NET ZERO+
Building Climate
and Economic Resilience

Leveraging positive tipping points in the race to net zero

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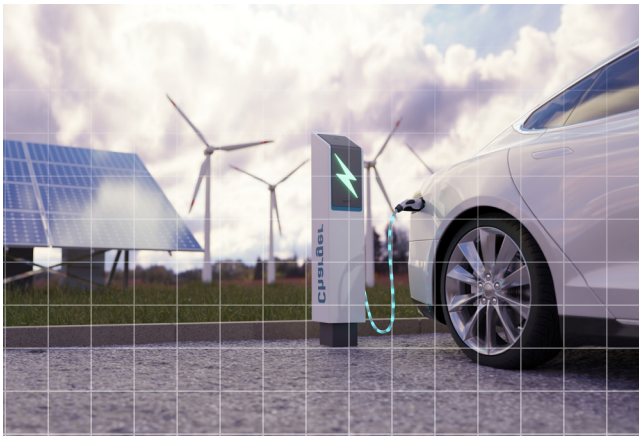

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Abstract

Triggering positive tipping points – where crossing a critical threshold leads to a self-propelling shift to a new system state – may play a crucial role in rapidly accelerating emissions reductions. Recent breakthroughs in the uptake of solar and wind power, battery storage and electric vehicles in leading markets suggest that change at the pace and scale needed is possible. This paper introduces the concept of positive tipping points and its implications for climate policymaking, setting out the dynamics that enable such systems transformations, and taking stock of the enabling conditions and policy measures that can lead to rapid change. Through operationalising the positive tipping points concept, policymakers can better direct policy efforts, leveraging the potential for tipping cascades – where crossing a tipping point in one system pushes other systems past tipping thresholds – while managing potential unintended consequences.

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The Net Zero+ project

The OECD's *Horizontal Project on Building Climate and Economic Resilience: Net Zero+* harnesses the multidisciplinary reach of the OECD to support governments to drive the swift transformational change needed to tackle climate change. The project provides analyses and insights for governments to accelerate and scale up climate action: driving a rapid and resilient transition to net zero while building economic and societal resilience to impacts of climate change.

Executive summary

Tipping points (where a small change past a threshold triggers a self-propelling shift to a new system state) are mostly associated with harmful systemic change in the natural world – for example the collapse of ice sheets or coral reefs – that threaten climate and ecological stability. However, socio-economic systems may also exhibit tipping dynamics, and these dynamics can lead to beneficial or positive, as well as negative, outcomes.

The scale and speed of the transition needed to limit global warming to 1.5ºC means that triggering positive tipping points may play a crucial role in rapidly accelerating the reduction of greenhouse gas emissions. Recent breakthroughs in the uptake of solar and wind power, battery storage and electric vehicles in leading markets suggest that change at the pace and scale needed is possible.

This paper introduces the positive tipping points concept and its implications for climate policymaking, setting out the dynamics that enable such rapid systems transformations. It illustrates these with examples from selected systems, taking stock of the enabling conditions and policy measures that can lead to rapid change. It further discusses how policymakers can operationalise the positive tipping points concept to better direct policy efforts, also considering the potential for tipping cascades (where crossing a tipping point in one system helps to push other systems across tipping thresholds) as well as the need to manage potential unintended consequences.

Key messages

- A positive tipping point is *a critical threshold beyond which a system substantially reorganises, often abruptly, and/or irreversibly, in a way that is predominantly beneficial*. A small additional change at a tipping threshold causes a disproportionately large effect, due to the triggering of self-reinforcing feedbacks.
- The concept of positive tipping points provides an important framework for assessing progress on climate mitigation and identifying opportunities for accelerating change, and can help policymakers prioritise their efforts.
- Not all technologies, services or behaviours exhibit the potential for positive tipping points. The potential for a positive tipping point in any sector of human activity depends on the ability for *reinforcing feedbacks* to overpower *balancing feedbacks* and support self-propelling (accelerating) change. Reinforcing feedbacks are predicated on the concept of increasing returns to adoption, where a product, service or behaviour becomes increasingly attractive (e.g. in terms of cost or quality) the more people have already bought into, used, or adopted it. Positive tipping points may be more likely in systems characterised by high volumes of standardised and modular products or services.
- Recent trends suggest that tipping dynamics may already be playing out in some systems. However, caution is warranted when interpreting these trends, as they are underpinned by generous government support schemes that have led to overcapacity and a concentration of production in a few countries, primarily China. This highlights the central role of policy in driving

progress, but equally questions whether such trends can truly already be labelled as "self-propelling".

- The levelised cost of electricity from solar and wind is already lower than for coal and gas in multiple markets. Deployment is increasing rapidly, with solar and wind accounting for over 80% of global power capacity additions in 2023. For every doubling of installed solar capacity, prices have fallen by 20%.
- Electric cars as a percentage of global sales of new cars has increased from 4% in 2020 to 18% in 2023. Similar patterns of rapid adoption apply for 2- and 3 wheeled vehicles, especially in densely urbanised areas.
- Batteries have seen exponential improvements in energy density coupled with rapid cost reductions (e.g. from ~2500 USD/kWh in 2000 to <100 USD/kWh today). Global battery manufacturing capacity is on an exponential trajectory, growing from <100 GWh/y in 2010 to 3200 GWh/y in 2023.
- Interlinkages across these three systems also show potential for a tipping cascade, with developments in battery technologies feeding back into renewable expansion through better energy storage which in turn permits further transport electrification and battery development.

- Other examples of systems that show potential for positive tipping include:
  - Clean hydrogen, where costs could decrease by 66% by 2030 (subject to market uptake, cheaper electrolysers and cheaper renewable energy costs). Electrolysers are modular and fairly standardised and so show considerable promise for a potential tipping point if learning-by-doing and economies of scale can be leveraged.
  - Food systems may also be susceptible to positive tipping, both on the supply and demand side, through the development of alternative proteins and dietary shifts respectively. The latter in particular points to the potential for social contagion and norm diffusion to unleash vast behavioural transformations that will also be necessary in other systems, such as transport.
- Positive tipping points must not be mistaken for an 'easy fix' but understood as the result of a managed process to create the enabling conditions for rapid change. Key challenges for policymakers include:
  - Despite the positive trends outlined above, considerable barriers to further progress remain, such as the need to invest in infrastructure (e.g., electricity grids and charging stations), overcome financing constraints (especially in EMDEs), manage critical minerals bottlenecks and supply-chain risks, and address political and societal backlash.
  - Policymakers need to understand how far along in the transition targeted systems are so that they can choose the right policy packages to accelerate progress. Identifying positive tipping points and managing their dynamics is complex and will require new indicators and a transdisciplinary approach. It will also require anticipation and strategic foresight to understand how systems are likely to develop, including in the context of parallel developments such as the increasing power of AI. This also includes knowing when to stop or slow down policy efforts as they no longer become necessary or appropriate to sustain or accelerate change.
  - Policymakers should consider whether, by increasing policy stringency in the short term, self-propelling feedbacks can be unleashed earlier, thereby reducing the need for policy intervention and public investment in the longer term. At the same time, policymakers will need to balance potentially high-risk/high-reward strategies with lower risk options and gradual policy implementation to build enabling conditions.
  - International co-operation is essential, as tipping points rely on scale, with co-ordination around specific sectors, for example on hard-to-abate sectors, a promising means to drive progress.
  - Policymakers need to manage potential unintended consequences of triggering positive tipping points. A rapid transition could lead to significant stranded assets, both financially and in terms

of human and physical capital. Governments need to be prepared for non-linear change, using strategic foresight to better manage potential disruptions and risks.

- Reliance on generous government support risks trade and other economic distortions, concentrating production capacity in only the few countries able to afford it. This could pose policymakers with a critical challenge of balancing the need for decarbonisation and sustained innovation with competing priorities of maintaining a level playing field on global markets and ensuring energy security.
- The transition to a net-zero-emissions global economy is the largest structural economic change ever deliberately attempted in human history, and it cannot be expected to unfold without disruption. The alternative of unmanaged climate change would be disruptive and dangerous on an altogether different scale.

Table of contents

FIGURES

1 Introduction

Greenhouse gas (GHG) emissions need to be halved by 2030 and reach net zero by mid-century to limit global temperature increase to 1.5°C with limited or no overshoot this century (IPCC, 2023[1]). Beyond +1.5°C, ecosystem breakdown and the risk of crossing Earth System tipping points become increasingly likely (Ripple et al., 2024[2]). Already, at 1.3°C of global warming, five Earth system elements – the Greenland ice sheet, West Antarctic ice sheet, warm water coral reefs, permafrost regions, and the North Atlantic sub-polar gyre – are at risk of crossing tipping points (Lenton et al., 2023[3]). A transition away from fossil fuels, the primary cause of global warming, is underway, but needs to happen many times faster (OECD, 2022[4]). Decades of inadequate climate action means that incremental change is no longer an option.

Tipping points are mostly associated with harmful systemic change in the natural world that threaten climate and ecological stability (Lenton et al., 2008[5]). However, beneficial tipping points in natural systems[1] are also possible. Human (social) systems can also have both negative (harmful) and positive (beneficial) tipping points. Positive tipping points in human systems are most often associated with the uptake or deployment of new technologies, following an S-curve of accelerating adoption (Rogers, 2003[6]). But positive tipping points can also involve social-cultural behaviours. Importantly, positive tipping points imply that individual and collective actors/agents can intervene in a systems trajectory to enable desired change (Milkoreit, 2022[7]; Winkelmann et al., 2022[8]). These dynamics are well documented within economic literature and complement established theories in sustainable transitions research that explain how niche innovations can, under the right conditions, expand exponentially and displace existing technologies, practices, or institutions (Geels, 2024[9]; Geels and Ayoub, 2023[10]).

The scale and speed of the transition needed to remain within 1.5°C means that triggering positive tipping points is now needed to rapidly accelerate change. Recent breakthroughs in the uptake of solar and wind power, battery storage, electric vehicles and heat pumps demonstrate how research, innovation and policy can effectively respond at the required scale and pace of change (IEA, IREA and UN Climate Change High-Level Champions, 2022[11]; Meldrum et al., 2023[12]). Policymakers can leverage positive tipping dynamics to accelerate progress and prioritise policy interventions that offer the most transformative potential.

This paper introduces positive tipping points and their implications for climate policymaking. It defines positive tipping points and sets out key dynamics that enable such rapid systems transformations. It then develops a framework for policymakers to operationalise the positive tipping points concept to better direct policy efforts. It illustrates this approach through examples from key systems, taking stock the enabling conditions and policy measures that can trigger swift change. It also considers the potential for tipping cascades, as well as the importance of anticipating unintended consequences

2 Positive tipping elements and tipping points

In alignment with previous OECD work on "negative" Earth system tipping points (OECD, 2022[4]), a positive tipping point is defined here as *a critical threshold beyond which a system substantially reorganises, often abruptly, and/or irreversibly, in a way that is predominantly beneficial* (Lenton et al., 2023[3]). A small additional change or *sensitive intervention* at or close to a tipping threshold causes a disproportionately large effect, due to the triggering of self-reinforcing feedbacks (Lenton et al., 2022[13]; Mealy et al., 2023[14]). *Substantial reorganisation* is usually taken to mean majority-to-universal adoption of a desired technology, practice, or behaviour, but could also apply to other outcomes, for example change that significantly reduces GHG emissions.[2] Change is difficult to reverse, but not impossible. New feedbacks can bring the system to another equilibrium (Ayoub and Geels, 2024[15]).

"Predominantly beneficial" is a value judgement based on the normative collective goal of a sustainable future for all within safe and just Earth system boundaries (Box 1) (Ripple et al., 2024[2]); (Rockström et al., 2023[16]).[3] Transformations currently underway in some countries, in power, transport, battery storage and building heating sectors – for example the rapid uptake of renewable solar and wind power and the switch to battery electric vehicles and active travel – have been labelled as positive tipping points (Nijsse et al., 2023[17]; Nijsse et al., 2024[18]). However, it is important to note that if the increase in renewable energy supply is equal to or slower than an increase in energy demand, such positive tipping points would not necessarily result in displacing polluting technologies or lead to emissions reductions.

Not all outcomes of positive tipping are equally positive for climate action. In line with the "**avoid-shift-improve**" framework (Creutzig et al., 2022[19]), the greatest benefit or positive outcome is often to **avoid** using energy and material-intensive and polluting products or services in the first place. The next best outcome is to **shift** to less harmful products or services or to improve their environmental performance. For example, although some countries may have already crossed a tipping point in terms of **improving** the environmental performance of private vehicles through the introduction of battery electric vehicles, an even more effective option in terms of reducing emissions and environmental harm may actually be to **avoid** unnecessary travelling altogether, for example in favour of teleworking, or to **shift** to least environmentally harmful methods of travel, such as walking, cycling or public transportation powered by renewable energy.

In addition to considering whether the outcomes of positive tipping are first-best outcomes in terms of climate action, other factors such as economic efficiency, societal well-being, etc. should also be considered. Given the self-reinforcing dynamics of positive tipping, there is a risk that crossing tipping points could lock-in second-best technologies or practices.

Box 1. Ethics and risks of positive tipping points

What is "positive" or "beneficial" is a value judgement. In the context of the climate and other environmental crises, tipping points may be considered normatively "positive" where they rapidly reduce the drivers of normatively "negative" Earth system impacts and tipping points such as greenhouse gas emissions or deforestation. However, the transition also needs to be just and inclusive. What needs to change, who is being asked to change, where the change and its impacts will be felt, and by whom, all require careful consideration.

The transition pathway to net zero may not be universally seen as "positive". Workers connected to fossil fuel industries may fear for their livelihoods and communities. Well-designed policies need to be in place to ensure that mining of minerals critical for the green transition, such as cobalt and lithium, respect human rights and contribute to improve the economic, social, and environmental well-being of resource-rich regions. If a renewable energy oligopoly replaces the existing fossil fuel energy oligopoly, people might not see much "positive" change in terms of energy access or affordability. Many people, while being broadly in favour of the long-term benefits of climate action, may be reluctant to accept some of the immediate costs and changes to their lifestyles.

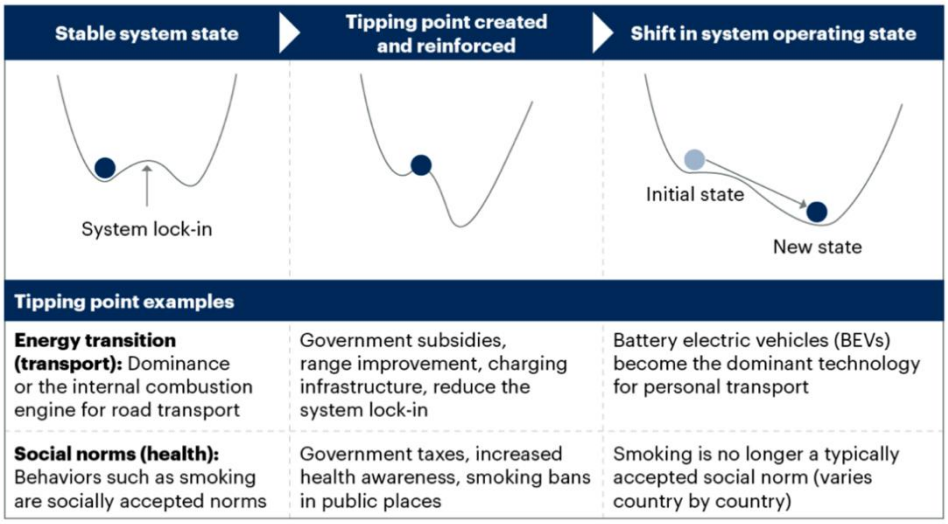
These are difficult ethical decisions and trade-offs that weigh costs, often immediate and direct, against benefits, often long-term and diffuse, on imaginary scales of justice and well-being. But these decisions and trade-offs also need to incorporate the grave risks of triggering Earth system tipping points and the billions of people who will be exposed to potentially catastrophic conditions if climate policy targets are not met.

Source: (Pereira et al., 2023[20]; Pereira et al., 2024[21]).

Enablers and drivers of positive tipping points

The key determinant of tipping of a given system is the relative strength of balancing and reinforcing feedbacks. Prior to a tipping point, balancing feedbacks dominate – the stronger they are, the greater they resist systems change (system resilience). Using the ball-in-valley metaphor (Figure 1), strong balancing feedbacks are represented by a steep-sided valley that quickly returns a perturbed ball to its original state. Policy and other interventions can create the enabling or threshold conditions for a tipping point by weakening balancing feedbacks and strengthening reinforcing feedbacks, leading to a loss of system stability or resilience (the valley becomes shallower)[4]. At the tipping point these forces are balanced, allowing for only a further, minor triggering intervention to tip the balance in favour of reinforcing feedbacks that can (temporarily) cause self-propelling, self-accelerating change to a new system state (an alternative valley). Eventually, as the new technology, idea or behaviour reaches majority adoption, the rate of change slows, balancing feedbacks reassert dominance, and the new system state develops its own resilience.

Figure 1. The ball-in-valley metaphor illustrates positive tipping point dynamics



Tipping point examples		
Energy transition (transport): Dominance or the internal combustion engine for road transport	Government subsidies, range improvement, charging infrastructure, reduce the system lock-in	Battery electric vehicles (BEVs) become the dominant technology for personal transport
Social norms (health): Behaviors such as smoking are socially accepted norms	Government taxes, increased health awareness, smoking bans in public places	Smoking is no longer a typically accepted social norm (varies country by country)

Source: (Lenton et al., 2023[3]).

The potential for a positive tipping point in any sector of human activity depends on the ability for reinforcing feedbacks to overpower balancing feedbacks and become strong enough to support self-propelling (accelerating) change (Lenton et al., 2022[13]). Balancing feedbacks that resist disruption to dominant, incumbent systems include:

- **Lock-in or system inertia**. This can take the form of institutional, infrastructural, technological, or psychosocial inertia (in which habits, social norms, customs, and beliefs are difficult to change) (Unruh, 2000[22]).
- **Negative discourses**. Persuasive narratives and mis- and disinformation promoted by vested and ideological interests to protect incumbents and obstruct niche innovations (Tindall, Stoddart and Dunlap, 2022[23]; Kulin, Johansson Sevä and Dunlap, 2021[24]; Dunlap and McCright, 2015[25]; Oreskes & Conway, 2010[26]).

The concept of reinforcing feedbacks that accelerate the adoption of desired niche innovations is based on the logic of increasing returns to adoption.[5] This is essentially a positive feedback cycle in which a product, service or behaviour becomes increasingly attractive (e.g. in terms of cost or quality) the more people have already bought into, used or adopted it (Arthur, 1989[27]). Key reinforcing feedbacks include:

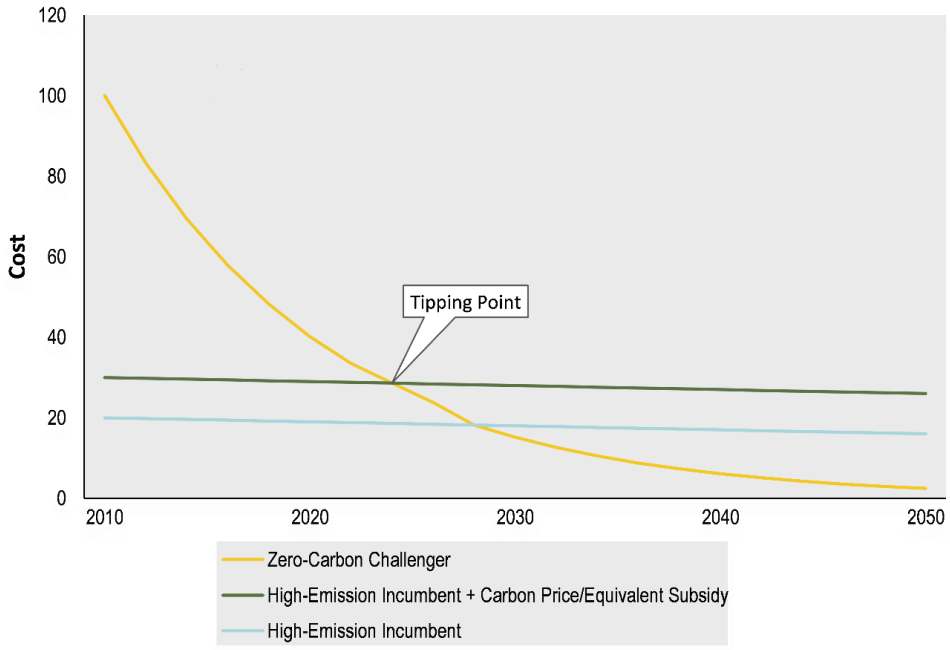
- **Learning-by-doing**, or learning curves, apply to innovations as workers and firms learn from experience, improve processes, and discover and incorporate efficiencies as they go. This leads to unit costs falling by a fixed percentage (typically between 10 and 30%) for every cumulative doubling of production (according to Wrights Law). In other words, the more one makes of something, the better they get at making it (Yelle, 1979[28]; Wright, 1936[29]).
- **Economies of scale** are generated as the rate of production increases faster than the costs of production, leading to lower unit costs, which further increases demand, which further increases production, and so on in a self-propelling feedback loop. The more one produces of something, the less expensive it becomes (Bejan, Almerbatti and Lorente, 2017[30]).
- **Network and co-ordination effects** are a form of reinforcing feedback whereby the value of a good or service increases the more people use it, for example social media platforms or renewable energy networks. The more people who use something, the more people who want to use it (Kandori, Mailath and Rob, 1993[31]; Centola and Macy, 2007[32]).

- **Technological reinforcement**. The more an innovation is used, the more additional technologies and practices emerge that complement it and make it more useful (Lenton et al., 2022[13]).
- **Social contagion.** Adoption of a new behaviour, idea, or social norm makes it easier for others to adopt due to social learning, imitation, and conformity (Centola et al., 2018[33]); (Granovetter, 1978[34]).

Enabling conditions define the threshold at which tipping can occur (Lenton et al., 2022[13]). These include factors such as affordability and attractiveness (Meldrum et al., 2023[35]). For example, when innovations reach cost parity with incumbent products or services, uptake typically begins to accelerate (Figure 2).

However, cost parity is not by itself always a sufficient condition to trigger tipping points. Greater attractiveness in terms of quality, performance, status-enhancement or convenience is also often necessary. Policies that help improve attractiveness – e.g. by removing barriers to adoption such as perceived lack of performance, quality, etc – are therefore valuable tools for effective policy intervention. For example, policies aimed at improving the performance of batteries for electric vehicles to alleviate range anxiety, or policies aimed at making the purchase of heat pumps or solar panels more attractive and convenient through trial periods, money-back guarantees, tax credits, financing, and educational campaigns, may help reduce buyer hesitation and accelerate adoption.

Figure 2. Affordability (price parity with incumbent) often enables a tipping point in adoption



Source: Adapted from (Meldrum et al., 2023[35]).

How positive tipping points are identified

Identifying potential positive tipping points relies on first identifying a system of interest by geographical area and by sector, e.g. light-duty private transport in Berlin. The system's boundaries can be of any scale, depending on the policymaker's responsibilities and ambition – from the global energy system to a local energy co-operative; from the food system of an entire country to that of a single town, university campus

or hospital. Identifying the potential for positive tipping then relies on a) looking for evidence of tipping in analogous systems, and b) assessing how well the system fits with the tipping points theory.

Evidence that a system, or an analogous one, has tipped elsewhere or previously can provide an initial indication of tipping potential. For example, to determine if a tipping point for heat pumps in Switzerland is possible, there is encouraging data on the exponential uptake of heat pumps in Norway, Finland, Denmark and Sweden. However, systems are complex, and evidence of tipping elsewhere or previously does not necessarily mean the same is possible for a given system. Building a qualitative map of the key elements of a system, its interactions and feedbacks, is essential to discover if it has qualities associated with a tipping point (Box 2). Here, a critical task is to identify and measure the relative (potential) strengths of reinforcing versus balancing feedbacks.

Similarly, when identifying the potential for positive tipping cascades between multiple systems, it is important to identify and measure the relative strengths of interactive feedbacks between them. If sufficient data is available, the system's stocks and flows[6] can also be quantified and the system's network can be structured to understand how the system behaves, for example through a quantitative system dynamics model.

Using these two approaches in tandem can provide an initial assessment of confidence in a system's tipping potential.

Box 2. Mapping system feedback loops

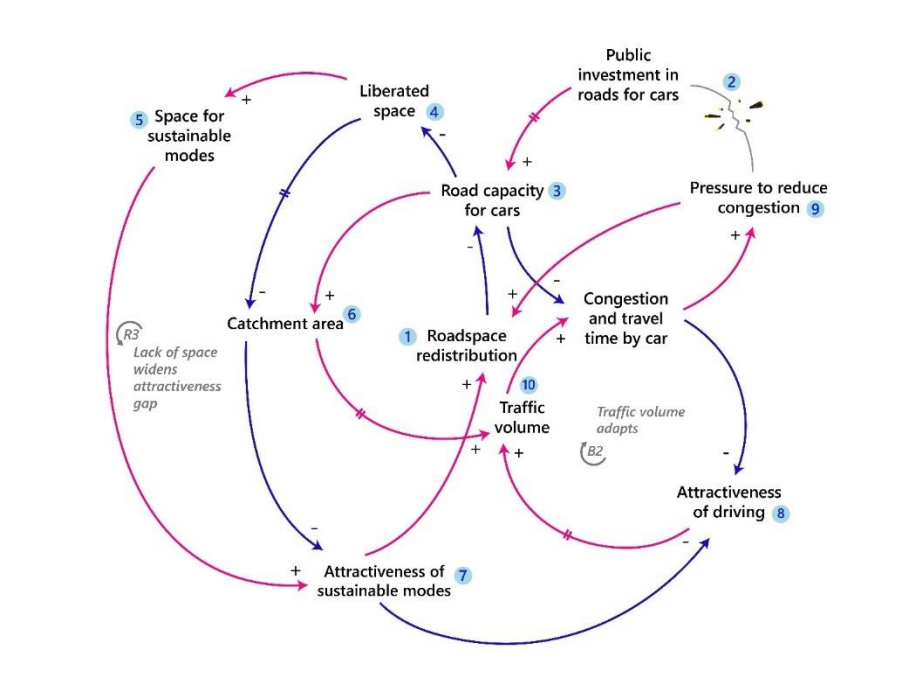
The OECD has developed a framework to identify the transformative potential of policies, built on a core principle of systems thinking: that the results and patterns of observed behaviour are not independent from, but rather caused by, the structure of a system.

Transformative policies are defined as those able to modify a system structure, so that systems foster – by design – patterns of behaviour aligned with desired results. In systems jargon, transformative policies "push" on high leverage points, namely places in which a small intervention may lead to a system transformation capable of triggering large behavioural changes.

The notions of *transformative policies* and *high leverage points* are intrinsically linked to the concept of positive tipping points discussed in this paper. To identify transformative policies, the OECD methodology highlights the importance of understanding the feedback loop structure of the system a policy is trying to transform. Understanding this system structure is fundamental to identifying *where to intervene* in the system *to trigger positive tipping points*. The methodology helps to shed light on dominant feedback loops in the system and assess whether a policy leaves the system structure intact, changes the dominance of existing loops, or creates new loops with the potential to become dominant.

Figure 3 provides an example of a policy with high transformative potential (the potential to trigger a positive tipping point) in the transport sector if implemented at scale. The policy aims to transform the system structure by affecting a key stock in the system: public space. Its transformative potential lies in disrupting the dynamic of induced car demand while introducing a new dynamic that induces demand for sustainable modes of transport.

Figure 3. System dynamics underlying induced car demand



Note: The coloured arrows show the relationship between variables. A pink arrow between variables means that they vary in the same direction: an increase in a variable leads to an increase in the variable it points to; a decrease in a variable leads to a decrease in the variable it points to. A blue arrow means that variables vary in the opposite direction: an increase in a variable leads to a decrease in the variable it points to; a decrease in a variable leads to an increase in the variable it points to. Arrows marked by a "||"- symbol indicate a delayed effect. Each loop label (e.g. B1) denotes a feedback loop. A feedback loop is either reinforcing (R) or balancing (B).

Source: (OECD, 2025[36]).

In addition to the causal loop diagram illustrated in Figure 3, the OECD framework uses two other systemic tools to identify the transformative potential of policies: stock and flow analysis, and Meadows' leverage points framework. When used in combination, these tools trigger questions such as whether a policy strengthens or weakens feedback loops, can change a loop's dominance, or lead to the creation of new loops. See (OECD, 2025[36]) for more information.

Note: Evidence shows that, when implemented at scale, road space redistribution can lead to significant reductions in traffic volume (Cairns, Atkins and Goodwin, 2002[37]; Rapid Transition Alliance, 2019[38]).

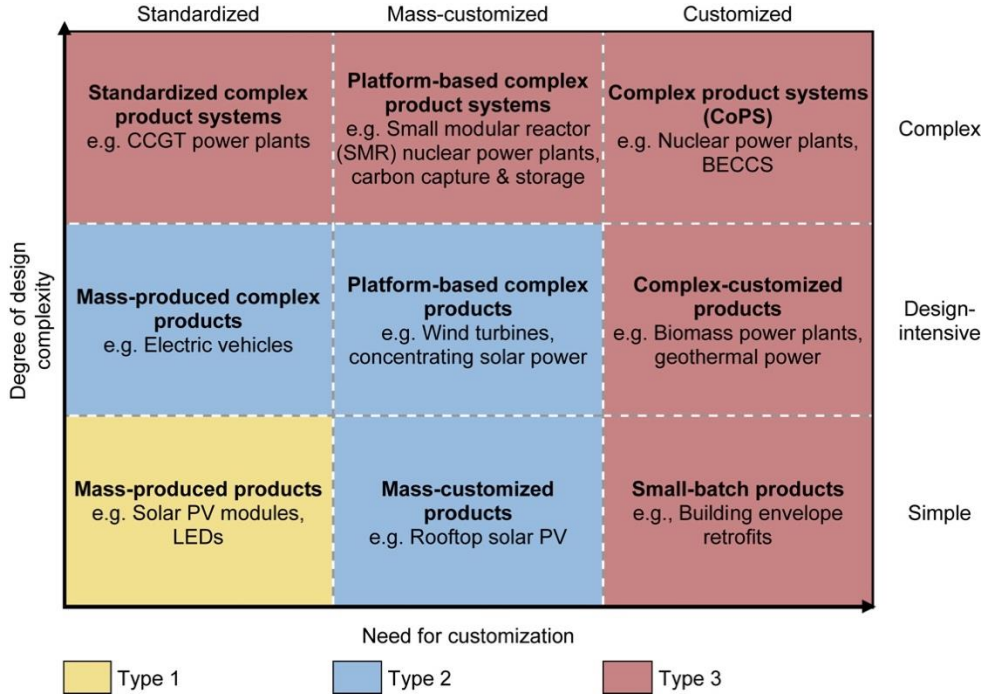
Source: (Meadows, 2008[39]; Sterman, 2000[40]; Innovation, 2020[41]).

Positive tipping points may be more likely in systems where high volumes of simple, standardised products or services are created – i.e. where there is high modularity, such as with solar PVs and batteries (Meldrum et al., 2023[35]; Systemiq and Kadin Net Zero Hub, 2023[42]). For example, Figure 4 categorises different energy technologies into three types based on their design complexity and need for customisation. Each type requires different national and international innovation and deployment policy (Malhotra and Schmidt, 2020[43]).

- Type 1: strong reinforcing feedbacks – e.g. economies of scale, steep learning curves, contagion effects – can drive self-propelling, accelerating change. Access to global markets induces innovation.

- Type 2: technologies provide opportunities for national green industrial policies to invest in domestic production, infrastructure development, and participation in global value chains (Malhotra and Schmidt, 2020[43]).
- Type 3: highly complex, bespoke technologies with high capital costs and long replacement rates, such as nuclear power stations or chemical manufacturing plants. Here there are no obvious strong reinforcing feedbacks to drive change (Meldrum et al., 2023[35]). Advancing these technologies requires both national industrial policy and international co-ordination between projects at regional or global scale.

Figure 4. Where to find technologies with positive tipping points



Source: (Malhotra and Schmidt, 2020[43]).

Not all previous cases of social-technological change have involved tipping points, and not all rapid reductions in GHG emissions can be considered the result of positive tipping. For example, the COVID-19 pandemic led to rapid emissions reductions due to lockdown regulations, but these quickly returned to pre-pandemic levels when regulations were lifted. The factors that caused the emissions reductions were neither self-propelling nor sustained/irreversible. Similarly, not all sectors responsible for anthropogenic GHG emissions should be expected to have the potential to tip in a self-propelling way to a zero- or low emissions alternative.

3 Positive tipping points already emerging for decarbonising the global economy

Globally, the largest sources of greenhouse gas emissions come from electricity and heat production (~34%), industry (~24%), agriculture, forestry and other land use (~22%), and transport (~15%) (IPCC, 2022[44]). For each of these sectors, there are opportunities for positive tipping points that would substantially reduce or eliminate emissions by shifting to alternative technologies and behaviours. Evidence suggests that positive tipping points are already being crossed, or are close to being crossed, in decarbonising electricity generation through the transition to solar photovoltaics and wind, and in road passenger transport (9% of GHG emissions) through the transition to battery electric vehicles. This section presents the evidence for these tipping points and the amplifying feedbacks that drive them, explains how policies and other interventions have successfully created the enabling conditions that trigger them, and highlights remaining barriers and balancing feedbacks that could be addressed to accelerate their progress.

Power systems

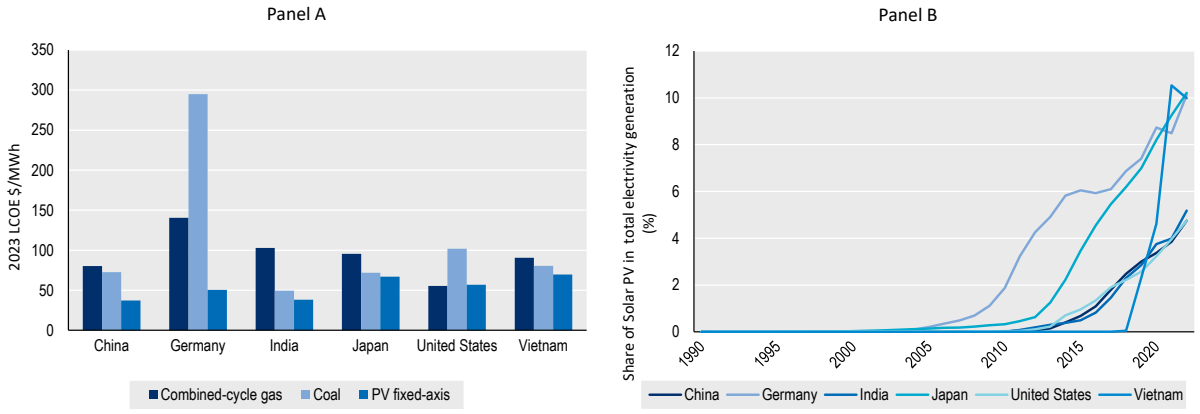
Rapid transformation of the energy system is essential to decarbonisation. While a transition to clean electricity has traditionally been seen as costly and dependent on subsidies or taxation, renewables are now cost-competitive with coal globally and increasingly competitive with natural gas (BloombergNEF, 2023[45]), and are on an exponential growth curve globally driven by strong amplifying feedbacks. This suggests that renewable technologies may have already crossed a tipping point, with profound consequences for global energy systems (Nijsse et al., 2023[17]).

Evidence for positive tipping points in the uptake of renewable power

Solar photovoltaic (solar PV) cells and wind turbines, the two key technologies driving decarbonisation of electricity generation, are highly modular with relatively rapid development and deployment cycles. These traits make them prone to amplifying feedbacks whereby increasing adoption leads to lower costs and better performance as production volumes increase.

Price-parity thresholds – at which the levelised cost of electricity (LCOE) from solar or wind becomes less expensive than energy generated by fossil fuels – are often seen as synonymous with positive tipping points for decarbonising utility-scale electricity generation and have already been crossed in multiple markets (Figure 5). Fossil fuel costs, meanwhile, are highly (and increasingly) volatile and show no long-term decrease (Way et al., 2022[46]; Kreps, 2020[47]). Thus, renewables are increasingly a more attractive investment for developers and governments in terms of better returns and energy security and resilience. Deployment is increasing rapidly, with solar and wind accounting for over 80% of global power capacity additions in 2023 (IRENA, 2024[48]).

Figure 5. Solar PV LCOE compared to coal and gas/solar PV share of electricity generation in selected countries



Source: (Our World in Data, 2024[49]; BloombergNEF, 2023[50]).

Less modular technologies, such as nuclear power and carbon capture, utilisation and storage (CCUS), may also demonstrate learning rates and cost reductions with economies of scale, though these are likely to occur less rapidly. For example, the LCOE for nuclear generation (including small modular reactors) is unlikely to fall more than 50% by 2050, even in optimistic scenarios (Abou-Jaoude et al., 2024[51]).

Achieving economies of scale in large industrial infrastructure for CCUS hubs can come with considerable co-ordination challenges, as all components of the value chain (i.e. removal, transportation, storage and/or end-users) must be developed in sync (McKinsey, 2022[52]). While cost reductions are possible, e.g. the 35% reduction in large-scale CO_2 capture costs between first- and second-generation plants (IEA, 2021[53]), existing revenue streams such as enhanced oil recovery prolong the use of fossil fuels, and alternatives such as hydrogen production are immature. Carbon pricing and/or other financial and regulatory tools that enable CCUS to be economically competitive are therefore likely to be essential to enable their deployment at scale (McKinsey, 2022[52]).

Key feedbacks and enabling conditions for positive tipping points in renewable power

Investment in research and development and strong policy focus on market expansion in a few key countries have been critical in creating the enabling conditions for tipping points in renewable energy deployment. For solar PV, the US in the 1970s, Japan in the 1990s, Germany in the 2000s and China since 2010 have each played a vital role. In wind power, Denmark, the UK and China have been important leaders. In all of these countries, policies were instrumental in setting clear deployment targets, providing subsidies (e.g. feed-in-tariffs) and other mechanisms to incentivise adoption and grow domestic markets, as well as in investing in supply chain capacity and skills in manufacturing and installation (Nemet, 2019[54]; Geels and Ayoub, 2023[10]).

The market expansion achieved through these policy interventions was essential to achieve economies of scale and learning-by-doing. Costs have fallen and the performance of each solar panel or turbine has improved as production has increased, leading to a high “technological learning rate”. This is especially true for solar PV, the costs of which have declined by 80-90% each decade since 1960. For every doubling of installed solar capacity, prices have fallen by 20% (Nijsse et al., 2023[17]). In the last two years alone, solar panel costs have decreased by 30% (IEA, 2024[55]).

Falling prices have increasingly made solar PV and wind economically competitive with coal and natural gas in markets across the world, driving deployment. Between 2010-2020, the cost of solar PV fell by 15%

per year while installed capacity increased by 25% per year (Nijsse et al., 2023[17]), a trend which pushed solar to reach 14% of total global generation in 2023.

In the first half of 2023, the LCOE for both solar PV and onshore wind was just over USD 40 per MWh, roughly half that of coal or gas (BloombergNEF, 2023[45]). The remarkable learning rates in these technologies are considered likely to continue, with forecast prices of USD 15-31 per MWh for solar and USD 23-37 for wind in 2030 (Bond et al., 2023[56]). Capital investment has been adept at predicting the pace of change: in 2023 solar PV attracted more capital investment than all other energy investments combined and was expected to do so again in 2024 (IEA, 2024[55]).

Increasing returns to adoption are not the only amplifying feedbacks driving renewable energy tipping points. Strong policies in leading countries have boosted private sector confidence, driving investment and stronger business strategies (Nemet, 2019[54]). This has created feedbacks to policymakers via lobbying and other influences, encouraging and legitimising further policy support. Similar feedbacks can exist between policymakers and the public, driving greater public support for renewable energy deployment and stronger political mandates. These can be reinforced through upstream engagement and envisioning, and deliberative approaches to governance (Box 2). Positive user experiences, such as with rooftop solar panels, demonstrate the successful deployment of renewables and their cost and performance benefits, generating wider public support and social contagion among neighbouring households. Combined, these multiple feedbacks reduce costs and increase the acceptability of renewable energy while creating path dependencies in policy and business strategies, infrastructure investments, and institutions (Geels and Ayoub, 2023[10]).

It is important to note that this exponential global trend is highly geographically skewed. In 2023, China accounted for 63% of global net additions in total renewable capacity (IRENA, n.d.[57]). Over the past two decades, China's strong policy focus on growing both manufacturing capacity and domestic demand for solar PV, supported by significant state financing, has enabled rapid cost reductions. This has allowed China to capture a huge portion of the global market and made it difficult for other producers to compete, while supply chain constraints and financial headwinds have constrained or stalled growth in the rest of the world.

The role of producer subsidies and excessive production capacity in reducing module prices is often overlooked when considering whether renewable energy has truly crossed a tipping point. Manufacturing capacity is currently at three times the rate of installation (OECD, 2025[58]), and even optimistic projections of renewable energy deployment seem unlikely to be able to entirely absorb current and planned production capacity. This raises questions about whether cost declines are truly self-propelling or are propped up by producer support and resultant oversupply.

Removing balancing feedbacks and unlocking enabling conditions

Although it now appears inevitable that solar PV will be cheaper than fossil-fuel based generation in almost all markets by 2027 (Nijsse et al., 2023[17]) (with wind remaining least expensive in the UK and Scandinavia until the 2030s), other system interactions still have the potential to weaken reinforcing feedbacks or act as balancing feedbacks, slowing or blocking the transition to renewables even in markets which have previously seen exponential growth (Ayoub and Geels, 2024[15]). For example, while strong policy and subsidies for solar PV in Germany were key to driving down costs and rapid acceleration of installation in the early 2000s, this slowed significantly after 2010 as a result of the removal of subsidies, increasing Chinese competition in manufacturing, and shifting public opinion (Ayoub and Geels, 2024[15]). New policy mixes since 2016 have since restimulated growth. Such examples demonstrate that it can be challenging to identify when or whether a transformation becomes truly self-propelling – i.e. that the trend would continue even after support measures are withdrawn. They also serve to illustrate the importance of a strategic approach to policy sequencing to unlock the enabling conditions for further growth as systems evolve.

Grid stability: Solar- and wind-dominated power systems provide intermittent generation capacity, with vulnerability to periods of low wind and darkness, meaning that their rate of penetration can become self-limiting (IRENA, 2023[59]). They are also more likely to produce during times of overproduction, with insufficient grid resilience and flexibility forcing energy providers to sell at lower prices than, for example, gas generators, making them less competitive. This can be partly offset with improved storage (i.e. in batteries, pumped hydropower etc.), grid connections, and demand-response (Shafiullah, Ahmed and Al-Sulaiman, 2022[60]). Here, barriers to growth are being further reduced by innovation and falling prices in key complementary technologies for renewable power, including innovation in digital smart-grid platforms for supply and demand management (Dileep, 2020[61]). Most significantly, battery storage is also following an exponential pathway of performance improvements and declining costs, such that it is rapidly becoming cost-effective and already achieving high rates of deployment in some markets (IEA, 2024[62]). In 2022, 40% of solar PV developments globally were built with on-site battery storage, while in California the rate was over 95% (Box 4) (RMI, 2023[63]). However, substantial policy support and public finance are needed to upgrade grid infrastructure to support more flexible balancing of supply and demand as electricity demand rises with electrification in other sectors (transport, heating etc.) (IRENA, 2023[59]).

Availability of finance: Finance for low-carbon projects is highly concentrated in high-income countries, reflecting lower investor confidence, high-risk premiums and a higher cost of capital in emerging markets and developing economies (EMDEs). While renewable energy is likely to be lower-cost over its lifetime due to low operational costs, any infrastructure development has relatively high capital expenditure requirements, which poses a significant challenge in developing countries with under-developed domestic capital markets and limited access to international finance (Montague, Raiser and Lee, 2024[64]). This is despite many of the world's poorest countries having huge solar and wind generation potential. There is significant room for strategic policymaking and investment to improve enabling environments for countries across the world to take advantage of falling costs of energy generation and enter the “race to the top”.

Notwithstanding the improving commercial profiles of many clean energy investments, and, consequently, improving prospects for financing investments through the private sector, public finance will still play a significant role in many markets. This is because significant parts of the energy system are more difficult to commercialise, most notably transmission and distribution networks. Moreover, the risk-return profile (perceived or real) in many geographies will continue to be unfavourable for commercial investment.

Public finance, however, can be used more creatively to crowd-in, rather than compete with, private finance. In this regard, it can serve two objectives. First, public finance can be used to de-risk commercial investment, including through blended finance. Key tools are likely to be instruments such debt guarantees and other mechanisms to absorb currency and investment risks. Second, international financial and technical assistance can be used to support improvements in enabling conditions in EMDEs to tackle the underlying structural issues that deter private investment in the first place, for example by building domestic financial capacity and deepening local capital markets (OECD, 2023[65]; Ameli, Kothari and Rickman, 2023[66]).

Once these barriers are removed, network effects can cause financial actors to quickly crowd in to a new growth area, turning the vicious cycle (i.e. balancing feedback) of chronic under-investment, lack of growth and low investor confidence, into a “virtuous cycle” (i.e. a helpful reinforcing feedback) of increasing growth and investment. There are already signs of investment in the rest of the world picking up, with significant progress in India, Brazil, Namibia and other parts of South-East Asia and Africa, reflecting new policy initiatives. Investment in improved grid infrastructure in Africa has almost doubled between 2020 and 2024, and is now at over USD 40 billion. It is expected that in 2024 87% of capital expenditure on electricity generation in the Global South will be in clean energy, with total new solar and wind capacity to increase by 60% to 77GW (Vikram Singh, 2024[67]).

Institutional lock-in along with resistance from declining industries: In some countries, initial rapid growth in renewables has been slowed by political or social backlash (balancing feedbacks) (Ayoub and

Geels, 2024[15]). Potential for this is strong where a rapid renewable energy transition puts jobs associated with fossil fuels at risk (13 million jobs globally) (IEA, 2024[68]), for example in communities close to extraction sites and other industrial sites. Policy to provide alternatives and develop skills for new industries may be able to mitigate these impacts in some cases, and new coalitions of actors who benefit from the transition (e.g. people with jobs in clean energy) may counteract this resistance, but the impacts in many cases may not be evenly or equitably distributed (Nijsse et al., 2023[17]). Where sufficient social and political buy-in is lacking, changing conditions (economic, political or otherwise) can lead to withdrawal of policy support and stall deployment. For example, in the UK these effects led to stalling solar PV installations since 2015 (Ayoub and Geels, 2024[15]), and a ten year block on planning permission for onshore wind power (Ministry of Housing, Communities & Local Government, 2024[69]).

Supply chains: A renewables-powered future is likely to be metal- and mineral-intensive, requiring increasing production of raw materials including lithium, copper, cobalt, nickel, aluminium and rare-earth minerals. Supply chains for many of these are geographically concentrated and geopolitically sensitive and have potential for bottlenecks to disrupt the pace of deployment (IEA, 2024[70]). In some cases, these may be eased by research into substitutions (e.g. sodium for lithium in batteries), development of circular and recycling processes, and perhaps most significantly through demand reduction achieved through efficiency improvements and wider systemic and behavioural changes that lower overall energy demand (OECD, 2024[71]; IEA, 2023[72]).

Box 3. How did solar power become competitive with fossil fuels?

The current exponential growth in solar power capacity additions, powered by price reductions and performance increases, may now be self-propelling but was never inevitable. Passing the solar PV tipping point is the result of deliberate government policies in a number of countries, combining critical innovations, political campaigning/advocacy, and policy induced financial investments.

Originally invented in 1883, the first commercially available solar cell was released in 1954 by Bell Labs in the United States, finding an initial niche market in solar power for satellites. The 1973 oil crisis triggered further public investment in the US, with then President Jimmy Carter setting a high-profile target for rooftop solar generation which drove technological improvements in cell design and production methods.

As a major oil importer, Japan also invested in R&D following the oil crisis and took the lead in solar PV development when the Reagan administration pulled funding for US programmes. Japanese innovation found a new niche for solar cells in consumer electronics, and government targets in the 1990s drove further uptake in rooftop solar installation, especially through establishing economic incentives to consumers by enabling them to sell excess power back to the grid. By 2000, solar panels had fallen in price by a factor of 20, with Japanese firms taking nearly 50% of global market share.

In the early 2000s, strong political mandates for the German Green Party led to legislated targets for solar power and drove rapid demand with strong incentives through feed-in tariffs. Social contagion played an important role in public uptake, with early adopters providing information to neighbours.

Around this time, the Chinese government began heavily subsidising the domestic production of solar PVs. Together with strong demand from Germany, Chinese production experienced rapid growth. This also attracted international finance which contributed towards a 100-fold increase in manufacturing capacity between 2005-2010, pushing prices down and capturing 60% of global market share. Since 2010 the Chinese government has provided targeted support, opening a huge domestic market and further driving steep price declines.

Clear government strategies implemented as strong policy have been critical to driving innovation and building the confidence of investors across this development cycle, enabling solar PV to move from a niche innovation to the cheapest source of power globally.

However, governments should exercise caution in providing producer support, which is increasing globally and comes with considerable distortionary risks. The effectiveness of producer subsidies will ultimately depend on what other countries are doing. The recent experiences of Meyer Burger (solar) and Northvolt (batteries), which, despite generous subsidies, could not compete with Chinese companies enjoying larger state backing and a protected market back home, offer important lessons on the risks of green industrial policy and the accelerating green technology race.

Source: (Unruh, 2000[22]; OECD, 2024[73]).

Passenger road transport

The availability of affordable renewable energy makes electrification a key pathway to efficient, rapid decarbonisation in other high emitting sectors such as domestic heating, industry and – critically – transport, which contributes 22% of global emissions from energy use, 45% of which comes from private passenger road transport.

In many environments, electrifying road passenger transport should be seen as one component of a broader approach to systemic change in mobility, following the avoid-shift-improve approach to reduce dependency on individual car ownership through supporting increasing adoption of active transport and public transport with multiple potential benefits beyond decarbonisation (Lenton et al., 2023[3]; OECD, 2021[74]; OECD, 2022[75]). These shifts can also follow non-linear pathways driven by feedbacks, in which policy support and positive user experiences crucial, with governance and leadership at sub-national and city levels playing an important role (for an example of systemic transformation in the transport system, see Box 2). Demonstration effects, where other cities or jurisdictions follow the example of innovators, may be a mechanism for scaling adoption of successful approaches (Lenton et al., 2023[3]) and could be facilitated by respected convenors such as OECD or C40 cities.

Evidence for positive tipping points in the uptake of battery electric vehicles

BEVs have seen dramatic cost declines and performance improvements since 2010. Due to innovation, policy leadership through setting adoption targets and mandates, and industry investment (Geels and Ayoub, 2023[10]), particularly in leading markets, their adoption is accelerating rapidly. Electric cars as a percentage of global sales of new cars increased from 4% in 2020 to 18% in 2023 (Mercure et al., n.d.[76]; IEA, n.d.[77]). However, this increase is concentrated in a few major markets, namely China (~60%), Europe (~25%) and the United States (10%), and, as for trends in renewable energy deployment, is driven by generous subsidies, particularly in China (OECD, 2024[73]). Similar patterns of rapid adoption apply for 2- and 3-wheeled vehicles, especially in densely urbanised areas, with China and India the leading markets for these vehicles (McKinsey, 2020[78]).

The total cost of ownership (TCO) over the full lifespan of BEVs is below that of ICEVs in most markets, due to low maintenance costs and low costs of home charging, though this differential has been reduced somewhat by higher electricity prices since 2022. Consumer behaviour, however, suggests that price parity with ICEVs at point of purchase (i.e. sticker price) should be considered the more important threshold; this is expected to be reached in the major markets of Europe, China and USA before 2030 (Mercure et al., n.d.[76]; EEIST, 2023[79]). In Norway, sticker-price parity was reached in 2012, and was a major driver of a BEV tipping point complemented by strong policy support providing multiple other benefits (e.g. free parking) to users (Sharpe and Lenton, 2021[80]).

Statistical signals demonstrate that sales of ICEVs are increasingly slow to recover (or even fail to recover) from shocks such as fuel price rises or the COVID-19 pandemic, indicating a loss of resilience in ICEVs' incumbency comparable to the loss of resilience seen in ecological systems before a tipping point (Mercure et al., n.d.[76]). In contrast, sales of BEVs have been resilient to the same shocks (albeit subject to other constraints, such as supply chain bottlenecks).

Key feedbacks and enabling conditions for positive tipping points in BEV adoption

Early adopters of BEVs were chiefly urban or suburban users, driving mostly short journeys and willing to pay more for a zero emissions vehicle (Geels and Ayoub, 2023[10]). Accelerating adoption has been driven by economies of scale and learning-by-doing as new leaders such as Tesla and BYD, as well as most legacy automakers, have established new design principles and mass production lines for BEVs, and diversified production to compete in a variety of niches (e.g. sedan, compact, crossover, SUV). The capacity to do this is enhanced by modular, adaptable approaches enabling multiple models to be built on a single platform. Key performance improvements include range and charging power, innovation in driver experience, EV-specific tyres and low cost of maintenance relative to ICEVs, but the single most important element in cost reductions and performance improvements has been in battery technology development (Geels and Ayoub, 2023[10]; Mercure et al., 2024[81]; Sharpe and Lenton, 2021[82]) (Box 4).

Throughout, tight feedbacks between policy, industry and EV users have accelerated consumer interest and learning rates for BEVs. Initial subsidies and tax credits for purchases played a key role in establishing and expanding the BEV market. The 2015 "Dieselgate" scandal, after which Volkswagen Group announced a major reorientation towards BEVs, prompting several other large automakers to follow, also seems to have tipped policymakers' perceptions in favour of BEVs as a long-term solution for decarbonising transport. Beginning in 2017, political commitments to ending sales of ICEVs were announced in multiple markets, some of which have since become legislated mandates (Geels and Ayoub, 2023[10]). The market certainty provided by mandates in particular has driven a further uptick in investment in BEVs and the supply chains necessary for their manufacture. While this has been accompanied by significant lobbying by automakers to delay or remove mandates, investments made in manufacturing capacity introduce major path dependencies. Globally, automakers and EV battery manufacturers have committed to investing USD 1.2 trillion in the EV transition (Khatib, 2024[83]).

Policy interventions have also been instrumental in accelerating deployment of BEV charging infrastructure (Geels and Ayoub, 2023[10]), a key enabling condition for widespread adoption (Tikoudis et al., 2024[84]). Globally, deployment of public charging infrastructure has approximately kept pace with adoption of BEVs, showing impressive deployment rates to maintain a global average of roughly 7-10 EVs per charger (Mercure et al., 2024[81]; Anadón Martínez and Sumper, 2023[85]). Nevertheless, users frequently report lack of charging infrastructure as a barrier to use or purchase BEVs, and proactive policy to accelerate deployment is likely to be a key enabler of an accelerated tipping point. Complementary technologies such as digital platforms for ride-sharing, car-sharing and other models of mobility as a service can also amplify feedbacks by making BEVs more accessible to people who are unlikely or unable to purchase their own vehicle.

Barriers and balancing feedbacks slowing BEV adoption

The BEV transition has considerable momentum, appears close to passing tipping points in key markets, and is currently described by the IEA as on track to meet decarbonisation targets (Mercure et al., n.d.[76]; IEA, n.d.[86]). However, global BEV sales are dominated by a few leading markets, and even within those not all enabling conditions for self-propelling change have been fulfilled (Mey, Mangalagiu and Lilliestam, 2024[87]), with sales in some showing signs of slowing due to weakening reinforcing feedbacks. Balancing feedbacks and other obstacles which could be overcome to accelerate the transition include:

- **Weak or withdrawn incentives** (e.g. subsidy or tax credits) can delay the time taken to reach price parity for BEVs, or strengthen public perception of BEVs as expensive, limiting market growth (Ayoub and Geels, 2024[15]). To avoid this delay, governments need to be willing to intervene to support EVs with strong incentives that are maintained until cost competitiveness is reached.
- **Lack of charging infrastructure** makes EVs less accessible and attractive to potential buyers (Anadón Martínez and Sumper, 2023[85]; Tikoudis et al., 2024[84]). Governments need to prioritize public and private investment and the optimal location of EV charging stations in public locations (Yuvaraj et al., 2024[88]).
- **Resistance from incumbents.** For large, established automakers, building new products and production lines is costly and technically challenging. Where manufacturers face higher operating costs (e.g. in Europe) they are finding it difficult to compete with challenges from new competitors (e.g. BYD and other new Chinese brands), presenting risks in a sector which is key to major economies (e.g. Germany) (Meckling and Nahm, 2018[89]). There is still considerable industry lobbying to delay or remove electric vehicle mandates, negative media campaigns (up to and including disinformation campaigns) targeted at wider publics to maintain negative perceptions of BEVs (Corradi, Sica and Morone, 2023[90]; Szabó and Newell, 2024[91]).
- **Trade policy** may feed back in multiple complex ways to affect the speed of the transition. While opening markets to the least expensive imported products (currently Chinese) would likely accelerate the transition in the short-term, it may strengthen resistance from domestic manufacturers (Meckling and Nahm, 2018[89]). Where domestic industries face lower profits or job losses as a result, this can trigger wider societal backlash. Building skills and capacity and reaping the wider economic and social dividend of supporting domestic industries may ultimately lead to a deeper and faster transition (as with offshore wind in the UK and Denmark) (Geels and Ayoub, 2023[10]).
- **Supply chain bottlenecks** and volatility in prices of critical minerals. A typical EV requires six times more mineral inputs than an ICEV (excluding steel and aluminium) (IEA, 2021[92]). Demand for cobalt, lithium, manganese, and nickel in 2030 has been projected to be 39.6, 19.6. 5.2. and 4.7 times greater than in 2015, respectively (Jones, Elliott and Nguyen-Tien, 2020[93]). As has been mentioned above with respect to the renewable energy transition and also relates to batteries (Box 4), supply chains for many of the critical minerals required for EVs are geographically concentrated and geopolitically sensitive and could potentially disrupt the pace of EV deployment (IEA, 2024[70]). Governments need to assess these risks and develop resilient supply chains and recycling systems.
- **Public perceptions** of BEVs remain mixed, with many still feeling range anxiety, noting lack of charging infrastructure, retaining a perception of BEVs as expensive, or expressing concern about the environmental and social footprint of green technology supply chains (Pamidimukkala et al., 2024[94]). These concerns, while often legitimate, can be enhanced or propagated by misinformation campaigns, which, for example, highlight downsides of BEVs without comparing them with corresponding statistics for ICEVs. The total extractive footprint required for green technologies, for example, is far smaller than the current footprint of fossil-fuel based industries (Ritchie, 2024[95]). Behaviourally informed interventions[7], such as attention accuracy prompts and digital media literacy education, can improve policy responses to stop the spread of mis- and disinformation (OECD, 2017[96]; OECD, 2022[97]).
- **Lack of access in some markets**, e.g. in middle- and low-middle- income countries that rely on imported used vehicles from other countries. Although some early generation BEVs are now available on used car markets, they cannot compete with the used market for ICEVs and so will take time to reach MICs and LMICs (ITF, 2023[98]). In countries where electricity access is secure and decarbonisation of electricity production is already underway, there may be significant potential

to follow the trend of Asian leaders such as China and India in cultivating a strong market for 2 and 3-wheeler EVs, particularly when considering the co-benefits of reduced air pollution.

Box 4. Battery technology as a catalyst for positive tipping cascades

Battery technology is critical to positive tipping points in both transport and renewable energy deployment, and links the two in an example of a "positive tipping cascade" whereby price reductions and performance improvements driven by increasing adoption of BEVs can make batteries cost-effective for storage of renewable energy, which in turn would further strengthen feedbacks driving deployment of solar PV and wind for electricity generation and transport electrification (Geels and Ayoub, 2023[10]; Sharpe and Lenton, 2021[80]; Nijsse et al., 2024[18]).

Key reinforcing feedbacks in battery technology

Driven initially by innovation in consumer electronics and accelerated by rapid S-curves in the adoption of smartphones, battery electric vehicles are now the key drivers of demand for batteries, driving exponential improvements in energy density coupled with rapid cost reductions (e.g. from ~USD 2500/kWh in 2000 to <USD100/kWh today). Since 1991, costs have fallen by 19% for every doubling in deployment, while top-tier energy density has improved 18% for every doubling since 2012 – an accelerated learning rate compared to previous decades, which indicates an accelerating pace of innovation as new markets open (RMI, 2023[63]).

Global battery manufacturing capacity is also on an exponential trajectory, growing from <100 GWh/y in 2010 to 3200 GWh/y in 2023, with China's announced investments in manufacturing capacity estimated at triple global demand in 2025 according to Bloomberg New Energy Finance (OECD, 2024[73]). This raises the risk of oversupply, but demand is also likely to rise significantly as performance and cost improvements make batteries competitive in new markets such as light haulage and stationary energy storage. The latter is now likely at the beginning of its own exponential growth phase, with annual storage additions growing 45% year-on-year since 2018, reaching 35 GWh/y in 2022 and an estimated 99 GWh/y in 2023 (RMI, 2023[63]).

As deployment of stationary energy storage accelerates, it improves the performance of solar PV and wind by smoothing their intermittent generation, increasing their competitiveness with fossil fuels and further accelerating their deployment. In the longer term, this is likely to drive down energy prices and reinforce the electrification of transport and other sectors such as domestic heating (Nijsse et al., 2024[18]).

Balancing feedbacks and barriers slowing improvements in battery technology

Supply chain bottlenecks and dependence on critical minerals Both critical mineral extraction and battery manufacturing are highly geographically concentrated, presenting risks and potential bottlenecks that could affect supply, especially with demand for critical minerals growing very rapidly. These can be mitigated to some extent by developing recycling systems and circular economies for critical minerals, while increases in battery energy density, BEV efficiency, and improvements in battery chemistry and battery lifetimes are likely to substantially reduce mineral requirements in the long term. The most optimistic projections estimate that on current trends peak mineral requirements may be reached as early as the mid-2030s, with near-zero mining demand by 2050 (Walter et al., 2024[99]).

4 The potential for positive tipping points in other sectors

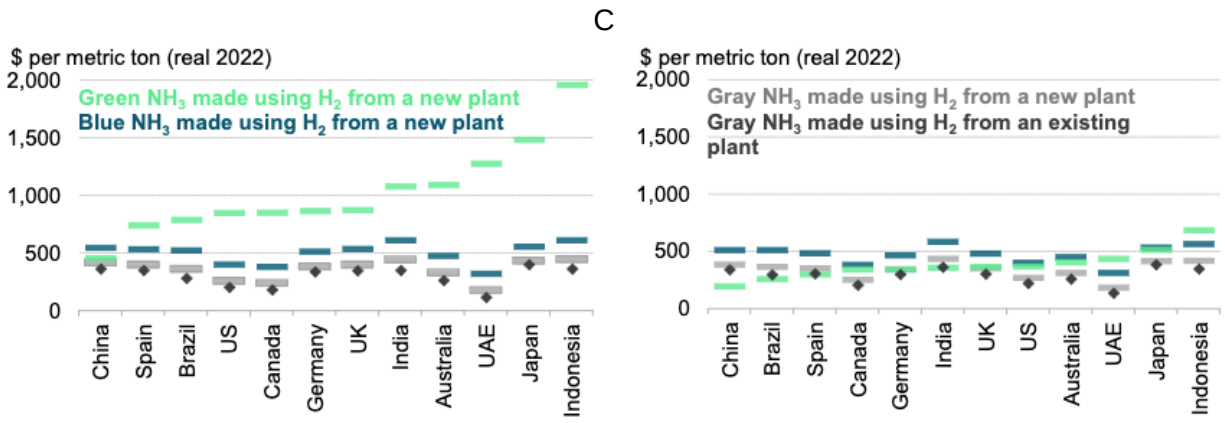
Clean hydrogen

Clean hydrogen[8] offers a sustainable alternative for storing and transferring renewable energy to provide power through combustion engines and fuel cells. It also has the potential to become a "super-leverage point" for policy interventions, as cost-effective clean hydrogen could transform so called hard-to-abate sectors of the economy such as steel, chemicals and cement manufacturing and other processes requiring industrial heat. For example, using clean hydrogen mixed with nitrogen separated from air to make green ammonia could become a sustainable fuel for long-range shipping, and produce sustainable fertilisers for agriculture. Clean hydrogen also comes with significant trade implications and could offer key opportunities for EMDE's endowed with low-cost cheap renewable energy potential, possibly reshuffling the overall industrial landscape (Cordonnier and Saygin, 2022[100]).

Evidence for positive tipping points in clean hydrogen adoption

Clean hydrogen represented less than 0.1% of global hydrogen production in 2023 (IEA, 2023[101]), and at USD 3-10/kg costs two to three times more than grey hydrogen (OECD/The World Bank, 2024[102]; IRENA, 2021[103]). However, clean hydrogen costs are expected to decrease 66% by 2030 (subject to market uptake, and less-expensive electrolysers and lower renewable energy costs) (IRENA, 2021[103]). As clean hydrogen capacity grows, clean ammonia is expected to become less expensive than conventional ammonia in most markets from 2034 (Figure 6) (BloombergNEF, 2024[104]). This could unleash a virtuous cycle: as demand for clean ammonia increases, demand for clean hydrogen electrolysers used in green ammonia manufacturing plants will also increase, reducing the costs of electrolysis, and thereby both clean hydrogen and ammonia, through learning curves and economies of scale – key reinforcing feedbacks. 18% cost reductions per doubling of output have been experienced for hydrogen electrolysers (IRENA, 2020[105]).

Figure 6. Cost of ammonia production in 2023 and 2030



Note: Uses levelised cost of hydrogen from BloombergNEF's 2023 Hydrogen Levelized Cost Update: Green Beats Grey as input for cost of ammonia production.
Source: (BloombergNEF, 2024[104]).

Key feedbacks, enabling conditions and barriers

Global hydrogen demand is increasing, and while clean hydrogen currently only plays a marginal role, announced projects, if realised, would lead to significant clean hydrogen growth, with production potentially reaching 49 Mtpa in 2030 (IEA, 2024[106]). However, there are significant innovation and infrastructure challenges to be overcome before clean hydrogen production can be scaled up to these levels.

- First, at current costs, hydrogen requires significant policy support, through public investment, mandates and financial incentives to crowd-in the private investment needed for clean hydrogen projects to be developed. By creating the enabling conditions to stimulate market uptake, policy can facilitate learning-by-doing and economies of scale to help clean hydrogen become cost-competitive. Electrolysers are already modular and fairly standardised, indicating that fast learning curves and cost reductions are possible.
- Clean hydrogen also relies on the availability of inexpensive renewable energy, which, as discussed above, requires overcoming challenges to scaling up deployment in regions, often EMDEs, with large potential for solar, wind or hydroelectric power.
- The storage and transportation of hydrogen also present significant challenges (due to its bulk hydrogen occupies almost four times the volume of fossil gas) and risks (because of its ability to embrittle metal, causing leaks, and because it is highly explosive when mixed with air). This makes effective risk-based regulation and international co-operation on standards important enabling conditions for its widespread use (OECD, 2023[107]).
- Finally, the availability of critical materials for clean hydrogen electrolysers has also been flagged as a key material bottleneck, for example iridium, if proton membrane technology continues to be used (McKinsey, 2024[108]).

Policy interventions to bring forward a positive tipping point in the manufacture of clean hydrogen therefore rely on providing enabling conditions and removing barriers or balancing feedbacks in the following areas:

- **Key materials.** Public/private investment in innovations to fast-track technologies with new electrolyser materials (Bingoto et al., 2023[109]), for example to replace iridium. Clean hydrogen is projected to face significant bottlenecks in the supply of iridium needed to meet demand expectations (McKinsey, 2024[108]). However, this risk may partly be neutralised if other

technologies prove cost-effective, such as electrolysers based on proton exchange membrane technology that could utilise other materials such as biopolymers (Ahmad et al., 2022[110]).

- **Manufacturing.** Investment in larger production facilities and automation could speed up economies of scale and decrease construction and manufacturing costs by 40% by 2030 and 80% in the longer term (IRENA, 2020[105]).
- **Infrastructure.** In order to realise the potential for scaling up clean hydrogen, considerable investments in new infrastructure, such as fueling stations, transport capacity (pipelines and shipping) and storage terminals, are needed (McKinsey, 2024[108]). There are 470 hydrogen refuelling stations in the world (IRENA, 2021[103]). Existing infrastructure (e.g. gas pipelines) could be repurposed for transport (McKinsey, 2024[108]) – there are currently only 5000 km of hydrogen transmission pipelines around the world, compared to more than 3 million km for natural gas (IRENA, 2021[103]) – but there is disagreement about the cost and suitability of repurposing gas pipelines (Télessy, Barner and Holz, 2024[111]), and not all regions of the world have existing infrastructures. Industrial hydrogen "hubs" could reduce the need for hydrogen transportation but will require significant planning and investment. There is also considerable uncertainty around projected hydrogen demand and uptake in a range of application scenarios (McKinsey & Company, 2024[112]). Active mandates and infrastructural investment will likely be needed to signal clear government support for clean hydrogen and facilitate the decarbonisation of existing hydrogen demand (McKinsey & Company, 2024[112]).
- **Cost Parity**. the cost competitiveness of clean hydrogen relies on rapidly accelerating the availability of low-cost renewable electricity. Eliminating fossil fuel subsidies, raising carbon prices, and introducing mandates on clean hydrogen in steel production, shipping fuel and fertilisers could be transformative policies, especially if enacted as a co-ordinated policy action between the main producers. A combination of high fossil fuel prices, low renewable electricity costs, and low electrolyser costs would lower the cost of clean hydrogen and boost the adoption of green ammonia (Lee and Saygin, 2023[113]).
- **Public investment**. In all regions, public investment will be key to the future of clean hydrogen, as the current return on investment and higher costs make it unattractive for private investment alone. Key markets are already providing considerable support. Clean hydrogen is a key element in China's energy decarbonisation strategy, as emphasised in its long-term development plan (Li et al., 2022[114]). China is already the world's largest hydrogen producer and consumer, with more than 33 million tons of annual demand. The United States could also see a surge of new clean hydrogen capacity. The Inflation Reduction Act is projected to invest approximately USD 369 billion in Energy Security and Climate Change programs over ten years, although the exact number of hydrogen projects supported depends on projects meeting eligibility criteria (OECD/The World Bank, 2024[102]). The European Union's Green Deal also has an investment, supply- and demand-side 'EU Hydrogen strategy' that aims to transform its clean hydrogen economy to "produce 10 million tonnes and import 10 million tonnes" by 2030 (European Commission, 2020[115]). India, Japan, Germany and other governments have also set ambitious hydrogen strategies and targets (OECD/The World Bank, 2024[102]).

Sustainable food systems

Food, agriculture and land use are linked to major environmental challenges. Food systems globally account for an estimated 25-33% of global GHG emissions (and are a major source of methane emissions), and also contribute importantly to deforestation, water use, biodiversity loss, and other issues (OECD, 2021[116]). Addressing these problems requires interventions along the entirety of the supply chain, from agricultural production, processing and distribution to consumption, food loss and waste, biodiversity loss and land access and management[9].

While recognising that other elements of the food system, such as sustainable farming practices, are also important, this section focuses on two areas with high potential for positive tipping points – the first being demand-side and the second supply-side: 1) the potential for rapid dietary shifts away from unsustainable overconsumption of livestock products, and 2) the potential for rapid scaling of alternative proteins. Livestock uses 80% of agricultural land (either for grazing or growing animal feed) but only provides 18% of food calories and 37% of proteins consumed worldwide (Poore and Nemecek, 2018[117]). Dietary trends that lead to the overconsumption of meat (especially red meat) and dairy also present a major human health concern (Giner and Brooks, 2019[118]; Placzek, 2021[119]). Changes in diets could therefore potentially help with both sustainability and nutritional challenges (Tallard et al., 2022[120]). However, meat consumption continues to increase globally, in both developing and developed countries (though at a lower rate in developed countries). (OECD/FAO, 2023[121]) A transformation to healthy, sustainable diets is urgently needed.

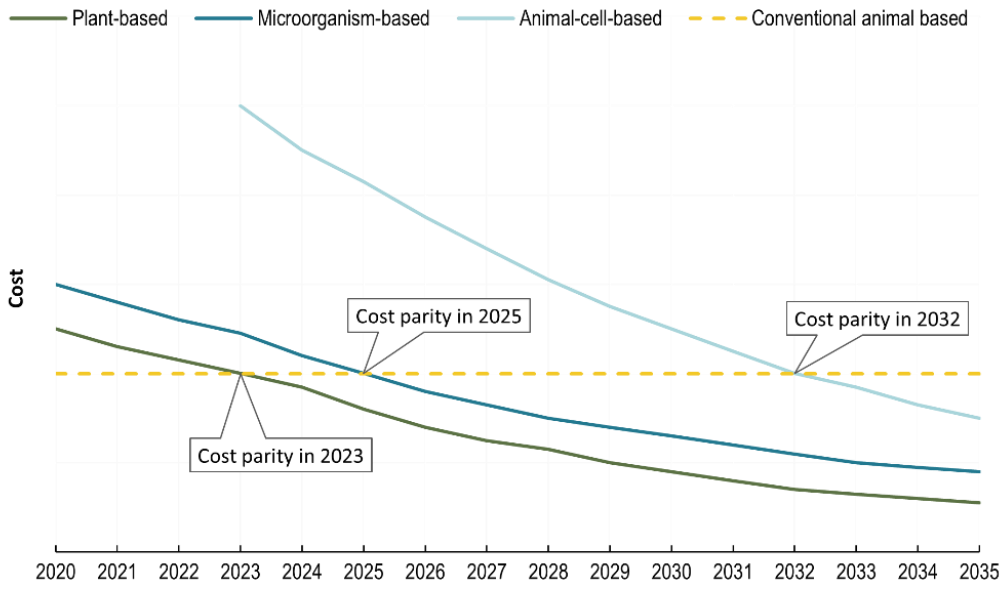
Evidence for positive tipping points in the uptake of sustainable diets

Behavioural norms around dietary choices have been demonstrated to be highly influenced by social networks (i.e. by peers and key influencers) (Higgs, 2015[122]; OECD, 2024[123]; OECD, 2025[124]). These could act as a balancing effect if people prefer to stick with the dietary habits of their peer group, but once a change in habits gets underway the same network effects could accelerate dietary change, potentially creating a positive tipping point through social contagion. Dietary choices are also strongly influenced by choice architecture and exposure to alternatives, as demonstrated by experiments manipulating menu choices in public cafeteria spaces (discussed below).

There are already some indications that a shift in diets away from livestock products is underway in some contexts. An increase in the number of (often educated, environmentally conscious) people in the United Kingdom identifying as vegan, vegetarian or flexitarian indicates growing numbers of people making conscious food choices aligned primarily with health concerns and with sustainability values (Stewart et al., 2021[125]). Wider trends in diet in some markets indicate declining rates of consumption of livestock products (e.g. 15% decline in UK from 2008-2019 (Stewart et al., 2021[125])) and are associated with animal welfare as well as climate and nature concerns. At the same time, there is also evidence that some population groups are resistant to change (Hassett et al., 2024[126]).

In addition, three types of alternative proteins currently show potential for positive tipping: plant-based protein, microorganism protein, and animal-cell based protein (Frezal, Nenert and Gay, 2022[127]). A recent forecast predicted that these could reach tipping points (thresholds of accelerating adoption) at different times, based on when they become comparable to conventional animal-based products in terms of cost, taste and texture (Figure 7) (Meldrum et al., 2023[35]). Although globally, the alternative protein market remains a niche market that occupied only 2% of the total market in 2020, private investment in the sector has grown rapidly. (Good Food Institute, 2024[128]) Some observers predict that the market share of these alternatives could reach 10% by 2035 and, depending on policy and technological advances, could even reach 20% (Witte et al., 2021[129]).

Figure 7. Separate times alternative proteins reach parity in cost, taste and texture



Source: Authors adapted from (Meldrum et al., 2023[35]).

Plant-based meat substitutes are already experiencing reinforcing feedback as economies of scale and learning curves are rapidly reducing their price and improving their quality and taste (Meldrum et al., 2023[35]; Soemali et al., 2023[130]). Projections point to the continuation of this trend. The Asia-Pacific region has the fastest-growing market for alternative proteins (with an expected 18.5% annual growth rate between 2021 and 2027). China's plant-based market is forecast to grow 20-25% p.a. (Meldrum et al., 2023[35]), followed by the US (17.5% expected growth p.a. 2021-2027) and Europe (12% expected growth p.a. 2021-2028) (Talwar et al., 2024[131]). The growth rates for plant-based replacements for dairy products are also strong in North America, Europe and East Asia, although the evidence on their environmental impact and relative health benefits is contested (OECD/FAO, 2023[121]).

Key feedbacks and enablers for positive tipping points in sustainable diets

Individual consumers can, to varying degrees, already shift their diets away from livestock and towards alternative proteins. However, to pass a tipping point, substantial action would be needed in areas such as corporate and public procurement policy, technological innovation, labelling and other information schemes, political advocacy and coalition-building, financial aid and reskilling to support workers and businesses in the transition, supply chain restructuring, and other active and passive behavioural 'nudging' measures to help shift dietary choice, habits and social norms (Lenton et al., 2023[3]; Aschemann-Witzel and Schulze, 2023[132]; Fesenfeld, 2023[133]).

Positive experiences with livestock alternatives and vegetarian meals are the most important predictor of an individual's intentions to reduce meat consumption, with wider social norms and information exposure also playing key roles (Paul Fesenfeld et al., 2023[134]). Choice architecture – providing more options for reduced meat or vegetarian meals - can thus be a powerful enabler for facilitating dietary behaviour change. For example, in an experimental study in UK cafeterias, doubling the share of plant-based meals offered to 50% of all meals led to an increase in sales of between approximately 40% and 80% within weeks, with no effect on profitability (Garnett et al., 2019[135]). As noted earlier, the cost and performance (in terms of flavour, texture, nutrition, and other characteristics) of livestock alternatives is expected to

improve over time through increasing returns and learning effects as the sector grows. A narrowing gap with conventional animal-based products could in turn induce greater demand, reinforcing positive experiences and uptake. Avoidance of meat by reducing consumption and shifting to alternative proteins is an appropriate example of the Avoid-Shift-Improve framework.

Social norms are also essential drivers of dietary behaviour and could in theory be leveraged to enable rapid behavioural change (Herman, Roth and Polivy, 2003[136]). It is well established that social norms around eating have a powerful effect on both food choices and amounts consumed (Higgs, 2015[122]). The rapid diffusion of these norms across society due to contagion effects, technological reinforcement, and network effects could in theory enable a positive tipping point to self-propelling, accelerating change in diets.

Health co-benefits of sustainable food choices may also be instrumental as positive reinforcers of dietary changes, particularly among those who are less motivated by environmental reasons. Educational campaigns framed in terms of personal health benefits, economic benefits, and/or by exploiting innate aversions to potential losses by highlighting the negative outcomes of unhealthy diets could also be an effective means to promote more environmentally friendly diets (OECD, 2023[137]). Studies show that the availability/accessibility, convenience, affordability, taste, freshness and texture of foods tend to be more important influencers of food choices and environmental impacts (OECD, 2023[137]). Powerful synergistic messaging could strengthen individual motivations for behaviour change, as well as strengthening the contagion effect of social norms.

Balancing feedbacks and barriers

Significant obstacles remain before a systemic shift in diets in high-income countries can be successful. Cultural and religious practices around food, as well as attitudes and habits towards meat and dairy consumption are often deeply embedded within society. One implication is that consumer behaviour might be difficult to change (Hassett et al., 2024[126]). This can result in a reluctance to reduce meat consumption, which in some countries is perceived as “real” food, more nutritious food, and as more “manly” food[134,135]. Policymakers may also be reluctant for change, and the political will for change fluctuates over time and with changes of government. For example, in 2018 France introduced a mandate (EGalim law) for one vegetarian meal per week in school canteens, but the regulation is not currently being enforced (Avallone et al., 2023[138]). Diets and their environmental impacts depend on geographical, socio-economic and cultural contexts and policy recommendations need to be sensitive to these differences (OECD, 2023[137]).

There are also important balancing feedbacks on the supply side in terms of infrastructural and institutional path dependencies in food supply chains, from farming practices to the supermarket shelf. The production and processing of animal-based foods is an important economic activity, and the sector is also politically active, posing barriers to policy action (Fesenfeld, 2024[139]).

Policy interventions for dietary shifts

Historical interventions intended to induce dietary shifts have tended to be quite narrowly focused on taxation or top-down public information campaigns and have led to mixed results. On the one hand, Mexico’s sugar tax reduced consumption of sugary beverages by 6% and increased water purchases by 16%, with particularly strong uptake by low-income communities (Colchero, Molina and Guerrero-López, 2017[140]). On the other hand, various Danish information campaigns to encourage healthier food choices have proven ineffectual and have been criticised for focusing too narrowly on single levers of change that are unlikely to have deep and sustainable effects on behavior (Mandagmorgen, 2024[141]).

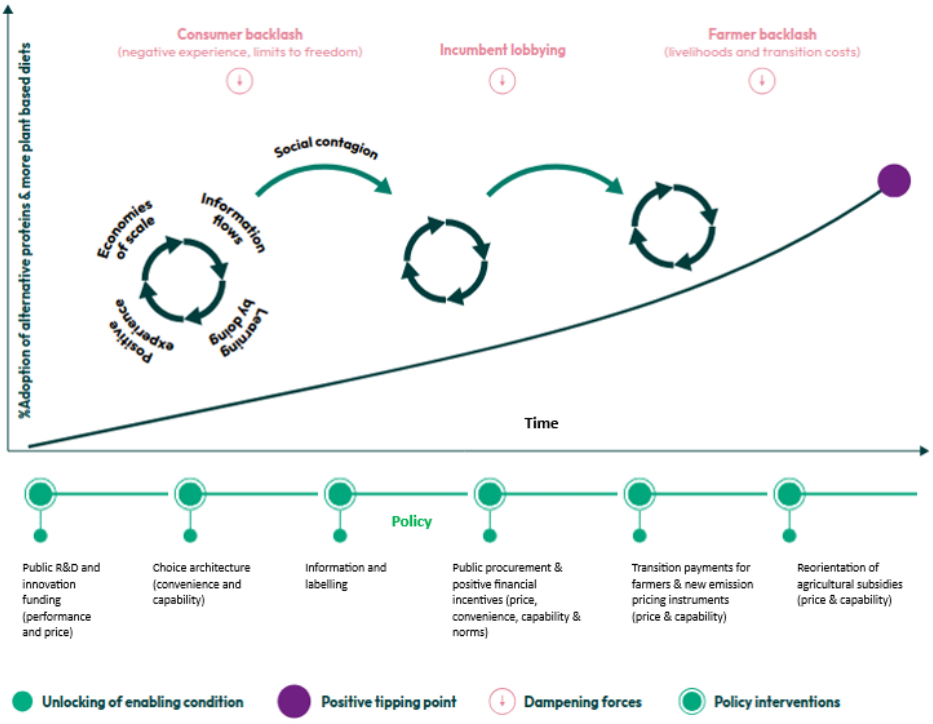
Alternative approaches to creating change have seen much more sustainable effects by recognising the need to take a more holistic approach. For example, the New Nordic Cuisine movement, which focuses on

community building and local motivations to enhance sustainability, has changed the Nordic culinary landscape permanently and manifested in changes in diets more broadly (Madkulturen, 2024[142]).

Policy interventions can create or strengthen feedback loops between increasing production, falling costs and prices, improved products and consumer experiences, and increasing awareness and demand. To unlock these feedbacks, policy could be designed and implemented to sequentially overcome the key barriers to production and adoption of livestock alternatives. A possible theory of change is suggested in Figure 8, which identifies several possible policy interventions:

- **Public R&D and innovation funding:** Public investment in R&D and scaling production of alternative proteins could accelerate product improvement and de-risk private investment. Global public investment is currently low (over USD 1 billion per year), but growing and diversifying (Global Food Institute, 2023[143]).
- **Choice architecture:** Public and private institutions can play an important role in increasing exposure to dietary alternatives in their own cafeterias, with increases in the availability of vegetarian meals in institutional dining spaces strongly linked to increased sales (Garnett et al., 2019[135]).
- **Improving food labelling:** Improved labelling schemes could influence consumers to purchase more sustainable and healthier food and beverage products (Grunert, Hieke and Wills, 2014[144]; Cecchini and Warin, 2015[145]).
- **Public procurement:** The public sector accounts for significant food sales in most developed economies through key sectors such as schools and health services (5-6% of national sales in EU and UK). Adjusting procurement toward plant-based and alternative proteins, at little-to-no extra cost, can encourage the uptake of these products. It can also produce network and demonstration effects of new and socially acceptable food and beverage practices, which could in turn facilitate wider public support for policy to support the transition (Fesenfeld, 2024[139]).
- **Helping farmers with the transition:** Supporting farmers, especially intensive livestock farmers, to transition to alternative business models, e.g. through transition payments, payments for ecosystem services, supporting agriphotovoltaics etc., may help to reduce instances of farmer backlash and facilitate a faster transition (Rieger et al., 2023[146]; Morais-da-Silva et al., 2022[147]). Effective policymaking depends on skilled convenors who can break down the silos and overcome disagreements around facts, interests, and values (OECD, 2021[116]).

Figure 8. Strategic policy sequencing can accelerate momentum in adoption of livestock

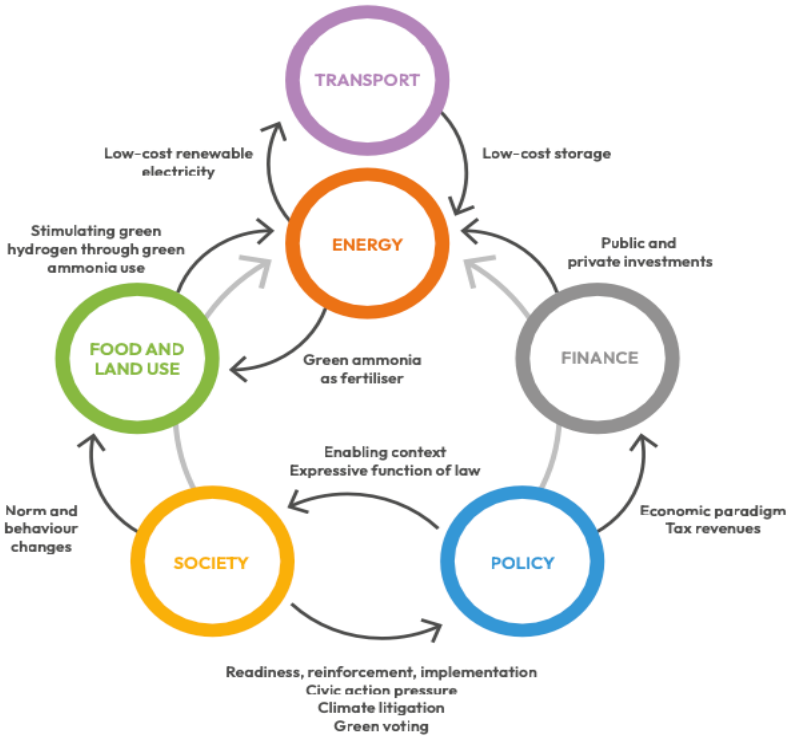


Source: Adapted from (FOLU, 2021[148]).

5 Interactions and tipping cascades

Systems do not exist in isolation from one another and their interlinkages mean that crossing tipping points in one system could cascade through other systems (Sharpe and Lenton, 2021[82]). For example, ever more affordable and powerful batteries positively reinforce and bring forward tipping points to renewable energy generation by helping to solve storage and supply-demand issues. Ever more affordable renewable energy is then able to assist tipping points in electric vehicle sales, the electrification of mobility more generally, and the production of clean hydrogen – which in turn improves the economic case for green steel, and green ammonia for fertilisers and for shipping fuel (Figure 9) (Lenton et al., 2023[3]).

Figure 9. Overview of system interactions that can create positive tipping cascades

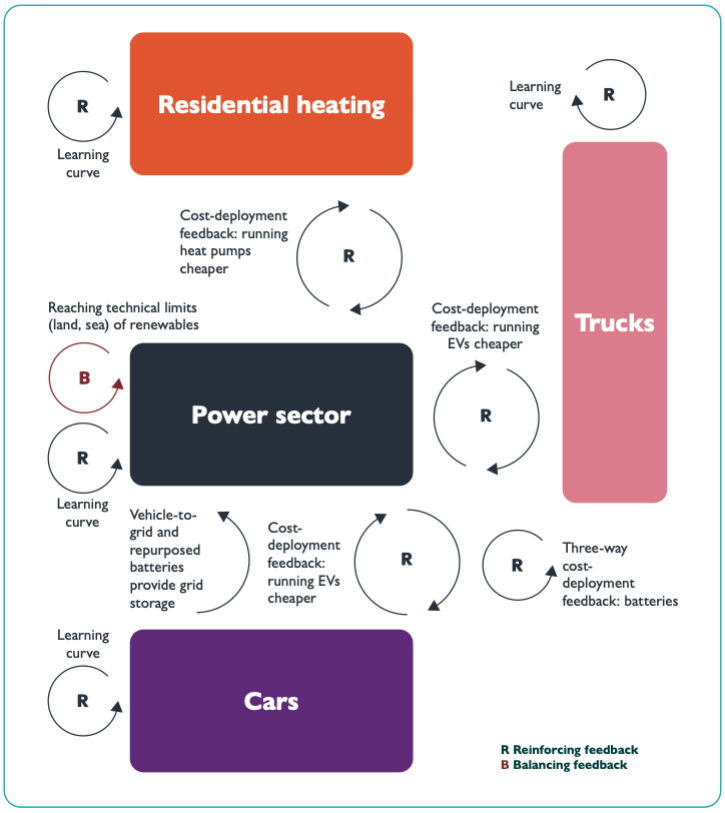


Source: (Lenton et al., 2023[3]).

Policies that assist one sector generally help to bring forward tipping points in the other sectors (Meldrum et al., 2023[35]). Dynamic modelling using empirical data has been used to compare the effect of a carbon tax, a clean technology subsidy, and a mandate, in four key systems (Nijsse et al., 2024[18]): power, passenger vehicles, heavy road transport (trucks) and residential heating. These four systems are closely connected (Figure 10). The growing demand for electric cars, trucks and heat pumps is increasing electricity demand and investment in renewable energy. This is driving down the cost of renewable electricity and the relative cost of clean technologies in other sectors like clean hydrogen. The increasing

need for batteries in electric cars also reduces their cost and improves their performance, which increases their use in heavy-duty vehicles and in the power sector for energy storage when their recharging capacity falls below 80% (second-life battery storage). The increasing use of EVs with vehicle-to-grid charging capabilities provides even more system supply-demand balancing and further reduces renewable energy costs.

Figure 10. Reinforcing feedback loops within and between four key sectors



Source: (Nijsse et al., 2024[18]).

The modelling results show that co-ordinated policy packages, and particularly mandates, can significantly increase and bring forward the potential for triggering positive tipping cascades across these interlinked systems. In terms of "super-leverage points" – policies that have the most powerful positive influence across multiple sectors – a zero-emissions mandate for cars has been proposed as the single most effective policy intervention because of its close interaction with the power, battery, heavy-duty vehicle and residential heating sectors (Meldrum et al., 2023[35]). Policies such as charging infrastructure investment are also important for zero-emissions vehicles. A coal phase-out mandate in the power sector also has a strong super-leverage point influence in bringing forward positive tipping points in the residential heating and heavy road transport sectors, by up to four years in some countries. Mandates in the four sectors together could bring forward tipping points in heating, cars and trucks within two to eight years. In the context of needing to halve global GHG emissions by 2030 (in five years), this is a significant finding (Nijsse et al., 2024[18]).

Other policies can further amplify the effectiveness of technology deployment policies of subsidies, taxes and mandates. These include policies to reduce energy demand to help power system balancing, policies to improve home insulation to lower heating and cooling demand, increase heat pump efficiency, and the

use of houses as thermal batteries, smart vehicle charging to reduce peaks in power demand, grid infrastructure investment, and workforce training. In line with the avoid-shift-improve framework, it is significantly easier and more cost-effective to decarbonise by reducing overall energy demand while simultaneously improving energy security, enhancing quality of life and reducing the costs and risks associated with carbon removal technologies.

6 Implications for policymakers

The adoption of renewable solar and wind power is accelerating across the world, accounting for 80% of additional global power capacity in 2023. Sales of electric vehicles, batteries for mobility and storage, and heat pumps are also accelerating in leading markets. Faster and more geographically balanced progress is needed, but these examples demonstrate that a clean technology transformation at the pace and scale required to meet climate goals is possible, and that policy plays a crucial role in driving these transformations (Geels, 2024[9]). The concept of positive tipping points provides an important framework through which to assess this progress, and the potential for policy to leverage these dynamics to further accelerate change.

The positive tipping point concept can help policymakers prioritise their efforts. Not all technologies, services or behaviours exhibit the potential for positive tipping points. Policy should focus on those that do, and these tend to be highly standardisable, replicable and scalable options. For example, the modular nature of solar panels, enabling standardised, mass production partly accounts for its extraordinary cost curves. By contrast, each new nuclear power plant needs to be redesigned. At the same time, some of the technologies, services or behaviours required may not exhibit potential for tipping themselves but can act as important enablers of tipping points for other technologies, services or behaviours. For example, good building insulation is an enabling factor for other tipping points because it reduces seasonal peaks in electricity demand, which lowers heating costs, and makes the adoption of heat pumps more viable. Leveraging positive tipping points should not rely solely on high risk/high reward strategies and relies critically on building enabling conditions through achievable and gradual policy interventions.

Similarly, some technologies, services or behaviours may be closer to tipping or easier to tip than others. Policymakers will need to balance prioritising crossing tipping points in the near-term with efforts to support progress in systems that are still far from reaching such thresholds. This is well illustrated in the example of the solar PV sector used in this paper, where crossing tipping points seems to be close, but more systemic efforts at transforming transportation systems away from private vehicle use and promoting BEVs are needed.

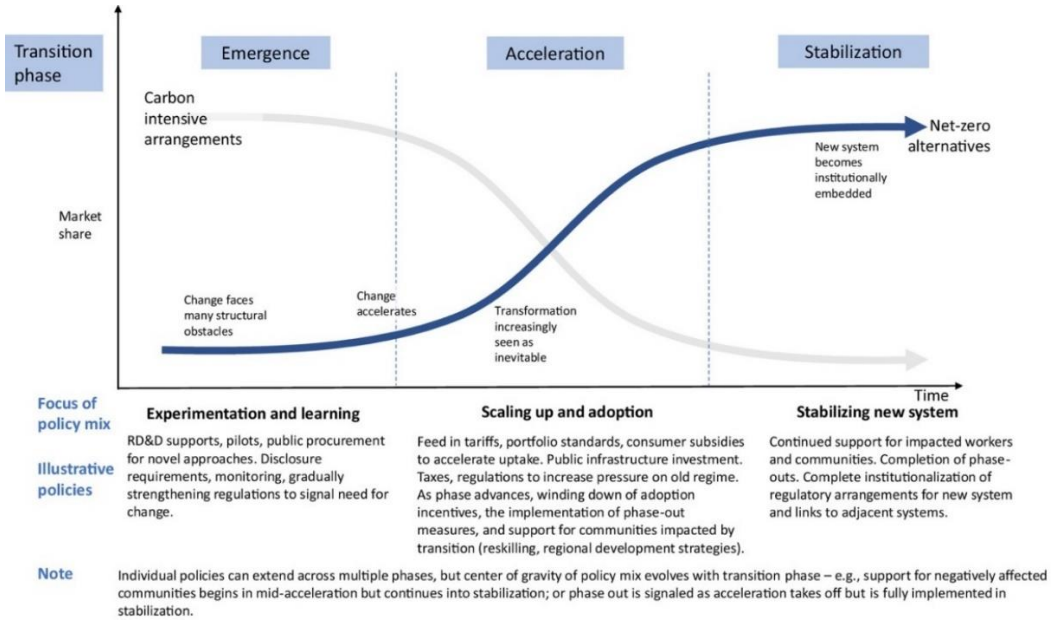
Positive tipping fundamentally relies on the existence of an alternative technology, service or behaviour, making continuous and consistent support for basic research and innovation an essential enabling condition for future tipping. Much of the focus on climate policy efforts to date has been targeted towards deploying existing technologies and more could be done to support innovation and research and development (OECD, 2023[149]).

Positive tipping points must not be mistaken for an easy fix but understood as the result of a deliberate process to create enabling conditions for rapid change tailored to individual contexts. Cases of positive tipping – the transition to wind power in Denmark, the market for electric vehicles in Norway, or the phase out of coal-fired power in the United Kingdom – were the result of years or decades of political organisation, policy advocacy and implementation. Governments need a coherent, cross-departmental and multi-stakeholder approach to advance innovation, bring down clean technology costs, crowd-in investment, encourage low-carbon lifestyles, and build a democratic mandate for rapid change through the government-citizen interface (Willis, Curato and Smith, 2022[150]; Boswell, Dean and Smith, 2022[151]; OECD, 2025[152]). The combination of policies that will be most effective is specific to each jurisdiction and sector and will evolve through the transition over time (Geels, 2024[9]) (Figure 11), with studies suggesting

that accelerating progress requires different forms of intervention at each stage of the transition (Geels, 2024[9]; IPCC, 2023[1]; Grubb et al., 2024[153]):

- **In the early, emergence phase**, incumbent technologies, practices and norms are displaced, slowly at first, but then at an accelerating pace. Support for research, development, and demonstration of new technologies, complemented by targeted, strategic investment and other measures such as subsidies or public procurement policies create early markets and enable first deployment. Other policies only become effective once minimum deployment thresholds are reached.
- **In mid-transition or acceleration phase**, market-shaping policies such as regulation, subsidy and tax give the new technologies an advantage over the old, enabling their faster diffusion. Investment, confidence and demand grow rapidly, and costs fall. This can be supported by investing in infrastructure, supply chains, and other forms of industrial policy.
- **In the later, stabilisation stage**, deeper reconfiguration of market, regulatory, social and institutional structures ensure that economic activity is increasingly reorganised around the new set of technologies. This can include training people in the skills needed for new industries, and supporting workers and communities affected by the loss of the old industries (Geels, 2024[9]; IPCC, 2023[1]).

Figure 11. Turning policy mixes into transition phases



Source: reproduced from (Meadowcroft and Rosenbloom, 2023[154]).

A key challenge for policymakers is understanding how far along in the transition targeted systems are so that they can choose the right policy packages to accelerate progress. This also includes knowing when to stop or slow down policy efforts as the transition shifts into a different phase. Developing new and better indicators of progress towards tipping thresholds will be critical to help policymakers operationalise the tipping points concept.

As well as implementing appropriate sequences of policies to accelerate the transition, a tipping points lens offers policymakers new ways to set the stringency of policies to bring forward tipping points. By increasing policy stringency in the short term, self-propelling feedbacks can be unleased earlier, thereby reducing the need for policy intervention and public investment in the longer term and enabling tax revenues to be better spent on other technologies/policy priorities. Tax and subsidy combinations can be designed to achieve an earlier crossing of the cost parity threshold between clean technologies and fossil fuels, while being revenue neutral for the government. Early in the transition, when clean technologies have a small share of the market, a small tax on the sale of each fossil fueled product can fund a large subsidy on the purchase of each clean technology product. For example, a tax of USD 160 on the sale of each mid-range internal combustion engine car in Europe in 2023 could fund a subsidy of USD 1,600 on the purchase of each mid-range electric vehicle, achieving ownership cost-parity while maintaining revenue neutrality (Lam et al., 2023[155]). Similarly, the stringency of energy efficiency or carbon intensity regulations can be set to make the most polluting technologies unviable, forcing a reallocation of investment towards the new technologies.

Leveraging positive tipping points is fundamentally about anticipating future developments. Strategic foresight, including through scenario building, is therefore crucial. Through foresight, governments can better understand, project and anticipate market developments, technological trends, or how changes in behaviour might evolve. Foresight tools are also integral to better understanding interlinkages between systems and how these will evolve as systems transform, and are thereby an important component to leveraging the potential for tipping cascades. In addition, all these changes also need to be considered in the context of other developments. For example, the development of AI may have critical implications for technological progress and how effectively governments can facilitate positive tipping. At the same time, AI comes with great risks. Strategic foresight could help governments navigate both the desirable and undesirable implications from the deployment of AI in effectively facilitating positive tipping.

International co-operation

Countries can achieve significant co-ordination gains by working together in the right kind of ways: aligning research and development programmes to achieve faster innovation; co-ordinating on deployment policies to create stronger signals for investment, larger economies of scale, and faster cost reduction; and agreeing standards and trade measures to create level playing fields where necessary in global markets (Victor, Geels and Sharpe, 2019[156]). Diplomacy is most likely to be able to achieve these gains if it is sector-specific, action-focused, and plurilateral (involving a critical mass of countries able to shift the global market in a given sector) (see Box 5) (IEA, IREA and UN Climate Change High-Level Champions, 2022[11]).

International co-ordination can help trigger a positive tipping cascade across multiple sectors – for example if the USA, China and the European Union introduced a mandate for zero emission vehicles by 2035, this could help to trigger another tipping point in cost parity for heavy-duty electric vehicles, and then another in the cost and performance of batteries for energy storage and supply-demand balancing of renewable electricity, lowering its cost enough for a tipping point in the cost-competitive production of clean hydrogen (Sharpe, 2023[157]). Unco-ordinated policies could dampen these feedback effects and fall short of the necessary thresholds to trigger such tipping cascades.

Independent analysis has repeatedly found that the potential for practical international co-operation to accelerate progress towards these goals remains far from fully exploited (IEA, IREA and UN Climate Change High-Level Champions, 2022[11]; IEA; UN Climate Change High-Level Champions, 2024[158]). As governments consider their updated ‘Nationally Determined Contributions,’ for submission to the UNFCCC in 2025, they could benefit from thinking beyond unilateral national action and considering and committing to specific forms of practical international co-operation in each of the emitting sectors.

Box 5. Catalytic co-operation: the potential for a tipping point in international diplomacy

International co-operation on climate is essential but remains incredibly difficult to achieve. Climate action is a public good and so suffers from a collective action challenge where countries, businesses and individuals have an incentive to free ride on the efforts of others. Much thinking and research has gone into how to solve this co-ordination challenge, some even argue that the collective action problem misrepresents the key barriers holding back more ambitious climate policies. One emerging strand of research argues that international co-operation on climate can leverage the same tipping points dynamics described in this paper to overcome these co-ordination challenges.

Under this strand of research, coalitions of first movers can catalyse further co-operation by other, reducing the costs and increasing the attractiveness of key technologies, services and practices (Hale, 2020[159]). Through continued engagement in global governance arrangements such as the UNFCCC and Paris Agreement, these experiences can be shared, and previously cautious actors can update their preferences (Aykut, Morena and Foyer, 2020[160]). This could catalyse virtuous cycles of co-operation on climate action, with countries taking the lead becoming 'norm entrepreneurs. If a critical mass eventually adopts the new norm this can create a tipping point in terms of international co-operation (Corbett, Xu and Weller, 2019[161]; Constantino, Skaredina and Ivanova, 2023[162]).

It is also important to recognise that barriers and challenges to decarbonisation vary across sectors and co-ordination is essential (Rayner, Oberthür and Hermwille, 2021[163]). For example, in the renewable power sector upfront investment costs are high and the marginal costs of mitigation are low, whereas the marginal costs of low-carbon technologies in many energy-intensive industries are high and they are exposed to international competition, meaning that national legislation could make them vulnerable. Political, institutional, and technological barriers also vary – for example, the technological solutions for road transport transitions already exist, whereas solutions for many heavy industries and aviation are still experimental or theoretical. Coalitions of countries need to work together to leverage specific interventions that can trigger the appropriate tipping dynamics and catalyse wider international co-operation (Hale, 2020[159]).

Risks of unintended consequences

There is a risk that the transition to a post-carbon economy, while on the one hand accelerating GDP growth (desirable), would also increase economic, political, and financial instability, and volatility (undesirable). This risk may be even greater with a more rapid transition – as characterised by positive tipping points.

As an example of economic risk, the pace of the transition required to meet climate goals puts the value of existing carbon-dependent capital at risk of premature depreciation. This is a risk that extends well beyond the physical capital of fossil fuel assets and reserves if the risk to human capital is included, i.e. occupations and livelihoods. A recent study quantified the current value and turnover timescales of existing global human and produced capital and compared the rate at which it naturally depreciates against the rate at which it would be required to depreciate to achieve climate targets. It found that achieving net zero in 2050 by ending carbon intensive investment in 2020 would put up to USD 117 trillion of global capital value at risk. Delaying the end of carbon-intensive investment to 2030 implies a much greater risk of up to USD 557 trillion (37% of total current capital), around three quarters of which is human capital. Reducing these risks would require co-ordinated intervention across government – for example in departments of finance, education, and training, to train people in the skills that will increasingly be needed and to reduce training for occupations that may soon cease to exist (Chester et al., 2024[164]).

The policies being implemented to drive the net-zero transition also come with specific risks and potential trade-offs vis-à-vis other policy priorities. For example, the recent wave of green industrial policy packages implemented by major economies bring with them risks of trade distortions, overcapacity, geographic skew and elevated costs (OECD, 2024[73]; OECD, 2025[58]) (see also the discussion of government support for solar PV production in Box 3). These risks can be mitigated through careful policy design and international co-operation, but if left unmanaged could have considerable implications for economic growth, trade, development and security. Excess production capacity along the solar-supply chain driven by generous government support has already led to a concentration of production capacity in China (OECD, 2025[58]). With similar geographic concentration seen in many other low-carbon technologies, governments now face difficult trade-offs, needing to balance often conflicting policy priorities such as decarbonising the energy system and sustaining innovation while also ensuring energy security and a level playing field on global markets.

Other examples of unintended consequences include the need to ensure a rapid increase in demand for critical minerals does not lead to adverse outcomes for human health and well-being along the critical mineral supply chain, due, for example, to environmental damage and pollution from mining activities, or to adverse working conditions. Governments need to ensure that even an accelerated transition characterised by positive tipping points remains a just and equitable transition (OECD, 2025 Forthcoming[165]). This includes considering potential adverse labour market impacts as incumbent industries in decline struggle to adapt, the need to consider the distributional outcomes of climate policies, as well as the importance of considering equity across countries, with many developing countries already voicing concerns about being “left behind” in the clean-technology race.

Given the extreme risks of climate change and the delay in embarking seriously on the low carbon transition, there is no ‘business as usual’ pathway for the coming decades. The transition to a net zero emission global economy is the largest structural economic change ever deliberately attempted in human history, and it cannot be expected to unfold without disruption. This highlights the central importance of strategic foresight in ensuring these disruptions are anticipated and well managed. The alternative of unmanaged climate change would be disruptive and dangerous on an altogether different scale.

7 Summary and conclusion

The positive tipping points concept offers policymakers a useful framework to help accelerate the transition to net zero. By highlighting how a small change past a threshold can trigger a self-propelling shift to a new system state, positive tipping points imply that a rapid and wide-reaching transition to net zero remains in reach. Innovative technologies improve when they start being deployed at scale, and when people develop new habits, norms, infrastructures and regulations to support them. Solar power is now the cheapest form of electricity in history. Technological change can become self-perpetuating due to self-reinforcing feedbacks such as economies of scale and learning-by-doing: the more units made, the less expensive each unit becomes and the better the manufacturer becomes at making it, which makes it more attractive to buy. Network effects are also strongly reinforcing accelerators of positive change: the more people who drive electric vehicles the bigger the incentive to install public chargers, which makes more people confident about driving electric vehicles long distances.

While not all technologies, services or behaviours exhibit the potential for positive tipping points, by prioritising efforts towards those that do, policymakers can leverage self-reinforcing system dynamics to rapidly accelerate climate action. Recent trends in key technologies including solar, wind, electric vehicles and batteries highlight that rapid progress is possible, and that positive tipping points may already have been crossed in some systems. Climate policy, particularly government support, was crucial to driving these trends. This highlights the critical role governments can play in leveraging tipping point dynamics. However, generous government support also comes with considerable risks and has already led to geographic concentration of production, with implications for international co-operation and open markets.

Similar dynamics can be unleashed in other systems such as clean hydrogen and can cascade across systems to further accelerate progress. However, governments will need to pick the right policy packages, appropriate to various scales, contexts and sectors, to leverage and facilitate these dynamics. emphasise building the enabling conditions for further progress, including through easing access to finance, delivering the infrastructure needed to support rapid deployment, and managing stakeholder engagement and public support for climate policies. But policymakers also need to remain aware of potential unintended consequences such as stranded assets or questions relating to the just transition. Anticipating future developments and disruptions can help governments ensure positive tipping points lead to lasting, sustainable change.

To inform government efforts, further evidence is needed. Better indicators to understand the potential for positive tipping and ways to measure at what stage of transition a given system is, are fundamental to enabling governments to operationalise the positive tipping points concept. Exploring the potential for positive tipping in behavioural change is also critical, as technological progress alone is not enough to meet the net-zero goal.

Notes

[1] Such beneficial natural tipping points also have positive implications for climate mitigation efforts, with nature-based solutions and ecosystem restoration key to leveraging the vast mitigation potential through carbon sequestration. The IPCC estimates that the sequestration capacity of global ecosystems, and particularly forests, could reach 1-7GtCO2 annually by 2050 (IPCC, 2023[1]).

[2] The positive tipping points concept can also apply to other environmental issues such as biodiversity loss or pollution. Interlinkages between environmental issues mean that positive tipping points in one area could also have implications in another, for example through increased ecosystem resilience and carbon sequestration through enhanced biodiversity.

[3] The concept of safe and just Earth system boundaries and the Doughnut model of social and planetary boundaries are frameworks for defining a sustainable safe operating space or "corridor" for humanity – situated between minimum just social foundations for human development and maximum human impacts that can be safely assimilated by the Earth's biophysical capacities (Rockström et al., 2023[16]; Raworth, K, 2017[168]).

[4] Resilience is the capacity of a system to return to its stable state after a perturbation, measured as its recovery rate from disturbance (Moser et al., 2019[166]; Folke, 2016[167]). Loss of system resilience (instability) increases as the system reaches a tipping point. For tipping points that should be avoided, loss of resilience is normatively undesirable. However, for positive tipping points, loss of resilience of the unsustainable systems are targeted for transformation is desirable.

[5] These feedbacks can also exist for incumbent products, services or behaviours and so could also lead to system resilience through lock-in or negative discourses. Fossil fuels have benefitted from learning-by-doing, economies of scale, network effects, technological reinforcement, and social contagion to become the dominant energy sources.

[6] Stocks are the elements of dynamic systems that can accumulate or be depleted over time and have a certain value at a given moment – e.g. the number of people or electric cars in a country at time X. Flows change a stock with inflows (that add to the stock) and outflows (that subtract from the stock) and are typically measured over an interval of time – for example, the number of births or new electric cars sold in one year.

[7] The use of behavioural insights to enhance climate action, including through addressing mis- and disinformation, is explored in depth in the policy papers on demand-side policies (OECD, 2025[124]) and on the government-citizen interface (OECD, 2025[152]).

[8] Clean hydrogen can be produced from various sources, including hydrogen production from fossil fuels with carbon capture and storage (also known as blue hydrogen) and from biochemical conversion of biomass or from water electrolysis using renewable electricity (known as renewable hydrogen or green hydrogen). Over the last years, other "colours" have been used to designate various hydrogen production routes, such as pink hydrogen (electrolysis powered by nuclear energy), turquoise hydrogen (methane pyrolysis to produce hydrogen and solid carbon) or white hydrogen (geological hydrogen found in underground deposits). However, many jurisdictions and international organisations are now

promoting the definition of hydrogen based on carbon dioxide equivalent rather than on a colour system, arguing that reducing greenhouse gas emissions is the primary purpose for clean hydrogen development [COM/TAD/ENV/JWPTE(2023)6/REV2].

[9] Demand-side policies to reduce emissions in the food system are also explored in depth in (OECD, 2025[124]).

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Triggering positive tipping points – where crossing a critical threshold leads to a self-propelling shift to a new system state – may play a crucial role in rapidly accelerating emissions reductions. Recent breakthroughs in the uptake of solar and wind power, battery storage and electric vehicles in leading markets suggest that change at the pace and scale needed is possible. This paper introduces the concept of positive tipping points and its implications for climate policymaking, setting out the dynamics that enable such systems transformations, and taking stock of the enabling conditions and policy measures that can lead to rapid change. Through operationalising the positive tipping points concept, policymakers can better direct policy efforts, leveraging the potential for tipping cascades – where crossing a tipping point in one system pushes other systems past tipping thresholds – while managing potential unintended consequences.

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