing can be rapidly reversed (Lenton et al., 2008). Importantly, in social systems, new feedbacks may evolve over time. Hence, transitions that are initially reversible may engender reinforcing feedbacks that make them increasingly difficult to reverse over time. For example, policy support triggering growth of a new technology sector and associated jobs can bring political irreversibility – a change of government that wants to reverse that support may find itself unable to do so.

Sometimes, in interconnected complex systems, the activation of one tipping point can increase the likelihood of triggering another at a larger scale, and then another at a still larger scale. We call this an 'upward-scaling tipping cascade'. The progression can take place in scales that are temporal (towards a greater degree of permanence), spatial (expanding to affect a larger geographical area), or defined in terms of system boundaries (e.g. from a product, to an economic sector, to an economy of many sectors). Here we do not require that passing one tipping point makes a larger scale one *inevitable*, just more likely, but in the strongest case, such 'domino dynamics' can occur.

Upward-scaling tipping cascades can cause rapid change on very large scales (Lenton, 2020). For example, the global financial crisis of 2008–9 followed this pattern: home-loan defaults triggered devaluation of collateralized debt obligations, which triggered bank and insurer insolvency, which led to a credit crunch, and wider consequences still felt today. In ecosystems, upward-scaling 'trophic cascades' can be triggered by the removal or (re)introduction of a single 'keystone species'– for example, wolves in Yellowstone national park (Ripple & Beschta, 2012). Upward-scaling cascades of climate tipping points are also possible (Lenton et al., 2019).

Equally, several past 'socio-technical transitions' started with disruptive technological innovations in niches that cascaded upwards through tipping points to society-wide change (Smith et al., 2005). For example, the invention and refinement of the steam engine triggered a massive expansion of coal mining and the creation of a rail transport network, propelling the industrial revolution in England. At the start of the twentieth century, the transition from horse-drawn carriages to fossil-fuelled cars happened in just over a decade in US cities. In fact, each historical transition in primary fuel supply – from wood through coal to oil and gas – was of this type (Smith et al., 2005).

As new technologies diffuse through markets and societies, they tend to benefit from multiple reinforcing feedbacks (Arthur, 1989). These include learning-by-doing (the more something is made, the better it can be made), economies of scale (the more it is made, the more cheaply it can be made), and the emergence of complementary technologies (the more something is used, the more technologies emerge that make it more useful). As a result, technology diffusion is self-generating, self-accelerating, and over time becomes increasingly difficult to reverse. Any tipping point that gives a new technology a substantial new advantage – e.g. greater market share, easier access to finance, or broader social acceptability – is likely to strengthen these reinforcing feedbacks, further amplifying its effect.

Technology diffusion feedbacks can interact with social contagion – reinforcing social feedbacks and tipping points in the adoption of norms, behaviours, and new products. These include tipping points in social convention, whereby a population-wide consensus can be overturned by a group with a minority viewpoint once it reaches a critical mass (Centola et al., 2018).

Looking ahead, tipping points and tipping cascades could conceivably be activated to meet climate change goals – which require rapid system transitions in power, transport, buildings, industry, and agriculture at the global scale (Rogelj et al., 2018). Whilst many factors – social, cultural, technological, economic and political – can influence a transition (Waisman et al., 2019), policy can make a critical difference – by investing in research and development of new technologies, redirecting support from incumbents to disruptors, and reconfiguring markets and institutions (Geels & Schot, 2007). From a policymaker's perspective, if a tipping point converts a small change in input to a large change in outcome, then an upward-scaling tipping cascade could in principle offer the maximum possible 'bang for your buck'.

The connection of countries by flows of finance, knowledge, technology, trade, and transport means the options for global decarbonization are not limited to unilateral policy and multilateral agreements. Small groups of countries with sufficient political or economic influence in a given sector, coordinating their actions, may be able to catalyze change at the global scale (Victor et al., 2019). This implies a possible goal for international cooperation of activating a tipping cascade. We now consider how such tipping cascades could be brought about in two sectors important to global emissions.

Light road transport

Electric vehicles (EVs) currently account for around 2–3% of new car sales globally. There is evidence that they are benefitting from the reinforcing feedbacks of technology diffusion. As production volumes increase, the performance of batteries is improving, and so is the performance of the important complementary technology of charging infrastructure. At the same time, the cost of batteries (a determining factor of the cost of the car) is falling rapidly. As performance improves and costs fall, EV sales are growing rapidly, and the car industry is allocating EVs an increasing share of its investment (BNEF, 2020a).

Policy is playing a critical role in driving this process. Regulatory standards that limit vehicles' allowable fuel efficiency or CO_2 intensity, or that require a proportion of a manufacturers' sales to be EVs, are propelling the transition in major markets including the EU and China. Jurisdictions including the UK, California, France, Canada, Norway, and the Netherlands have set phase-out dates for the sale of new petrol and diesel cars, sending a clear signal to industry of the need to shift production to new technologies. Public investment in charging infrastructure, purchase incentives for EVs, city-level policies such as clean air zones, and public communications of the benefits of EVs, are all helping to change incentives for both manufacturers and consumers. Progress in the technology in turn enables stronger policy: in November 2020, the UK brought forward its phase-out date for new petrol and diesel cars from 2040 (a target set two years ago) to 2030.

At this early stage of the transition, growth in EVs' share of the market needs policy support to maintain, not least because EVs still cost more to manufacture than conventional cars and so are less profitable for manufacturers, and their higher price makes them less attractive to consumers (although their running costs are much lower).

The share of EVs in new car sales is higher in countries with stronger policies (IEA, 2019c). One measure of the strength of policy is the ownership cost differential between EVs and conventional vehicles, after any taxes and subsidies are taken into account. The relationship between this measure, and EV market share, appears to be strongly non-linear (Figure 1). Norway's EV market share now stands at over 50%, over ten times higher than almost any other country (IEA, 2019c). Norway has many policies to support EV uptake, but one of them is unique. In the words of the Norwegian Electric Vehicle Association: 'The progressive tax system makes most EV models cheaper to buy compared to a similar petrol model … This is the main reason why the Norwegian EV market is so successful compared to any other country' (Norsk Elbilforening, 2020). Norway appears to have activated a tipping point in consumer preference: making EVs more attractive than petrol cars to consumers. With a policy input somewhat stronger than its equivalent in other countries, it has achieved a disproportionately large outcome. The result is a world-leading pace of transition.

Norway's national-scale tipping point is not irreversible. Removal of the policy support could return the system to its previous state, where EVs become more expensive to buy, and therefore petrol cars return to being more attractive to consumers. However, the longer the policy maintains the system in its new state, the more it will allow the reinforcing feedbacks of diffusion to operate, increasing the likelihood of change becoming permanent (Figure 2).

Similarly, in all countries where the EV market share is growing, withdrawal of policy support (of all the kinds mentioned above) could still see balancing feedbacks from market competition and the power of incumbent industry bring back the state of petrol and diesel dominance. But a second tipping point in the economics of the auto sector will occur when EVs reach cost parity with conventional cars without assistance from tax or subsidy (Figure 2). Afterwards, policy support will be much less needed, as the reinforcing feedbacks of increasing returns to scale will dominate system behaviour. As EVs become ever cheaper, consumers will increasingly prefer to buy them, manufacturers will prefer to make them, investors will be more willing to invest in charging infrastructure, and even governments that care nothing for climate change will want to support the transition in their own countries.

Countries that follow Norway's example in activating the first tipping point – using strong incentives to change consumer behaviour at a national level – as well as those that use regulations and phaseout commitments to change industry investment, will greatly strengthen the feedbacks of diffusion. In doing so, they will bring forward the second tipping point, in the economics of the auto sector at the global level. In this upward-scaling tipping cascade, the second tipping point operates at a larger scale than the first in all three of the dimensions of space (geographical area), time (degree of permanence), and system boundary (qualitatively defined).

A small number of countries could make a large contribution to accelerating the activation of this global tipping point. Three quarters of the cars sold globally are bought by consumers in just ten countries (p.73 of Victor et al., 2019). Just three jurisdictions – the EU, China, and California – account for around a half of these purchases, and their interests are already aligned with the transition. California has already set a target for all new car sales to be zero emission by 2035. The EU aims to achieve net zero economy-wide emissions by 2050, and road transport is one of the easier sectors for early decarbonization. China wants to reduce its oil imports, improve its air quality, and strengthen its competitiveness in auto manufacturing (much more achievable in the context of a transition to EVs); and has set itself a target of carbon neutrality by 2060.

Each of these countries and jurisdictions already implements some form of regulatory standards to limit the emissions of cars sold in their markets. Individually, they are deterred from setting steep regulatory trajectories towards zero emission vehicles by the cost differential that remains between EVs and conventional cars. None of the five largest national car markets, nor the EU, has yet committed to a date for the phaseout of fossil fuel vehicles. But acting together, for example by agreeing to make a coordinated move to steep regulatory trajectories, the three jurisdictions we highlight could be confident that their combined policy signals would rapidly shift investment throughout the global industry, accelerating the increase in EV production and the decrease in EV costs. By bringing forward the cost-parity tipping point, this could trigger a spatial cascade of tipping points in consumer behaviour through the global network of national car markets, replicating on a global scale what we now see happening in Norway, but this time without the need for subsidy.

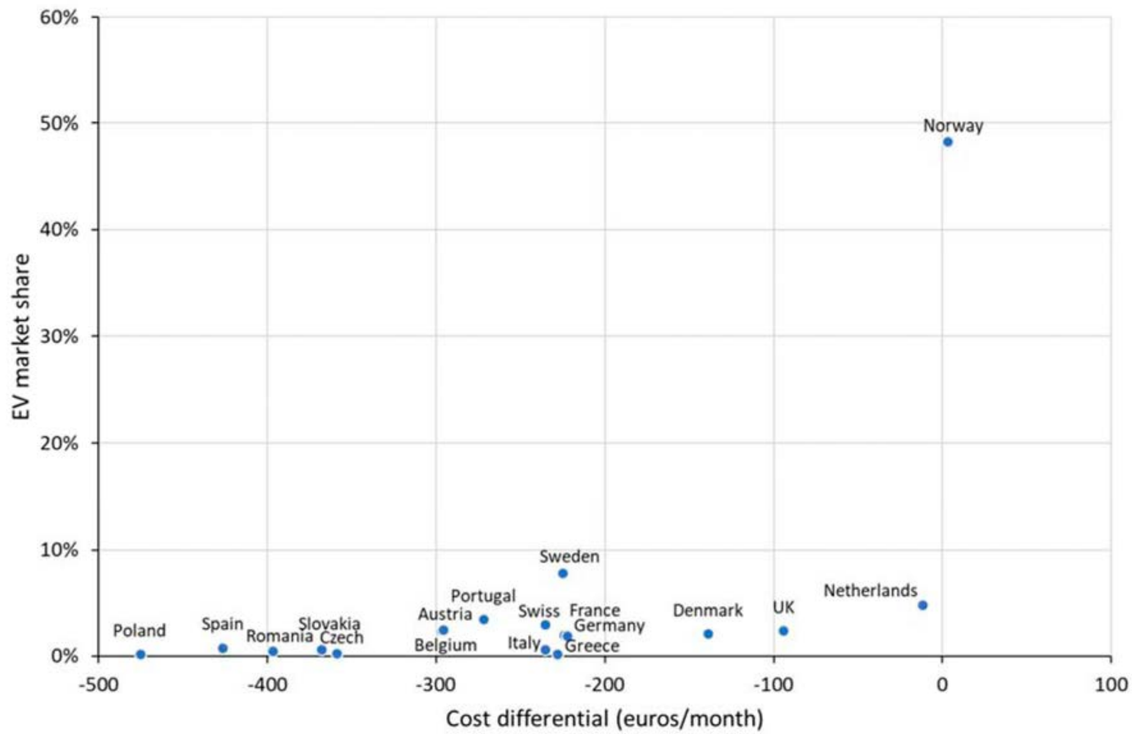

Figure 1. Electric vehicle (EV) market share in a sample of 18 European countries as a function of cost differential expressed as average of equivalent petrol or diesel vehicle minus EV (monthly cost of ownership in euros). Data from LeasePlan and statista.

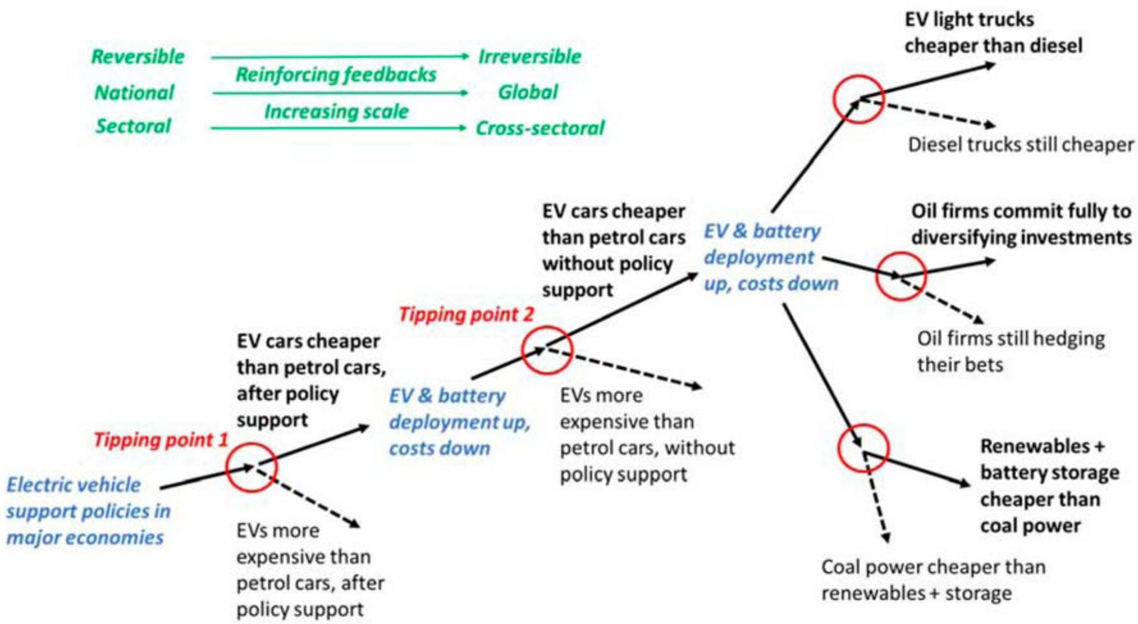

Figure 2. Electric vehicle tipping cascade.

This positive-sum cooperation could in turn increase the chances of crossing other important tipping points (Figure 2). First, the massive scaling up of batteries and electric drivetrain technology within the automotive sector would bring down the costs of zero emission trucks, buses, and other larger vehicles. Second, a rapid transition in road transport would deprive oil companies of their largest market, strongly incentivizing diversification of investment, potentially into hydrogen or synthetic fuel production – critical for the decarbonization of industry, aviation, and shipping. Third, accelerated growth of battery production and reduction in battery cost would make cheaper energy storage available for the power sector, supporting cost-effective integration of renewable power into electricity systems. This could help to tip the power sector – where emissions are still growing – into an irreversible transition.

Power

Solar and wind power provide only around 7% of global electricity generation (IEA, 2020), but they accounted for roughly two thirds of global generating capacity additions in 2019 (IRENA, 2020). The reinforcing feedbacks of diffusion are operating strongly, with rapid cost reductions persisting over decades, and the development of complementary technologies including batteries, demand-side response, and smart grids. The pace of growth of renewable power has consistently outperformed expectations, with global deployment of solar power in 2020 being over ten times higher than was projected fifteen years ago (Beinhocker et al., 2018). Meanwhile, coal power has experienced the opposite, with analysts' expectations of its future growth prospects repeatedly revised downward (Bullard, 2020). Plans for nearly 900 GW of new coal plants have been cancelled within the last five years (Shearer, 2019).

Policy has been, and continues to be, a strong driver of this transition. Research and development of renewables technologies, subsidies for their deployment, power sector market reforms, carbon pricing, and investments in infrastructure are all making mutually reinforcing contributions.

Within this context of unfolding transition, the UK's experience stands out. Over recent years, the UK has decarbonized its power sector faster than any other large country (Staffell et al., 2018). Tipping points have played a role in this performance. Between late 2015 and 2018, the UK's carbon price – a combination of a fixed tax (of £9/tCO_2 from April 2013, and £18/tCO_2 since April 2015) and the price generated by the EU Emissions Trading Scheme – exceeded the coal-to-gas switching price, making gas cheaper than coal (Figure 3a). This tipped the system, reversing the position of these two fuels in the merit order – by which different technologies are called on to meet demand for electricity. In this way, a small change in the relative prices of carbon, coal and gas led to a disproportionately large decrease in the number of hours coal plants could generate electricity – and revenue. While across the EU, this only occurred for a few months in 2017, in the UK the carbon price floor ensured that these conditions persisted for a few years.

Even before this tipping point was crossed, the UK's coal use had been falling as renewables, air quality regulations and carbon pricing cut its market share and profitability. These factors combined with crossing the coal-to-gas tipping point to push the system past a second tipping point: that of coal plant profitability. As the utility analyst Peter Atherton commented in April 2016: 'The economics of coal have deteriorated dramatically over the last 18 months … the increase in the carbon tax … flipped the economics over from barely profitable to loss-making.' The fall in coal power generation accelerated after 2015, as the tipping into unprofitability hastened the closure of coal plants – an irreversible change, since it involved the demolition of physical assets.

These two tipping points could be the start of an upward-scaling tipping cascade (Figure 4). The first tipping point changed the state of the electricity market, in a reversible way, since it could be changed back by a rise in the price of gas compared to coal. This contributed to the activation of the second tipping point, which changed the state of the economics of coal power (a larger system). In the context of other factors likely to have been influencing expectations about the future of coal power (such as the UK's carbon budgets, and the ongoing growth of renewables), this second tipping point led to harder-to-reverse changes.

Crossing these two tipping points at the national level resulted in a ~75% reduction in coal use over ~5 years (Figure 3b). Arguably this gave the UK government the confidence to launch a global campaign in 2017 to phase out unabated coal from the power sector – the Powering Past Coal Alliance (PPCA). Now with over a hundred members committed to this goal, covering more than a third of coal capacity in the OECD, the PPCA can reasonably claim to be influencing investor and policymaker expectations about the global future of coal power.

Solar and wind can already generate electricity more cheaply than fossil fuels, but the growth in their share of global power generation is held back by a range of factors – including vested interests, inertia in electricity market design and business models, inadequate grid infrastructure, and high financing costs – whose relative importance varies between countries. In many developing countries, the high financing costs of renewables are a significant barrier to investment (Schmidt, 2014). If the PPCA's strengthening of negative investor expectations contributes to increasing the cost of capital for new coal plants, then together with measures to reduce the financing costs of renewables, it could help trigger a third tipping point in power systems around the world (Figure 4): the point at which in each market, the cost of capital for new renewable generation dips below that of coal.

Positive-sum cooperation between small groups of countries could bring this tipping point closer. China, Japan, and South Korea together provide much of the international financing for new coal power plants (Urgewald, 2019). Each has industrial interests for doing so, which conflict with their interest in climate stability – the latter expressed by their national commitments to net zero emissions and carbon neutrality, all made within the last few months. If one were to stop, they risk the other two stepping in to take the market. An agreement between the three to stop financing new coal could overcome this disincentive, and significantly raise the cost of coal capital globally.

Policy reforms, financial de-risking instruments and concessional lending can reduce the cost of capital for renewables, making a critical difference to their competitiveness with respect to fossil fuels (Waissbein et al., 2013). Support for improvements in investor decision-making could also help, as institutional inertia can lead to assessments of risk and return that are more backward-looking than forward-looking, favouring incumbents (Johnson et al., 2020).

The international community already provides considerable assistance for transitions to clean power, with this receiving a large share of international climate finance. There is scope for stronger coordination between donor countries and multilateral development banks to provide a more coherent offer of support to developing countries. This could include larger packages of finance at lower cost, supporting large-scale

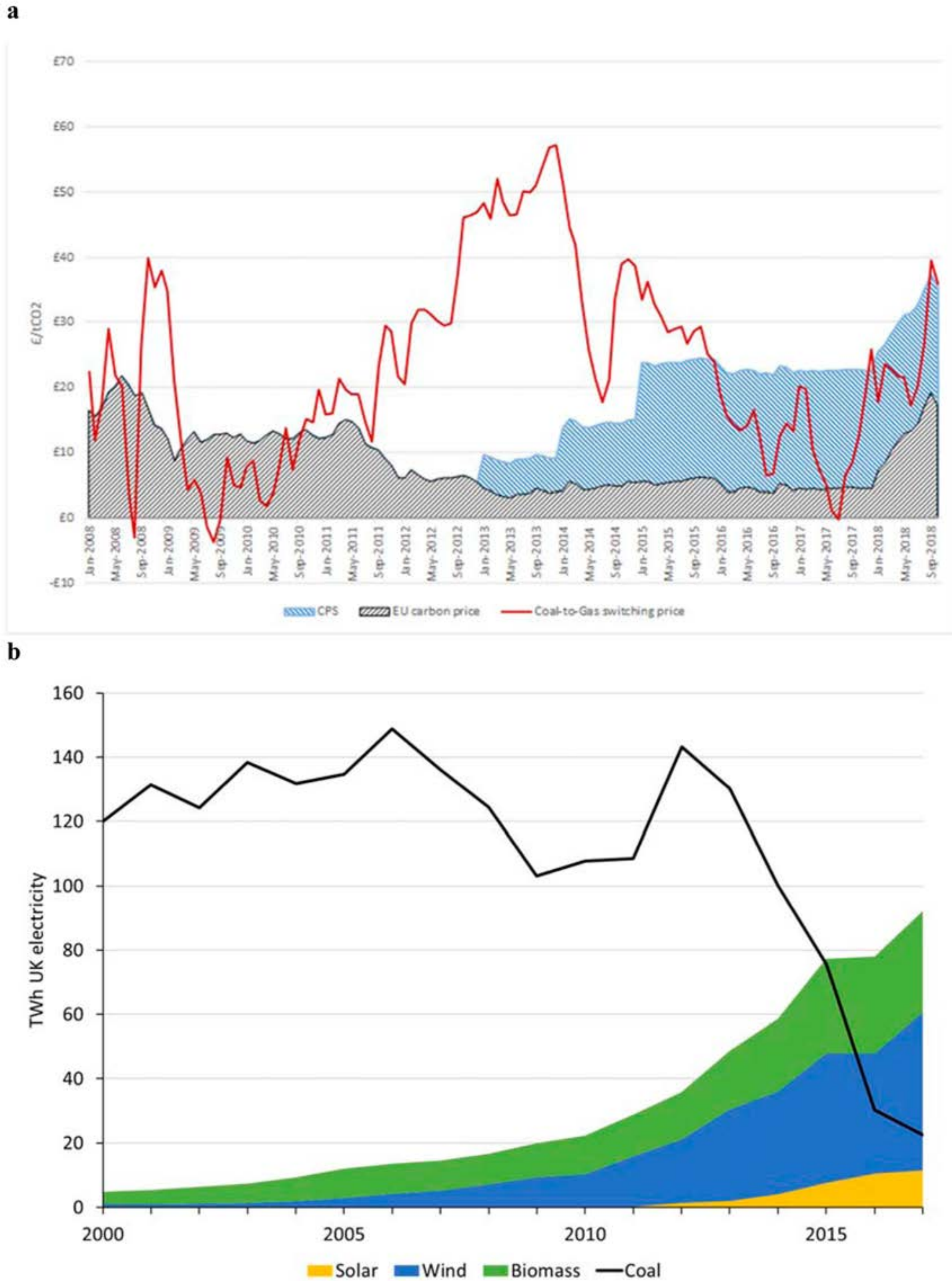

Figure 3. Tipping point away from coal in UK power generation. a. Coal-to-gas switching price (at which they are equally profitable) in the UK 2008–2018 (red; £ tCO_2^{-1}; see Supplementary Information) compared to the UK's carbon price; the EU Emissions Trading Scheme price (grey) plus the UK Carbon Price Support (CPS) tax (blue). Data from ICIS, Intercontinental Exchange and Bloomberg. Chart created by Philippe Guiblin. b. UK electricity generation (TWh) from coal and renewables 2000–2017. Data from BEIS.

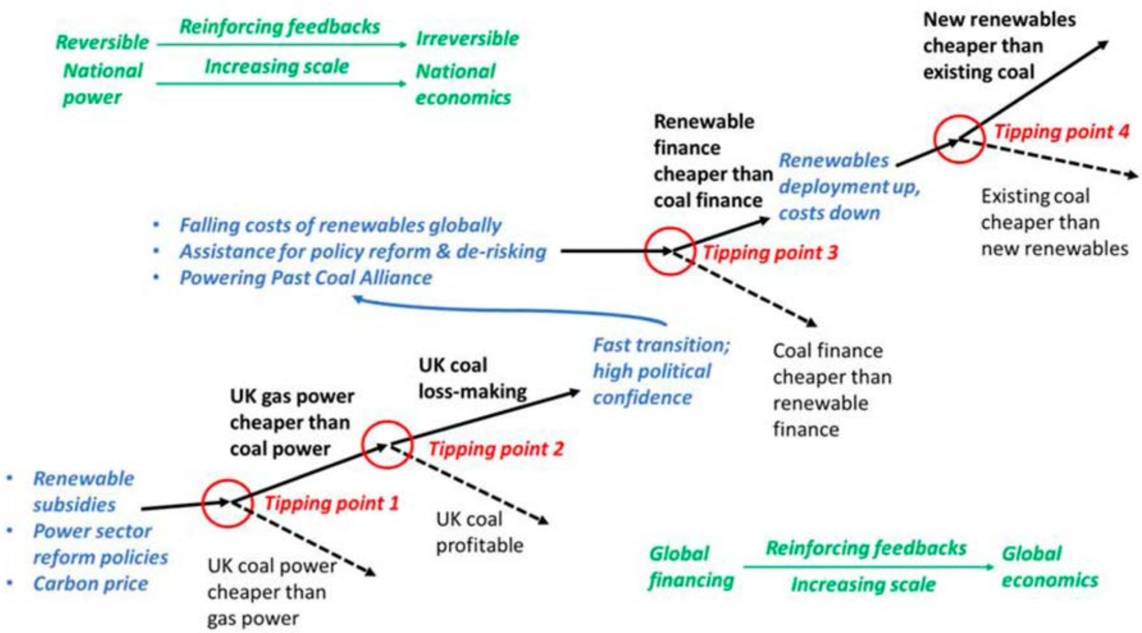

Figure 4. Power sector tipping cascade.

and transformative clean power investment programmes rather than a multitude of small projects (p.58 of Victor et al., 2019). If recipient countries also implement the market reforms necessary for renewables to compete effectively within their power systems, the cost of capital of renewables could be brought below that of coal in all of the countries that are currently planning to build new coal plants (as is already the case in much of the developed world). There is good reason to believe that this is possible: the weighted average cost of capital (WACC) for a typical coal power project in countries without a World Bank loan has been estimated at 13% (Brookings, 2011), whereas for renewable projects a WACC of 7.5% has been suggested (varying by market, technology and year) (p43 of IRENA, 2019).

Such a global tipping of the relative financing costs for coal and renewables would be likely to accelerate the trend of cancellations of planned new coal plants (Global Energy Monitor, 2020). If current plans to build a further 500 GW of coal power capacity – on top of the 2000 GW in operation – were to be replaced with plans for more renewables, global power sector emissions would finally begin to go down instead of up.

Meanwhile, each time a country succeeds in reforming its markets to enable faster growth of renewables, it adds to the reinforcing feedbacks of diffusion operating at the global level. With each doubling of global deployment of solar and wind power, their costs fall by 28% and 15% respectively (BNEF, 2020b). With each fall in cost, renewables become economically attractive in a wider range of countries and sectors. In some countries, this process is already beginning to trigger a fourth tipping point as new renewables become cheaper than existing coal power (Figure 4) (IRENA, 2019), triggering widespread closure of coal plants with useful life remaining. Beyond the power sector, low cost clean electricity can expand the options for decarbonization of large parts of transport, heating and cooling, and industry (Energy Transitions Commission, 2017), contributing to a global low carbon transition at the economy-wide scale.

A different principle for policy

Policy analysis based on the principles of welfare economics is generally concerned with optimizing allocative efficiency: making the best use of fixed resources at a given moment in time (HM Treasury, 2018; Kattel et al., 2018). Economists have long recommended an economy-wide carbon price for addressing climate change on the basis that it would equate marginal abatement costs across all sources of emissions (Stavins, 2020), thereby optimizing allocative efficiency.

Decarbonizing the global economy in time to avoid dangerous climate change, however, is arguably primarily a challenge of dynamic efficiency: changing and creating economic resources and structures effectively and efficiently over the course of time (Huerta de Soto, 2009). Making effective policy to achieve system transitions requires a form of analysis that considers all possible dynamic states of a system, rather than assuming the special state of equilibrium.

Systems thinking can support this, through identifying and manipulating feedbacks to bring about desired changes in a system (Meadows, 2009). Its applications include policymaking, business strategy, and the design and management of organizations and institutions (OECD, 2019). A systems view of low carbon innovation and transitions suggests that targeted investment is more efficient than carbon pricing in the early stages of a transition, since it directly supports the reinforcing feedbacks of technology development and diffusion (Grubb et al., 2017). Most of the progress the world has made so far in low carbon transitions has been achieved through just such targeted investment (Hallegatte & Rozenberg, 2019).

The case made here for tipping points fits within this framework. To activate a tipping point for change in a desired direction is to achieve a high level of dynamic efficiency: a relatively modest input leading to a disproportionately large outcome. This is a particular application of systems thinking – since the consideration of feedbacks can be important to understanding both the value of tipping points and their likely locations – as in the examples discussed above.

Our two examples show that tax and subsidy policies that bring clean technologies below the threshold of cost-parity with fossil fuel technologies can lead to disproportionately rapid decarbonization, when applied in a context of other supporting policies. (The importance of that context should not, of course, be underestimated. Without charging infrastructure for electric vehicles, or grid connections for renewables, cost-competitiveness is not even a possibility.)

If this policy approach seems obvious, then it may seem puzzling that it is not yet a widely taken one: our two examples have both led to world-leading rates of decarbonization within their sectors. The explanation may be that policymakers, following traditional economic advice, are not looking for tipping points. If carbon prices are set equal to some estimated 'social cost of carbon', intended to internalize the externality of dangerous climate change, there is no reason to expect this to correspond to a level that will activate tipping points. Furthermore, if the same carbon price is applied across the whole economy, it may be much lower than needed to activate tipping points in some sectors, while being much higher than needed in others. Similarly, the opportunity to activate upward-scaling tipping cascades will be missed if the value of decarbonization policies is judged only on their immediate effects within a given jurisdiction. Marginal abatement costs curves can be used to rank policies according to the cost per tonne of emissions reduction directly achieved. However, this calculation reflects neither the potential for clean technology costs to come down through learning and economies of scale, nor the possibility of influencing wider changes in the same or other sectors.

The aim of activating tipping points and tipping cascades therefore constitutes a different starting point for policy, one that can be useful when the priority is to achieve dynamic rather than allocative efficiency. The two examples described above were identified retrospectively, by comparing system behaviour over time (in the power example) or across countries (in the transport example). Similar tipping points could be identified in advance by analogy: in many sectors, in many countries, it may be possible to identify a cost parity threshold at which a zero emission technology will begin to outcompete a fossil fuel technology. For example, a future point at which the cost of producing hydrogen from renewables drops below that of producing hydrogen from fossil fuels has been identified (Wood Mackenzie, 2020).

A broader range of tipping points to accelerate decarbonization, including those of a more social or political nature, could be identified by studying the dynamics of the relevant systems (Farmer et al., 2019; Lenton, 2020). To identify the potential to trigger tipping points and cascades within these systems, methods developed for early warning of environmental tipping points could be deployed (Lenton, 2020). These hinge on detecting a slowing recovery rate of an incumbent regime to perturbations. For example, temporal fluctuations in pertinent price indexes, e.g. the share price of coal firms, could be analysed for this signal of 'critical slowing down'. This could be complemented by analysing social media data to see whether spikes of collective attention on new technologies and associated products, e.g. EVs, are getting more resilient (i.e. decaying more slowly) over time.

Conclusions: a tipping point in cooperation

The positive tipping cascades that we have described are by no means inevitable. Many barriers to transition exist, which will need many policies to overcome. But our examples do suggest a plausible route through which a relatively small number of initial actions could catalyze large changes at the global scale.

We offer these two examples – light road transport and power – to illustrate the logic of tipping cascades, and to encourage potential partners to join together in doing the tipping. The UK government is actively working to catalyze these processes of change in its role as Presidency of the 26th Conference of the Parties (COP 26) of the UN Framework Convention on Climate Change, scheduled to take place in Glasgow in November 2021 (Sharma, 2020).

If either of these efforts – in power or road transport – succeed, the most important effect could be to tip perceptions of the potential for international cooperation on climate change. Academic literature has often portrayed global emissions reduction as a negative-sum or zero-sum game – assuming that it can only come at a cost. Diplomacy is now largely focused on encouraging countries to strengthen their unilateral commitments ('Nationally Determined Contributions'). The demonstration of positive-sum cooperation, with a small number of actions leading to large-scale changes in the global economy and emissions, could change this, leading to an increasing focus on the search for similar opportunities in other sectors. While the power and light road transport sectors are promising candidates for early activation of tipping points at the global scale because of the relative maturity of their low carbon technologies, many other possibilities exist. Targeted investment and international cooperation could bring forward the points when electric aeroplanes outcompete jet-fuelled planes in short-haul aviation (Systemiq, 2020); when alternative protein becomes cheaper than meat from animals (Systemiq, 2020); as well as when hydrogen produced from renewables becomes lower cost than hydrogen from fossil fuels (Wood Mackenzie, 2020).

In summary, the activation of tipping points can lead to rapid change in the global economy. A more deliberate search for tipping points and tipping cascades could identify opportunities to accelerate decarbonization, offering plausible grounds for hope that the Paris Agreement goals could still be met. This implies a new and different guiding principle for both policy and diplomacy.

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