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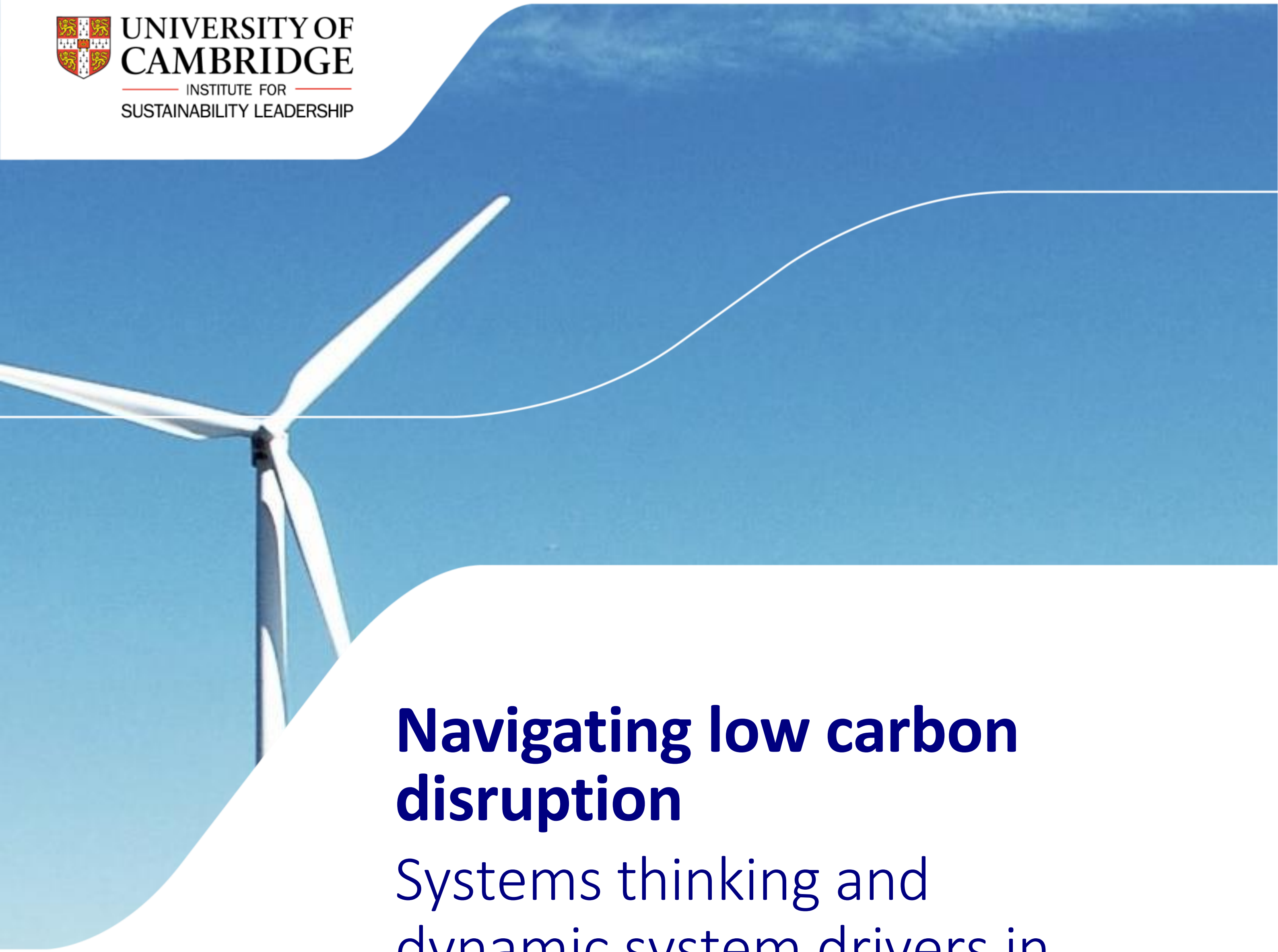

Navigating low carbon disruption

Systems thinking and dynamic system drivers in power, road transport and agriculture

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Executive summary

Successful business, finance and governance require the ability to make sense of the world's complex, interconnected and ever-changing systems. To help navigate this challenge, businesses, investors, governments and individuals would benefit from incorporating 'systems thinking' into their decision-making. This means embracing the complexity and interconnectedness of whole real-world systems, rather than attempting to distil out individual parts or phenomena in isolation. It also means recognising that the feedbacks and interactions which emerge from this interconnectedness lead to non-linear system behaviour, emergent phenomena, path-dependence and irreversibility. In practice, these mean that systems can exhibit exponential or step change, the whole is greater than the sum of the parts, small changes today can lead to qualitatively different future states, and change can be impossible to undo, respectively.

Systems thinking is particularly critical for approaching societal challenges such as climate change mitigation, which demands overarching and economy-wide transformation. As history shows, transformation processes produce opportunities and risks – and winners and losers. Indeed, achieving global decarbonisation goals will necessarily entail *disruption* – existential challenges to incumbents which cannot be overcome through incremental means – in numerous economic, technological, business, institutional and cultural systems.

Dynamic system drivers (DSD) framework

We present a framework for characterising, anticipating and influencing market disruption. The framework focuses on five dynamic system drivers which can either promote or hinder system disruption:

1. **Driver 1 – Planet:** Earth systems (including but not limited to the climate, biosphere, atmosphere and water and biogeochemical cycles) directly enable and constrain human activity. The planet also indirectly influences systems by exerting pressures on the other four system drivers.
2. **Driver 2 – Technology:** Technological change has unseated incumbents throughout history. Technological change can be either incremental or radical and either sustaining or disruptive. The direction in which technology drives the dynamic of the system depends on who is innovating and to what end.
3. **Driver 3 – Government:** Targets and policies direct business activity towards societal goals, while regulation directly dictates the parameters for business operation.
4. **Driver 4 – Finance:** Through the allocation of capital based on risks and returns, investors influence the system dynamic by filtering innovations and business models.
5. **Driver 5 – Citizens:** Citizens can shape systems in their capacity as consumers, voters and activists, deriving collective strength from numbers. In the long term, businesses, governments, investors and innovators all ultimately answer to the public.

The system drivers have three key properties. First, each system driver can both sustain and disrupt the status quo. Indeed, the drivers generally exert simultaneous sustaining and disruptive influences along different system dimensions. Second, in periods of equilibrium, system drivers tend to sustain incumbent systems on balance, but during disruption events they can flip to exert a net disruptive influence. These flips can serve as bellwethers of broader disruption. Third, the system drivers are highly interconnected. This gives rise to balancing and reinforcing feedbacks between them, which in turn produces non-linear system behaviour.

Operationalising the framework and inevitable disruption

As governments, citizens and many businesses coalesce around the Paris Agreement targets, low carbon disruption seems increasingly inevitable. Industries and firms that are currently responsible for greenhouse gas (GHG) emissions will have to adapt their technologies and – in many cases – their core strategies and business models; otherwise, they risk obsolescence. This is not simply a moral imperative: in numerous sectors and socio-technical systems, low carbon technology clusters and paradigms threaten incumbents with advantages in cost and other attributes. In many instances, the gaps are widening at exponential rates. Newcomers and established businesses alike can capitalise on the low carbon transition by embracing and innovating towards the opportunities it provides. Conversely, those that resist change may be left behind.

We demonstrate how the dynamic system driver framework can be operationalised to analyse low carbon disruption processes in three sectors: electrical power, road transport and agriculture. For the past century, these systems have been dominated by emissions-intensive incumbents: coal and gas in power generation, oil-powered internal combustion engine (ICE) vehicles in road transport, and conventional protein production from methane-intensive industrial livestock agriculture. These incumbents now appear vulnerable to disruption, though the immediacy, certainty and magnitude of this disruption vary between the sectors.

Sectoral deep dives: disruption in power, road transport and agriculture

Disruption is well underway in the power sector, driven largely by cost-competitive renewable energy technologies and an appetite for decarbonisation from governments, entrepreneurs and investors. Some sustaining influences still exist, namely (a) regulatory barriers to renewables siting and development, and (b) underdeveloped technologies and markets for managing the intermittency of renewables. Based on our application of the DSD framework, the following leverage points could accelerate decarbonisation:

1. Innovate in intermittency management.
2. Eliminate regulatory barriers to renewables deployment.
3. Foster international collaboration.
4. Finance the scale-up of renewable electricity systems.
5. Improve public opinion of renewables.

Low carbon distribution is also underway in the road transport sector, but at a more nascent stage than in the power sector. Battery electric vehicles (BEVs) seem poised to disrupt ICE vehicles, buoyed by growing support from governments, investors and consumers. Citizens remain the greatest sustaining influence in this sector as high upfront costs, low public charger availability and range anxiety contribute to consumer wariness. In this sector, we identify the following leverage points:

1. Scale up BEV production to meet growing demand.
2. Establish diverse and circular supply chains.
3. Invest in (smart) charging networks and electricity grids.
4. Reduce reliance on the personal automobile.
5. Leverage the power of incumbents.

The agriculture sector is in an incipient stage of its low carbon transition, and therefore disruption to incumbents is only just beginning. However, the pieces are falling into place. The sector is both a major contributor towards – and highly vulnerable to – climate change and other forms of environmental degradation. Industrial animal agriculture has accelerated both environmental degradation and threats to human health via obesity, antibiotic resistance and zoonotic disease. Some form of disruption seems inevitable, whether this comes from inhospitable planetary conditions for agriculture (eg drought, heatwaves, flooding, other extreme weather events and sea level rise) or increasingly realistic and cost-competitive alternative proteins. Here, the leverage points are as follows:

1. Pursue 'climate-smart' synergies.
2. Close information and capacity gaps.
3. Reform policy to promote just decarbonisation.
4. Explore diverse avenues for decarbonisation and disruption.
5. Seek local solutions.

Encapsulated in the first point, climate-smart agriculture (CSA) can promote a 'triple win' of increased productivity, decreased climate impacts and enhanced climate resilience, but its implementation depends heavily on strategic intervention at the leverage points outlined above.

An inflection point: looming risk and opportunity

Due to the delay in climate change mitigation action, low carbon disruption has become necessary to avert climate catastrophe. Indeed, accelerating and reinforcing feedbacks between dynamic planetary conditions, technology, government, finance and citizens have made low carbon disruption inevitable in many sectors. Even sectors which are dominated today by emissions-intensive incumbents could be rapidly and irreversibly disrupted by changes in the state of these system drivers. Low carbon disruption processes create winners and losers, but their identities are not set in stone. Businesses, governments, investors and communities that adapt by embracing the opportunities provided by radical low carbon innovation will position themselves as leaders in a low carbon future. Those that stubbornly resist change face long-term decline.

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Abbreviations

BEV	Battery electric vehicle
CCUS	Carbon capture, utilisation and storage
CSA	Climate-smart agriculture
DER	Distributed energy resource
DSD	Dynamic system drivers
ETS	Emissions trading scheme
FMCG	Fast-moving consumer goods
GDP	Gross domestic product
GHG	Greenhouse gas
ICE	Internal combustion engine
ICT	Information and communication technology
LCOE	Levelised cost of electricity
MaaS	Mobility-as-a-service
NIMBY	Not in my backyard
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic
SSP	Shared socioeconomic pathway
YCS	Yield constraint score
ZEV	Zero emissions vehicle

1. Introduction

"No man ever steps in the same river twice, for it's not the same river and he's not the same man. There is nothing permanent except change."

Heraclitus of Ephesus

Markets resemble natural ecosystems in many ways. Firms are created and destroyed constantly in an environment of increasing competition for resources and market share. New entrants challenge incumbents, who can either adapt or become obsolete and disappear. Most of the time, the adaptation necessary to survive is only marginal. Incremental changes in products or processes allow firms to remain competitive and even gain marginal advantages. In some cases, however, companies face a *market disruption*: an existential challenge that cannot be overcome through incremental improvements.

1.1 Understanding disruption is critical to business success

There are many well-documented cases of market disruption. Automobiles displaced horse-drawn carriages. Steamships displaced sailing ships. Steam (and later electric) power displaced water power in factories. Smartphones displaced non-internet cell phones, which had in turn displaced landlines. Finally, streaming video services displaced video mailing services, which had previously displaced movie rental stores and, to some extent, cinemas. In all these cases, incumbents who did not adapt to the new market realities declined into obsolescence. But how is it possible that they were not able to anticipate the changes happening in their sectors? There is an extensive body of literature addressing this question. Christensen describes this process as "disruptive innovation".[1] According to Christensen, incumbents pay more attention to the most profitable segments of the market, while leaving space for the competition within the less-profitable segments. As technology advances over time, new entrants improve their products and services, which then facilitates the challenge to the core market segments. By the time incumbents realise the threat, it is often too late.

Today, the global economy faces an existential challenge, in the same way that local ecosystems and individual firms do. In the face of the monumental environmental risks of climate change and biodiversity loss, disruption will extend beyond technologies and markets. A 'business-as-usual' path is no longer a viable option: environmental challenges will irrevocably disrupt the planet and economies unless these challenges can be ameliorated by deep low carbon and nature-positive disruption. Disruption is coming one way or another – either with climate change itself or through the measures taken to mitigate its effects (in fact, some of each is inevitable).[2] Under these conditions, the challenge is not only to anticipate but also to manage disruption, directing it along a sustainable path. Therefore, building a framework that can help us anticipate and manage disruption is paramount. Such is the aim of this report, which seeks to identify (a) the systemic factors which hinder change and (b) the forces driving disruption and to establish how best to direct them in the context of the low carbon transition.

1.2 Disruption is the norm, not the exception

Technological progress is based on cumulative knowledge. *We are dwarfs standing on the shoulders of giants*. As our understanding of the universe improves, we accelerate the pace of progress. This accelerated path bears a resemblance to the process of evolution, which follows the same principle but proceeds orders of magnitude slower.[3]

Knowledge is typically described as a global public good.[4] Even if fully shared, however, knowledge is developed in niches: specialised 'pockets' (eg universities, research and development centres or firms) which interact through multidimensional networks. As a result of discrete (in contrast to continuous) interactions across the different knowledge sources, innovation[5] happens in bursts. It is not a smooth process – ie one advance after another – but rather eruptions of new products and processes clustered around areas of strategic common interest. Series of interrelated technological advances lead to periods of 'creative destruction', which subsequently give birth to 'innovation waves'. These waves have been well studied by numerous authors across different disciplines.[6] They typically start with *radical innovations* – non-incremental innovations which demand novel knowledge, skills, capacities or competencies – in strategic niches, such as the steam engine or the transistor. As momentum builds behind radical innovations, new business models and opportunities appear and society is fundamentally pushed in a new direction.[7]

According to the influential work of Geels,[8] transformations are driven by interactions happening within and across three main analytical levels: the niche (or micro) level, the socio-technical regime (or meso) level and the landscape (or macro) level. Protected niches nurture knowledge production and exchange, facilitating the emergence of radical innovations. For these radical innovations to succeed, they need to create momentum through price or performance improvements and support from powerful actors (eg policy and finance). While many of these innovations fail (and therefore disappear), others succeed, gain access to global markets and ultimately influence the incumbent socio-technical regime. In the case of particularly disruptive technologies, their influence is not confined to the regime level but instead produces shifts at the macro or landscape level. As the landscape changes, the disruptor becomes the incumbent – new innovations are then created to challenge its position in a never-ending cycle of disruption and transformation.

These innovation waves represent clear examples of the disruption process: recurrent system-level disruptions which reshape the global economy. In each historical wave, new sectors and industries were created while others disappeared. Disruption is intrinsic to this process and – as we move forward – it is important to recognise that change is inevitable. The question, therefore, is not how to *produce* or *avoid* change, but rather how to *influence* it so that such shifts promote social good and address global challenges such as climate change.

1.3 Lessons from past transitions

Environmental sustainability is frequently highlighted as one of the drivers of the upcoming ("sixth") innovation wave.[9] Planetary boundaries[10] – limits for a safe and stable operating space for humanity – are becoming an increasingly important catalyst for innovation and disruption, in contrast with previous socio-technical transitions. For instance, climate change is shaping global decision-making. No longer only a public policy issue, climate change mitigation has become a strategic industry which both public and private financiers are keen to exploit.[11] Green energy and other low carbon technologies, alongside cross-cutting innovations such as biotechnology, artificial intelligence and automation, are expected to transform society in the coming decades.

There is a vast amount of literature describing past technological transitions, especially in the energy sector.[12] The dynamics around the "grand energy transitions"[*,13] have been particularly well studied. Although energy is not the only system vulnerable to disruption, historical disruption in the energy system can illuminate the causes, effects and mechanisms of disruption more generally. Some common patterns emerge in global disruptions of energy markets:

1. **Superior technologies lead to disruption.** Some innovations with superior technical characteristics have been able to create, expand and eventually disrupt markets, even if they started at higher prices than the incumbent. Classic examples are steam and internal combustion engines. Modern examples include the iPhone and Tesla. An important caveat is that disruption can also come 'from below'. Technologies which initially underperform but have specific characteristics that are valuable to consumers can gain traction in small, less-profitable segments of the market, and then disrupt the entire market as they get better and more competitive. Personal computers are a good example: initially, they were slower and more expensive than mechanical typewriters, but technical improvements and cost reductions led to complete market disruption.

2. **Incumbents take the hit.** Past transitions have had major impacts on incumbent industries. Some industries have declined, while others have disappeared. This has created profound economic transformations which extend beyond the primary disrupted sector.[14] To survive, it is insufficient for incumbents to merely recognise and adopt new technologies; rather, they must seriously explore the new business opportunities provided by disruptive technologies and reorganise their core business strategies accordingly. For instance, while Kodak developed some digital cameras, they predominantly clung to their core film and photofinishing business. This made them vulnerable to disruption by more adaptive firms such as Fujifilm, which embraced the business opportunities enabled by digitalisation such as healthcare, document services and optical devices.[15]

3. **Price shocks matter.** Prices play a crucial role in creating incentives to stimulate technological transitions. Price shocks act as catalysts, especially when they coincide with broader societal forces.[16] A classic example was the energy crisis of the 1970s, which led to large-scale R&D programmes focused on alternative technologies such as renewables and nuclear energy.[17]

4. **Sailing ship effect.** A relevant factor to determine the speed of a transition is the reaction of incumbents to new competition. In some cases – before being ultimately superseded – threatened incumbents fight back. This creates a 'sailing ship' effect: the advent of a competing new technology stimulates 'last gasp' innovation in an incumbent technology, making it more efficient and competitive. A classic example was the improvements in sailing ships after the introduction of the steamship.[18] A more modern example is incremental innovation in the 2000s and 2010s to improve ICE efficiency, rather than embracing electromobility.[19]

5. **Clusters and technological lock-in.** Technologies do not change individually; rather, they do so in clusters and are influenced by 'spillovers' – applications outside the initial domain of the

[*] The term "grand energy transitions" refers to two major changes in the global energy sector. The first one corresponds to the rise of coal (during the Industrial Revolution) as the dominant energy resource globally. The second refers to the transition from coal to oil (early twentieth century) as the dominant energy resource globally. The ongoing transformation of the global energy systems is sometimes described as the third grand energy transition (Podobnik, 2005).

technology. For instance, stationary steam engines were first introduced for pumping water outside coal mines but were later applied to power generation, manufacturing and transport. Information and communication technology (ICT) first appeared in the scientific arena but expanded rapidly to productive applications and is now pervasive in everyday life. These cluster and spillover effects lead to technological co-dependency, which results in strong path dependence. As a consequence, markets create entry barriers which lead to technological lock-in. Incumbents benefit from this as technological lock-in slows down the transition and eventual disruption processes.

6. **Policy and governments play a role.** Radical innovations at early stages of development usually bear too much risk for the private sector to step in. Governments tend to be the main risk-takers, implementing programmes for the long-term development of highly uncertain technologies and industries. Sometimes these efforts pay off (eg solar photovoltaic (PV) supply chains in Germany and China), sometimes they fail (eg Solyndra in the US), and sometimes results take longer than expected (eg nuclear fusion energy).

7. **Finance fuels the transitions.** Technological innovations need the help of financiers to scale up. Innovation waves include periods of speculative finance, during which investors bet on promising technologies with the expectation of them becoming the new incumbents. While financiers act as a natural filter which separates successful from failed innovations, speculation also leads to financial bubbles. Examples include the 'railroad mania' of the 1840s and the 'dot-com' bubble of the late 1990s.

8. **End users are important.** The pace of technological uptake is driven by the rise in demand for underlying services. Therefore, end use applications drive supply-side transformations.[20] In the energy sector, for instance, final consumers are not interested in purchasing energy per se, but rather in the final services it provides (eg light, transportation or heat). Indeed, it was the demand for light, after the invention of the electric bulb, which drove up the demand for electricity and – in turn – led to the technological progress associated with its production.[21]

Another overarching lesson from past technological transitions is that technology tends to diffuse following a sigmoid (or S-shaped) pattern, as characterised by Rogers.[22] While different mathematical descriptions have been proposed to describe this phenomenon, the empirical evidence for the S-shaped pattern has accumulated and now become widely accepted.[23] The overall process is shown in Figure 1.

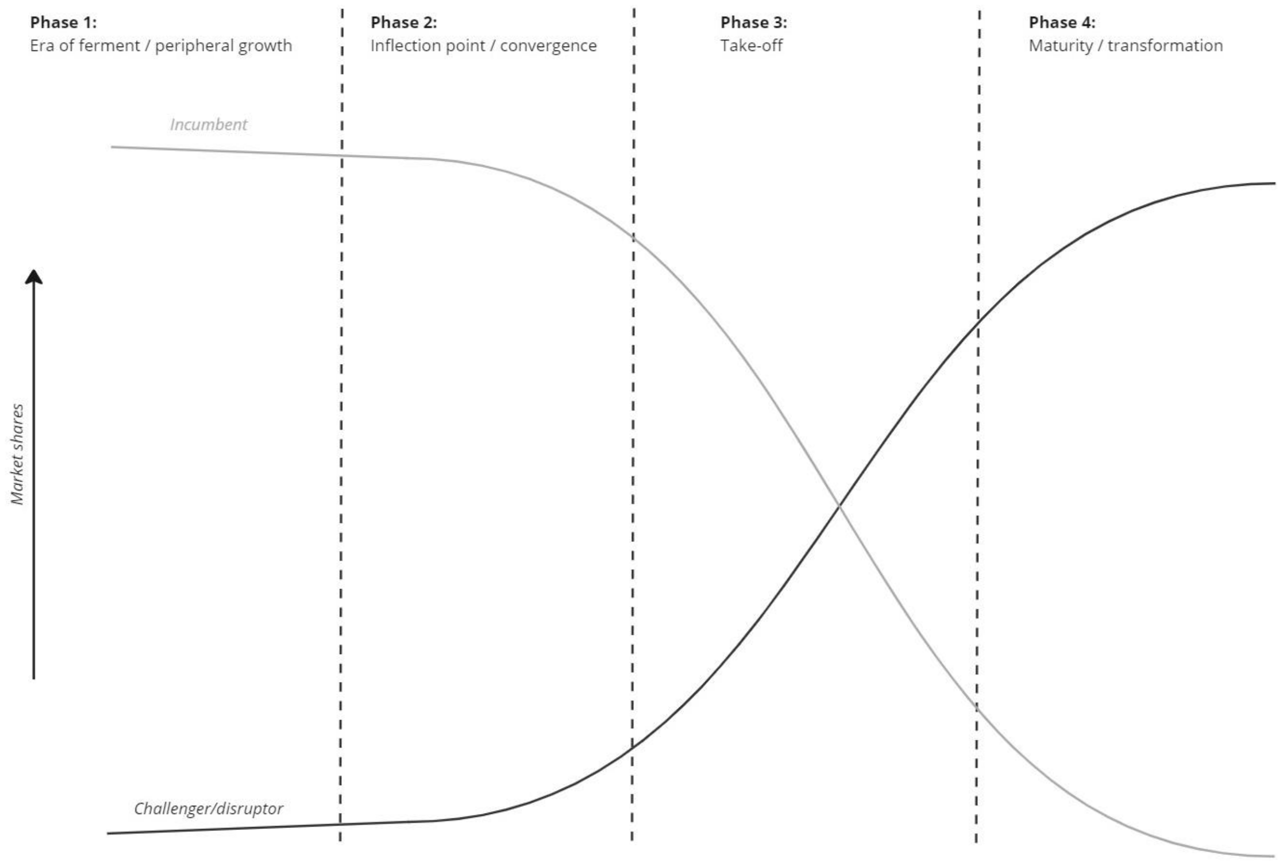

Figure 1: Archetypal S-shaped curves of technological diffusion and decline.

Disruption proceeds in four phases:

1. In the "era of ferment"[24], innovations with disruptive potential emerge in "peripheral niches".[25]
2. As different technical and market-related factors start to converge around a "dominant design", diffusion reaches an inflection point, after which the process accelerates exponentially.[26]
3. As the new technology takes off, the incumbent can no longer maintain its market-dominant position, and gradually the challenger becomes the new market leader.
4. Finally, market saturation is achieved. Several factors determine the final level of market penetration and the overall speed of the transition.

For some technologies, such as microwaves or cell phones, the diffusion process can happen very rapidly (eg only a few years). For others, such as flush toilets, it can take several decades. Figure 2 demonstrates this phenomenon: it shows technologies diffusing along S-shaped curves at varying rates.[27] Note also the decline of landlines, which coincides with the rise of disruptive cellular phones. The variation in timescales of historical technological change is an important lesson: we do not have much time to address climate change. To avert climate catastrophe, the low carbon transition must be far-reaching and fast. Therefore, understanding the drivers of S-shaped disruption is critical for accelerating the process.

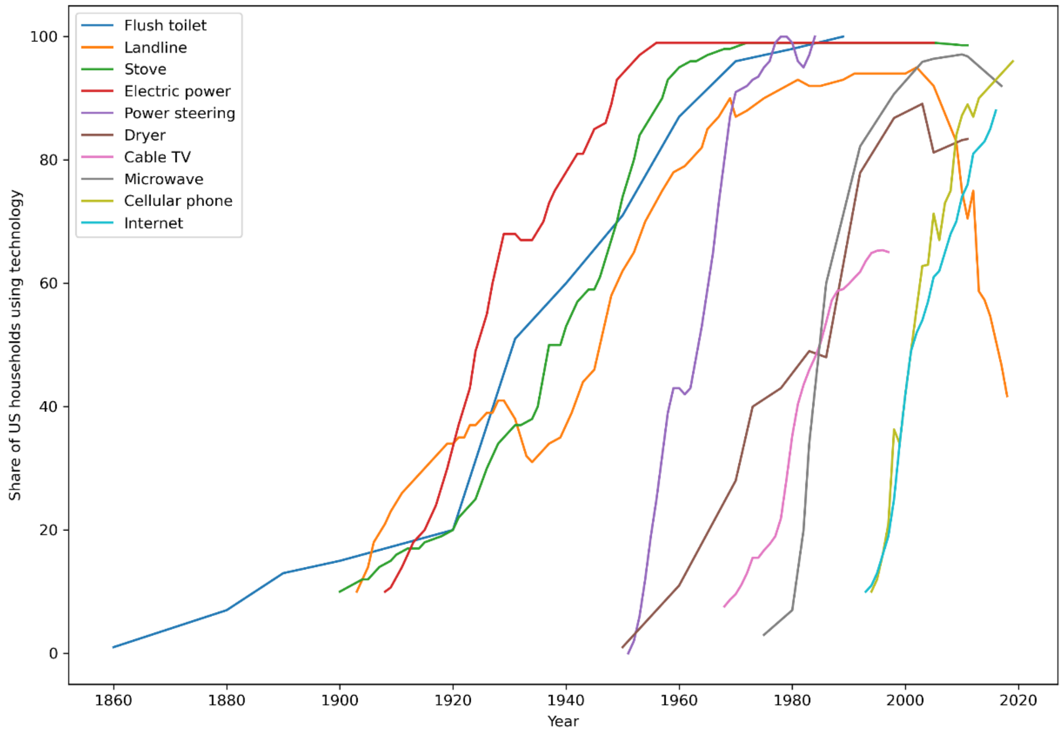

Figure 2: Technological diffusion in US households, 1860–2019.

1.4 Summary of contents

Chapter 2 of this report describes the dynamic system drivers (DSD) framework for characterising, anticipating and influencing disruption. Chapter 3 discusses how the framework can be operationalised and applied to low carbon transition. Chapters 4, 5 and 6 apply the DSD framework to three sectors: electrical power, road transport and agriculture. They assess the state and nature of disruption in these sectors and identify the key leverage points for accelerating decarbonisation. The assessments in Chapters 4, 5 and 6 are supported by the appendices (A, B and C), which reference the academic literature and industry reports. Chapter 7 concludes by synthesising the report's main messages and reiterating our applied business perspective on the risks and opportunities associated with inevitable low carbon disruption.

2. The dynamic system drivers framework

In this report, we introduce five *dynamic system drivers*: interconnected forces which shape socio-technical systems.[*,28] This chapter introduces these system drivers, discusses their potential to sustain and disrupt systems over time, and describes their interlinkages. Examining the current state and anticipated future movement of system drivers can help characterise past and ongoing disruption, anticipate upcoming disruption, and determine how to shape and accelerate desirable forms of disruption. This last point is crucial in the climate change context: one way or another, the twin forces of climate change and socio-technical change will disrupt economic systems. Businesses can navigate this change by embracing disruptive technologies, strategies and business models while working to accelerate decarbonisation.

2.1 Dynamic system drivers

The DSD framework identifies five dynamic system drivers which influence socio-technical systems and can make or break market disruption. The system drivers operate largely as part of the meso-level "socio-technical regime" of Geels's multi-level perspective (see section 1.2).[29] Our framework seeks to clarify the linkages and processes that govern these system drivers and to characterise the process by which they actively influence their own reconfiguration and broader market disruption. The dynamic system drivers are shown in Figure 3 and described below.

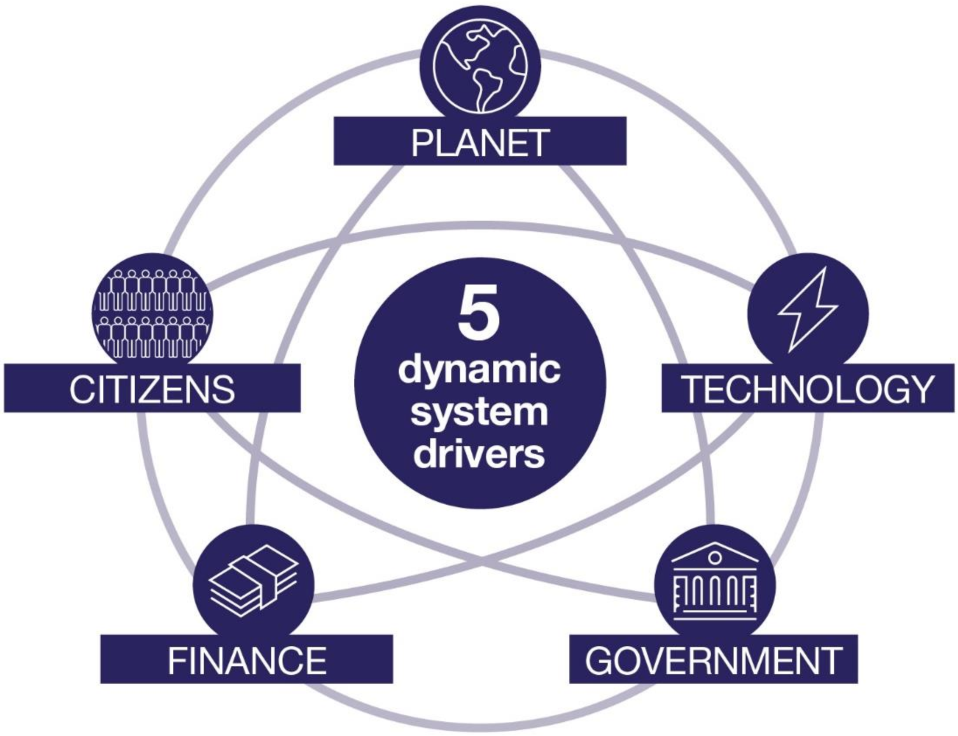

Figure 3: The dynamic system drivers.

[*] Socio-technical systems theory stresses the "reciprocal interrelationship" between humans and technologies (which can be defined broadly as applied knowledge), emphasising the complexity lent to real-world systems by these interactions (Ropohl, 1999).

1. **Planet.** "Planetary boundaries" define limits for a safe and stable operating space for humanity.[30] From the nine planetary boundaries identified,[*] climate change and biosphere integrity (ie biodiversity) are recognised as "core planetary boundaries" because they impact all the other boundaries and are seen as fundamentally important to the overarching Earth system. The planet drives socio-technical systems by imposing limits on the resources (including a stable climate) which influence the economy; indeed, many contemporary social and economic systems are highly vulnerable to planetary and environmental change. In the climate context, we face an inevitable degree of each of mitigation, adaptation and suffering. The question is "what the mix is going to be" of these three.[31] Crucially, the planet system driver is not a matter of altruistic environmental protection; rather, it deals with material risks to business and the global economy – up to USD 178 trillion for climate change alone[32] – which stem from ongoing environmental change.
2. **Technology.** Technology is a broad concept: its definition ranges from tangible objects and skills to production methods, symbols and ideologies.[33] It is an important driver of change, either through radical and disruptive innovations (including products, processes, markets, institutions and culture) or through incremental changes which can either stabilise or destabilise incumbent regimes. The impact of technological development on systems depends on who is innovating and to what end.
3. **Government.** This system driver encapsulates policy, regulation and law at the local, regional, national and international levels. Policies provide the economy with a sense of direction and define parameters within which businesses function. Regulation dictates what type of businesses can operate and how, and the law holds businesses (and other actors) accountable for transgressions. Government policy, regulation and law vary across space and time, making them a dynamic force which both responds to and pre-empts developments in other system drivers.
4. **Finance.** The cost of – and ease of access to – capital are crucial determinants of success at all system levels, from individual firms to entire industries and supply chains. Therefore, the extent to which financial sector institutions allocate capital to and assume risk from innovators can catalyse or block an innovation's disruptive potential.
5. **Citizens.** Citizens are consumers, activists, constituents and (in democracies) voters. In many sub-systems operating within capitalistic economies, consumer preferences and demand are the primary drivers of production. Therefore, the way that expectations, information and norms move through networks of heterogeneous and often less-than-rational[34] consumers is critical to processes of system sustenance and disruption.

2.2 Sustaining and disruptive potential

Each system driver can contribute to system disruption but may also act as a sustaining force. Indeed, in periods of stability before or after instances of disruption, system drivers tend to support and sustain

[*] The nine identified planetary boundaries are climate change, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biochemical flows, freshwater use, land-system change, biosphere integrity and novel entities (new substances that have the potential for unwanted geophysical and/or biological effects, such as microplastics).

incumbent systems. Established incumbents have the most resources to innovate, so the evolution of technologies and markets often serves incumbent systems via incremental innovations – economies of scale and learning – which reinforce incumbents' dominance.[35]

Incumbent systems breed sustaining technological and market evolution by shaping cultural norms and techno-economic paradigms, making it easier for innovators to conceptualise innovations which extend and sustain incumbent systems.[36] Policies and laws often promote stability and are often influenced by the interests of incumbent industries, for instance through lobbying.[37] Financial capital is often available in larger quantities and at a lower cost to incumbents, who are perceived as least risky (this is what Perez refers to as a "harmonious marriage" between financial and production capital).[38] Citizens are also more likely to opt for familiar products and services,[39] even preferring incrementally new products over radically new products.[40] This further reinforces incumbent systems at equilibrium. Finally, while incumbent systems may ultimately be incompatible with planetary boundaries, the signs of danger or risk may be either too difficult to detect or perceived as too distant to present much of a disruptive pressure at present.[41]

On the other hand, each system driver can also facilitate and accelerate disruption. Environmental change and pressure from planetary boundaries can make certain technologies, business models or ways of living untenable. Radical and potentially disruptive innovations can experience multiple dimensions of 'learning' as they develop and scale, which can lead to virtuous cycles and self-sustaining diffusion.[42] Indeed, technology is often the earliest of the system drivers to meaningfully promote disruption: 'disruptive' and 'innovative' have practically become synonymous in non-technical language.

Policy and law can exert disruptive influence when governments 'change the rules of the game' in pursuit of enhanced social welfare (eg prosperity, public health, education or environmental protection). Financiers can turn their support from incumbents to disruptors as mature socio-technical regimes begin to stagnate,[43] untenable risks emerge within new system states,[44] and investors recognise greater opportunities to create long-term value elsewhere.[45] Finally, citizens can promote disruption when incumbent systems are seen as immoral or otherwise undesirable, or when consumers desire novel value propositions that can only be provided under systemic disruption.[46]

2.3 Change in influence over time

Central to the framework is the idea that the system drivers are *dynamic.* In most systems, each driver exerts both sustaining and disruptive influences along many dimensions. Over the course of systemic disruption, the system drivers may *flip* from largely sustaining to largely disruptive, while sustaining influences may weaken along with declining incumbents. This happens as citizens, governments, investors and innovators recognise changing conditions and adjust their positions to embrace a new paradigm. Therefore, it is possible to recognise ongoing disruption – and anticipate upcoming disruption – by analysing not only the current state of the system drivers but also their directions and magnitudes of change over time.

2.4 Linkages and influence between system drivers

Each of the five system drivers is influenced by the broader human and environmental context. This context includes elements such as current levels of natural resource use and prevailing 'enabling technologies' (which today include digital and telecommunications technologies and may eventually include nanotechnology, biotechnology, cleantech and artificial intelligence). The context in which system drivers operate also includes prevailing values and paradigms concerning the role of consumers, governments, finance and innovators in society. Disruption can feed back into the broader system context via influence on the socio-technical landscape and techno-economic paradigm; however, changes at this scale may be thought of more as a product of disruption than as an accelerator or inhibitor of disruption.

System drivers are not independent and exert direct bidirectional influence on one another. For instance, governments define the rules under which technology companies operate while, at the same time, technological evolution influences policy. The mechanisms by which system drivers influence one another are described in Table 1. Each cell describes the column driver's influence on the row driver. Shaded cells describe feedbacks within individual system drivers.

Table 1: System driver influences on one another.

	Planet	Technology	Government	Finance	Citizens
Planet	Evidence of tipping points and feedbacks in many planetary systems.	Technology, policy, investment or behavioural change which slows or reverses the transgression of planetary boundaries can reduce environmental risks (economic and geographic scale depends on the nature of this change). Conversely, accelerated environmental degradation may intensify disruptive environmental pressures.			
Technology	Planetary boundaries select for innovations which are resilient to (and, via other system drivers, less responsible for) planetary change.	Exponential technological change due to various types of technological learning.	Policy and regulation define the spaces in which innovators operate.	The cost of, and ease of access to, capital can be decisive factors in the success or failure of an innovation.	Entrepreneurs respond to and innovate towards consumer demand, even if initially only in small niches.
Government	Governments may implement policy to stay within planetary boundaries, adapt to planetary instabilities, or both.	Policy, regulation and law evolve as new innovations present both challenges and opportunities (eg regulation around artificial intelligence).	Policy innovation can spread rapidly between jurisdictions and regions.	Financial markets can signal to governments which industries, asset classes or broader systems are on the rise or in decline.	Governments in democracies are directly accountable to public opinion, and governments worldwide strive to promote their constituents' well-being, although their definitions may vary.
Finance	Planetary boundaries increase the risk of some investments, pushing finance towards more resilient and sustainable options.	Changing innovation attributes (including but not limited to cost) may attract capital or even shift financial paradigms.	Policy and law, or even the expectation of future policy or law, can alter asset valuations and financial best practices. Financial	Financial contagion.	In capitalistic systems, financial capital is allocated according to expected returns or to maximise long-term value creation, both of which depend heavily on consumer

			regulation defines the 'rules of the game' for finance.		preferences and public opinion.
Citizens	As the risks of transgressing planetary boundaries become evident, informed and financially capable consumers gradually shift their preferences towards more sustainable options.	Although initially unfamiliar, new innovations may eventually sway consumer choice via improved or novel attributes, including but not limited to lower operating costs.	Policy, regulation and law shape what is available at what price point to consumers, and public procurement can promote the visibility and familiarity of novel innovations.	By changing prices, evolving financial conditions influence the attractiveness of different goods and services.	Consumer preferences can change exponentially as early adoption promotes familiarity and visibility. Grassroots movements can breed further activism and awareness.

3. The DSD framework and climate change

The DSD framework could be applied to analyse any of a broad range of system disruptions in any economic sector or facet of society. In this report we focus on *low carbon disruption*: the non-incremental transformation of socio-technical and economic systems away from high GHG emissions and towards low GHG emissions. This chapter describes how low carbon disruption can be seen as a special case of our general theoretical disruption framework. It defines key terms in this context, maps out an archetypal process of low carbon disruption, describes how the DSD framework can be operationalised, and presents an applied business perspective on low carbon disruption.

3.1 Physical and transition risks

In the context of the low carbon transition, disruption can be both accelerated and hindered by the five system drivers. Planetary boundaries exert disruptive influence primarily as "physical risks",[47] which can be either chronic (eg sustained higher temperatures, desertification or sea level rise) or acute (eg extreme weather events, acute heatwaves or flooding).[48] Physical climate risks pose direct threats to some industries (eg beachfront property and agriculture in many vulnerable regions) and could therefore accelerate disruption in favour of more resilient alternatives. Moreover, the threat of physical risks across human systems is beginning to spur innovators, governments, investors and consumers to turn to climate change mitigation and adaptation solutions.

The other four system drivers (technology, government, finance and citizens) can exert disruptive influence as different dimensions of "transition risk".[49] Policies, litigation, innovation, consumer choice and finance explicitly motivated by decarbonisation will aim to accelerate low carbon disruption. Of course, these system drivers can also exert disruptive influence independently from transition risks. For instance, low carbon technologies may simply outcompete incumbents on the basis of price, policies may be primarily motivated by non-climate concerns (eg energy security), investors may act purely to maximise long-term returns, and consumers may choose to adopt low carbon innovations purely on the basis of price and attributes (as opposed to the 'warm glow' of choosing a sustainable product).

System drivers can also delay low carbon disruption by sustaining incumbent systems. As Chapters 4, 5 and 6 demonstrate, governments, finance and citizens have historically sustained high-emissions systems, and in many cases continue to do so today.

3.2 An archetypal low carbon disruption process

Low carbon disruption entails overturning, displacing, destabilising or making obsolete incumbent and emissions-intensive technological, institutional or cultural systems. It is not inherently a given that low carbon disruption will play out across the economy; however, both science and economics suggest that it is inevitable in many sectors. This is illustrated in Chapters 4, 5 and 6, which focus on the power, road transport and agriculture sectors, respectively.

Low carbon disruption could manifest as any or all of the following:

1. Direct replacement of high carbon technologies with low carbon alternatives (eg drop-in replacement of coal and gas power generation with renewable energy plus storage).

2. Shifting business practices and norms (eg the rise of shared mobility services challenging the dominance of the personal automobile).
3. Shifting culture (eg shifts towards plant-based dishes and diets).

Indeed, deep decarbonisation will likely necessitate all three of these types of system change. Over the course of these disruption processes, system drivers work both to sustain and disrupt, and often flip from sustaining influences to disrupting influences.

Figure 4 shows a theoretical, archetypal process of low carbon disruption. Disrupting influences are shown in blue and sustaining influences are shown in red. The four phases of system disruption are superimposed. During phase 1, system disruption faces resistance from most of the system drivers, which work to sustain incumbent systems. The exception is planetary boundaries (ie physical risks in the climate context), which may exert a disruptive influence but be perceived as too distant to influence the other system drivers or systems themselves. During phase 2, sustaining influences from the system drivers begin to weaken, and some disruptive influence emerges. During phase 3, the disrupting system's take-off is enabled by largely disruptive influences from all five system drivers. Finally, in phase 4, what was once disruptive becomes the new norm; at this point, the new system state is sustained by all five system drivers, which have re-organised around it.

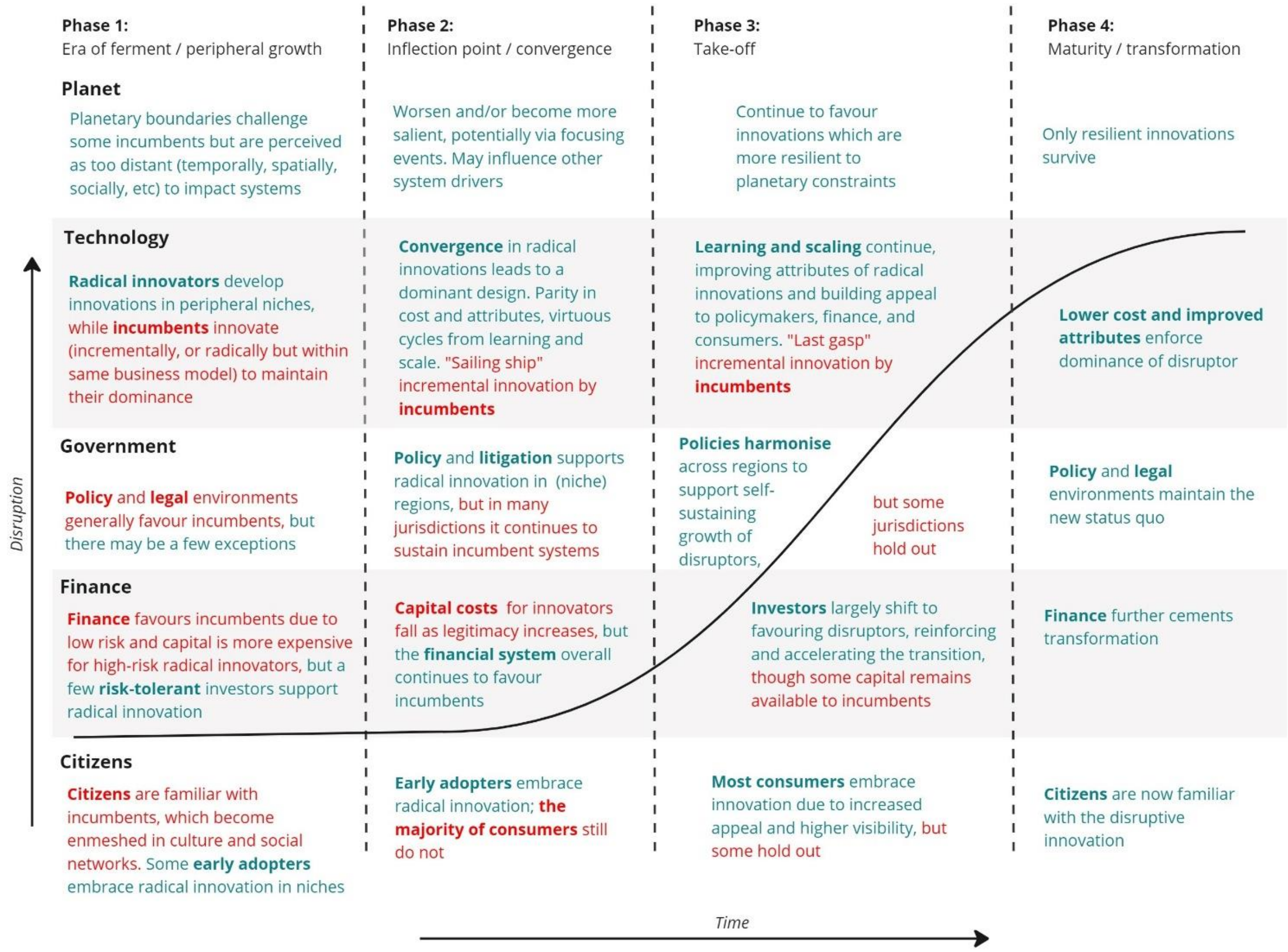

Figure 4: An archetypal low carbon disruption process.

The dynamic nature of system driver influences is represented stylistically in Figure 5. In this figure, the direction of the arrows denotes sustaining versus disruptive influence, and the arrow length denotes the magnitude of influence. Disruptive innovation systems, which often include radical innovations, initially face steep resistance. However, as system drivers evolve, they increasingly work to disrupt incumbent systems. For planetary boundaries, this may occur when acute physical risks or climate-related "focusing events"[50] make it clear that incumbent systems are untenable in a future impacted by climate change. The influence of technologies and markets becomes more disruptive over time as virtuous innovation cycles and "positive tipping points"[51] shift innovative power towards low carbon disruptors and away from high carbon incumbents. This changes the risk associated with incumbent and disruptive systems, which increases both investors' openness to disruptive systems and their recognition of the potential for stranded assets in incumbent systems. Policies shift over time as governments strive to meet Paris Agreement ambitions and domestic decarbonisation targets, and in response to shifting pressures from markets, finance and public opinion. As disruption proceeds, disruptive systems begin to match incumbents in visibility and attractiveness, which shifts consumer preferences away from incumbents and towards disruptors.

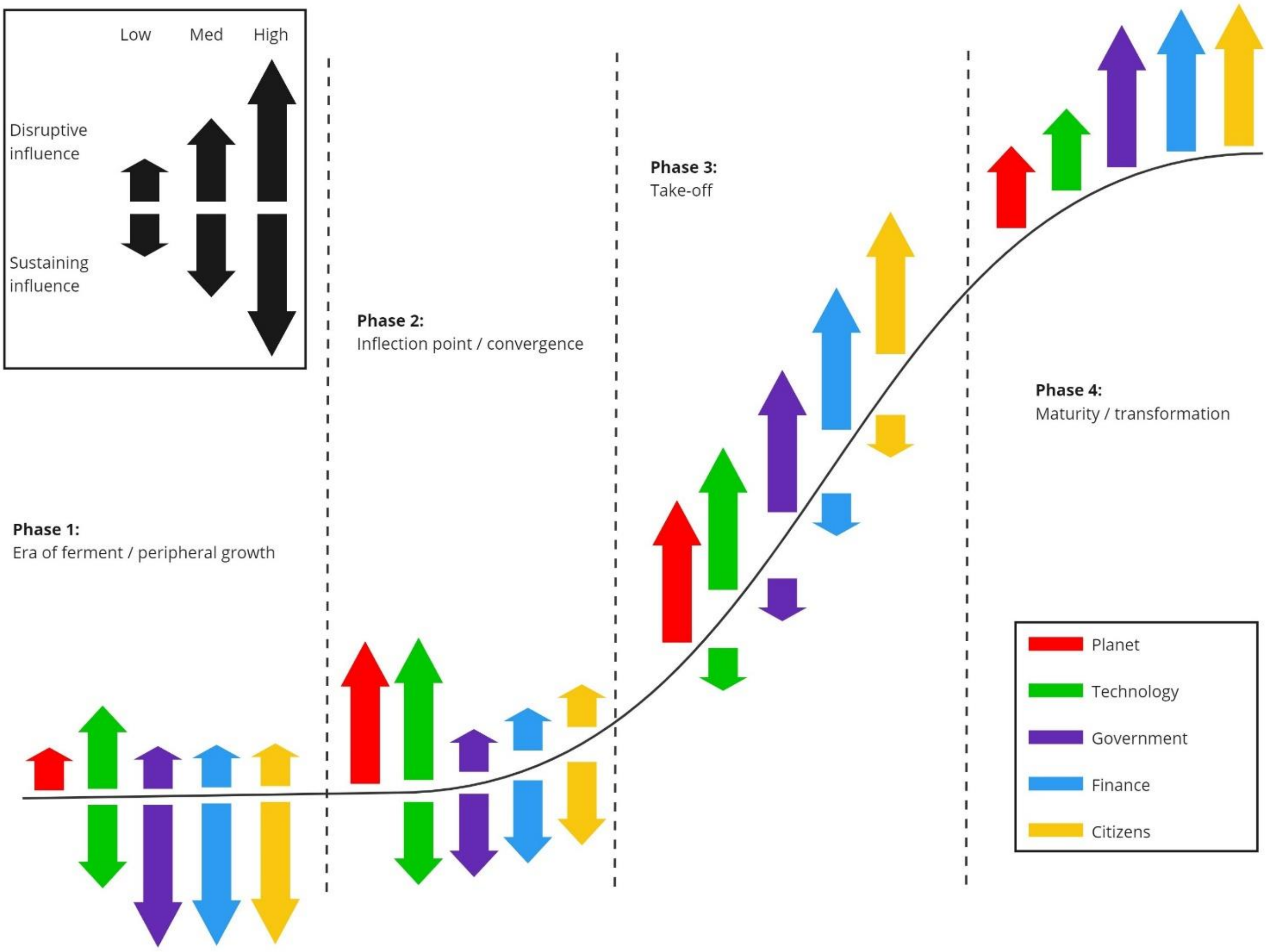

Figure 5: Example sustaining and disrupting influences over time.

It is important to note that the 'y-axis' in the figure, and indeed in disruption processes more generally, does not necessarily correspond to a single disruptive technology or innovation. For instance, disruption in the power sector extends far beyond a single technology or even technological cluster, although it is clear that renewable energy will play a critical role in at least the near and medium terms. Rather, this axis represents disruption more broadly: the extent to which a socio-techno-economic system faces existential challenges and adapts or changes accordingly. A key corollary is that the nature of disruption may become clearer the more disrupted a system becomes. For instance, as Chapters 4, 5 and 6 demonstrate, the new market leaders in power and road transport (renewables and BEVs, respectively) can be forecasted with higher confidence than those in agriculture (regenerative and climate-smart animal products; plant-based, fermented or cultivated alternative proteins; plant-based whole foods; insects; or something yet unforeseen) because disruption is more nascent in agriculture.

3.3 Operationalising the framework

The DSD framework establishes that system change is driven by five dynamic system drivers: planet, technology, government, finance and citizens. These system drivers have three characteristics:

1. Each system driver has the potential to both disrupt and sustain systems. Indeed, the drivers often exert simultaneously sustaining and disruptive influences on different parts or dimensions of a system.
2. The disruptive and sustaining influences of the system drivers are highly dynamic and change over time. In equilibrium, the drivers tend to sustain systems. 'Flips' from net sustaining to net disruptive influences can serve as bellwethers of broader system disruption.
3. The system drivers are highly interconnected, exerting bidirectional influence on one another. This contributes to balancing and reinforcing feedbacks between the drivers. These feedbacks can give rise to lock-in, but also cyclical, irreversible and self-sustaining disruption.

The DSD framework's operating domain is flexible: it can be applied across geographic scales (ie local, regional, national or global) and systemic scales (ie specific technologies or behaviours, economic sectors, or entire socio-techno-economic systems such as energy supply and use). Chapters 4, 5 and 6 focus on global economic sectors (power, road transport and agriculture) but the framework could equally be applied at more granular or broader levels. For instance, individual businesses – incumbents and start-ups alike – could apply the framework by examining cross-cutting system drivers (eg technology and policy across multiple sectors). This would help clarify the risks and opportunities of low carbon disruption in the context of their business operations and could illuminate promising strategic directions.

Operationalising the framework consists of four steps:

1. Gather evidence to answer key questions about each of the system drivers. This evidence should help answer five broad questions which relate to the system driver's sustaining and disruptive influences, history and future, and linkages to other system drivers. These five questions are posed and visualised in Figure 6.
2. Once these questions have been addressed and sufficient evidence has been gathered, the sustaining and disruptive influences for each system driver can be summarised in tabular form and their magnitudes (eg low, medium or high) estimated. See Table 2 and Figure 10 for examples in the power sector.
3. The results of the previous two steps are synthesised to assess the current status of, and future prospects for, disruption in the system of interest. The more net disruptive influence on the system, the further along it is likely to be in its process of disruption. That is, more mature and appealing disruptors which have greater resilience to planetary risk and enjoy support from

governments, finance and citizens can more easily and rapidly displace incumbents. Visually, this helps to 'position' the system along the disruption phases and S-shaped curve shown in Figure 5 (this is shown in Figure 10 for the power sector).

4. Use the results of steps 1, 2 and 3 to identify leverage points for navigating disruption. In the climate change context, businesses can navigate disruption by working to accelerate just decarbonisation in line with global goals, while building their own resilience to physical and transition risks. In other words, *disrupt or be disrupted.*

Figure 6: Key questions to ask for each system driver.

There are two important considerations when identifying leverage points:

1. What are the greatest challenges and barriers to disruption? These tend to be the greatest sustaining influences as identified in step 2. In some cases, sustaining influences stem from undesirable attributes of disruption (eg critical mineral requirements of electric vehicle batteries or smallholder livestock farming livelihoods which might be lost to alternative proteins). In these cases, there is not only a question of how to accelerate disruption, but how to influence it to co-produce socially desirable outcomes. Often, removing sustaining influences can unlock 'low hanging fruits', where large gains can be made by only small changes in policy, innovation, messaging or cultural norms. For instance, technologies already exist to enhance energy efficiency in buildings and drought tolerance in cropland, but policy, finance and information gaps hinder their deployment.
2. How can feedbacks and synergies be exploited to positively influence disruption? Particularly well-connected system drivers can provide opportunities to qualitatively change system states with less intrusive interventions via feedbacks and tipping points. Such leverage points often correspond to system drivers with high disruptive potential but low disruptive influence at present. These leverage points can create the enabling conditions to induce positive tipping points for rapid and self-sustaining decarbonisation.

Chapters 4, 5 and 6 apply the DSD framework as described in this section to analyse low carbon disruption in the global electric power, transport and agriculture sectors.

3.4 An applied business perspective on disruption

As incumbent systems fall into decline, there will be both positive and negative implications. Low carbon disruption has obvious benefits: it will mitigate the existential threat of climate change while also promoting numerous social co-benefits, including improved health, energy access and security, comfort, ecosystem integrity, productivity and employment.[52] On the other hand, individual firms and employees might experience detrimental disruption from the low carbon transition as revenue streams and jobs are lost in certain sectors or geographies. A growing body of literature describes the importance of a "just transition" to mitigate the potentially adverse impacts (eg on employment) caused by low carbon disruption.[53]

For businesses, systemic low carbon disruption has several practical implications. As the system drivers coalesce around disruption, businesses operating within incumbent systems may become obsolete if they do not adapt. Adaptation may be achievable by embracing low carbon technological innovations while maintaining business models; however, in many cases, entire business models or even business paradigms must shift to align with low carbon practice. Such realignment demands that businesses redefine organisational purpose and strategy, embrace new technologies and practices, and engage with other stakeholders (eg competitors, businesses in complementary industries and along supply chains, policymakers, financiers and the public). In doing so, businesses can themselves become disruptors and accelerate the low carbon transition. This is easier said than done: low carbon realignment can entail high upfront costs and – perhaps more importantly – a willingness to reconsider core strategies. Indeed, many businesses have thus far failed to embrace low carbon disruption. For instance, the fossil fuel industry has long worked to delay low carbon disruption, employing tactics historically used by other now-disrupted industries.[54] That said, the existential risk to emissions-intensive businesses which refuse to adapt has never been higher (and we expect it will continue to increase) due to compounding physical and transition risks.[55] Continuing to resist low carbon disruption has become a dangerous game.

Low carbon disruption also brings numerous business opportunities. Disruptive start-ups and incumbents alike can capitalise on opportunities to provide low carbon technologies and services, as well as the enabling and ancillary services upon which low carbon value chains will rely. Businesses which innovate towards low carbon disruption will position themselves as leaders in a low carbon economy and will benefit from supportive policy, financial and reputational environments while maintaining compatibility with planetary boundaries and future markets.

4. Power: disruption well underway

This chapter demonstrates how the DSD framework can be operationalised to characterise ongoing disruption in the power sector: specifically, the disruption of fossil fuels by low-cost renewables such as solar PV and wind. We analyse the current state and history of each system driver. From this analysis, we draw conclusions about the nature of power sector disruption and describe leverage points for accelerating decarbonisation in this sector. Please see Appendix A for a more detailed analysis of the system drivers and their impact on the power sector.

4.1 System drivers in the power sector context

Planetary change poses a threat to the power sector as a whole; on balance, however, the planet represents neither a very strong direct disruptive nor direct sustaining influence. Point-source infrastructure (such as thermal power plants, ports and pipelines) is vulnerable to extreme weather, which could disrupt incumbents in the sector. Water stress could hurt both fossil fuel generation (ie thermal coal and gas) but also some low carbon generation (ie nuclear and hydroelectric). Land use competition, meanwhile, could hinder the expansion of solar PV and wind. Planning for resilience to planetary change is crucial to ensure energy availability and security, but it will not be a clear driver of change in the power sector. Of course, the power sector's substantial GHG emissions and contribution to climate change today expose it to a high degree of transition risk (ie asset stranding), but we consider this to be an indirect disruptive influence as it is mediated via other system drivers.

Technological change is a major driver of current disruption trends in the power sector and looks to be a crucial disruptive influence in the coming decades. Figure 7 shows global installed capacity of wind and solar PV[56] and levelised costs of electricity (LCOE) for wind and solar PV compared to the fossil fuel generation cost range[57] over the years 2010 to 2021. As the figure demonstrates, levelised generating costs for solar PV and both onshore and offshore wind have plummeted in recent years, now falling at the very low end of (or completely below) the cost range for fossil fuel generation. This cost decline has gone hand in hand with an exponential rise in renewables deployment, especially solar PV and offshore wind. Costs have also fallen for batteries and hydrogen electrolysers, both of which can add flexibility to electric power grids and further enable the integration of intermittent solar and wind energy.

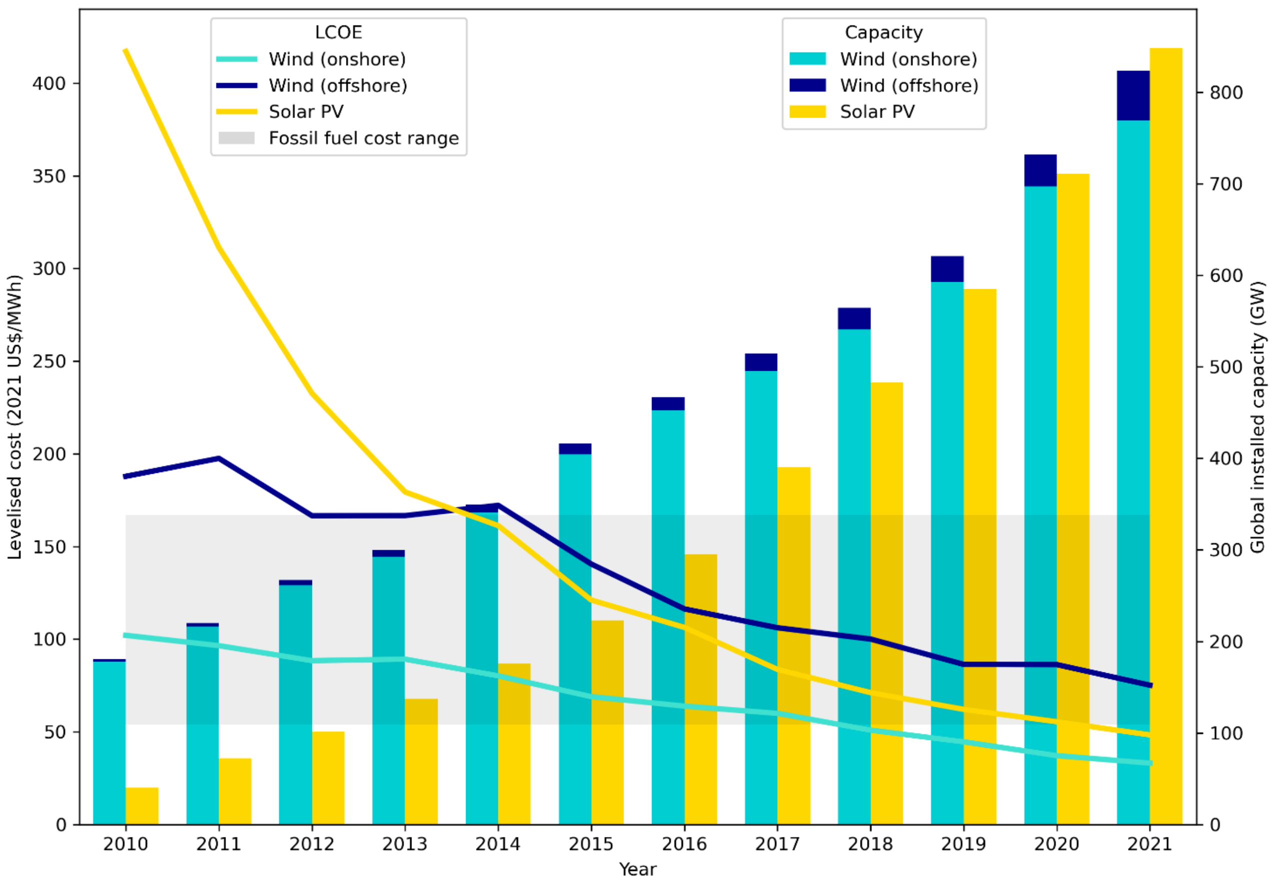

Figure 7: Installed capacity and LCOE for wind and solar PV, 2010–21.

The sector still faces some technological challenges: the intermittency of solar and wind energy means that integrating very high shares of these technologies in the power mix will require innovative approaches to energy storage, transmission, low carbon dispatchable generation and demand-side management. However, the picture is much rosier than even a decade ago, when without government support renewables were far more expensive than fossil fuel generation. Technological innovation in carbon capture, utilisation and storage (CCUS) technology could lock in fossil fuel dominance in the power sector and hinder or delay disruption by renewables. However, the sluggish historical pace of innovation and cost declines in CCUS technology, compared with the consistent and exponential cost declines experienced by renewables and storage, suggests that this is only a weak sustaining influence.

Solar PV and wind energy now account for the majority of new electricity-generating capacity additions worldwide, as Figure 8 shows.[58] In the figure, 'Others' includes capacity additions for nuclear, oil & diesel, biomass & waste, other fossil fuels and geothermal.

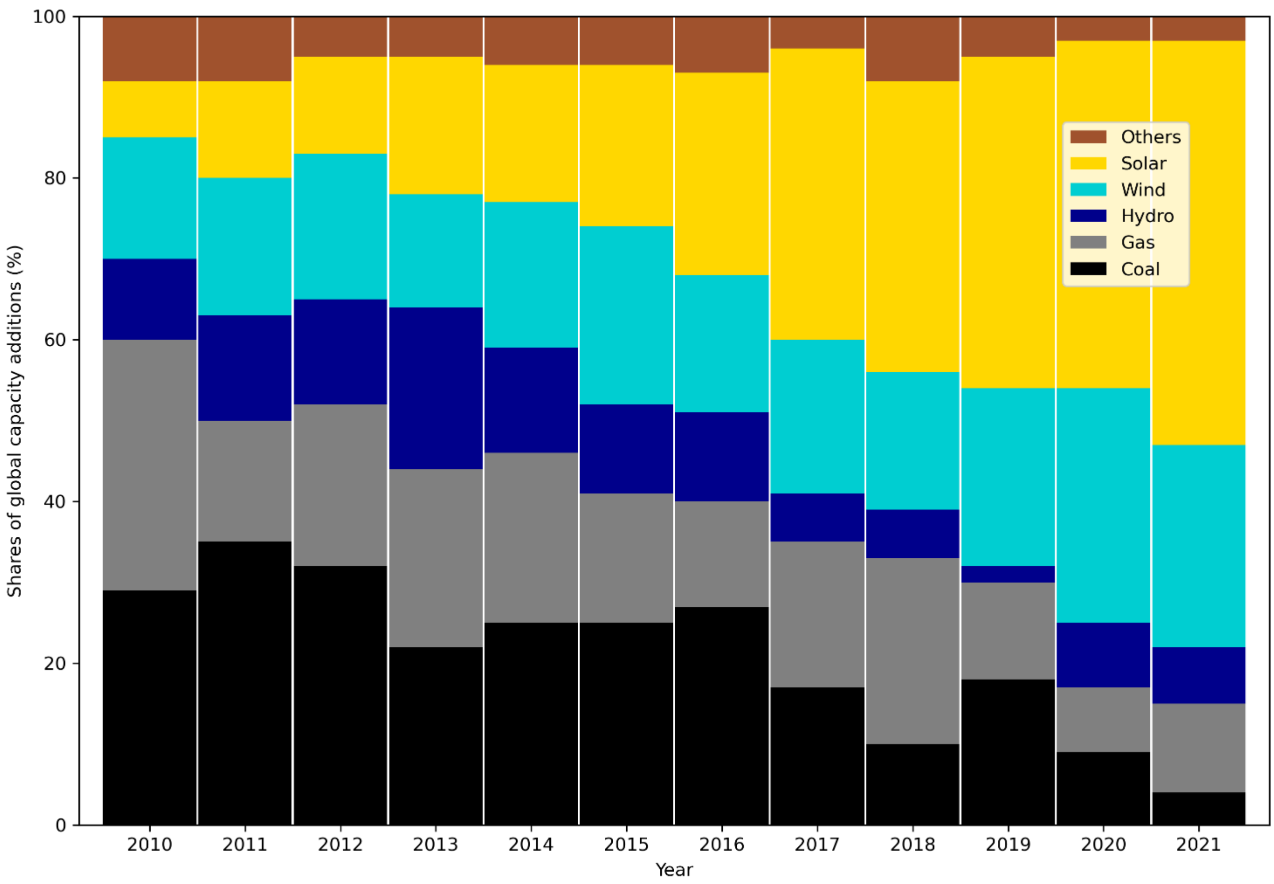

Figure 8: Shares of global new power capacity additions by source, 2010–21.

The story of CCUS serves as a warning for incumbents in other sectors. Many decades ago, when climate science was settled but renewable energy was still more expensive than fossil fuels, incumbents could have invested meaningful time and resources towards developing CCUS. This might have made their core business models compatible with a low carbon future, thereby preserving a path to future viability. Instead, they lobbied against regulation, spread doubt about climate science consensus,[59] and incrementally improved their technology's efficiency and environmental impact to preserve their near-term dominance.

As fossil fuels in the power sector face imminent disruption, CCUS is heralded by some incumbents (and governments) as a potential solution although it has experienced persistent delays to implementation at industrial scale.[60] While CCUS could provide an attractive option for decarbonising harder-to-abate sectors such as concrete and steelmaking, it no longer appears to be viable in the power sector: it simply cannot compete with renewables plus storage on a cost basis other than for 'peaker' load balancing and emergency backup generation. The only remaining recourse is for electricity generators, utilities and users to radically reconfigure in alignment with a renewables-centred system. However, it is important to remember that this path was not inevitable. Early and radical innovation could have staved off disruption, as it still can in other sectors.

Government policy has historically sustained incumbents in the power sector through fossil fuel subsidies. Fossil fuel subsidies (both explicit and implicit, ie subsidies below the socially efficient cost) continue to sustain fossil fuels in the power sector, as do regulatory barriers to renewables expansion. Furthermore, fossil fuel exporting states continue to support fossil fuel extraction as a source of fiscal revenue and to enhance energy security. However, government policy in many countries with ambitious climate targets has rapidly shifted such that this system driver now exerts a largely disruptive influence on the power sector.

For example, carbon pricing is shifting investment incentives across the global power sector: over half of global electricity generation is covered by either a carbon price or emissions trading scheme (ETS). Figure 9 shows global coverage of electricity generation[61] by carbon pricing[62] (either carbon tax or ETS). Only those carbon pricing schemes which cover the power sector are included. For Canada, the US and China, subnational-level data from 2017,[63] 2021[64] and 2018,[65] respectively were used to estimate each province or state's share of the national total. Note that this figure does not show emissions coverage, which has been estimated at both lower[66] and higher[67] levels. Although emissions coverage may be more useful for thinking about the emissions reduction potential of decarbonisation policy, electricity generation coverage is more useful for thinking about market disruption potential. Since China's introduction of a power sector ETS in 2021 (which roughly doubled electricity generation coverage of carbon pricing), carbon pricing has enhanced the cost advantage of renewables in most of the global market, above and beyond their levelised cost advantage. We expect this will trigger further innovation and cost reductions, which will only accelerate low carbon disruption.

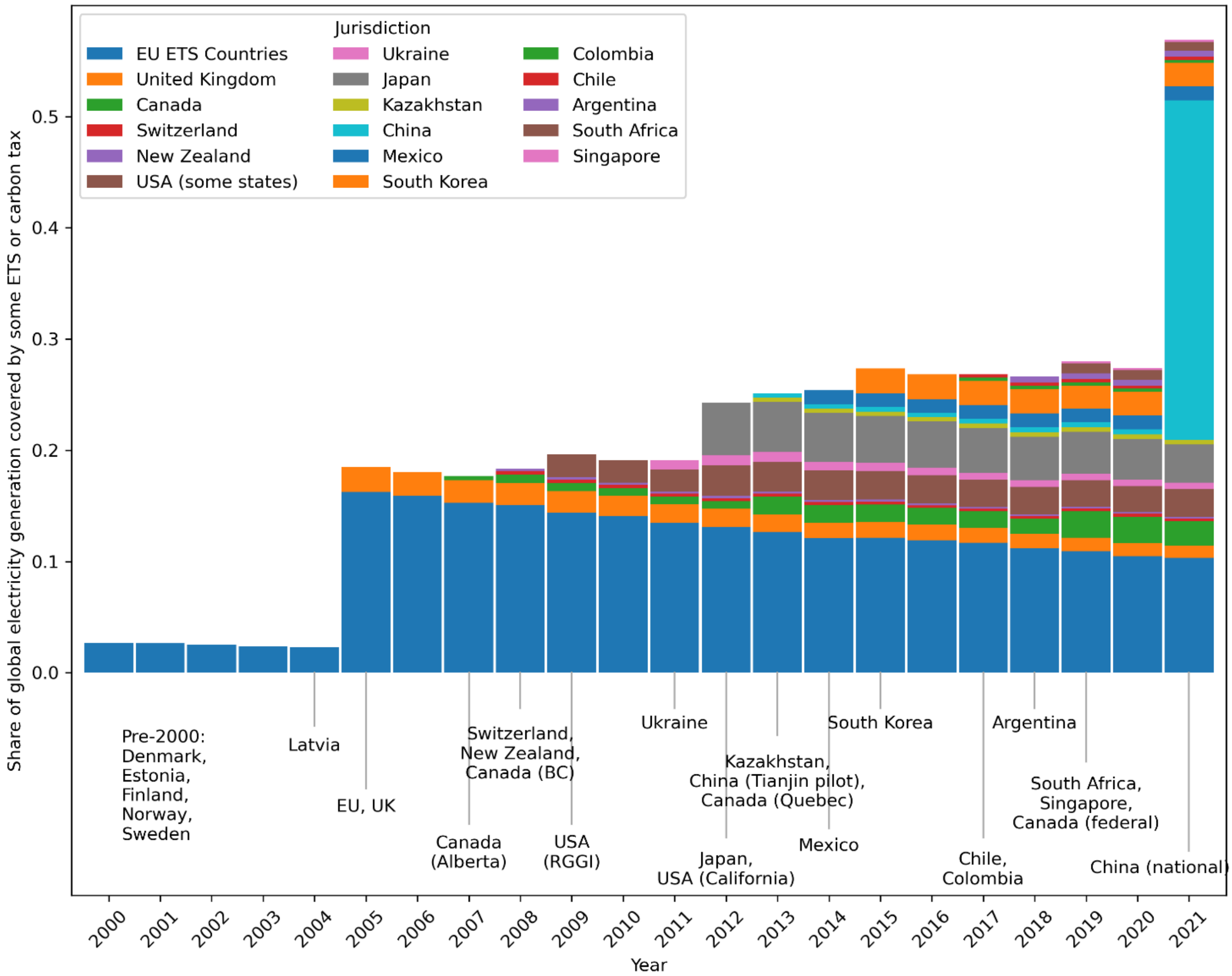

Figure 9: Share of global electricity generation covered by carbon pricing, 2000–21.

In addition to carbon pricing 'stick' policies, governments now find themselves in what has been dubbed a 'clean energy arms race' to support domestic renewable energy sectors through 'carrot' industrial policy, most notably the Inflation Reduction Act in the US and the Green Deal Industrial Plan in the EU. This has only accelerated in response to Russia's war in Ukraine, which has highlighted the energy security risks associated with continued reliance on fossil fuel imports. Indeed, low carbon electricity now appears to be the option which *enhances* energy independence and security in most of the world.

Finance, which has long sustained fossil fuel energy systems by providing upfront capital and insurance in such a capital-intensive sector, has also shifted in recent years to become an agent of disruption. As the perceived risk of renewables falls, so too does the cost of capital for renewable energy projects. Simultaneously, fossil fuel investors now face higher capital costs and insurance premiums as physical and transition climate risks become clearer. Some challenges remain, such as financing riskier energy storage projects and other renewables-enabling ancillary services; however, finance has – on balance – become yet another disruptive force.

Lastly, citizens may contribute to power sector disruption. Although individual consumers have less market power in this highly centralised market than in, say, the vehicle or food markets, many have nevertheless played a role as owners of distributed energy resources (DERs) – most notably, rooftop solar PV. Even though rooftop solar PV represents a minority of current and projected global solar PV installed capacity, it remains a substantial source of renewable energy.[68] Furthermore, distributed energy storage could play a key role in balancing renewables intermittency.[69] While DERs have historically been available only to wealthy consumers, they could proliferate more widely if enabling conditions are established via policy and financial incentives.

Citizens can also effect system change as investors, activists and voters. Community energy projects show promise as a means of further accelerating renewables deployment, and citizens in many jurisdictions increasingly support government policies which embrace renewables and reject fossil fuels. Local resistance and the prevalence of 'not in my backyard' (NIMBY) sentiment could hinder renewables deployments, but this is likely to only slow – rather than prevent – the sector's ongoing low carbon transformation.

4.2 Disruption assessment

Disruption is well underway in the power sector. Low-cost renewable energy, especially solar PV and wind, now represents a scalable and low-cost alternative to fossil fuels for generating electricity. Beyond the technological innovation that has made this possible, government policy continues to support the expansion of low carbon electricity at the expense of conventional fossil fuel generation. Finance is further supporting this transition: the cost of capital has fallen for low carbon technologies and is expected to rise for fossil fuel generation as investors increasingly price in physical and transition climate risks. The latter includes the risk of stranded assets due to economic unviability. There are still some sustaining influences in the power sector in the form of regulatory and financial barriers to renewables deployment; technical and policy challenges facing ancillary services such as energy storage, transmission and distribution; and lingering local public opposition to renewable energy projects. However, the balance of influences on the sector is overwhelmingly disruptive, as summarised in Table 2 and shown graphically in Figure 10. In Table 2, light shading represents low influence, medium shading represents medium influence and dark shading (with white text) represents high influence.

Table 2: Disruptive and sustaining influences in the power sector.

	Disruptive influences	Sustaining influences
Planet	Physical risk to point-source generation and fuel distribution from climate change, water stress to thermal generation, indirect impact via transition risks	Physical risk from climate change, water stress and land use competition for various low carbon technologies
Technology	Cost reductions for renewables (solar PV and wind), batteries and hydrogen electrolysers	Intermittency management with ancillary services, lock-in potential from carbon capture and storage
Government	Decarbonisation policy (regulation, carbon pricing, low carbon subsidies, feed-in tariffs), climate damage litigation risk, long-term energy security advantages of renewables	Regulatory barriers to renewables construction and grid integration, energy security and revenue concerns for fossil fuel exporters, geopolitical concerns around critical minerals
Finance	Increasing cost of capital and insurance for fossil fuel generation considering stranded asset risk, decreasing perceived risk of renewables	Financial barriers for ancillary services (storage, transmission, distribution), shrinking fiscal space and low private sector participation in renewables investment in some countries
Citizens	DER ownership, community energy investment, voting and activism to accelerate fossil fuel phase-out	Local public opposition to renewables (NIMBY)

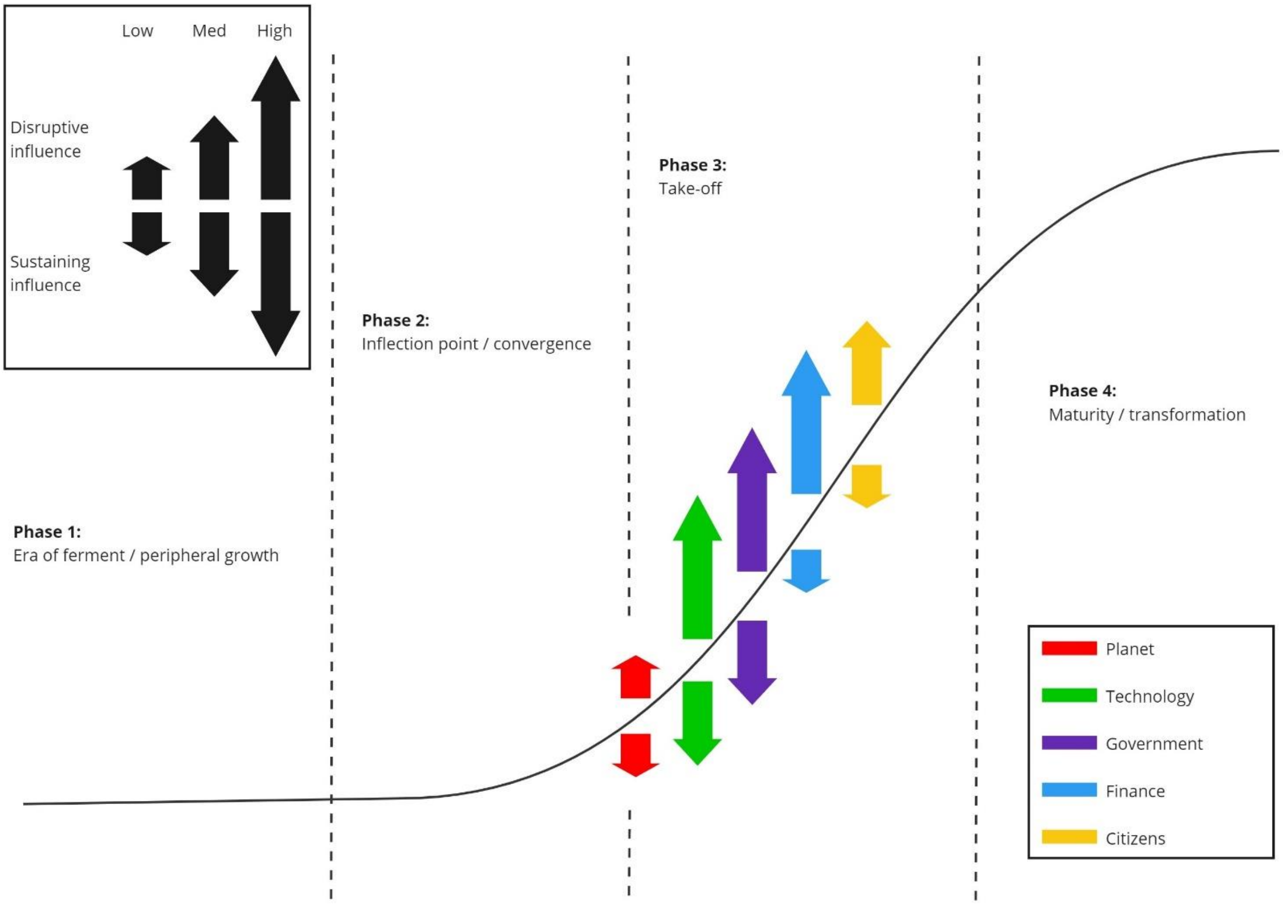

Figure 10: Disruptive and sustaining influences in the power sector.

4.3 Leverage points

The following leverage points were identified following our analysis of imminent near-term disruption in the power sector. As Section 2.3 describes, these correspond to lingering barriers and sustaining influences which can be feasibly and quickly overcome, and also to opportunities to promote synergies and feedbacks both within and between system drivers.

1. **Innovate in intermittency management.** Government-supported clean energy innovation has been a key driver of low carbon disruption to date, but insufficient attention has been paid to the ancillary services required by high shares of intermittent renewable energy: energy storage, transmission, distribution, zero emissions dispatchable power and demand-side management. Indeed, despite technology's high disruptive influence, it also poses a moderate sustaining influence as energy storage, transmission, distribution and demand management are currently far too underdeveloped to support high levels of renewables integration. Firms can radically innovate towards this challenge on multiple fronts. On the supply side, they can advance energy storage and smart grid technology. On the demand side, they can create business models which enable more flexible energy use profiles in both their own operations and consumer operation of their products. This may be rewarded by a future dominated by low-marginal-cost energy. That said, reaping these rewards relies on electricity, capacity and ancillary service markets which reflect the true cost of energy and incentivise energy use during periods of low net demand. This is a crucial area for policy innovation and regulatory reform. Investors and entrepreneurs should recognise

the radically new opportunity presented by a future in which temporally shifting supply is as (or nearly as) valuable as generation, and temporally shifting demand is as (or nearly as) valuable as conservation.

2. **Eliminate regulatory barriers to renewables deployment.** Renewables produce cheaper energy on average than fossil fuels and can, in many regions, advance energy independence and security. However, their deployment can be impeded by regulatory barriers such as long and complex permitting processes, long waitlists for grid integration, and limited access to finance given high upfront costs (capital costs constitute a particularly high share of levelised costs for renewables due to low or non-existent fuel, operations and maintenance costs). Limited financial access is particularly problematic in higher-risk markets such as emerging economies. Weakening and reversing these sustaining influences (primarily in the government and finance system drivers) should be pursued with the same urgency as strengthening disruptive influences to achieve decarbonisation objectives. Governments should seek ways to reduce permitting times and grid integration waitlists (eg through higher resource allocation to reviewing agencies) while balancing the environmental and justice concerns associated with project siting and development. Innovative financial instruments – born from collaboration between investors, insurers, governments and the private sector – would further reduce barriers to renewables deployment.

3. **Foster international collaboration.** In an internationally collaborative environment, renewable energy deployment anywhere will breed cost reductions everywhere as supply chains scale and technological learning 'spills over' across borders. International co-operation can also be a source of much-needed flexibility to counter intermittency: continent-scale networked power grids can reduce the need for energy storage.[70] On the other hand, geopolitical competition could stifle low carbon transformation as supply chain and raw material bottlenecks hinder production. This is particularly true for critical mineral resources, which are geographically concentrated but of crucial importance worldwide. It is therefore critical that actors in the private, public and financial sectors work to foster a radically collaborative environment for the expansion of renewable energy and ancillary services worldwide (and to ramp up circularity and resource recovery to reduce this reliance in the first place). This also entails a high level of technology and knowledge transfer: just because solar PV and wind energy *can* be deployed at a lower cost than fossil fuels, they may not be if gaps persist in knowledge, workforce skills and capital. Technology transfer and low carbon power financing is a critical enabler of sustainable development, particularly given the air quality and health co-benefits of power sector decarbonisation. International collaboration could transform planetary, technological and regulatory sustaining influences into interlinked disruptive influences to accelerate decarbonisation.

4. **Finance the scale-up of renewable electricity systems.** It is increasingly clear that decarbonising electricity generation is more a question of scale and speed than of technological invention. Mature technologies already exist for low carbon power generation, but immense sums of capital will be required to scale renewable generation, electric power grids and intermittency management technologies at the pace required to achieve Paris Agreement targets. This will require innovative financing instruments and unwavering commitment from public and private actors alike. Finance already represents a disruptive influence, but an even more concerted effort is needed to achieve ambitious climate targets.

5. **Improve public opinion of renewables.** Solar PV and wind continue to face political and local opposition which further hinders their deployment. Some of this opposition is fuelled by mis- and disinformation about renewable energy, but much of it is simply a product of ‘not in my backyard’ (NIMBYism) which can nonetheless bring project planning to a grinding halt. Such opposition fuels sustaining influences in the government and citizens system drivers, but public and grassroots information campaigning could help overcome this barrier. In part, this could entail framing the continuation of the status quo as an active violation of environmental justice principles: while a wind farm or solar PV array might somewhat alter the landscape, this pales in comparison to the impacts of fossil fuel power plants and refineries on the local air quality and environment (which disproportionately affect low-income and marginalised communities at present).

5. Road transport: disruption taking off

This chapter applies the DSD framework to more nascent disruption in the context of private car use within the road transport sector. BEVs have emerged as a dominant technology, which appears poised to overtake incumbent ICE vehicles and thereby disrupt the latter's entire service and supply chains. Although only a tiny fraction of all cars on the road are BEVs, they accounted for 14 per cent of new car sales in 2022 – over a tenfold increase from their share in 2017.[71] As in the power sector, analysing the state of the five system drivers and characterising disruption in this context can help identify leverage points to accelerate road transport decarbonisation. A more in-depth review of system drivers in the road transport sector appears in Appendix B.

5.1 System drivers in the road transport sector context

The planet exerts neither a very strong disruptive nor sustaining influence on the road transport sector. Infrastructure is at increased risk of damage from natural disasters made more severe and frequent by climate change. While this impacts both high carbon and low carbon transport modes alike, it presents the opportunity to rebuild infrastructure to be more climate-friendly (eg by including bus or bicycle lanes). On the other hand, BEVs have high mineral requirements – including some critical mineral resources, such as lithium, nickel and cobalt – which the planet may only barely be able to accommodate.

Technology and technological change exert a substantial disruptive influence in the sector. As Figure 11 shows, the global BEV and plug-in hybrid electric vehicle (PHEV) fleets have grown exponentially over the past decade.[72] Simultaneously, the cost of lithium-ion battery packs – which currently drive the lion's share of upfront costs for BEVs and PHEVs – has fallen drastically, accelerating this market change.[73] Battery costs increased slightly from 2021 to 2022 due to supply chain constraints and rising raw materials prices, but they are expected to fall again in 2024 and beyond.[74] Although PHEVs still produce tailpipe emissions and sustain the dominance of the ICE in new automobiles, we include them because their proliferation spurs further innovation in batteries, which are likely to eventually unseat ICEs completely.

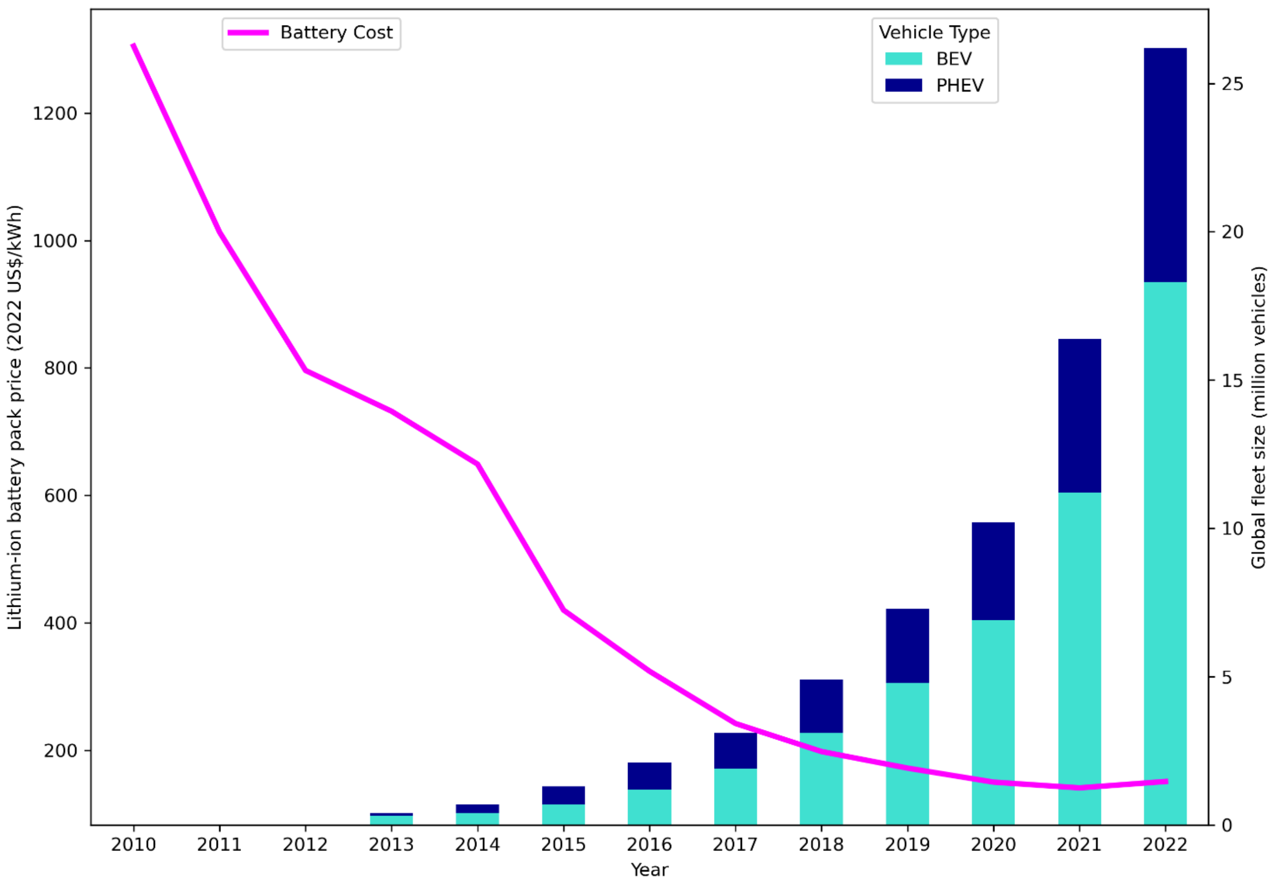

Figure 11: Lithium-ion battery pack price and BEV+PHEV fleet size, 2010–22.

Another dimension of technological disruption in road transport concerns ICT technologies, specifically mobility-as-a-service (MaaS) and autonomous driving. These innovations, especially in tandem, could reduce the number of cars on the road and further accelerate ICE disruption by BEVs. BEVs outperform ICE vehicles in both cases. For MaaS, this is due to the importance of operating as opposed to upfront costs (where BEVs shine) when vehicle utilisation is higher, whereas autonomous driving is outperformed by the lower latency of electric vehicle drivetrains and the stable power provided by onboard batteries for sensing and computation. It should be noted that all these innovations, and the rise of BEVs in general, serve to sustain many incumbent components of the road transport sector (road networks, the automotive industry, car culture, etc). This chapter focuses on the low carbon disruption triggered by BEVs replacing ICEs on the road, but further lifecycle emissions reductions could be achieved by disrupting the personal vehicle paradigm more broadly via walking, cycling and public transport.

Government policy exerts a disruptive influence in the road transport sector: in recent years, many governments have introduced zero emissions vehicle (ZEV) mandate targets or legislation, which require a certain proportion of new vehicle sales to be ZEV by a certain year. As Figure 12 shows, these ZEV mandates now cover much of the globe.[75] In particular, the world's largest vehicle markets (China, the EU, the US and Japan) each have partial or total ZEV mandates in place for the year 2035.

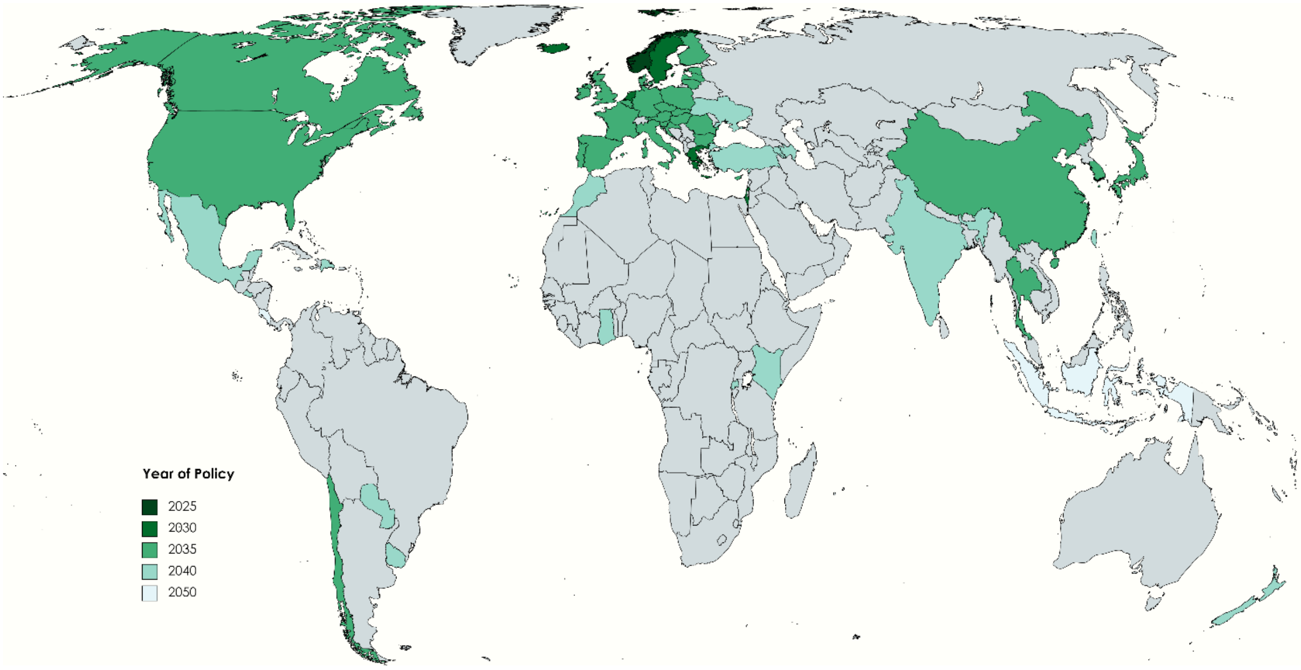

Figure 12: Vehicle decarbonisation targets or policy by country.

In fact, the vast majority of global new vehicle sales are now covered by a ZEV mandate. Figure 13 shows the proportion of 2021 passenger vehicle sales[76] covered by decarbonisation policy, coloured by region and the year of the target or policy (eg 100 per cent ZEV sales or 100 per cent ZEVs in public procurement by 2035). Countries with targets or policies are allocated a wedge each, while uncovered countries are grouped. Countries with over 1 million passenger vehicle sales in 2021 are labelled. Note that some countries have mandated ZEVs before 2035 (ie 2025 or 2030 – see Figure 12). Over three-quarters of 2021 sales are covered by a 2035 mandate, and even more are covered by a 2040 or 2050 mandate.

These ZEV mandates encourage manufacturers to innovate in and expand their BEV and other ZEV production, which should further induce cost declines and performance improvements for these disruptive technologies. In contrast with the power sector (and especially with the agriculture sector), governments exert little sustaining influence in the road transport sector. Petrol is already taxed in many regions, which means its economic subsidy (accounting for climate change and other externalities) is lower than for other fossil fuels, although governments in some oil-exporting countries continue to prop up the industry.

Other policy instruments which support BEVs could accelerate road transport decarbonisation. For instance, BEV subsidies in Norway have worked synergistically with an expansive charging network and social network effects to promote a rapid transition to BEVs.[77] Similar subsidies elsewhere, coupled with more stringent near-term fuel efficiency standards on ICE vehicles, could further accelerate low carbon market disruption in road transport.[78]

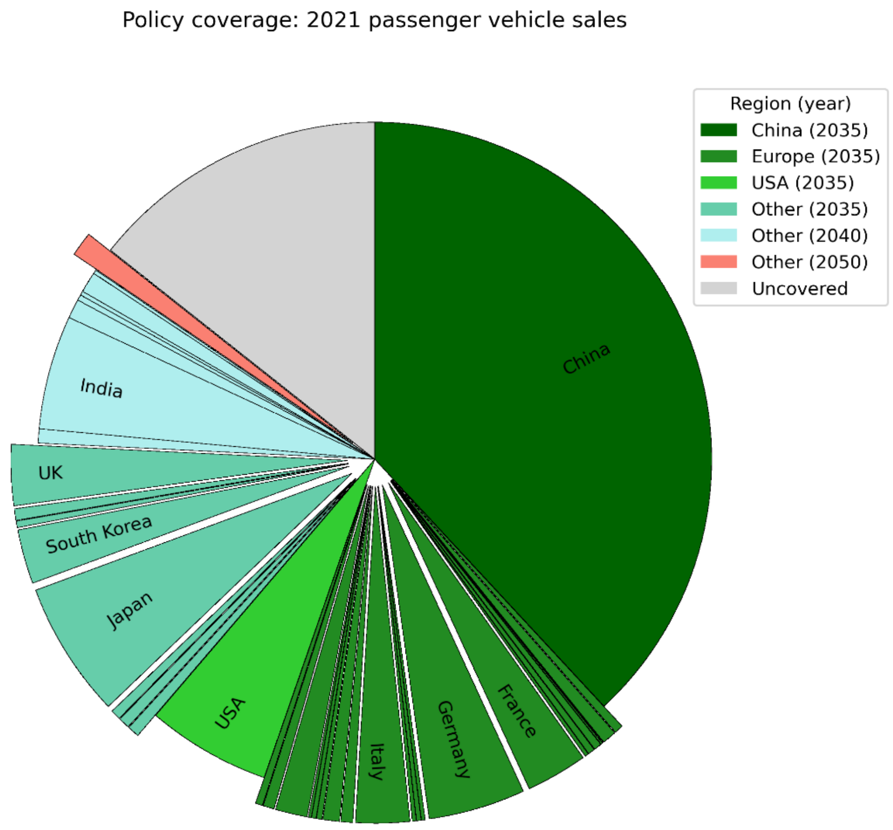

Figure 13: Passenger vehicle sales coverage of ZEV mandates.

Finance could further aid and accelerate road transport disruption. At the level of investment in research, development and production of BEVs and other ZEVs, lower costs of capital will spur further innovation and enable more widespread deployment of low carbon vehicles. Recent years have seen a major influx of capital to BEV development by incumbent automotive manufacturers and disruptive market entrants alike. Because BEVs tend to be characterised – for now – by higher upfront costs and lower operating costs than ICE vehicles, innovative financing instruments at the point of purchase may also accelerate this transition. Although the lack of widespread and attractive financing options specific to BEVs represents a minor sustaining influence in this sector, there is already some progress in developing 'green auto loans' to facilitate greater BEV adoption.

Citizens exert a substantial *gross* disruptive influence on the road transport sector (see below for a discussion of citizens' sustaining influence). Because vehicle purchase decisions are made at the individual level, consumer sentiment and preferences are central to the evolution of the market. A high and increasing proportion of the population is open to the idea of driving a BEV, as consumers are attracted not only to the lower lifecycle emissions but also to lower fuel and maintenance costs, and performance features such as rapid acceleration and a quieter cabin. Given the power of social networks and availability biases, consumer enthusiasm about BEVs is likely to increase in the coming years as the vehicles become more commonplace. Even more disruptive is the fact that consumers are increasingly rejecting car ownership, turning instead to walking, cycling, MaaS and public transport. This trend is strongest among young adults, who would be the car buyers of the future. If this trend accelerates, the dominance of the personal vehicle itself could be challenged in the medium and long terms. However, in the near term, the disruption of ICEs by ZEVs (particularly BEVs) seems more likely.

Despite its disruptive potential, consumer sentiment simultaneously presents the greatest barrier to BEV adoption, thereby sustaining the incumbent ICE-dominated road transport system. Consumers who are unwilling to purchase a BEV cite high upfront prices, short driving ranges ('range anxiety'), long charging times and a lack of public chargers as the most important factors. In this area, developments spurred by other system drivers may be able to ameliorate these fears. Beyond decreased costs, battery innovation has increased driving ranges such that many new BEVs can travel as far on a single charge as an ICE vehicle on a single tank of fuel.[79] Charging infrastructure also figures to proliferate in the coming years.

Figure 14 shows the projected average direct current charging power accepted by new BEVs in the US,[80] the corresponding time to charge to 500 km of range (assuming driving efficiency of 6 km/kWh, in line with an efficient new BEV[81]), and the projected number of public charging stations in North America[82] through 2030. As the figure shows, the number of public charging stations in the US is expected to increase exponentially over the next decade (due to industrial policy and an influx of capital), while a roughly exponential increase in DC charging rate (owing to technological innovation) leads to a roughly linear decrease in the time required to fully charge a BEV. Similar trends are expected in other major vehicle markets, and the rest of the global market is likely to follow. All told, there is reason to believe that consumer hesitancy around BEVs could decrease sharply in the near term, thereby accelerating disruption.

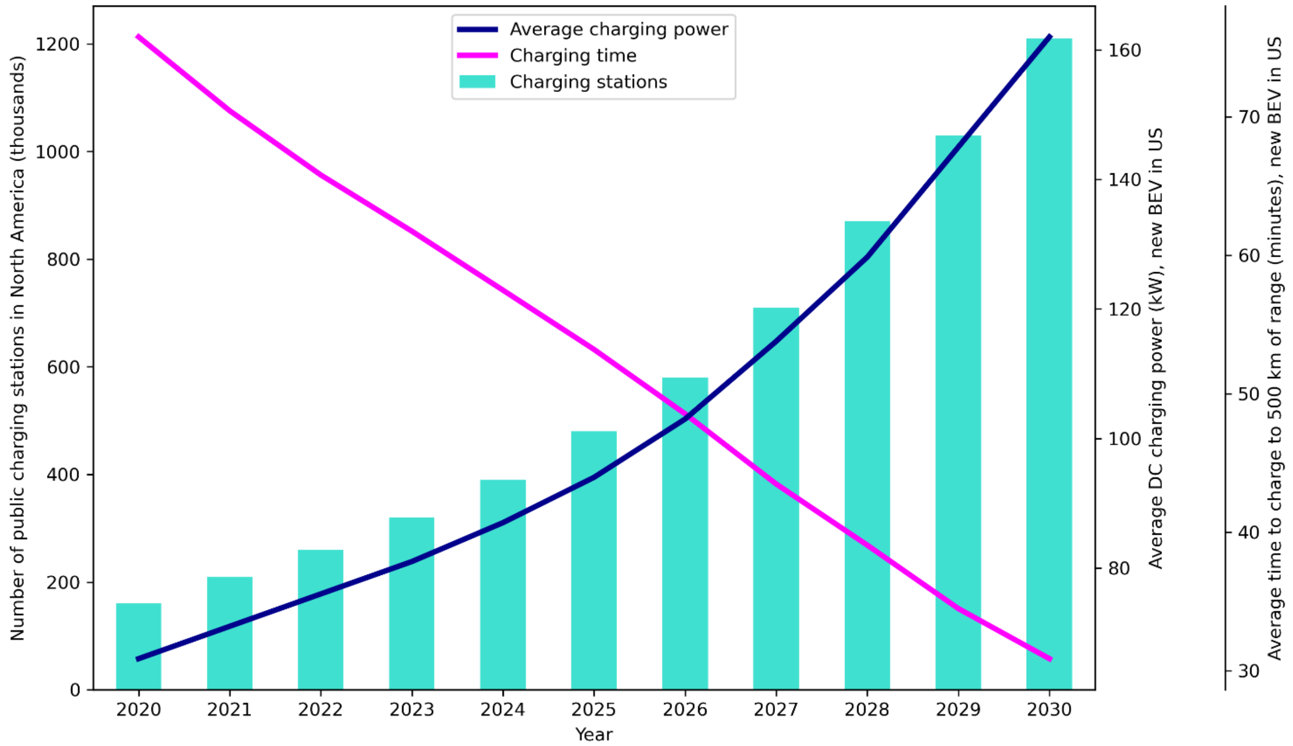

Figure 14: Charging power, time and prevalence in the US, 2020–30.

5.2 Disruption assessment

Disruption is at a more nascent stage in the road transport sector than in the power sector. The primary technology threatening incumbent ICE vehicles – the BEV – is less mature than solar PV or wind energy, as it has not yet reached parity in upfront cost with ICE vehicles in most markets (although lifetime costs tend to be lower). In this sector, governments, finance and citizens also exert weaker – albeit still disruptive – influences than in the power sector. In the spirit of the DSD framework, we see this as both a symptom and a result of the sector's more moderate current level of disruption. That said, the pieces are in place for the road transport sector to be disrupted in the next two decades, particularly via continued technological improvement, supportive government policy and increasing consumer familiarity with BEVs. Table 3 summarises the state of the system drivers and Figure 15 visualises our disruption assessment. Light shading in Table 3 represents low influence, medium shading represents medium influence and dark shading (with white text) represents high influence.

Table 3: Disruptive and sustaining influences in the road transport sector.

	Disruptive influences	Sustaining influences
Planet	Damage to infrastructure presents opportunities to rebuild differently, indirect impact via transition risks	Critical mineral constraints for BEVs
Technology	Rapid cost reductions in batteries and corresponding proliferation in BEVs, co-ordination feedback between BEVs and charging infrastructure, ICT innovations such as MaaS and autonomous driving	Underdeveloped public charging infrastructure, persisting profit gap for automakers (less profit from BEVs), even BEVs sustain the auto industry and 'car culture'
Government	Increasing ZEV mandates, public procurement programmes and incentives for consumers to choose ZEVs/BEVs	Fiscal income from fuel production (for fossil fuel exporters), strong automotive lobby
Finance	Increasing investment in low carbon transport and some green auto loans	Finance is still a barrier for BEV purchase as terms of loan can make or break affordability
Citizens	Increasing consumer enthusiasm about and openness to BEVs and non-automobile transport	Range anxiety, perception of unavailable and slow charging, high upfront price

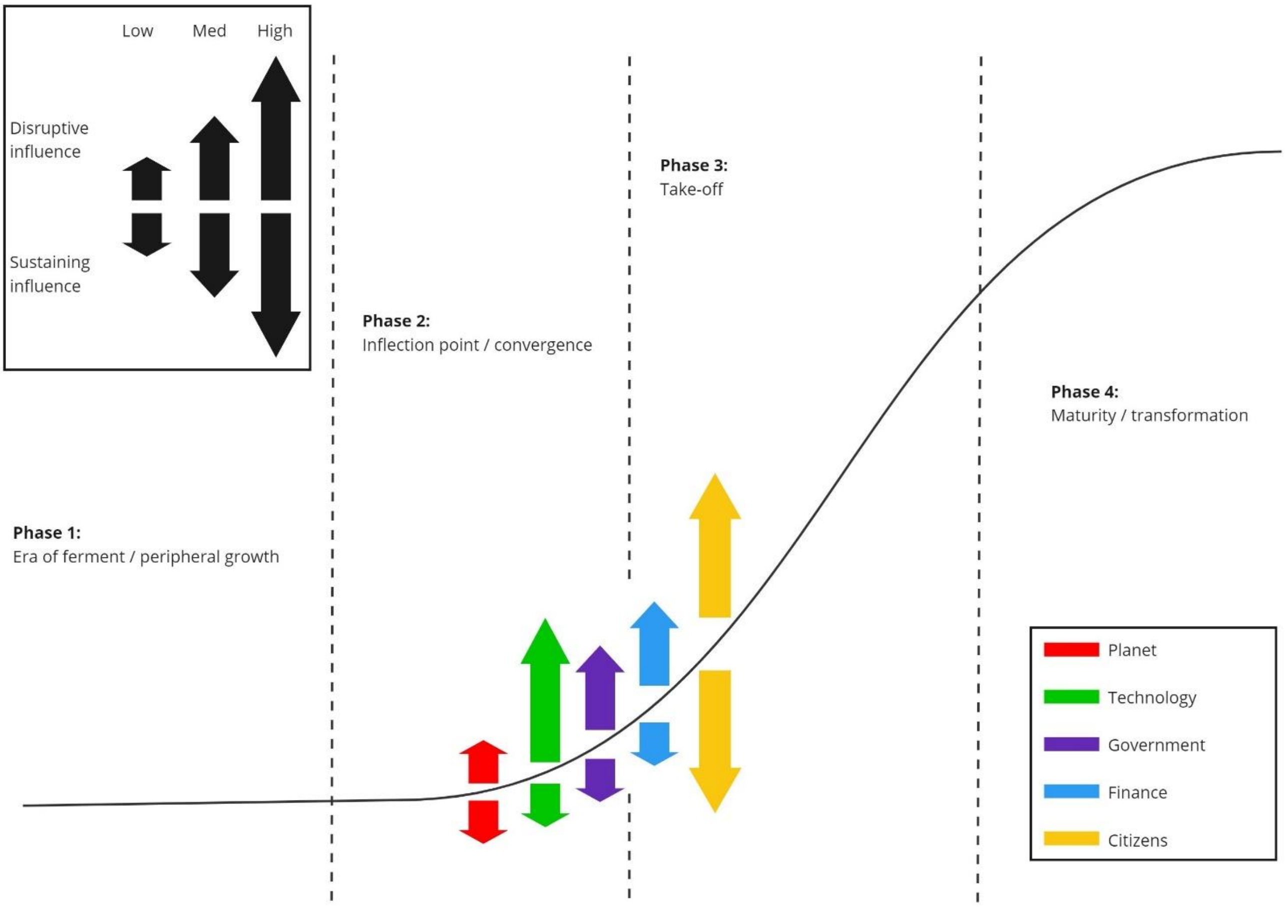

Figure 15: Disruptive and sustaining influences in the road transport sector.

5.3 Leverage points

Disruption appears inevitable and imminent in the road transport sector, due in large part to looming ICE bans in many countries. However, the exact formula for this disruption is less clear than the power sector's solar-wind-battery future. BEVs seem poised to dominate in the near and medium terms, but barriers exist in the form of mineral requirements and consumer wariness. These leverage points could help incumbents, disruptors and governments navigate future road transport disruption by paving the way for the 'BEV revolution' while maintaining openness to radically new transport paradigms.

1. **Scale up BEV production to meet growing demand.** Demand currently outstrips supply for BEVs. Messaging from governments and investors worldwide is clear that the future is dim for vehicles which produce tailpipe emissions. Furthermore, we expect consumer interest in BEVs to increase as BEV technology improves, charging networks proliferate and social contagion takes hold. Those manufacturers that can deliver will reap the rewards of the transition. Scaling up production will unlock synergies between the system drivers: technology will improve, investment will be perceived as safer and consumer wariness will decline as familiarity increases. This, in turn, will unlock the full potential of consumers as disruption drivers.
2. **Establish diverse and circular supply chains.** Critical mineral resource constraints have already slowed BEV diffusion. Indeed, the recent uptick in battery prices (which largely drive BEV sticker prices) was a direct result of global supply chain and raw material bottlenecks. Securing future BEV

supply chains requires three broad actions to eliminate or minimise this sustaining influence. First, mineral production and transport should be scaled to meet demand, though it is important to consider the environmental and justice implications of new mining activity. Second, governments, investors and entrepreneurs should aggressively pursue innovation which minimises reliance on critical minerals, either by reducing use of or substituting those materials. Third, and most importantly, priority should be placed on promoting circularity in BEV supply chains. Batteries have limited lifetimes, and circularity in the battery value chain is crucial to prevent future disruption and costly environmental degradation, including waste and contamination.

3. **Invest in (smart) charging networks and electricity grids.** Sparsity of public chargers is cited by consumers as a major barrier to BEV adoption; indeed, it is responsible in part for the gross sustaining influence posed by citizens. Both public charging networks and electric grid infrastructure are vastly underdeveloped to handle the demand from an entirely electrified vehicle fleet. Substantial investment from both public and private sources is required to close this gap. Doing so will trigger reinforcing co-ordination feedback: a larger and denser charging network will incentivise higher BEV adoption, which in turn will support and make profitable a larger charging network. Radical innovations such as high-speed battery swapping (rather than charging) could also trigger feedback loops by assuaging consumer fears about charging time.[83] Furthermore, smart technologies such as bidirectional vehicle-to-grid charging could contribute valuable flexibility to power grids and cost savings to drivers.

4. **Reduce reliance on the personal automobile.** A transition from ICE vehicles to BEVs in the next decade or two is crucial for reducing GHG emissions from road transport in the near term, and it now appears to be inevitable given the forecasted cost advantages of electrified mobility. However, there are reasons to pursue a shift away from this transport paradigm: personal automobiles are resource-intensive and inefficient, they enable careless and inefficient land use via urban sprawl, and they are expensive to both society (ie accidents and congestion) and individuals. BEVs are further constrained in the long term by critical mineral requirements, barring radical advances in circularity. Moving towards a transport paradigm emphasising human-centric urban design, walking, cycling and public transport would be easier on the planet and potentially more viable in the long term. Even a shift towards ride-sharing and MaaS could greatly reduce the number of vehicles on the road, producing positive externalities ranging from decreased critical mineral demand to lower levels of noise and congestion in cities. Shared and communal mobility could also enable shorter driving ranges for those personal automobiles which remain: most driving needs can be met by low-cost, less-resource-intensive short-range BEVs as long as drivers have access to long-range vehicles a few days a year.[84]

5. **Leverage the power of incumbents.** Although Tesla and BYD – two ‘disruptor’ all-electric vehicle manufacturers – remain the world leaders in BEV production, many of the biggest players in the BEV revolution are now incumbents such as Toyota, General Motors and Volkswagen. While these historically dominant firms would have enjoyed an even better market position had they embraced BEVs long ago, their ability to make a rapid shift may preserve their relevance. Incumbents are often influential in financial and policy decision-making, so this shift could cascade into other system drivers. Indeed, the powerful automotive lobby continues to contribute to governments’ sustaining influence in the sector, so a push in the opposite direction from those same incumbents could be profoundly disruptive. Looking ahead, incumbents may need to even

more radically change their business models to stay relevant in a disrupted road transport sector. Recall that both Fujifilm and Kodak developed digital cameras; however, only Fujifilm survived by embracing new digital imaging possibilities. In road transport, unconnected personal automobiles may eventually become outdated. Those firms that are best able to adapt to a radically new low carbon, ICT- and data-driven transport model may be best positioned to lead in the long term.

6. Agriculture: disruption imminent

While the energy system dominates the climate change mitigation conversation, there is an increasing awareness of the importance of non-energy sectors. Chief among these is the food and agriculture system; indeed, it is estimated that even if fossil fuel emissions were halted immediately, GHG emissions from the food system could preclude achieving the global 1.5°C target (and even the less ambitious 2°C target) by the end of the century.[85]

Low carbon transformation in the food and agriculture system will be pursued with increasing urgency for two primary reasons. First, a large proportion of GHG emissions from agriculture is methane, a short-lived but highly potent GHG. As the climate emergency is increasingly recognised as such, we expect that the mitigation emphasis will shift from purely reducing CO_2-equivalent emissions to controlling the rate of warming, which in turn will lead to a growing spotlight on methane. Second, the food system crisis extends far beyond climate. Industrial-scale agriculture is responsible for biodiversity loss; freshwater and land use; and a crisis of human health via obesity, zoonotic disease and antibiotic resistance.

This chapter focuses specifically on low carbon market disruption facing the livestock agriculture system. Industrial livestock agriculture is the main contributor to the sector's GHG emissions and other adverse environmental impacts, and it is highly vulnerable to climate change (both physical and transition risks). Low carbon disruption in this context could refer both to technological shifts which decrease livestock's GHG emissions footprint, or equally to the displacement of animal agriculture altogether by alternative proteins. See Appendix C for a more detailed analysis of the system drivers, which are summarised below.

6.1 System drivers in the agriculture sector context

The agriculture sector, and livestock in particular, are responsible for substantial transgressions of planetary boundaries. These range from climate and biodiversity impacts to considerable freshwater and land footprints to disruptions of nitrogen and phosphorous cycles. Although the planetary boundaries framework is still relatively new and some of its transgressions (notably the biogeochemical flows) have not prompted responses commensurate with their severity, we expect that further deterioration of environmental conditions will turn policy, financial and consumer attention towards the greatest offenders. The planet, then, could indirectly disrupt the agriculture sector by sounding the alarm on the current system's inherent unsustainability.

More directly, the planet will disrupt agriculture as climate change and other environmental change creates an increasingly inhospitable context for farming. Already, crop yields are substantially constrained by ozone, pests and diseases, soil nutrients, heat stress and aridity. Figure 16 shows aggregated yield constraint scores (YCS) for the effect of five key crop stresses (ozone, pests and diseases, soil nutrients, heat stress and aridity) on the production of four staple crops (maize, rice, soybean and wheat).[86] YCS are based on current environmental conditions and are shown only for regions with substantial crop production. Many of these stresses (ie pests and diseases, heat stress and aridity) project to intensify in a warming world, and the depletion of soil nutrients by intensive industrial systems will accelerate this damage. In its current state, agriculture seems to be digging its own grave, exacerbating the very environmental conditions which will make current levels of production untenable. Of course, this has tragic implications for food security and justice worldwide. In the livestock context, this means feed will become increasingly scarce and expensive – a considerable share of maize and soybean crops are used for livestock feed.

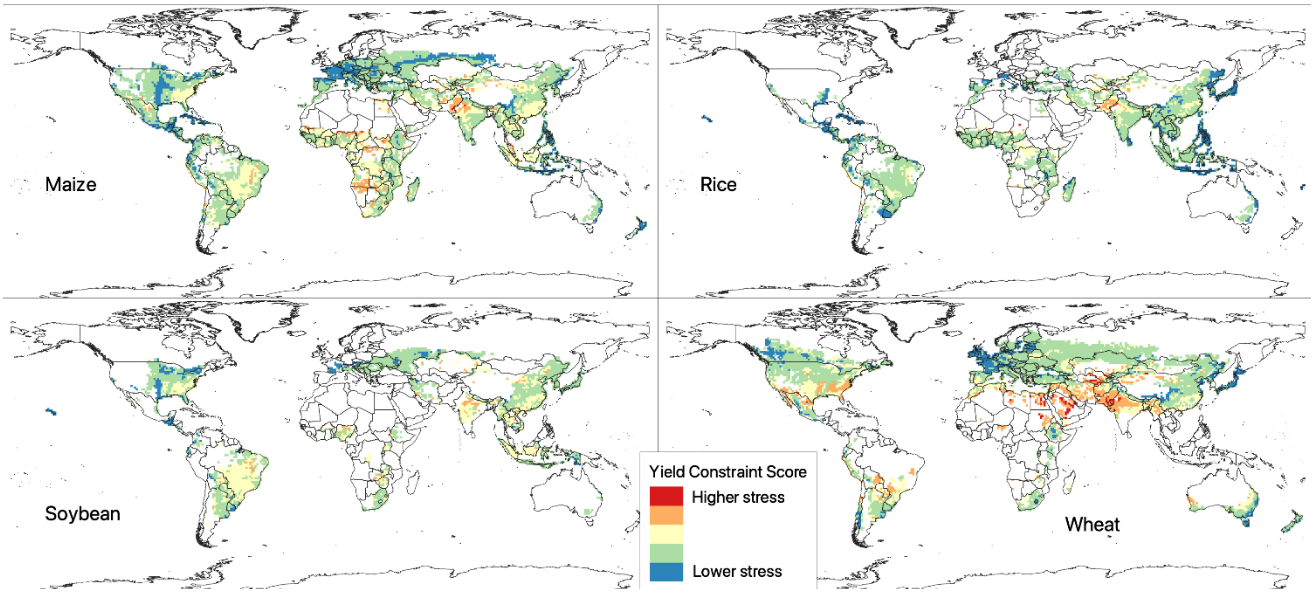

Figure 16: Aggregate YCS for four staple crops.

Livestock are similarly impacted by a changing environment. Beyond a constrained feedstock supply, animals themselves will suffer from increased heat stress to the detriment of their welfare and productivity. Figure 17 shows the proportion of animals expected to experience at least one day of extreme heat stress in 2020, and in 2050 and 2090 under different climate change scenarios and shared socioeconomic pathways (SSPs).[87] SSP5–8.5 represents a case of high warming, while SSP1–2.6 is consistent with a two degree global average temperature rise. Although the high warming scenario (SSP5–8.5) now seems unlikely due to the low cost of renewable energy,[88] this illustrates the gap in animal welfare productivity under low- versus high-warming scenarios. While most of the world's livestock could be spared from extreme heat stress if decarbonisation action is ambitiously pursued, business-as-usual will be highly disruptive to livestock in most of the world.

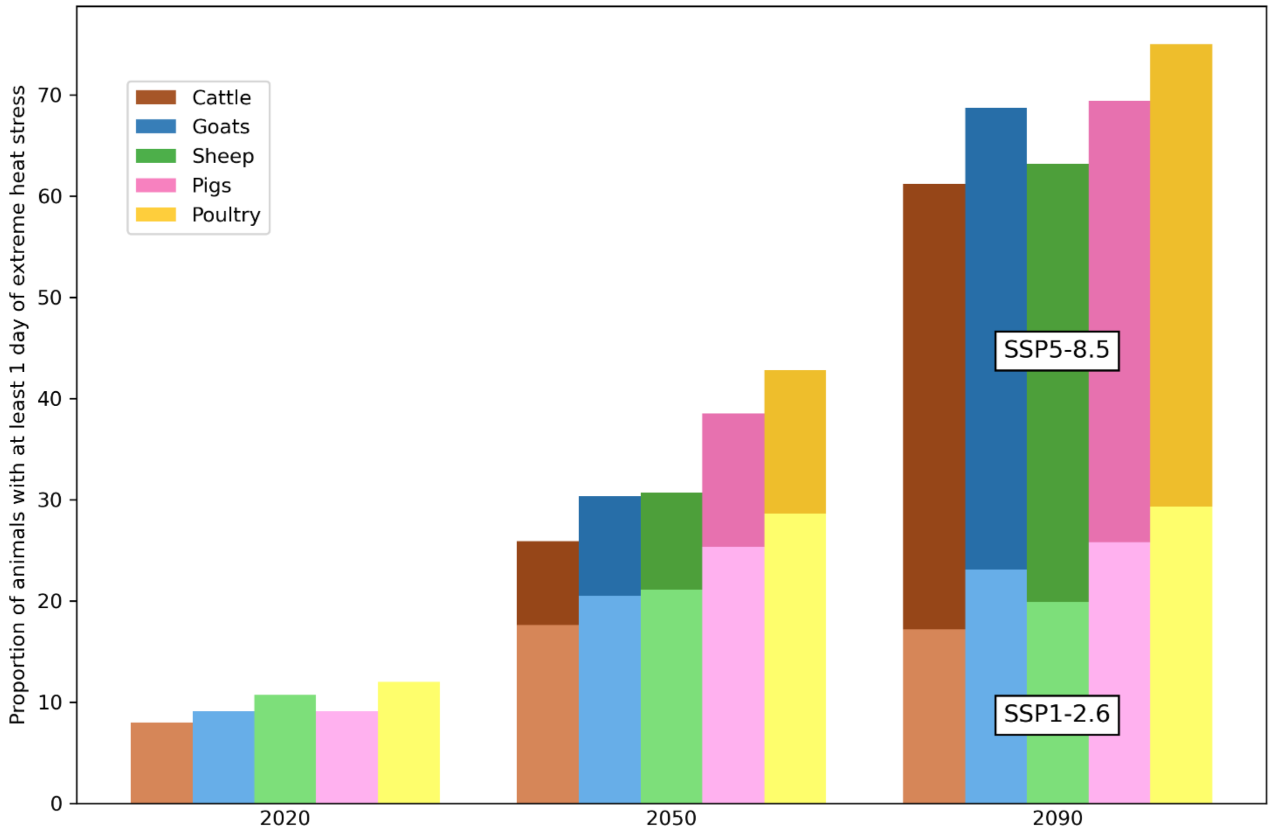

Figure 17: Extreme heat stress in the global animal population.

Technology represents another major disruptive force in this sector. Alternative proteins – plant-based, fermented from micro-organisms, and cultured or 'lab-grown' from animal cells – have experienced exponential cost declines (like renewables and vehicle batteries) in recent years. They are now approaching parity in cost, taste and texture with dairy, meat, seafood and eggs, while presenting more environmentally friendly (and often healthier) alternatives.

Figure 18 shows market share projections for alternative proteins from a variety of sources.[89] Dashed vertical lines represent the years at which alternative proteins with realistic taste and texture achieve cost parity with conventional alternatives in the US and EU.[90] The line labelled 'A' denotes plant-based protein, 'B' denotes fermented protein, and 'C' denotes cultured protein. The three alternative protein technologies are expected to achieve cost parity with conventional proteins at varying points in the next decade, and their market share is projected to grow accordingly. Note that while market share projections vary widely, an S-shaped diffusion trajectory is observed like in past technological transitions (highlighted by the shaded region).

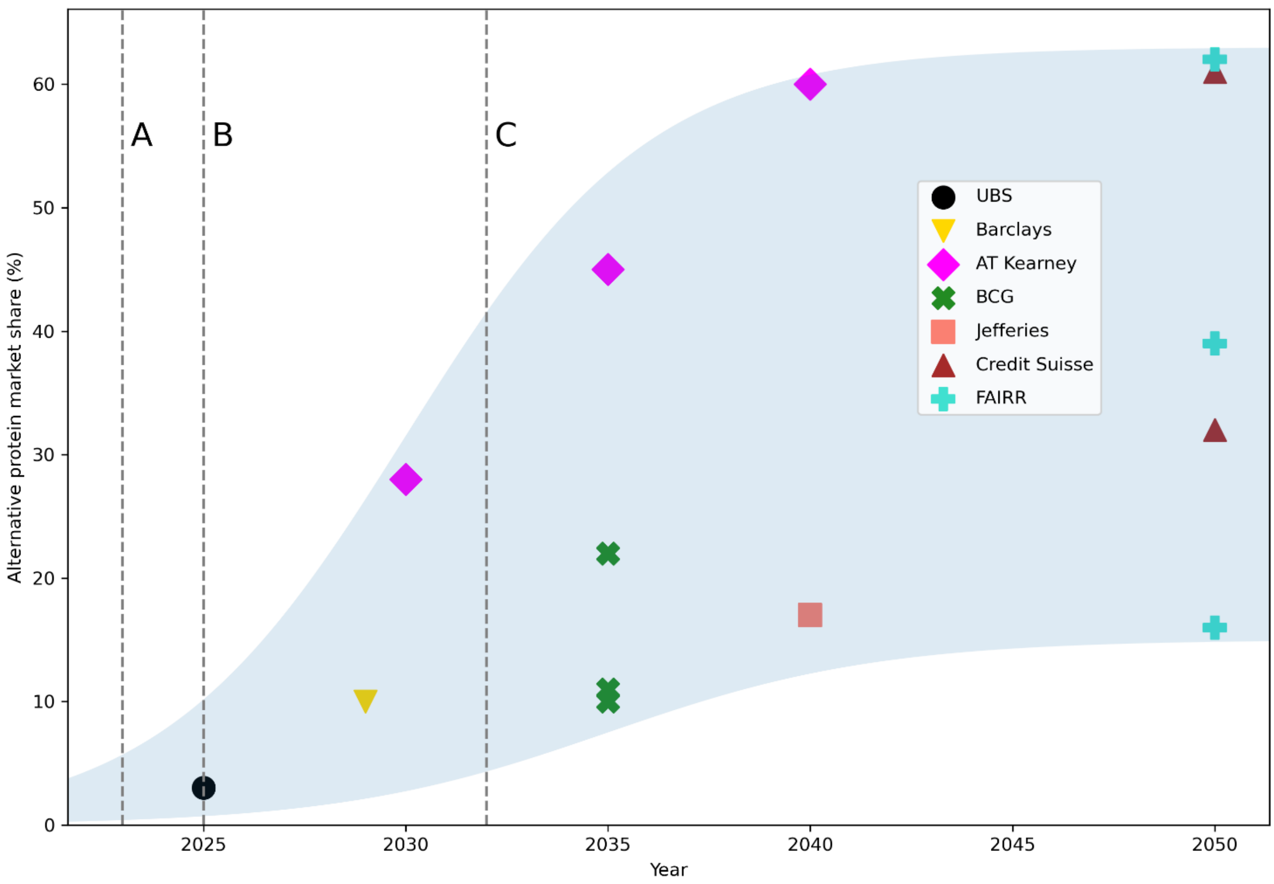

Figure 18: Alternative protein market share projections, 2023–50.

Technology also holds the potential to sustain the livestock industry, so long as it addresses pressing environmental concerns. Climate-smart and regenerative farming techniques, as well as innovations such as methane-reducing feedstock additives for ruminants, could in some cases reduce or even reverse the environmental footprint of livestock agriculture. Much like power utilities that shifted from fossil fuels to renewables and automotive manufacturers currently switching from ICE to BEV production, those farmers and supply chains that move early to adopt such innovative approaches to animal agriculture will build their own resilience to low carbon disruption. In doing so, they can ensure their own long-term viability, but will also accelerate the disruption of laggard competitors by demonstrating to governments, investors and consumers that today's environmentally damaging norm is not the only possible way to feed the world.

Government remains a strong sustaining influence in the agriculture sector, lagging behind the other system drivers. Governments across the world support agriculture, and particularly livestock systems, with substantial subsidies. Furthermore, alternative proteins are in many cases highly regulated: alternatives are often banned from using names or labelling associated with traditionally animal-based products, and in some cases innovative alternative protein production methods have been banned outright. These subsidies and regulations (at least nominally) protect the livelihoods of farmers who often survive on the thinnest of margins, which is certainly a noble motivation. Therefore, while a re-alignment of agricultural policy is critical to decarbonising the sector, it should centre just transition principles.

While government support for animal agriculture sustains the industry, it also underlies the extent to which the trajectory of the food system depends on government support and government action. If (and when) governments begin to include agriculture under carbon pricing programmes or other decarbonisation policies and targets, incumbents might be particularly vulnerable to this shift. History suggests that government policy and regulation are unlikely to *spur* low carbon disruption in the agriculture sector, but the eventual removal of livestock subsidies and protective regulations may act as both a bellwether and accelerator of disruption.

Finance is not yet a decisive system driver in this sector. On the one hand, investment in alternative proteins has skyrocketed in recent years, rising from essentially nothing to a multi-billion-dollar industry in the last decade. This is especially true for fermented and cultured proteins, which have taken off only in the last few years. Investors are beginning to become wary of the environmental and transition risks facing livestock agriculture, and some have embraced alternative proteins instead. At the same time, however, there is fear of an alternative protein 'bubble', leading some investors to worry about the long-term viability of the alternative protein market. Investment decreased from 2021 to 2022, although this was consistent with trends in the broader market. Indeed, most investors remain confident in the future of alternative proteins, and the number of investment deals in 2022 was higher than in any previous year. Figure 19 shows invested capital and deal counts for plant-based, fermented and cultured protein.[91] For 2022 investment,[92] disaggregation by type of alternative protein is unavailable. See Appendix C for a discussion of the decrease in investment from 2021 to 2022.

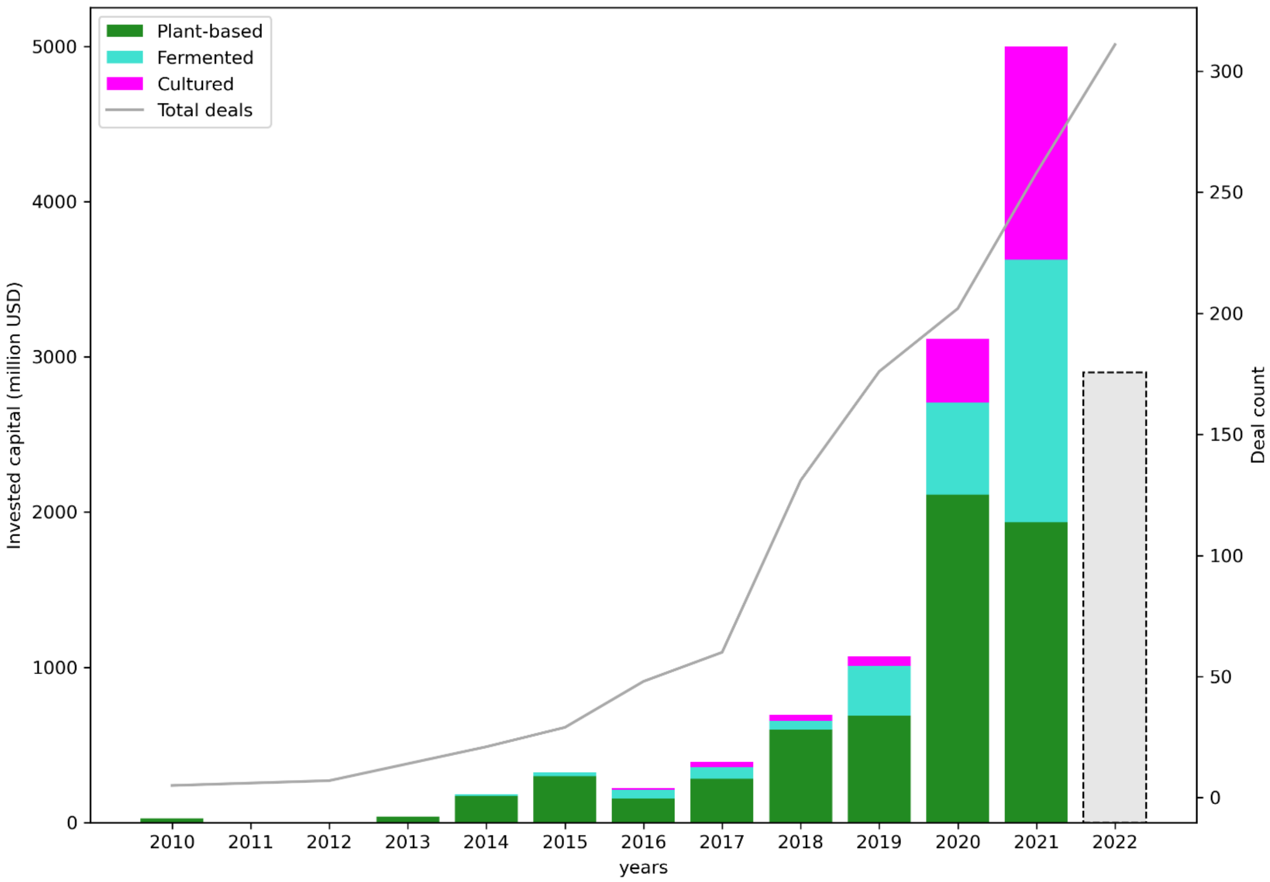

Figure 19: Alternative protein investment, 2010–22.

Lastly, citizens are a crucial system driver in the food system, as food purchases are ultimately a function of individual taste and decision-making. Historically, individual choice and consumer preferences have been a major sustaining influence on the food system; indeed, consumption of animal products such as meat and dairy is strongly reinforced by both individual (ie habitual) and social (ie cultural) feedbacks. Even today, many consumers remain sceptical of alternative proteins, which some perceive as highly processed or unnatural. On the other hand, acceptance of and enthusiasm for alternative proteins is rising. This may subsequently drive further investment and innovation, and eventually lead to a reversal of government support for intensive, industrial livestock. Citizens may also demand increased transparency about the environmental and health impacts of food in their capacity as consumers, activists and voters. This could alter the landscape in which the other system drivers operate, further accelerating low carbon and sustainability-driven disruption across the food system. Even if consumers are unwilling to give up animal products altogether, they may be willing to consider climate and environmental concerns when deciding *which* animal products to purchase. For instance, some consumers are reducing red meat consumption and correspondingly increasing their consumption of poultry.[93]

Although disruption has thus far been limited in the agriculture sector, the pieces are in place for it to reach an inflection point and 'take off' soon. While the sector currently lags behind power and road transport due to a combination of less mature low carbon technologies, poor government incentives and incomplete citizen enthusiasm, it has the potential to be disrupted at a faster pace. This is because the sector turns over quickly: livestock have far shorter lifetimes than coal-fired power plants or automobiles, at least in our current system. If innovators, governments, investors and consumers rally around climate-smart alternatives, entire portions of the agriculture sector could quickly collapse, sparing only those incumbents who braced for change by adopting innovations which enhance their resilience and minimise their environmental and health impacts.

6.2 Disruption assessment

Overall, disruption in agriculture remains nascent. As in the power and road transport sectors, multiple system drivers are exerting strong disruptive influences on the agriculture sector. Advances in alternative protein technologies threaten animal products with parity in price and appeal, and some consumers are beginning to abandon foods perceived to be environmentally damaging. Furthermore, and in stark contrast to the other sectors examined, the planet is likely to be a key disruptive force in this sector.

However, incumbent agricultural systems enjoy sustaining influences from system drivers far more than either fossil fuel power generation or ICE vehicles do. Livestock agriculture is sustained by government subsidies, continued innovation and financial support, and a loyal consumer base with deep habitual and cultural ties to conventional animal proteins. These sustaining influences have thus far slowed the process of disruption, but we believe an inflection point could soon be reached if these sustaining forces are eroded. Table 4 summarises the state of each system driver in the context of the agriculture sector, and Figure 20 visualises disruption nearing an inflection point. In Table 4, light shading once again represents low influence, medium shading represents medium influence and dark shading (with white text) represents high influence.

Table 4: Disruptive and sustaining influences in the agriculture sector.

	Disruptive influences	Sustaining influences
Planet	Responsible for substantial proportion of planetary boundary transgressions, also highly vulnerable to planetary change (impacts are most acute for large-scale, industrial animal agriculture systems), indirect impact via	None

	transition risks	
Technology	Rapid advances and cost declines in plant-based, fermented and cultured proteins	Technological advances have led to incredible yields and productivity of intensive, industrial agriculture (especially livestock), technologies could reduce livestock emissions (shielding them from transition risks)
Government	Some suggestions that methane will be further prioritised in the future	High agricultural subsidies and regulatory barriers for alternative proteins, agriculture often absent from decarbonisation policy portfolios, economic benefits from high carbon food exports
Finance	Investor wariness around environmentally destructive protein production, high levels of investment in alternatives	Fears of an alternative protein bubble
Citizens	Increasing enthusiasm around and openness to alternative proteins and dietary change	Strong habitual and cultural ties to food (especially meat, dairy, eggs and seafood)

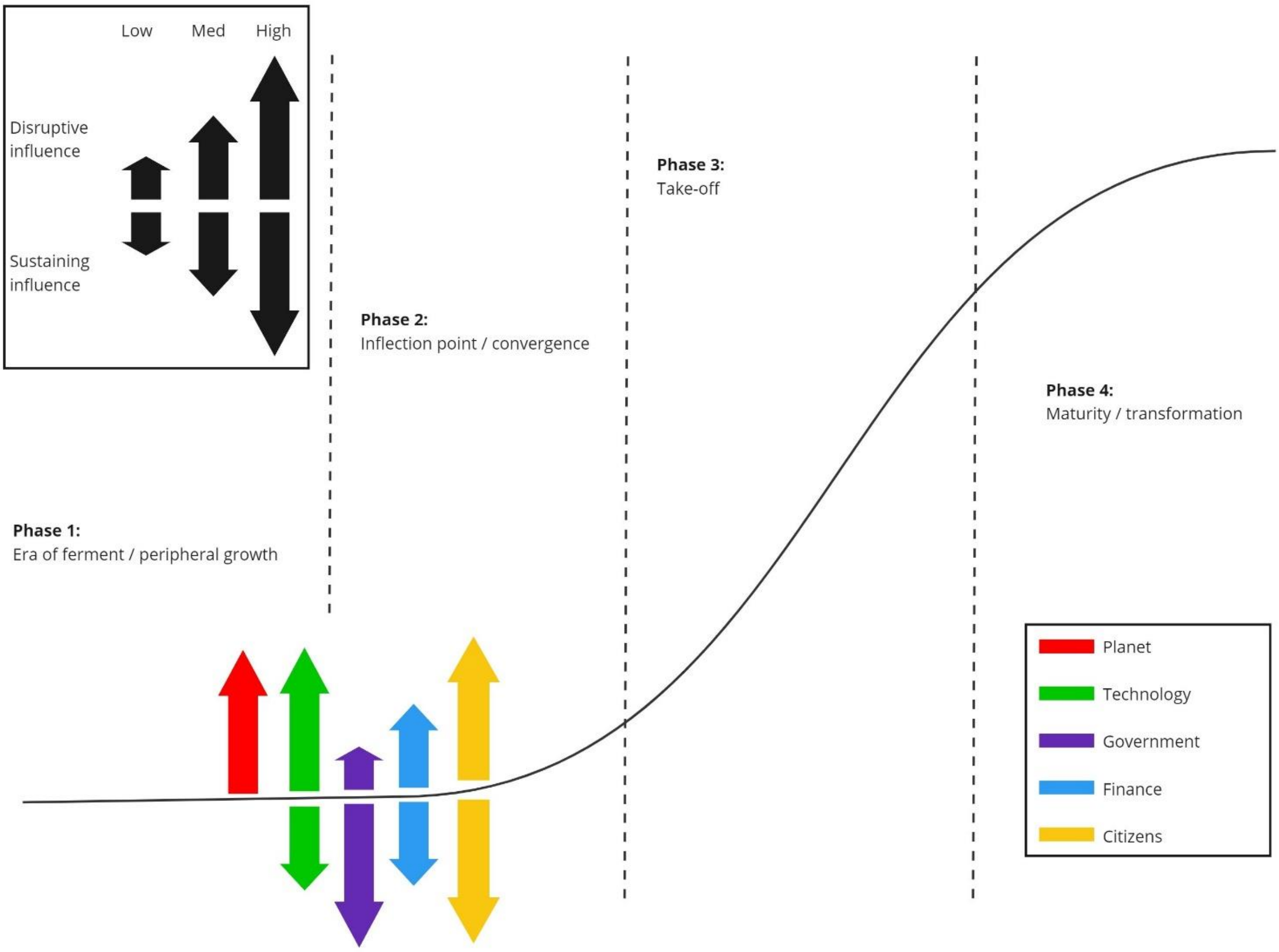

Figure 20: Disruptive and sustaining influences in the agriculture sector.

6.3 Leverage points

Disruption in agriculture is only just beginning. Incumbent agricultural methods, processes, businesses, institutions and supply chains remain dominant, with disruptors capturing only a small proportion of the market to date. This provides an opportunity unique among the studied sectors: we can learn from previous and ongoing instances of disruption to better manage and navigate disruption in the food system. As we have seen, planetary boundaries and the food system's own vulnerability suggest that disruption is inevitable, but there is still time to dictate the terms on which the disruption proceeds.

1. **Pursue disruption-smart synergies.** CSA promises a 'triple win': higher yields, increased resilience to physical climate risks and lower GHG emissions. In the spirit of the DSD framework, we propose 'disruption-smart' agriculture, which simultaneously pursues higher yields; increased resilience to disruptive physical and transition risks; and lower tolls on the climate, nature and human health (ie nutrition density rather than simply calorie density). True triple wins will not necessarily be possible for all types of agriculture in all areas: some forms of intensive and animal-based agriculture may simply be too environmentally damaging and vulnerable to planetary change. However, in many cases, such avenues already exist or could be identified with further research and experimentation.

2. **Close information and capacity gaps.** Disruption-smart triple wins represent major opportunities for profit and long-term resilience – so why are they not already being practised? The answer is that major gaps persist in knowledge and capacity: some climate-smart and easily adoptable agricultural practices, though millennia old, are simply unfamiliar to farmers. Others demand high upfront costs or specialised technology. Smallholder farms (less than two acres in size) make up 84 per cent of the world's farms and produce 35 per cent of our food, despite operating on only 12 per cent of agricultural land;[94] these farms are more likely to lack the capacity or capital to implement climate-smart reforms. The issue is exacerbated by the razor-thin margins so prevalent in agriculture. Disseminating information on climate-smart farming could help close these gaps, and financing will be critical for equipping farmers with the necessary technology and training. By weakening sustaining influences in the technology and finance system drivers, this leverage point represents an opportunity not only to accelerate decarbonisation but also to promote justice and sustainable development, especially if wealthy nations facilitate technology and capacity transfer to smallholder farmers in developing countries.

3. **Reform policy to promote just decarbonisation.** Government stands out as the only system driver currently exerting a substantial net-sustaining influence on the agriculture sector (in fact, it is the only net-sustaining system driver identified across the three studied sectors). Public policy can and should be aiding the low carbon transition, as it is in the power and road transport sectors. Instead, governments continue to subsidise industrial livestock agriculture systems while simultaneously slowing the alternative protein revolution with regulatory barriers. This comes at a major cost to the planet and long-term food security. Of course, it would be unwise and unjust to blindly sacrifice near-term food security and farm livelihoods in reckless pursuit of a more climate-smart system. However, governments could redirect farm (production) subsidies towards food (consumption) subsidies and reskilling support for farmers hoping to adopt more climate-smart practices or shift their production altogether (eg from conventional protein to alternative protein plus ecosystem services). Indeed, the triple win promised by CSA and alternative proteins would achieve numerous government goals simultaneously.

4. **Explore diverse avenues for decarbonisation and disruption.** Because disruption is only just beginning in the agriculture sector, its future is uncertain. The sector has not yet converged around a single low carbon solution or cluster of solutions, unlike the power (renewables) and

road transport (electric mobility) sectors. Incumbents could feasibly adopt regenerative and climate-smart practices such as feedstock additives, silvopasture and other types of agroforestry, methane capture from manure, and low-opportunity cost feed. Such practices might disrupt industrial feedlots, large-scale animal feed supply chains and other currently dominant practices; however, in doing so they could delay or even prevent the more fundamental disruption of animal agriculture by alternative proteins and dietary change. Of course, it would also be prudent to diversify into alternative proteins, as past trends in the power and road transport sectors demonstrate. In the medium and long terms, animals may be unable to compete with realistic, low-cost alternative proteins. It is likely, however, that there is room in a future food system for diverse methods of farming and food production which are resilient to planetary pressures, produce a healthy and secure supply of food, and help mitigate (rather than exacerbate) climate change and other environmental concerns. This leverage point recognises the sustaining influence of citizens via strong habitual and cultural ties to animal products. Although some dietary shifts will likely be necessary, diverse decarbonisation methods could 'meet consumers halfway' by simultaneously providing more disruption-smart animal products *and* alternative proteins.

5. **Seek local solutions.** Agriculture is far more place-dependent than power or road transport. Both its impacts (eg on biodiversity) and vulnerabilities (eg risk of flooding and soil nutrient depletion) vary widely from one geography to another. Different regions may face different disruptive and sustaining influences from citizens and governments based on the cultural and heritage dimensions of food. Furthermore, climate- and disruption-smart solutions may vary from region to region: for instance, the environmental and profitability benefits of regenerative agriculture vary across different agroecosystems.[95] It is therefore unlikely that disruption worldwide will be either precipitated or managed by a single technology or suite of technologies such as renewables or electrified mobility. Rather, farmers and regulators should turn to local information sources, such as ecology and indigenous knowledge, to inform local action. Cross-cutting technologies, such as ICT-enabled monitoring and precision agriculture, could help tailor climate-smart approaches to local contexts.

7. Conclusion

This report examines the process of low carbon market disruption, highlighting the interacting roles of technological innovation and other socio-technical forces. It introduces the dynamic system drivers (DSD) framework for characterising, anticipating and influencing disruption, which centres the planet, technology, government, finance and citizens as key drivers of system change. The system drivers themselves have three important properties: each can work to both sustain and disrupt systems, their sustaining and disruptive influences change over time, and they are highly interconnected.

Operationalising the framework entails first gathering evidence to answer key questions about the system drivers and then assigning magnitudes to sustaining and disruptive influences from each one. At that point, we can assess the current state and future potential for disruption and identify leverage points for accelerating disruption based on both sustaining influences and opportunities to exploit synergies and feedbacks between system drivers. This report applies the framework in the climate context by analysing ongoing and imminent low carbon disruption processes in the power, road transport and agriculture sectors. In doing so, it demonstrates how complex systems thinking can be applied to helping businesses, investors and governments navigate, accelerate and build resilience to the low carbon transition.

The power sector is currently undergoing advanced low carbon disruption. Given the emissions abatement and – as of recently – cost-saving opportunities presented by renewable energy, fossil fuel generation is rapidly giving way to exponentially proliferating solar PV and wind energy. Complete low carbon disruption still faces numerous barriers, many of which relate to the intermittency of solar PV and wind. Innovation, policy support and finance will be crucial in unlocking storage, smart grids, low carbon dispatchable generation and demand-side energy management to facilitate this transition. What is clear, however, is that incumbent fossil fuel electricity generators have missed the window of opportunity to be part of the disruption process and therefore face looming obsolescence. CCUS technology presently lags behind ambitions and will likely be outcompeted for baseload generation in the power sector by lower-cost renewables plus storage, leaving little recourse for businesses that decades ago chose to delay and deny rather than embrace low carbon opportunities. For other, more flexible businesses, myriad opportunities remain across the energy supply and use chain. These range from innovative ways to harness and balance renewable energy, to energy use which maximises the flexibility of demand rather than simply minimising its magnitude.

The road transport sector is at a more nascent stage of disruption, although disruption appears to have reached an inflection point. Government policy, investment and business strategy have converged around BEVs, which are poised to disrupt ICE vehicles and their associated supply chains and service networks. To some extent, citizens remain a sustaining influence due to consumer wariness around BEV prices, driving range and charge point scarcity; however, these concerns are likely to diminish over time as battery costs continue to decline, range and charging speeds continue to improve, charging networks are built out, and other forms of mobility provide alternatives to the personal vehicle paradigm. In this sector, incumbents in the ICE production and oil industries have delayed too long to stave off the disruption of the ICE vehicle. However, many of these same incumbents can build resilience and maintain relevance by embracing a new socio-technical regime centred around electrified and intelligent mobility. Indeed, many conventional automobile makers are emerging as powerhouse BEV manufacturers. Those that are serious about adapting their core business models and production capabilities to align with a low carbon transport future will fare the best in a disrupted sector, ameliorating acute disruption to their business practices. On the other hand, those that are adapting only superficially – favouring greenwashed messaging over core business change – will lose this opportunity for a head start and may be unable to adapt to ever-accelerating disruption.

Disruption is even more nascent in the agriculture sector, and not yet at an inflection point. There is no doubt that the sector will face transformative disruption: it has contributed to environmental and human health crises and is simultaneously highly vulnerable to climate change and other environmental degradation. What is less clear, however, is *how* the disruption will unfold and *who* will be disrupted. This is intuitive: in a complex world characterised by strong path-dependence, those sectors less far along their disruption processes face a wider range of possible futures. In practice, this affords businesses, governments, investors and citizens a higher degree of agency. Many different paths are possible for the agriculture sector, all of which could be far more compatible with planetary boundaries and human flourishing. One is a regenerative and circular farming system which includes some (though likely much less) livestock. Another would feature the in-place substitution of conventional proteins with plant-based, fermented and cultured proteins. Still another would centre dietary shifts towards whole food plant-based diets, lower carbon animal proteins such as insects, or both. These disruption paths have vastly different implications for incumbent farmers, livestock supply chains, entrepreneurs and consumers. By aggressively pursuing climate-smart innovations which reduce the GHG emissions of their operations (such as agroforestry, soil carbon sequestration and methane capture from manure) the livestock industry could meaningfully stave off at least some degree of disruption, as coal and gas electricity generation and ICE vehicles failed to do. If this opportunity is missed, intermediate food producers may turn to alternative proteins to minimise their own disruption exposure (akin to ICE vehicle manufacturers switching to BEV production). In reality, the future of food probably holds some combination of climate-smart farming, technological disruption and dietary change as planetary, market, institutional and cultural forces collude to transform the vulnerable agriculture sector.

It is said that change is the only constant in life. Past socio-technical transitions demonstrate that multiple interconnected forces work together to disrupt, or alter, systems. This disruption is highly path-dependent and irreversible, and it often creates winners and losers. Applying 'systems thinking' can help diverse stakeholders understand, navigate and influence this change. The DSD framework helps characterise the disruption process by grouping sustaining and disruptive pressures into five key drivers: planet, technology, government, finance and citizens. Understanding how these system drivers influence systems, influence each other and change over time can illuminate where a sector or system might be headed or how particular incumbents or innovators might fare in the future.

The key is that *disruption itself is inevitable, but the nature of the disruption is not*. Businesses, governments, investors and even coalitions of individuals can qualitatively alter future system evolution, especially by applying pressure early in the disruption process. In the climate context, planetary pressures and global decarbonisation commitments suggest that low carbon transformation is necessary; in many cases, technological and market realities suggest that it is inevitable. Those who embrace the radical and innovative opportunities afforded by low carbon disruption will thrive as leaders in a low carbon future. Those who deny and delay may face existential risk, as have so many deniers of change before them.

Appendix A: Power

The power sector: system driver assessment

This annexe presents a fuller picture of the history, current state and future outlook of each disruption driver in the context of the power sector.

Planet

The planet influences the power sector, but only to a minor extent and in both disruptive and sustaining directions. This is because both conventional and low carbon energy sources are prone to risk from planetary change. Energy infrastructure, like other forms of infrastructure, is vulnerable to climate change impacts such as extreme weather events. High winds, storms, heatwaves and flooding can temporarily incapacitate energy production and fuel transport, which can lead to major losses for energy suppliers and energy-using businesses alike.[96] The potential for disruption due to natural disasters and extreme weather may be higher for point sources such as thermal power plants and fuel distribution infrastructure; therefore, more distributed sources such as solar PV and wind hold a slight advantage over fossil fuels. Other low carbon generation (eg nuclear and biomass) does not enjoy this advantage. Regardless of generation technology, climate change poses a threat to all elements of the electricity system, including the efficiency of transmission and distribution networks. This vulnerability threatens the delivery of low carbon and high carbon power alike.[97] Therefore, ensuring climate resilience in power systems will be a critical objective in the coming decades.

Thermal power plants (ie coal, gas, oil, nuclear, biomass, waste and geothermal), which depend on freshwater availability for cooling, face further disruption from the freshwater use planetary boundary as droughts intensify due to climate change. Indeed, nearly half of the world's thermal electricity-generating capacity is located in highly water-stressed areas.[98] Water stress may therefore drive low carbon disruption in the power sector, but only for solar PV and wind. On the other hand, land use competition may hinder the deployment of solar PV and wind, which are less spatially energy dense than gas generation (by more than an order of magnitude).[99]

The physical risks to conventional energy infrastructure from climate change and freshwater use are balanced out by those to renewables from climate change and land use, such that the planet does not exert a strong net influence in the power sector.

Technology

The past decade has seen a tremendous shift in the landscape of power generation technologies. Renewable energy technologies – specifically solar PV and wind – have experienced dramatic cost reductions due to technological learning and economies of scale, and they are now the lowest-cost electricity sources in most markets.[100] Substantial cost reductions have also been observed for batteries and hydrogen electrolysers. Such technologies support a decarbonised power system by providing grid-scale energy storage, facilitating a higher share of renewables in the generation mix. Both theory and empirical observation suggest that these cost reductions will persist in the coming years owing to further induced innovation in production processes and supply chains, increased competition and economies of scale. As a result, a rapid transition to a low carbon power system could lead to trillions of dollars of cost savings annually, even before averted physical climate change damages are accounted for.[101] This transition is already underway: renewable deployment is increasing exponentially while costs continue to decline. Even now, technologies and markets are exerting a disruptive influence on incumbent, fossil-powered electricity systems.

Importantly, while public policy has helped drive this change (and will likely continue to do so),[102] the cost-competitiveness of renewables suggests that this disruptive influence will – to a large degree – be self-sustaining. Recent analysis found that over 800 GW of coal-fired capacity worldwide has *operating* costs higher than the *levelised* cost of new solar PV and wind capacity: in other words, retiring this coal-fired capacity today in favour of building new renewables capacity would lead to cost savings.[103] While gas generation is currently cheaper than coal in many regions and retains a flexibility advantage over renewables, building new renewables capacity is likely to be cheaper than operating existing gas capacity within the next 20 years.[104] Indeed, simulation modelling suggests that solar PV is likely to be the cheapest source of electricity (by levelised cost) in nearly every world region within the next ten years, even when accounting for costs of ancillary energy storage and excluding policy incentives.[105] The challenge now becomes supporting these cheap renewables with storage[106] and transmission[107] infrastructure.

The technological and market landscape has not always favoured fossil fuel disruption: since the turn of the century, the shale gas boom has made gas generation relatively cheap, which for many years sustained the dominance of fossil electricity.[108] Indeed, technology could still play a sustaining influence on conventional electric power systems: if CCUS can buck its historic trend of slow progress despite substantial investment,[109] it could sustain thermal power generation and fossil-fuelled systems via "reinforced lock-in".[110] But renewables currently represent a cost-saving alternative to fossil fuels – especially those utilising CCUS. Technology is now a key driving force in the disruption of fossil electricity. Energy suppliers that do not recognise this disruption risk facing long-term losses and obsolescence, even if their resistance to the renewables transition produces short-term profits.

Beyond its own strong influence on the power system, technological change is increasingly impacting other system drivers. Governments are more likely to pursue energy system decarbonisation considering the affordability of renewable electricity. Consumers will be more likely to choose electric vehicles or heat pumps as costs fall for those technologies and off-peak power prices fall from increased wind and solar PV generation. This, in turn, will increase electricity demand, further driving deployment of low-cost, low carbon renewables. Lastly, foreseeing the accelerated rollout and cost advantage of renewable energy and low carbon end uses, financial institutions are less likely to finance or insure high-emissions projects which might have lower expected lifetime returns. In the power system, the deployment and declining costs of renewables have likely already reached a tipping point, initiating an irreversible and self-reinforcing transformation.

Government

Government policy and regulation is a key system driver in the power sector. The government plays a central role in power generation itself – nearly two-thirds of global generating capacity is represented by state-owned enterprises.[111] In such a capital-intensive sector, long-term targets, capacity regulations, taxes and subsidies can substantially impact what types of generating capacity are built and operated. Historically, policy and regulation have worked to sustain conventional, fossil fuel-based electricity generation. Fossil fuel subsidies remain pervasive, largely motivated by issues of energy security, domestic energy services, and energy access and affordability.[112] Regulatory barriers also continue to impede rapid deployment of renewables and other low carbon electricity sources.[113] A powerful fossil fuel lobby continues to oppose decarbonisation policy in the power sector, which further impedes low carbon disruption.[114] However, the tide of policy, regulation and law relating to the electricity sector is rapidly turning. In response to the climate emergency, newfound cost advantages of renewables, and the multiple co-benefits of low carbon electricity (eg health and environmental improvements resulting from reduced local air pollution[115]), governments are increasingly committing to a low carbon electricity transition and – in many cases – backing up these commitments with power sector policy reform.

Ambitious decarbonisation policy could also disrupt fossil fuel energy systems by making them comparatively expensive or even illegal. For instance, a carbon price (tax or ETS) in the power generation and industrial sectors already exists in many jurisdictions: a 2022 OECD study of 71 countries found that nearly two-thirds of their power sector emissions were covered by a positive net effective carbon price – up from only one-third in 2018.[116] This decreases the competitiveness of high-emitting fossil fuel assets, further promoting disruption by low cost and low carbon renewables. Low carbon power still faces some policy barriers: renewables, for instance, face long planning and permitting timelines in many jurisdictions, and current power market structures are poorly suited to their intermittency.[117] Removing these policy hurdles would further accelerate low carbon disruption in this sector.

There is also a looming risk of litigation against high GHG emitters, which could be costly and disruptive. Political and legal innovation might create new precedents for holding emitters accountable. For instance, a Peruvian farmer recently filed a civil suit against German energy company RWE, seeking damages proportional to RWE's contribution to climate change which led to an increased flooding risk.[118] The case was initially unsuccessful and is currently under appeal; however, it demonstrates that, in an evolving legal climate, polluters may soon face risks stemming from their past and current actions. Furthermore, scientific innovations will continue to improve both the confidence with which damages can be attributed to human-caused warming and the confidence with which responsibility for warming can be attributed to individual emitters, only accelerating this trend.

Beyond Paris Agreement compliance and national decarbonisation ambitions, energy system decarbonisation may (somewhat surprisingly) be accelerated by governments' desire for energy independence and security. Renewable energy sources are available in most countries, they offer the possibility of decentralised energy production, and it is harder to disrupt renewable flows than conventional energy stocks.[119] All these factors may make low carbon energy systems more resilient and secure in the long term, and therefore more attractive to governments and financial institutions. Contrary to popular belief, electricity disruption as a geopolitical weapon is more difficult and less likely than disruption of fossil fuel supplies; this advantage may accelerate the electrification of end-use sectors.[120] Transitioning away from fossil fuels will also improve the trade balance for net fossil fuel importers, which include the major economies of the EU, China and India.[121] Conventional wisdom has held that self-interested countries will be slow to decarbonise because benefits are shared worldwide but costs are not, and indeed energy security concerns continue to produce some myopic government support for fossil fuels in the power sector. However, long-term geopolitical concerns surrounding energy security and independence may incentivise domestic energy decarbonisation policy for key players.

This process is already underway: following Russia's 2022 invasion of Ukraine, the European Commission quickly unveiled a plan to reduce dependence on Russian fossil fuel imports.[122] The REPowerEU plan calls for energy efficiency improvements and diversification of the conventional energy supply, but it also increases and accelerates the ambition of the EU's transition to renewable energy. Indeed, policy responses to the war seem to be accelerating the clean energy transition worldwide,[123] so much so that the International Energy Agency (IEA) directly credits energy security concerns and new policy with its projection that renewables capacity will double in the next five years.[124] Governments around the world may also embrace the decarbonisation of the energy system from a public health and cost-saving perspective: each year, air pollution is estimated to cause over 6 million premature deaths, nearly 100 billion days lived with illness, and over USD 8 trillion – or 6.1 per cent of global gross domestic product (GDP) – in health damages globally.[125]

Government policy, regulation and law also directly influence some of the other system drivers. Technological innovation trends will respond to public procurement; public investment in research and development; policies such as taxation, subsidies and feed-in tariffs; and direct regulation in the power sector. Furthermore, with investors responding to both existing policy and the expectation of future policies, government action can substantially influence financial paradigms and the cost of capital.[126]

Finance

In such a capital-intensive sector, finance critically impacts the true cost of infrastructure. Renewable energy technologies such as wind and solar PV have higher upfront costs than their fossil fuel counterparts (which are recouped later due to lower fuel and operational costs), so the cost of capital alone can determine whether renewables or fossil fuels are more attractive.[127] Until very recently, renewables faced high capital costs and limited financing options, driven in part by high costs and perceived risk.[128] Financial conditions, therefore, sustained the dominance of fossil-fuelled electricity production. However, this trend is now reversing in some regions, owing to the declining costs of renewables, an increasingly renewables-friendly policy environment and innovative new financing mechanisms. In Europe, for instance, where technology, governments and citizens tend to support renewables, low carbon electricity utilities have lower costs of capital than their higher emissions peers.[129] As other system drivers coalesce around renewables, we expect this trend will spread to the rest of the world, where low carbon utilities do not yet enjoy this capital cost advantage.

The financial system faces a high degree of risk relating to climate change. As retiring fossil fuel generating capacity early becomes an increasingly cost-saving and profit-maximising option – and as technological and policy trends continue to favour low carbon generation – fossil fuel reserves and generating capacity will be written down on energy companies' balance sheets. Potentially, these 'stranded assets' created could represent trillions of USD in financial losses.[130] This creates both credit and market risks for financial institutions, which also face liquidity, operational and reputational risks driven by technological, policy and public opinion shifts, respectively.[131] The multifaceted risk faced by financial institutions stems, in short, from a failure to appropriately price physical and transition climate change risks. Guidance has consequently called for this risk to be better integrated into financial stability monitoring and portfolio management.[132] As such, we expect financial institutions to make near-term efforts to better assess and price climate risk, in part via a 'carbon premium'.[133]

As investors and insurers recognise upcoming disruption and begin to price risk accordingly, fossil fuel incumbents in the power sector will likely face increased costs of both capital and insurance, and the risk of losing access to finance altogether. Indeed, insurers are increasingly unwilling to underwrite coal power projects (which are particularly emissions-intensive) due to the risk of asset stranding.[134] Financial institutions may refuse to finance other high-emissions energy projects and infrastructure due to similar risks, or to meet their own net zero transition plans as scope 3 emissions accounting improves. Companies that rely on fossil fuels for electricity production but lack credible low carbon transition plans may face restricted or more expensive capital, while those that embrace low carbon electricity generation may gain access to green financial processes and services.[135] That said, financial barriers still exist in the power sector: ancillary technologies such as batteries and upgraded transmission and distribution grids may impede power decarbonisation unless finance warms to them in the same way it has to renewables themselves. Finance, therefore, exists as a small sustaining influence in the power sector alongside its large disruptive influence.

We expect finance will be a key driver of future disruption, through its own influence and deep interconnection with other system drivers. Finance both influences and responds to government policy and technological innovation: capital costs and financing options can determine the feasibility of technological and policy trajectories, while developments in policy or the real economy can change risk perceptions and therefore asset valuations. This raises the potential for feedback loops in which individual actions can interact to produce amplified effects.[136] A cycle may emerge in which the potential for disruption in the energy system increases the perceived risk associated with high-emissions energy financing, which in turn leads to higher insurance premiums and capital costs for fossil fuels, accelerating system disruption.

Citizens

Electricity is highly fungible: households do not perceive a difference between electricity generated from different sources and are often unable to choose one type of generation over another. The power sector is therefore less impacted by citizens than, say, the consumer goods sector. Nonetheless, citizens hold some power to sustain or disrupt the electricity supply system. Public opinion on energy regulation is salient to public utility commissions, which ultimately answer to electricity consumers.[137] In some cases, this has sustained fossil fuel systems by hindering efforts to deploy renewable energy: for instance, despite its climate change mitigation potential, onshore wind energy has provoked considerable public opposition.[138] However, public awareness and acceptance of renewable energy is likely to increase as citizens become more aware of the dangers posed by climate change and the advantages of renewables over fossil fuels. Household DERs – such as rooftop solar PV and battery storage – hold considerable potential for furthering renewables deployment and the corresponding cost declines. Furthermore, community energy initiatives could accelerate the deployment of renewable energy by narrowing the ‘investment gap’ to achieve a low carbon power system.[139] Governments are ultimately answerable to their citizens, so public opposition to fossil fuels could influence decarbonisation policy at large scales; for instance, the Sierra Club’s “Beyond Coal” campaign has been very effective in accelerating the phase-out of coal generation in the US.[140] While citizens may not exert the same magnitude of influence in the power sector as government regulators or investors, we expect that they will nonetheless participate in the accelerating disruption process currently underway.

Appendix B: Road transport

The road transport sector: system driver assessment

This annexe presents a fuller picture of the history, current state and future outlook of each disruption driver in the context of the road transport sector.

Planet

Road transport in many regions is vulnerable to the physical impacts of climate change, including infrastructure damage from flooding, erosion and extreme weather.[141] However, this infrastructure vulnerability impacts conventional and zero emissions motor vehicles alike, and it also impacts the other modes of transportation (ie walking, cycling and public transport) which compete with them. The limited availability of critical minerals may constrain the pace of cost declines or the diffusion of EVs and other electrified modes of transport, given the higher reliance on critical minerals for low carbon transport than conventional vehicles.[142] However, stronger circular economy principles, as well as increased exploration for mineral resources owing to evolving market conditions and public policy, could ease this constraint.[143]

Ultimately, we believe planetary boundaries will not directly constitute a very impactful force in the context of low carbon road transport transformation (other than indirectly via transition risks to ICE vehicles). Incumbent, high-emissions transport systems may be sustained somewhat by electrified mobility's dependence on critical minerals. On the other hand, the planet may exert a disruptive influence on incumbent transport systems by forcing new investment in infrastructure resilience. By literally disrupting transport systems worldwide and forcing governments to invest in transport adaptation, physical climate risks give investors and policymakers the opportunity to invest in a lower carbon transport system. There is already evidence that transport infrastructure upgrades are being accompanied by transport decarbonisation efforts: for instance, while the recent US infrastructure expansion law includes spending on highway upgrades, it also includes substantial provisions for the expansion of rail, transit, pedestrian, cycling and EV charging infrastructure.[144]

Of course, we expect that planetary boundaries – and physical climate risk in particular – will be a major indirect influence on low carbon transport disruption. Road transport is a particularly salient source of GHG emissions, so innovators, governments, investors and consumers may be motivated by worsening climate impacts to pursue transport decarbonisation. This influence may be an important driver of disruption, but it depends on the evolution of those other system drivers.

Technology

Like renewable energy technologies, batteries have experienced tremendous cost declines in recent years. Lithium-ion battery packs, which currently represent the cheapest and best candidate for powering BEVs and electric buses, are six times cheaper today than they were a decade ago.[145] As a result, BEVs will likely reach parity in upfront price with ICE vehicles in the next few years, much earlier than was expected even a few years ago.[146] Although battery cost declines have stalled in the last year or two due to supply chain constraints precipitated by the COVID-19 pandemic and Russia's war in Ukraine,[147] we expect that cost declines will continue due to radical technological innovations and as battery manufacturers gain experience and skill. The observed and expected decline in cost of BEVs, coupled with global decarbonisation goals under the Paris Agreement, has increased confidence in a 'BEV tipping point': market-driven and irreversible displacement of ICE vehicles by BEVs.[148] As is the case with renewable energy, BEVs and PHEVs have experienced exponential growth in recent years and show no signs of slowing anytime soon. A lack of charging infrastructure presents a barrier to the widespread diffusion of BEVs;[149] however, the costs of charging infrastructure are declining as well, and their capabilities increasing, which bode well for low carbon transport disruption via electrification.[150] Furthermore, there is a substantial opportunity for technological innovation to promote twin disruptions in the power and road transport sectors: vehicle-to-grid charging as part of smart electricity grids could enable higher levels of renewables integration while reducing charging costs for BEV owners, thereby reducing lifetime ownership costs and accelerating their diffusion.[151]

Innovation in ICT solutions could further trigger disruption in road transport. Autonomous driving, which has historically been associated with BEVs, could accelerate BEV diffusion by augmenting their appeal to consumers.[152] That said, autonomous vehicles could increase overall vehicle use and sustain the dominance of personal vehicles by lowering the barriers to vehicle use (eg 'sending the car out' without a driver to pick up the kids from school). Innovations in MaaS could trigger further disruption by reducing the perceived need for personal vehicles[153] and could even promote public transport use by addressing the 'last mile' problem.[154] However, the use of MaaS in its current form (ride-hailing such as Uber) could displace public transport, walking or cycling and thereby impede more radical forms of low carbon transport disruption.[155]

Disruption in the transport sector due to technological innovation has been extensively studied: for instance, the disruption of horse- and rail-based transport by the development of the automobile.[156] The latter is somewhat ironic, as rail transport is now viewed as a key solution for decarbonising emissions-intensive long-distance road and air transport. Crucially, however, these historical disruptions demonstrate that as ingrained as transport modes may seem in socio-technical systems, they can be disrupted by technologies with a sufficient advantage in cost or other properties. The disruption of ICE vehicles by BEVs would be even easier because BEVs do not require much change in transport regulation or behaviour (aside from at the point of refuelling versus recharging). While BEVs and their dramatic cost reductions may accelerate the disruption of ICE vehicles and are therefore critical for low carbon disruption in the transport sector, it is important to note that they could also sustain the personal automobile system (including the associated urban planning paradigms and culture).[157] This might have adverse environmental and social impacts relative to car-free transit and denser urban design, due to the lifecycle emissions and mineral requirements of BEVs.[158] We encourage the inevitable disruption of ICE vehicles by BEVs, but we simultaneously support more radical innovations in transit technologies, shared mobility, urban planning and transport culture which might reduce the extent to which transport relies on automobiles in the first place.

As in the power sector, technological change impacts multiple other system drivers. Given the increasing and accelerating affordability and appeal of BEVs, governments are far more likely to embrace ambitious road transport decarbonisation policy such as ZEV mandates. Investors, confident in transport electrification, may be more willing to finance research, development and production of low carbon vehicles, as well as charging networks. Finally, consumers will be drawn to the lower prices, longer driving ranges and faster charging times enabled by technological innovation in this space. While some uncertainties remain regarding the continued exponential expansion of the BEV and PHEV market, a tipping point in the road transport sector seems imminent, resulting in the disruption of the ICE vehicle market and its ancillary systems (eg the petrol station network). Less certain is the extent to which modal shifts towards walkable and cyclable cities and public transport can disrupt the dominance of motor vehicle transport more broadly.

Government

Because most vehicles are purchased and driven by individual consumers, governments play a smaller direct role in road transport than in the power sector (although public procurement of BEVs by governments is a potential accelerator for low carbon transport disruption[159]). That said, the government plays a key role as a regulator in the transport sector. This is visible in everything from traffic laws to existing fuel economy standards worldwide. Governments can accelerate low carbon disruption in the road transport sector in three different ways:

1. Incentivising or accelerating the switch from ICE vehicles to BEVs through carrot or stick policy (ie subsidies for low carbon vehicles, ZEV mandates, fuel taxes or other interventions), or more directly through public procurement.
2. Incentivising or directly investing in BEV-enabling infrastructure such as public charging networks or more flexible and resilient power grids.
3. Incentivising or directly investing in infrastructure to reduce reliance on personal vehicles, such as public transport, walkable cities, cycle lanes and inter-city rail.

Road vehicle fuel tends not to be covered by existing carbon pricing and emissions trading programmes.[160] However, governments subsidise petrol (below the economically efficient price) less than they do other fossil fuels; indeed, petrol tends to be taxed rather than subsidised in terms of private cost (when externalities are ignored).[161] In fact, these fuel excises often far exceed the carbon price, if one exists, on a per-tonne basis. This suggests only a slight sustaining influence from government policy in the road transport sector, mostly from governments in fossil fuel exporting states. Furthermore, many governments around the world have embraced the BEV transition: several countries have set BEV or ZEV targets or mandates, effectively banning the sale of ICE vehicles from a certain date.[162] These ZEV mandates now cover the majority of the global automobile market, signalling governments' willingness to accelerate the transition to ZEVs. There is also evidence that governments are increasingly incorporating BEV enabling infrastructure, such as charging networks, into public infrastructure spending packages (eg in China[163] and the US[164]). These trends will enable further deployment of BEVs and non-motorised transportation modes, which will aid in the disruption of the incumbent ICE-dominated road transport system.

ZEV mandates and other transport decarbonisation policies send strong messages to automotive manufacturers, encouraging them to innovate in and scale up production of low carbon vehicles to maintain their relevance. Governments therefore exert a strong influence on technology in this sector. Public policy also signals to investors that BEVs represent the future and ICE vehicles do not; this could trigger a cycle of reinforcing feedbacks as investment flows away from ICEs and towards BEVs, thereby enabling more stringent policy. Governments also influence citizens: by providing subsidies for BEVs, governments in the US,[165] EU,[166] UK,[167] India,[168] and other regions have drastically changed the decision landscape for those looking to purchase new vehicles, and the result has been strong demand for BEVs.

While ZEV mandates will accelerate decarbonisation by contributing to the disruption of ICE vehicles by BEVs and other ZEVs, this policy can sustain and reinforce less desirable aspects of the road transport sector, such as a reliance on large, resource-intensive, long-range BEVs as opposed to public transport and shared mobility (which would enable shorter-range BEVs or cars taken off the road altogether). Indeed, ZEV mandates in California,[169] the UK[170] and China[171] all require a minimum range for vehicles to qualify. Human-centric urban design, public transport and regulatory recognition of the role that shorter-range BEVs could play in urban areas could lead to substantial cost and lifecycle emissions savings.

Finance

In the road transport sector, finance plays a key role in both the supply and demand sides. Because vehicle manufacture (including personal automobiles and shared modes of transport such as buses) is capital-intensive, investment decisions are sensitive to the availability cost of capital. In line with technological and policy advances, investment in electromobility has increased exponentially in recent years: BEVs and PHEVs together accounted for an estimated 65 per cent of end-use investment in the transport sector in 2021 and 75 per cent in 2022.[172] There has also been substantial investment in electric buses, including via public–private partnerships in India[173] and Chile.[174] These influxes of capital, and others like them, can trigger disruption on two fronts. First, investment in electric buses will spur technological advance in general electric mobility technologies, spilling over to light-duty BEVs and aiding in their disruption of ICE vehicles. Second, they may increase the appeal and availability of public transport options, which could disrupt the personal vehicle paradigm more broadly.

At the point of purchase, finance can play a key role in road transport disruption. Cars carry a high upfront cost, so most people finance automobile purchases; indeed, automotive finance penetration stands at about 70 per cent globally.[175] In this majority of cases, the terms of an auto loan can make or break a consumer's willingness and ability to purchase a vehicle. This is especially so for BEVs, which currently present higher upfront costs but lower running and maintenance costs. 'Green auto loans', which offer BEV buyers lower interest rates, extended repayment terms, or both, can be a powerful tool to increase the affordability and therefore diffusion potential of BEVs.[176] More generally, innovative financial instruments could play an important role in accelerating BEV uptake by individual consumers, and could be applied on larger scales to enable the expansion of public transport networks to further weaken our reliance on the personal automobile. As with other system drivers, innovations in financial instruments could weaken sustaining influences and strengthen disruptive influences in technology, government policy and consumer behaviour, contributing to reinforcing feedbacks between system drivers.

Citizens

Citizens play a prominent role in the road transport sector in their capacity as consumers: individual choices of whether to buy a car, and, if so, which type, ultimately determine the market direction and environmental impact of the sector. Historically, the rise of ICE vehicles over bicycles, horses, cable cars, trolleys, trains and even early BEVs was driven in large part by consumer preferences for ICE vehicles, deeply interwoven with a culture of individuality.[177] In this light, low carbon disruption in road transport may depend in large part on consumers' willingness to accept BEVs and other low carbon transport modes over ICE vehicles. Citizens remain a sustaining influence in some ways, impeding low carbon road transport disruption; however, in some markets consumers are embracing BEVs, which suggests that consumer choice could co-evolve alongside technology and policy to become a key disruptive influence.

Consumers in many markets remain sceptical of BEVs, and even more so of car-free living. The primary barriers to BEV adoption are the upfront vehicle price, scarcity of charging stations, and charging time.[178] At present, each of these reflects an advantage of ICE vehicles. Across the globe, BEVs cost more upfront (before government incentives) than their conventional counterparts; however, this tends to be more than offset by lower fuel and operating costs, leading to lower lifetime costs.[179] While some countries (notably China) have achieved the recommended charge point density of one public charger per ten vehicles, most countries still fall short, and even in China the relatively low market share of BEVs means that the geographic density of chargers may cause some drivers to feel 'range anxiety'.[180] Finally, charging a BEV at a public charging station certainly takes longer than refuelling an ICE vehicle, although many BEV owners rely on home charging and seldom use public chargers.

However, progress in other system drivers (notably technological change, government policy and finance) may substantially weaken, or even reverse, these barriers to adoption in the near term. Upfront vehicle costs are falling as battery technology advances, raw material costs decline, and BEV manufacturers achieve economies of scale. Combined with government incentives and green auto loans, this means that BEVs may reach cost parity with ICE vehicles earlier than expected.[181] BEV charging networks are expanding exponentially, and we expect that consumers will be increasingly comfortable with the prospect of BEV ownership as charging stations become as ubiquitous as petrol stations. Finally, new BEVs are increasingly able to accept very high charging power.[182] While BEV charging times will still surpass petrol refuelling times for the foreseeable future, this increase in accepted charging power will have an important impact: we estimate that by 2030, the average new American BEV will be able to charge to 500 km (the average range of an ICE vehicle) in half an hour. In practice, charging times on road trips will be even lower if drivers strategically use DC fast charging.

Driving an EV brings with it the 'warm glow' of a lower carbon footprint, but BEVs are increasingly also associated with a range of other value propositions such as a quieter and smoother drive, quick acceleration and the potential for autonomous driving. As these attributes continue to improve, and as the concerns of upfront costs, charger prevalence and charging time are ameliorated by trends in other system drivers, consumer preference could become a major driver of disruption in road transport.

Given the centrality of consumer choice in the road transport sector and in its disruption (the e-mobility transition and shifts to other modes of transport all involve individual decision-making) citizens exert a key influence on other system drivers. BMW, for instance, which notably has not committed to phasing out petrol-fuelled vehicles in the near or medium terms, cites continued consumer demand for ICE vehicles as a primary reason for resisting a complete BEV transition.[183] Similarly, if BEV demand does not materialise, national governments may come under pressure to relax ZEV mandates and other road transport decarbonisation policy. Although improved walking, cycling and public transport infrastructure would certainly help consumers ditch personal automobiles, governments ultimately answer to voters and may be hesitant to adopt policy or spending which is viewed as expensive, excessive or unnecessary. Finally, if demand for low carbon road transport does not increase as the financial sector currently expects, financial institutions may respond to an increase in perceived risk by offering restricted or more expensive capital to innovators, manufacturers and consumers of BEVs, charging infrastructure and other low carbon infrastructure. On the other hand, continued consumer enthusiasm about – and demand for – BEVs will strengthen the disruptive influences exerted by innovators, governments and finance. It remains to be seen if such a virtuous cycle can emerge for non-automobile transport, but if it does citizens will likely play a central role.

Appendix C: Agriculture

The agricultural sector: system driver assessment

This annexe presents a fuller picture of the history, current state and future outlook of each disruption driver in the context of the agriculture sector.

Planet

The food and agriculture system contributes to current and projected transgressions of all nine planetary boundaries.[184] Food production accounts for 75 per cent of all freshwater use worldwide and is a major source of air and water pollution.[185] It is also the most extensive global direct driver of land degradation[186] and altered biogeochemical cycles.[187] As global wealth has increased, diets have shifted to include more protein via animal products such as meat and dairy, which are particularly high-emitting and land intensive. Coupled with population growth, this gives current food production a considerable land footprint, which reduces the land available for carbon-sequestering forests and biodiversity-preserving natural habitats. If everyone on Earth ate the typical American diet, food production would require 98 per cent of *all* land area – an abject impossibility considering how much land is barren or covered by ice.[188] Of course, the food system itself is a key source of GHG emissions, contributing up to one-third of the global total.[189] Jarring as this figure is, the near-term impact on warming may be even greater, as a substantial share of agricultural emissions are methane, which is extremely potent but dissipates quickly.[190] Although methane accounts for less than one-fifth of CO_2-equivalent emissions when 100-year warming potentials are used, at current emissions levels it will be responsible for 41 per cent of global surface warming over the next 20 years.[191] In short, the incumbent food and agriculture system has widespread detrimental impacts on planetary systems.

Simultaneously, and somewhat ironically, the agricultural system is severely threatened by planetary system change, and particularly by physical climate risks. A warming planet will feature more frequent and more severe droughts, heatwaves, flooding and other extreme weather events, as well as continued sea level rise. All these endanger crops and livestock around the world and will thereby increase risks to food security.[192] Due to 'industrial amplifiers' such as degraded soils, simplified landscapes and intensive inputs, large-scale industrial agriculture – today's incumbent model – may experience worsened impacts from drought, flooding, encroaching pests and other physical disruptors.[193] Climate change may also exacerbate adverse crop impacts from diseases, ozone and aridity, which already constrain crop yields to varying extents worldwide.[194] Lastly, climate change will adversely impact the entire livestock supply chain. Beyond impacts at the point of feed and water resources, processing, storage, transport, retailing and labour, heat stress has immediate and long-lasting detrimental impacts on animal productivity, welfare, fertility and resilience; reduces the quality of animal products; and can increase rates of disease and animal mortality.[195] If farmers and supply chains do not plan for – and innovate in anticipation of – these physical risks, the industry could be severely disrupted by decimated yields in crop and livestock systems.

The planet is exerting a strong and disruptive influence on the agricultural sector, both via direct impacts on productivity and indirectly via agriculture's environmental footprint. In this light, advocates of CSA seek to transform food production to promote food security under the new realities of climate change.[196] They define three objectives: productivity gains in food production, resilience and adaptation to physical climate change impacts, and mitigation of agricultural GHG emissions.[197] Widespread adoption of CSA practices would simultaneously decrease the climate impact of the sector and build its resilience to future planetary change. CSA entails change in the state of each of the other system drivers. As planetary conditions evolve, there may be increasing pressure for entrepreneurs, governments, investors and consumers to both embrace innovative approaches to producing conventional food products and also turn to lower-impact, more resilient alternative products such as alternative proteins.

Technology

Technology in its current state exerts both sustaining and disruptive influences on the agriculture sector. On the one hand, technological innovation in farming and supply chain products and practices has led to unprecedented high yields and low costs in intensive, industrial agriculture applications. On the other, technological advances in alternative proteins threaten to irreversibly disrupt the powerful and incumbent animal agriculture system. Moving forward, technology can similarly serve to both sustain and disrupt incumbent industries. In many cases, product and process innovations can help food producers adapt to disruption from environmental shocks and changing policy, financial and consumer landscapes. However, those incumbents who do not adapt by embracing these innovations may face obsolescence as they are displaced by better-adapted competitors.

Alternative proteins could transform the agriculture industry by eventually undercutting animal agriculture in cost while offering substitute products that are more environmentally friendly and more resilient to planetary change. *Plant-based* dairy, meat, seafood and eggs remain the most popular form of alternative protein, and they continue to attract investment and market shares away from animal-based products.[198] While plant-based protein, like renewable energy and batteries, has experienced cost declines, it remains more expensive that conventional meat in most regions. Indeed, both price and taste are cited as barriers to wider adoption. However, with continued innovation in protein fractioning and functionalisation, structuring, scaling and manufacturing, plant-based proteins could soon achieve price, flavour and texture parity with animal proteins. In fact, BCG estimates that cost parity for plant-based proteins with realistic taste and texture could be achieved this year (2023) in the US and EU.[199] This would rapidly accelerate their diffusion and the corresponding disruption of animal agriculture.

In addition to plant-based protein, *fermented* and *cultured* proteins represent major innovation opportunities and potential disruption drivers. While these technologies are more nascent and further from cost parity, each offers advantages that could potentially trigger disruption in the animal protein market and broader food system. Precision fermentation, which uses genetically engineered micro-organisms to produce target molecules such as proteins and fats found in animal-based foods, could be key in revolutionising food production.[200] This technology can create unique flavours, textures and nutritional attributes in addition to mimicking the properties of conventional meat.[201] It could also serve as an enabling innovation for cultivated meat by reducing the cost of serum free media and other inputs.[202] As the field of synthetic biology advances and precision fermentation operations achieve economies of scale, it is expected that this form of protein will become cost competitive with animal protein in the near future. Cultivated meat has made recent gains in both cost-competitiveness and meat imitation. The cost of cultivated meat has fallen rapidly in recent years and is projected to fall to the same order of magnitude as conventional meat in the near term.[203] New 3D printing technology promises to create whole-tissue cultivated meat with very similar properties to conventional meat.[204] All these developments could contribute to disruption of livestock systems.

The food system features a high degree of business-to-business transaction, driven by dominant fast-moving consumer goods (FMCG) majors. If FMCG majors begin to favour alternative protein sources in their products due to lower costs and environmental impacts or better properties (eg flavour, nutrition or texture), they could trigger rapid disruption throughout food supply chains. Indeed, FMCG businesses already recognise protein diversification as a material concern, and today nearly all are investing resources into alternative protein innovation and development (in contrast, as recently as 2016, no FMCG majors were discussing protein diversification as a material risk or opportunity).[205] This demonstrates the unprecedented pace of innovation and disruption in this space.

Despite this existential threat from alternative proteins, technology could also help sustain animal agriculture through innovations which reduce livestock emissions (thereby increasing resilience to climate transition risks) and also enhance resilience to physical environmental risks. For instance, certain feedstock additives have been shown to reduce methane emissions from ruminant enteric fermentation by up to 90 per cent.[206] Silvopasture – a form of agroforestry which intentionally combines grasses, trees and legumes as feedstock for livestock grazing – represents an ideal form of CSA. It has been found to increase land productivity via healthier and more comfortable animals, enhance resilience to drought and extreme heat via improved soil quality and tree cover, and offset livestock emissions to a high degree via carbon sequestration in trees and soil.[207] Meat and dairy suppliers that embrace these innovations and demonstrably reduce their emissions will fare better in future regulatory environments and enjoy greater reputational benefits in comparison to those that do not.

More broadly, the food and agriculture system can build resilience to disruption by embracing circular and regenerative practices. Circular agriculture rests on three principles: use plant biomass by humans first as the primary food building block, recycle by-products of food production and consumption back into the food system, and use animals to transform biomass unsuitable for human consumption into nutritious food.[208] By feeding livestock 'low-opportunity cost feedstock' such as biomass from grasslands, crop residues, co-products of industrial food processing and food waste, the protein output of arable land can actually be increased relative to a vegan diet.[209] Moving towards regeneration and circularity in food production would drastically reduce the environmental footprint of the food and agriculture system. This may be an appealing option for incumbent farmers: although it entails radical innovation in farming processes and the prioritisation of different agricultural outputs (ie directly plant-based food with peripheral livestock, as opposed to livestock and feed crops at large scale), it also sustains the basic principle of farming the land to produce crops and livestock for human consumption. Circularity should go together with reductions in food waste. This requires both technological innovation and support in developing economies to increase the proportion of food that reaches plates in the first place, and cultural innovation and transformation in wealthy countries to reduce post-consumer food waste.

Disruptive pressures from governments, consumers and finance may be enabled and accelerated by the emerging presence of viable and increasingly low-cost alternatives – in this case, alternative proteins which incur a fraction of the environmental cost of animal-based incumbents. On the other hand, food producers that can innovate through this disruption by embracing low carbon production methods and altering business models can leverage technology to maintain their relevance in the sector. While the influence of technology is projected to be increasingly disruptive, incumbent players that innovate early and ambitiously to reduce their environmental footprint and enhance resilience may be able to leverage technology to maintain and sustain their relevance.

Government

Governments both historically and currently exert a sustaining influence on the food and agriculture system through substantial policy support for incumbents, delivered in part via considerable production subsidies. However, for a variety of reasons, governments may begin to re-evaluate this approach as the true environmental, health and social costs of modern agriculture are more widely recognised. Such a shift in food and agriculture policy could help catalyse a tipping point in the sector, ushering in irreversible low carbon disruption.

Agriculture's high GHG emissions, especially its high share of global methane emissions, could increasingly make it a target of decarbonisation policy as climate impacts worsen and focusing events highlight the urgency of the 'climate emergency'.[210] Furthermore, the modern food system has also created crises of health and inequality. The prevalent model of providing calories, rather than nutrition, has contributed to high rates of obesity and chronic disease worldwide. Antibiotics and chemical fertiliser, which are employed to increase crop and livestock yields, can lead to antibiotic-resistant pathogens and toxic residue in foods, respectively.[211] Industrialised livestock production promotes genetic similarity in animals and close living quarters; both factors increase the risk of zoonotic disease, which can easily be transmitted in meat processing plants.[212] Lastly, large-scale industrial agriculture has exacerbated land inequality since the 1980s.[213] This has grave implications for food security, especially in some of the developing countries most vulnerable to the adverse physical risks of climate change. All told, the global food system has been estimated to impose USD 12 trillion of hidden costs each year (exceeding its USD 10 trillion market value).[214] Animal agriculture – in particular, the production of meat and dairy – drives a high proportion of these costs. Clearly, the current food and agricultural system cannot be sustained. More than a purely moral imperative, there are concrete incentives for governments, acting in the public interest, to address the twin crises of methane emissions and a broken food system.

Governments worldwide are beginning to prioritise methane emissions reductions as their focus shifts to reducing both the rate of warming *and* absolute temperature rise. Recently, the EU and USA championed a Global Methane Pledge[215] that has been adopted by most of the world's countries. This pledge explicitly states that methane emissions from energy will be prioritised – a good thing, given the extent to which methane emissions abatement in the energy supply relies on government regulation. But the role of agriculture in global methane emissions is also recognised as a policy priority, even if direct agricultural regulation is notably missing. Businesses in the agricultural sector may soon be regulated or face a price for methane emissions: for instance, the New Zealand government has proposed a plan to price agricultural methane emissions,[216] and the Council of the EU will soon consider including non-CO_2 GHG emissions from agriculture in its ETS.[217] If this trend continues, there is the potential for major disruption throughout the food system as emissions externalities are priced into food products.

The food and agriculture system could be particularly sensitive to policy change for two reasons. First, agriculture is heavily supported by government policy today, to the tune of USD 630 billion annually.[218] Second, there is persistent strain on the economic viability of farming.[219] Farmers may be highly responsive to the government support they receive (and any conditions thereupon) due to low profit margins. Taken together, there is reason to believe that the current state of the food system is – to a high degree – a product of the agricultural support policy which exists today, and that it could shift rapidly if the nature of that support were to change. Germany has explicitly committed to redirecting subsidies away from carbon-intensive agriculture and towards low carbon food production and consumption; while this commitment is unique today, other jurisdictions may follow as food system disruption accumulates.[220] Lastly, governments hold immense power as food procurers; indeed, public procurement of alternative proteins was identified as one of three 'super-leverage points' for accelerating the low carbon transition across the economy.[221]

That said, governments worldwide remain stubbornly supportive of livestock systems and incumbent agricultural production methods. The EU's farm subsidy system, for instance, pays farmers on a per-hectare basis, which perversely rewards high levels of land use. Worse still, some environmentally damaging agricultural sub-sectors (such as beef, milk and sheep) are explicitly subsidised above and beyond the per-hectare rate.[222] Innovative alternative proteins also face substantial regulatory hurdles, which could impede their disruptive potential. For instance, EU regulation on Novel Food, genetically modified foods, and food naming and labelling could slow the diffusion of alternative proteins.[223] In an even bolder move, Italy recently moved to ban the production of cultured meat outright, nominally to preserve culinary heritage.[224] Strong livestock and farm lobbies around the world are likely to continue advocating these protective policies to stave off disruption. Eliminating these distortionary and perverse supports and regulations would be a crucial first step towards effective decarbonisation policy in the food and agriculture system.

If decarbonisation policy in the agricultural sector were to tighten, ripples would be felt across other disruption drivers: market-based policy would accelerate cost parity of alternative proteins and other low carbon technological innovations, and investment would likely shift from emissions-intensive businesses into lower carbon disruptors. Indeed, these phenomena could be triggered by even the suggestion or projection that policy might change.

Finance

The finance sector is beginning to feel, and take notice of, disruption in the food and agriculture system. Already, temperature rise has been attributed to tens of billions of dollars in crop insurance losses in the USA.[225] While the higher risk of crop and livestock failure may increase the cost of capital and insurance premiums for all farmers, intensive industrial operations are most vulnerable to physical climate risk and may therefore face the highest degree of financial disruption. Financial institutions are also likely to begin withdrawing investment from – or, at the very least, pricing in climate transition risks for – emissions-intensive livestock operations. For instance, investors have expressed concern about Brazilian beef production due to its poor environmental oversight and contribution to deforestation in the Amazon rainforest, and some investors have already excluded Brazilian beef producers from their funds.[226]

Considering physical and transition risks, investors may look to innovative foods such as alternative proteins to build their own resilience to this disruption, fulfil responsible or sustainable investing pledges, and capitalise on a rapidly changing market. Together, alternative proteins (plant-based, fermented and cultivated) attracted USD 5 billion in investment in 2021, and investment in these new technologies increased exponentially prior to 2022.[227] Although 2022 saw such investments fall to USD 2.9 billion, causing some worry that an alternative protein bubble had burst, this decrease was in line with broader investment trends, especially those in venture capital-funded sectors.[228] Indeed, of 125 surveyed investors, 46 per cent responded that their investment in alternative proteins slowed due to broad market and economic conditions and 45 per cent reported their alternative protein investments did not slow.[229]

Finance has traditionally sustained incumbents, who are seen as safe investments. A finance flip towards disruption could trigger further innovation in low carbon agricultural technologies and alternative foods, embolden more ambitious agriculture decarbonisation policy, and shape the landscape of familiar foods for consumers.

Citizens

Consumer preferences are an extremely material disruption driver in the food system. Food is deeply personal, and although choices are shaped by systemic factors, ultimate consumption decisions are largely made at the individual or household level. Historically, consumer preferences have exerted a sustaining influence on the food system: positive feedbacks associated with taste, habit, ease and cultural significance operating at the individual, social and market levels led to 'meat lock-in'.[230] However, citizens could potentially become a disruptive influence if currently nascent trends in dietary change and political pressure continue and amplify.

Motivated by concerns about environmental impact, health and animal ethics, many consumers are already limiting or completely cutting out animal products: in 2018, one-third of the UK population and rising was flexitarian, vegetarian or vegan.[231] Even consumers who do not change their diets may demand more transparency regarding the quality, safety and sustainability of the food they buy, which would likely encompass its emissions intensity.[232] This shift will reduce revenue streams for emissions-intensive animal agriculture and animal-derived food value chains, while presenting opportunities for new players in the food market.

Large-scale forfeiture of dairy, meat, seafood and eggs seems unlikely, at least in the short and medium term: food is so habitual and has deep cultural ties, which means that individuals are unlikely to meaningfully or rapidly change the way they shop, cook and eat. Furthermore, some consumers are reluctant to purchase alternative proteins, as they perceive them to be highly processed or unnatural.[233] However, it is possible that as technology progresses and alternative protein sources become more convincing and cost-competitive substitutes for animal protein, consumers will begin to embrace them and make in-place substitutions. For instance, while most Western consumers remain meat eaters, a survey found that 80 per cent of the UK and USA populations would be open to cultivated meat.[234] The rate is even higher among young people, who are the food consumers of the future. Similarly, while edible insects – another more sustainable meat alternative – have historically faced social and cultural barriers to adoption in many Western markets, a recent survey found that 72 per cent of American respondents were willing to try at least one insect-containing product.[235] Food and agricultural systems are highly responsive to demand: if beef is demanded at a lower level in one year, fewer cows will be bred in the next. This contrasts with the power and transport sectors, which feature long-lived capital assets. In agriculture, then, changing consumer preferences and consumption patterns could plausibly drive widespread and rapid disruption in concert with evolving technological, policy and financial landscapes. Therefore, while conventional proteins and intensive agricultural practices have not yet been disrupted to a great extent, their future disruption could be particularly rapid and irrevocable.

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