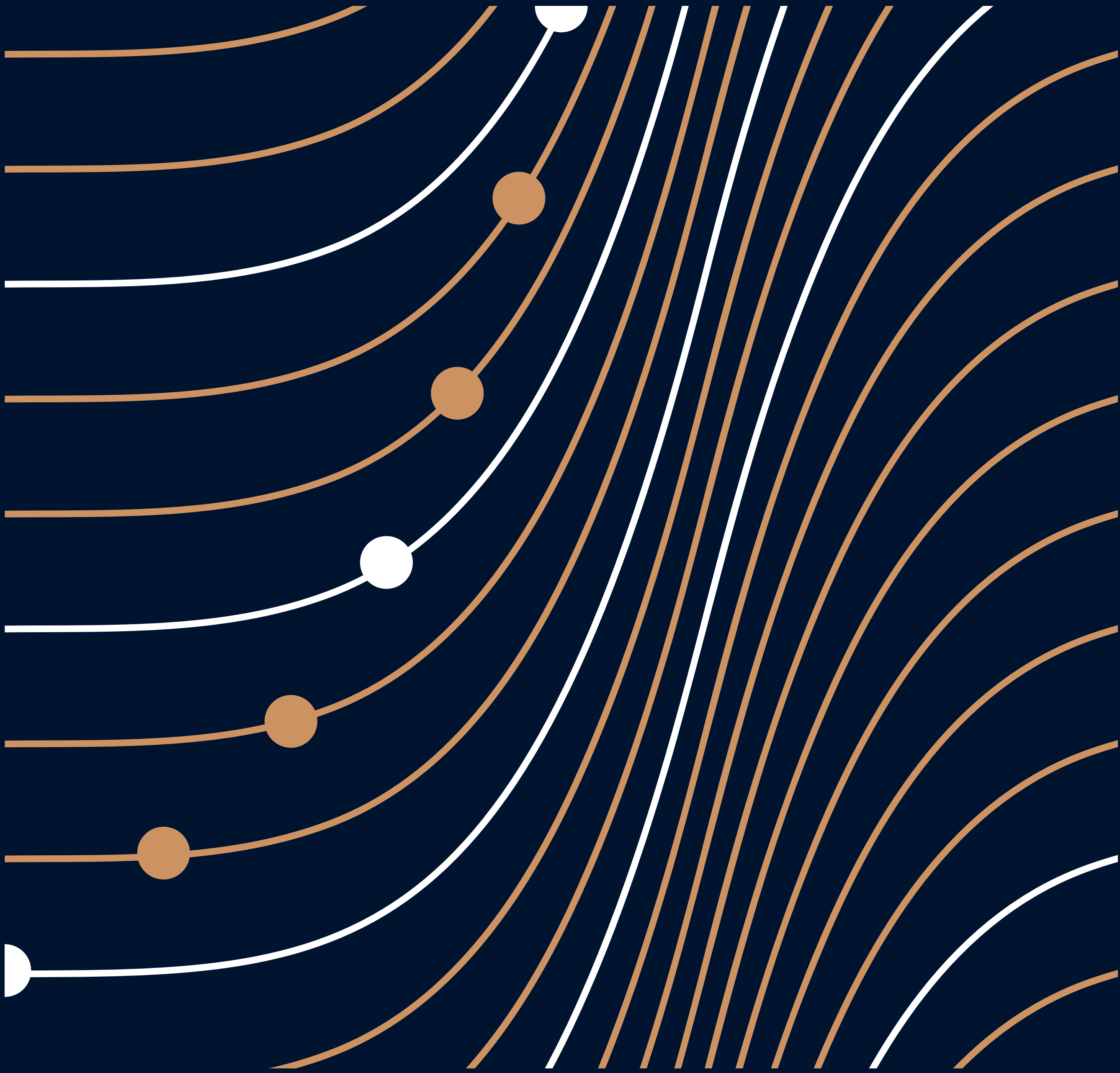

THE BREAKTHROUGH EFFECT: HOW TO TRIGGER A CASCADE OF TIPPING POINTS TO ACCELERATE THE NET ZERO TRANSITION

SYSTEMIQ
University of Exeter
BEZOS EARTH FUND

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ENDORSEMENTS

The Paris Effect made it clear that zero-carbon technologies are advancing rapidly and the next wave of creating prosperity lies in the drive to the net-zero economy. *The Breakthrough Effect* now shows us the 'How' – what the conditions are that countries, companies and investors should target to unleash accelerated growth and the new sources of prosperity. Wise policy makers and investors will aim for the opportunities, jobs and resilience that can be delivered only through a net-zero economy."

Pr. Nicholas Stern, Professor of Economics, Chair of the Grantham Research Institute on Climate Change and the Environment, London School of Economics

Pushing to reach net zero is a huge economic opportunity that companies can realise by innovating and doing the work to develop solutions. *The Breakthrough Effect* shows us where low-carbon solutions could become better than today's high-carbon incumbents: cheaper, more attractive to consumers, and widely available. Making this happen will require governments and climate innovators to work together."

Catherine McKenna, Chair of the UN High-Level Expert Group on the Net-Zero Emissions Commitments of Non-State Entities

We are embarking on one of the most fundamental and rapid industrial transformations in history. The transition to a net zero global economy will unlock huge potential for growth and value creation as businesses and governments decarbonise. The financial sector is poised to enable and accelerate this transition by directing capital to where it can have the biggest impact. *The Breakthrough Effect* highlights the positive climate tipping points where the transformation will take place soonest and most swiftly, acting as catalysts in the market to drive net zero solutions to scale."

Dr Celine Herweijer, Group Chief Sustainability Officer, HSBC

The world is increasingly realising that the transition to clean energy will not be linear but exponential, driven by technological feedback loops: the more renewables you build, the cheaper they get. By identifying tipping points, and focusing action on achieving them, the shift towards a net-zero economy can be accelerated. This report provides a best-in-class look at where we are on key tipping points, how we can achieve them, and the cascading impacts that achieving them will have."

Adair Turner, Chair, Energy Transitions Commission

The Paris Agreement inspired net zero ambitions from countries, companies and citizens. In turn this has accelerated low-carbon solutions – in some cases at exponential speed. *The Breakthrough Effect* shows us the power of human ingenuity, and of our individual and collective agency. It reaffirms the possibilities ahead if we – with deep intention – put our minds towards creating the conditions for positive tipping points."

Christiana Figueres, Co-host of the podcast Outrage and Optimism and former Executive Secretary, UN Convention on Climate Change (2010-2016)

Two years ago, *The Paris Effect – COP26 Edition* report made clear that the move towards a cleaner, decarbonised economy had gained unstoppable momentum, pushed forward by not only regulators but markets themselves. Today, *The Breakthrough Effect* report shows us where we could see solutions build a net-zero economy that outcompetes incumbents. As we reach these tipping points, we will see that unstoppable momentum turn into exponential growth."

Hubert Keller, Senior Partner, Lombard Odier

We are facing intersecting crises across the global economy, but we cannot slow progress on climate action. This is why public-private collaboration, a single-minded focus on implementation and ambitious innovation will be essential over the next decade. One of the most powerful things we can do is drive technology innovation that allows us to take more meaningful climate action which can help trigger a cascade of tipping points to accelerate the net zero transition."

Kate Brandt, Chief Sustainability Officer, Google

We know that radical shifts are required for meeting our climate and nature goals – from shifting diets, to restoring forests, to phasing out the internal combustion engine. How close are they to positive tipping points? And what are the barriers that must be removed so that change becomes irresistible and unstoppable? What's the special sauce that have led some issues to suddenly rise on the agenda and solutions emerge? This report helps us answer some of these essential questions."

Andrew Steer, President and CEO, The Bezos Earth Fund

Solar electricity is already the cheapest electricity in many parts of the world, and with decreasing prices of batteries, is expected to become the cheapest form of round-the-clock electricity before 2025. This has been made possible by a number of public policy interventions; similar interventions across the energy economy would help us move rapidly towards a global net zero emissions goal. As the authors of *The Breakthrough Effect* rightly point out, in many sectors, powerful reinforcing feedback can help bring forward the tipping points. The challenge, of course, is that no one should be left behind."

Ajay Mathur, Director General, International Solar Alliance

The Breakthrough Effect zeroes in on net zero tipping points which will transform major sectors of the real economy. Smart money should be looking to capture the upside of these real economy transitions as the market drives faster adoption of zero-carbon solutions."

Rhian-Mari Thomas, CEO of the Green Finance Institute

The transition to the net zero economy will happen exponentially. We know this. *The Breakthrough Effect* helps us understand where the tipping points lie that will set off unstoppable and accelerating change in sector after sector. Low-carbon technologies have advanced faster than expected already, and these tipping points are in striking distance, but not factored into most forecasts. If you want to remain competitive, read this report and set bolder targets now!"

Nigel Topping, UN Climate Change High Level Champion, COP26

Country ambitions on decarbonisation are too low. Systematically, governments are under-appreciating opportunities for exponential growth in low-carbon solutions once we reach tipping points. *The Breakthrough Effect* report provides a 'map' of where these tipping points lie and how to reach them faster. In addition, solutions are going to be cheaper than most policy makers realise. They can embrace the virtuous feedback loops that will speed progress. We need political leaders to study the data and drive these transitions at speed and scale, confident in explaining to their electorates that these pathways will deliver jobs, growth and more resilient economies."

Rachel Kyte, Dean, Fletcher School, Tufts University

ENDORSEMENTS

"I urge governments, investors and business leaders to use this important report to understand which actions they should prioritize today to drive the level of emissions cuts needed to get us on track for limiting global temperature rise to 1.5C. It is hugely encouraging to see that two of the technologies that are critical for halving emissions by 2030 – renewable electricity and storage, and electric vehicles – are already near the tipping point. But success is not guaranteed, nor is the speed of exponential growth post tipping point. Government policies and increased investment to rapidly scale up renewable electricity and charging infrastructure are essential to ensure that both renewables and EVs reach their full potential to cut emissions."

Maria Mendiluce, CEO, We Mean Business Coalition

"Market dynamics increasingly favor low-carbon technologies, with the rapidly falling costs of wind, solar, batteries, and electric vehicles already disrupting our economic systems. We have reached peak demand for fossil fuels and many clean energy solutions are competitive with, or cheaper than, fossil fuel alternatives. This disruption will only accelerate as the costs of clean energy technologies continue to fall. Governments, financial institutions, and corporate leaders should review *The Breakthrough Effect* to better understand and get ahead of the disruption that is underway."

Jon Creyts, CEO, RMI

"Building the net-zero economy is the next great wave of value creation for society. *The Breakthrough Effect* highlights that positive socioeconomic tipping points are within striking distance and lays out the map of where these tipping points lie. Working together across companies and with governments, we can capture this opportunity. The time is now."

Siddharth Sharma, Group Chief Sustainability Officer, Tata sons

"As zero-carbon solutions become competitive with fossil fuel-based incumbents, we reach tipping points that accelerate our capacity to scale deployment of sustainable infrastructure. This deployment – of charging networks, electricity grids and more – can in turn give rise to virtuous feedback loops that further lower costs and scalability. Development banks have a key role to play in emerging markets to marry private sector ideas and speed with the capacity of governments to drive this change at scale.

The Breakthrough Effect for the first time puts a clear spotlight on where these tipping points exist, showing where there are opportunities for strategic investment that will unlock exponential growth and value. Zero carbon solutions are not only good for people and planet, but also critical to create jobs and drive sustainable growth. Decarbonization is development, and there is no time to waste."

Ahmed M. Saeed, Vice President for East Asia, Southeast Asia and the Pacific / Asian Development Bank

"*The Breakthrough Effect* report highlights the importance and timeliness of thinking and acting in systems to accelerate the net-zero transformation. We need to consider how much more effective we could be if we comprehend, embrace and design for dynamics of change in human systems, from politics and policy to societal norms. I welcome a report that highlights the opportunity before us; one that calls for our policy decision-making to build and reflect an understanding of these system dynamics. The report further calls attention to the role of international cooperation in creating the conditions for positive 'super tipping points' and 'tipping point cascades'. This is extremely relevant to efforts underway in Europe through the Green Deal and EU Missions, which offer a case in point to put this into action across national and market boundaries, and extend that further to international partnerships, to create the conditions for global-scale systemic change."

Dr. Kirsten Dunlop, CEO, Climate-KIC Group

"*The Breakthrough Effect* report is essential reading for leaders in government and business and sets out clearly the positive tipping points we need to prioritise to cut greenhouse emissions fast. The science shows that we are now approaching dangerous thresholds – or negative tipping points – in multiple bio-physical systems that risk locking us into devastating climate change for generations to come. Five of the six possible negative tipping points at the current level of warming are in the Arctic and Antarctic. We must cut global carbon emissions in half by 2030 and this collaborative report sets the credible course with far-reaching effects across ten of the highest-emitting sectors. If you want bang for your buck then read this report!"

Pr. Gail Whiteman, Professor of Sustainability at the University of Exeter Business School and Founder of Arctic Basecamp

"Climate change is now a race between the problem, which risks becoming exponential, and our solutions, which still lack the speed and scale to keep up. *The Breakthrough Effect* is the clearest plan yet for how we trigger a wave of positive tipping points that can transform the global economy and set humanity and our planet on a safe and hopeful path. This is how we get the future we want, and it presents tremendous opportunities for the companies who drive the change."

Paul Polman, Board member at Systemiq and co-author of *"Net Positive: how courageous companies thrive by giving more than they take"*

"The world is on track for climate disaster – but we still have the chance to change course this decade and keep the 1.5 goal within reach. *The Breakthrough Effect* outlines targeted interventions that could not be more opportune. These three positive tipping points can cascade across sectors to induce the systems transformation urgently needed to slash emissions and create a future where people, climate and nature can thrive."

Ani Dasgupta, President and CEO, World Resources Institute

AUTHORS & ACKNOWLEDGEMENTS

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ABOUT THIS REPORT

'The Breakthrough Effect: How to trigger a cascade of tipping points to accelerate the net zero transition', developed by Systemiq in partnership with the University of Exeter and Simon Sharpe is a contribution to Systems Change Lab with the support of Bezos Earth Fund. The report examines where positive socio-economic tipping points may exist for zero-emission solutions and what conditions can activate these tipping points. When the conditions are set to trigger tipping points, reinforcing feedback loops become a dominant market driver and the adoption of zero-carbon solutions scales up an S-curve.

This assessment builds on Systemiq's prior work in 'The Paris Effect- COP26 Edition' report. That work highlighted the possibility that tipping points could be reached before 2030 for zero-emission solutions in sectors representing 90% of GHG emissions, and many could possibly be reached much sooner.

This new assessment probes into the nature of each tipping point, analysing the conditions required to activate them – across affordability, attractiveness and accessibility – and evaluates progress towards achieving said conditions. In addition, this assessment explores the links between sectors. These links suggest that crossing a tipping point in one sector can help to create the conditions that trigger a tipping point in other sectors, producing 'tipping cascades' across the highest-emitting sectors of the economy. The report presents three low-cost interventions that could create tipping cascades across ten sectors representing 70% of global emissions.

'The Breakthrough Effect' draws on research and analysis from hundreds of sources to summarise our existing knowledge on the target conditions required to trigger tipping points and the status of progress towards these so far. Crucially, it also highlights where the current evidence base is lacking and more research could help better understand and target tipping points.

Triggering tipping points and subsequent tipping cascades may be one of our most powerful tools for reducing emissions at pace and steering us away from climate catastrophe. Identifying key opportunities and making relatively small targeted changes can produce huge returns in terms of decarbonisation. High-emitting sectors of the economy do not exist in isolation – they are highly inter-connected, and zero-emission solutions can influence transitions in multiple sectors simultaneously.

ABOUT SYSTEMIQ

Systemiq, the system-change company, was founded in 2016 to drive the achievement of the Sustainable Development Goals and the Paris Agreement, by transforming markets and business models in five key systems: nature and food, materials and circularity, energy, urban areas, and sustainable finance. A certified B Corp, Systemiq combines strategic advisory with high-impact, on-the-ground work, and partners with business, finance, policy-makers and civil society to deliver system change. Systemiq has offices in Brazil, France, Germany, Indonesia, the Netherlands and the UK.

Find out more at **www.systemiq.earth**
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SIMON SHARPE

Simon Sharpe is Director of Economics at the Climate Champions Team, and a Senior Fellow at the World Resources Institute. He contributed to this report on an independent basis.

ABOUT UNIVERSITY OF EXETER

The University of Exeter is a Russell Group university that combines world-class research with high levels of student satisfaction. Exeter has over 30,000 students and is in the top 150 universities globally in both the QS World Rankings 2022 and THE World University Rankings 2023. In the 2021 Research Excellence Framework (REF), more than 99% of Exeter's research was rated as being of international quality. The University's 2030 Strategy sets out to use the power of education and research to create a sustainable, healthy and socially just future. The University of Exeter has established an exceptional environment and climate team with more than 1,500 researchers working in partnership with organisations across the globe, including some of the world's most influential climate scientists in the Global Systems Institute.

Learn more at: **www.exeter.ac.uk**
Contact: **pressoffice@exeter.ac.uk**

ABOUT SYSTEMS CHANGE LAB

Systems Change Lab is a collaborative initiative that aims to spur action at the pace and scale needed to tackle some of the world's greatest challenges: limiting global warming to 1.5°C, halting biodiversity loss and building a just economy. Convened by World Resources Institute and Bezos Earth Fund, Systems Change Lab supports the UN Climate Change High-Level Champions and works with key partners and funders including Climate Action Tracker (a project of NewClimate Institute and Climate Analytics), ClimateWorks Foundation, Global Environment Facility, Just Climate, Mission Possible Partnership, Systemiq, University of Exeter, and the University of Tokyo's Center for Global Commons, among others. Systems Change Lab is a component of the Global Commons Alliance.

Learn more: **systemschangelab.org**
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CONTEXT

The world is heading towards a series of climatic tipping points that risk causing irreversible damage to our planetary life-support systems. It is a hard reality that the world remains off-track for meeting our climate targets, with global temperatures already 1.2°C above pre-industrial levels and no credible pathway to limiting temperature increase to below 1.5°C based on current national commitments.[1,2] As recent evidence shows, we are now approaching thresholds – or tipping points – in multiple bio-physical systems that risk locking us into self-perpetuating climate change, i.e., change that will no longer be driven solely by our emissions, but also by irreversible processes we have set in motion. Five of these tipping points are possible at the current level of warming, including the collapse of the West Antarctic ice sheet and abrupt permafrost thaw.[3] It is therefore crucial to reduce global greenhouse gas emissions as quickly as possible to stay within safe planetary boundaries. Progress to date has been limited, with annual global emissions increasing again in 2022 to their highest levels ever.[4]

Yet in the face of these negative climatic tipping points, positive socio-economic tipping points offer an opportunity to rapidly increase the deployment of zero-emission solutions and drastically cut global emissions. Socio-economic tipping points arise when a set of conditions are reached that allow new technologies or practices to out-compete incumbents. After a tipping point is crossed, reinforcing feedback loops that drive self-accelerating progress are strengthened, and balancing feedback loops that resist change are weakened. Greater deployment of the solution brings improvements, prompting even more deployment. Learning by doing improves performance, economies of scale reduce costs, and the spread of new social norms increase acceptability. Producers, consumers, and investors move decisively towards the new solution, whose market share grows exponentially (up the slope of the 'S-curve' of adoption). Across many sectors of the economy, there is potential to cross tipping points, accelerating the deployment of zero-emission solutions. Triggering socio-economic tipping points alone will not be sufficient to reach global climate objectives, but it offers a powerful lever to accelerate the transition to a low-carbon economy and limit global warming.

Multiple historical examples of rapid technological transitions prove that new solutions can take over a market in just a few decades. In several cases, a rapid increase in deployment took place after some threshold of relative affordability was passed (e.g., UK coal to gas switch). The switch is also often supported by the new solution being more attractive to customers for non-cost reasons (e.g., household central heating systems offering benefits in health/safety and convenience in the US; cultural attitudes towards eating meat prompting the rise of vegetarian/flexitarian diets in Europe) or if accessibility is widespread (e.g., public charging station build out supported EV adoption in Norway).[5]

A FIRST TIPPING POINT HAS ALREADY BEEN CROSSED IN THE ELECTRICITY SECTOR AND ONE IS VERY CLOSE IN ROAD TRANSPORT.

In 2021, solar and wind were the cheapest sources of new power in countries representing 90% of electricity generation.[6] The clear cost competitiveness of renewables has led to a large ramp up in deployment, with solar and wind accounting for >75% of total new capacity additions globally last year. Similarly, electric vehicle sales are scaling up rapidly in leading markets, even while still 2-4 years ahead of sticker price parity with internal combustion vehicles.[7,8] The market is already adjusting to this future reality and in some geographies, such as Norway, the tipping point has been brought forward by electric vehicle subsidies.[9]

While reaching a tipping point results in reinforcing feedback loops becoming the core driver of the system's behaviour, the pace of the transition cannot be taken for granted. For example, in the power sector the transition can be slowed by obstacles in planning and permitting for renewable power and electricity network build-out, continued opposition from vested interests, legitimate concerns about the socio-economic consequences of the transition, and temporary constraints in the supply chains of critical minerals or components. These can be thought of as dampeners that can reduce the slope of the S-curve. Crossing the tipping point is vital as beyond this point incentives re-align behind the new solution, but enablers are still required after it is crossed to achieve a rapid transition. In this report we focus on elements required to reach the tipping points, flip the incentives in favour of the low-carbon solution, and unlock reinforcing feedback loops as a dominant market force.

[5] Please see figure 1 in supporting text and appendix A for references.

SECTOR TIPPING POINTS

In high-emitting sectors of the economy, it is vital to understand where tipping points exist that could propel accelerated adoption of zero-emission solutions.

For each high-emitting sector, there is often one solution that will provide the bulk of the supply-side decarbonisation in the transition to net-zero. For example, while reducing emissions in the shipping sector requires a range of actions, including efficiency improvements and battery-electric short-haul fleets, zero-carbon fuels – such as green ammonia – are expected to account for ~80% of the sector's final energy demand in a fully decarbonised system.[10] In many cases, these key zero-emission solutions have the potential to reach tipping points after which deployment could accelerate significantly.

The presence of a tipping point for a zero-emission solution depends crucially on the strength of reinforcing feedback loops:

- **In some sectors, there is evidence that powerful reinforcing feedback loops can occur and drive exponential growth along an S-curve.** This is most obvious where there is a clear trend of clean technology cost reduction as production scales up, enabling the new technology to become cost-competitive with the high-carbon incumbent. For example, the price of lithium-ion batteries has fallen by 90% over the last 10 years as output has risen from very low volumes.[11] Substantial price declines are likely to continue as electric vehicle demand drives greater production at scale, entrenching a cost advantage for electric vehicles relative to regular ICE vehicles.

- **In other sectors, there is less evidence that reinforcing feedback loops exist or could prove powerful enough to become the dominant market force, driving S-curve adoption of zero-emission solutions.** One example is heat pumps for building heating. A reinforcing feedback loop is present, as the cost of heat pumps comes down with economies of scale, though evidence is limited to the last 5 years in a few countries.[12] Heat pumps *could* provide heat at a somewhat lower operating cost than heating from gas, provided electricity is cheap enough (relative to the gas price) and with sufficiently high heat pump efficiency. However, the upfront cost of a heat pump (even with cost declines) could remain materially higher than that of a gas boiler. This cost differential would need to be bridged, e.g., with government subsidies, meaning that any scale-up in deployment could remain reliant on continued heat pump subsidies or regulation. Similarly, in the food and agriculture sector, the diffusion of new social norms and positive experiences could help accelerate the adoption of alternative proteins once a given threshold is reached, but at present this possibility is speculative. If such reinforcing feedback loops fail to materialise or to prove sufficiently strong enough to become the dominant force in the market, it is likely that zero-emission solutions in these sectors will not see exponential growth but instead follow a linear trajectory. In cases where S-curves do not take hold, even more effort is required to provide the scale and pace required for decarbonisation.

Action to drive down costs can bring forward positive tipping points. Well-designed policies can help zero-emissions solutions become cost competitive with incumbents at an earlier date. Targeted investment, subsidies, taxes, and market-shaping regulations can shift investment towards the zero-emission solution, strengthening the reinforcing feedbacks that bring down its costs. For example, in India, electric vehicle subsidies tripled between 2017 and 2021, supporting a rapid increases in sales, particularly for rickshaws where EV penetration is set to reach 45% this year.[13] The announcement of a production-linked incentive programme in 2021 is expected to boost investment in domestic manufacturing.[14]

In some sectors, such support can be temporary, lasting until the 'green premium' is eliminated. In other sectors, even once costs for low-carbon solutions come down, policy support might still be required to bridge the gap with fossil-based incumbents and stimulate large-scale deployment. For example, in sectors that will rely primarily on green hydrogen for decarbonisation – such as fertiliser and steel production, and long-distance shipping and aviation – a rise in hydrogen production can rapidly bring down prices to below $2/kg H2 in the coming years in favourable locations.[15] Yet even at $2/kg H2, a carbon price or equivalent subsidy of approx. $100/ton CO2 will be necessary for these solutions to reach cost parity with existing fossil-based technologies in these sectors (under conditions of *historical* fossil fuel prices, prior to recent price spikes).[16] In practice, it may be simpler in these cases for regulation to require the use of the zero-emission technology.

In addition to cost, action will be required to improve the attractiveness and accessibility of many zero-emissions solutions. For example, for alternative proteins to reach large-scale adoption, product taste and texture must be good enough, health and nutrition concerns overcome, and cultural shifts widespread to appeal to average mass market consumers. Public investment in research and development, and public communications campaigns, can support private sector efforts. For other zero-emission solutions, improving accessibility will be key to unlock S-curve growth. For example, to support the volumes of electric trucks required to reach a cost tipping point, approximately 2 million chargers must be installed globally.[17] This first wave of electric truck deployment can be accelerated by focusing investment in charger deployment on major transport hubs (e.g., high-volume trucking corridors).

We are making rapid progress towards potential tipping points for zero-emission solutions in some sectors; in others, the necessary conditions remain distant. In the power sector, for example, renewable energy coupled with battery storage is set to become cheaper than new gas or coal power in most regions globally within 2-3 years.[18] The key challenge now is to reduce planning and permitting timelines and increase investment in transmission and distribution infrastructure to ensure this does not constrain rates of new solar and wind build-out. However, in land use change, while some actions are being taken to incentivise preserving land (e.g., via new due diligence laws on commodities and increasing financial flows to nature-based solutions through carbon markets), land conversion (e.g., deforestation) rates remain historically high.

To reach these tipping points sooner, it helps to know the target so we can focus resources accordingly. This report is intended to serve as a map. It compiles existing evidence that indicates where tipping points might lie, so that more resources can be concentrated on reaching them faster.

At present our knowledge of tipping points remains incomplete. Today's evidence base does not provide a complete picture, and in many cases a close proxy is our best available information. Further research is required to build a more robust picture. For example, it could be helpful to do more analysis on the potential magnitude of network effects from installing ultra-fast charging stations for electric trucks, or the potential rate of social contagion for dietary shift towards alternative protein consumption across different regions.

TIPPING CASCADES

High-emitting sectors of the economy do not exist in isolation from each other – they are highly inter-connected, and zero-emission solutions can influence transitions in multiple sectors simultaneously.

For example, batteries serve as an enabling technology in both the power sector for stationary storage, and in road transport for electric cars and trucks. Increasing deployment in one sector will drive down battery costs for both sectors. The development of large-scale green hydrogen production will enable the decarbonisation of several industrial and long-distance transport sectors. Shifting to alternative proteins, thereby cutting demand for meat production, could reduce both pressure for land use change and emissions from livestock farming.

Links between sectors suggest that focussing effort on crossing one tipping point could increase the chances of triggering others – producing 'tipping cascades'. As with tipping points across sectors, the evidence provides differing levels of confidence that tipping cascades exist across sectors. For example:

i. **Passenger electric vehicles** are already at or close to a tipping point and are set to dominate projected demand for batteries, with estimates suggesting that electric vehicles will account for ~70% of total installed battery capacity in 2030.[19]

   Creating enabling conditions for an early electric vehicle tipping point (e.g., through **zero emission vehicle mandates** and **accelerated build out of charging infrastructure**) could also bring forward a tipping point for renewables coupled with battery storage in the power sector. Boosting EV adoption to 60% of total global vehicle sales would increase total battery production volumes by a factor of 10 from current levels.[20] This could in turn significantly reduce the **cost of electricity from renewables + storage solutions**, where battery costs often account for ~30% of the total cost of power.[21] The strength of the links between sectors and historical cost reductions provide high confidence in the potential for this tipping cascade.

ii. **Green ammonia use in fertiliser production** is well suited to early scale hydrogen use for three reasons:

   1 It has one of the lowest "green premiums" today for sectors reliant on green hydrogen to decarbonise (with ~+50% cost per ton premium vs. 'grey' ammonia);[22]

   2 Since green ammonia can be shipped at relatively low-cost (only adding <10% to the delivered cost),[23] it can be produced in regions with rich renewable resource and able to produce hydrogen at the lowest cost globally, and then transported internationally to fertiliser production sites;

   3 Ammonia (produced from fossil fuels) is already used in fertiliser production, meaning green ammonia can "drop-in" to replace grey ammonia with no change to the industrial equipment needed, different from some sectors where hydrogen or its derivative is not yet used (e.g., hydrogen-DRI steel plants).

   Creating enabling conditions for a green ammonia tipping point in fertiliser production, for example by **introducing a 25% blending mandate globally**, could drive the level of deployment in electrolysers required to reduce green hydrogen prices to $1.5/kg H2 in locations with cheap renewable electricity.[24] This could in turn help **unlock tipping points in green ammonia use for shipping and green hydrogen use in steel production**, where supported by a carbon price or equivalent subsidy of ~$100/ton CO2, or appropriate regulation.[25] The evidence supporting the potential for rapid costs reductions in green hydrogen production is relatively strong, but this remains a nascent industry with limited historical data, giving us moderate confidence in the existence of this tipping cascade.

[22] Figures based on historical gas prices, prior to the energy price spikes since 2021.
[24] Systemiq analysis based on various sources. See figure 6 for further explanation.

iii. Among the major categories of **alternative protein, plant-based proteins** are closest to reaching parity with conventional animal-based proteins on cost, taste and texture (2023).[26] Creating the enabling conditions to bring forward this tipping point, for example through **public procurement and public investment in research and development**, could lower the costs and enhance the effectiveness of key production technologies, such as extrusion and extrudable fat technologies. This could in turn bring forward the tipping points for microorganism and animal-cell based proteins, which also use these technologies. Together, these advances could help to increase alternative proteins' projected market share in 2035 from ~10% to ~20% (alongside other interventions),[27] significantly reducing emissions from livestock farming, especially methane emissions from cattle.

   In turn, the reduction in livestock farming as a practice could free up an estimated ~400-800 million hectares of land, equivalent to 7-15% of agricultural land today.[28] By reducing pressure for land conversion, this could help to reduce **the value of converting land (e.g., deforestation) relative to the value of protecting land**.

Many more links between sectors can be identified. For example, as buildings transition from primarily fossil-based heating solutions to electricity-based solutions, the roll out of heat pumps will both increase the demand for low-cost renewable energy and enable the roll-out of variable renewables (e.g., solar and wind) by providing demand-side flexibility to the power system.[29]

KEY ACTIONS

Different actions are required across every sector to bring forward positive tipping points, depending on the stage of development of their dominant zero-emission solutions.

Policymakers, corporates, and consumers all have important roles to play in helping to create the enabling conditions for a tipping point. For example, in the steel sector, as hydrogen-based production enters the niche market stage:

- Policymakers should focus on de-risking first-of-a-kind commercial projects with targeted financial support,
- Steel manufacturers can invest in the first near-zero emission production plants,
- Companies in steel-consuming sectors can help to create a market by committing to forward purchase agreements of green steel.

The world's largest-emitting countries are all moving forward. The USA's Inflation Reduction Act is a promising recent development, unlocking $369 billion in new funding and granting a $3/kg H2 credit to green hydrogen producers for 10 years after facilities come online, radically changing the economics of production. China has already shown what can be achieved with its comprehensive packages of policy support that rapidly expanded production of solar panels, helping to bring down costs all over the world. India has demonstrated the power of public procurement, first using this to bring down the costs of highly-efficient LED lighting by 85% in four years, and now beginning to repeat that success with electric buses.[30] The EU is starting to get serious about the decarbonisation of energy intensive industries, and is considering implementing a carbon border adjustment mechanism from 2026, a process that could set off a domino effect spreading more robust carbon prices or alternative policies of equivalent stringency in other regions.

International cooperation can greatly increase the chances of realising a positive tipping cascade in the global transition to a net zero economy. The positive feedbacks that drive cost and performance improvements in zero-emission solutions are stronger when actions are aligned internationally. This can create stronger incentives for investment, larger economies of scale, and level playing fields where they are needed.[31] For example, recent evidence suggests that if the 3 largest car markets were together to require all new car sales to be zero emission by 2035, this could bring forward the date of EV – ICE cost parity by up to 5 years.[32] Political interest in these coordination gains is increasing. In the Breakthrough Agenda, launched at COP26 in 2021, 45 countries representing 70% of global GDP committed to work together to make clean technologies and sustainable solutions the most affordable, accessible, and attractive option in each of the high-emitting sectors before the end of this decade. This report aims to help show where these tipping points lie. Action must be focused on the leverage points in each sector, and potentially on 'super-leverage points' that can catalyse tipping cascades across sectors, to make the Breakthrough Agenda vision a reality.

Alongside these opportunities, important risks must be mitigated to ensure the low-carbon transition is not derailed. Critical mineral supply chain risks must be carefully managed to avoid bottlenecks in deploying many zero-carbon energy solutions, while mitigating social and environmental risks. Improving material recovery and recycling systems will be crucial to ensure that supply keeps pace with rising demand and the transition's resource intensity is managed. It will also be crucial to re-train the workforce for new jobs in the low-carbon transition to ensure that skills shortages do not become a bottleneck, and to ensure a just transition.

The current energy price crisis is a shock to the economy that is causing hardship for consumers in many parts of the world. At the same time, it could temporarily lessen the difficulty of tipping emitting sectors towards sustainable alternatives to fossil fuels. The world is currently experiencing an exceptional spike in the price of oil and gas, driven largely by the ongoing conflict in Ukraine. This has made these fuels more costly than usual, imposing the equivalent of a $600-950/ton carbon tax,[33] significantly greater than the equivalent 'green premiums' for decarbonising all major high-emitting sectors of the economy. In the short-term, this creates an opportunity for zero-carbon technologies to be made competitive with less policy support than usual, in sectors including power, heating, road transport, and industry. Activating positive tipping points now would help to put clean technologies on a faster path of deployment and cost reduction, lessening the amount of policy support required in future when fossil fuel prices eventually fall again.

TABLE 1: STATUS OF TIPPING POINTS FOR KEY ZERO-EMISSION SOLUTIONS BY SECTOR

See sectoral slides for further explanation and sources supporting identified tipping points to reach mass market status, as well as focus areas for further research.

Affordability	No cost disadvantage	Point of parity is <5Y away	Point of parity is >5Y away (including policy support measures equivalent to <$100/ton CO2)
Attractiveness & Accessibility	No barrier to tipping point	Currently impeding tipping point but strong progress underway	Currently impeding tipping point with limited progress to date

Sector	Emissions	Solution in focus	Current state	Tipping point to reach 'mass market' state and unlock S-curve adoption	Confidence in tipping point	Tipping point enabling conditions			Progress headline
						Affordability	Attractiveness	Accessibility	
Power	26%	Solar, Wind + Storage	Niche/Mass Market	• Levelised cost of electricity (LCOE) of new solar/wind & battery storage (4+ hours, 40%) <u>less than</u> LCOE of new coal/gas power at ~<$50/MWh • Transmission and distribution annual investment ~$500bn globally	**High:** Strong learning effects + battery production economies of scale				**Battery costs down 90% from 2010, now at $130/kWh, and expected to reach $110/kWh by 2023. LCOE of solar + batteries already below $50/MWh and expected to be cheaper than gas power in the US by 2023.** Solar/wind jointly accounted for >75% of total new capacity additions globally last year, total share of generation >10%. Key inhibitors of more rapid adoption (i.e., steeper S-curve) include: **01** Greater investment needed in transmission + distribution infrastructure (from expected investment at $300bn in 2022 to $500bn in 2025), **02** Shorter planning + permitting timelines (all EU countries exceed legal permitting time limits, some by >5x).
Light-Duty Road	9%	Battery Electric Vehicles (BEVs)	Niche/Mass Market	• Sticker price of passenger BEVs <u>less than</u> price of internal combustion vehicles • ~5 million public chargers to support deployment levels required to reach tipping point	**High:** Battery production economies of scale + charging infrastructure network effects				**Cost parity is expected by 2025-26 in leading markets (EU, US, China).** Subsidies are closing the gap earlier in some markets, e.g., US IRA with $7.5k purchase credit + cost remain barriers in lagging markets. As at end 2021, 1.8 million public EV chargers installed globally.
Heavy-Duty Road	3%	Battery Electric Trucks (BETs)	Niche	• Total cost of ownership (TCO) of BETs <u>less than</u> ICE trucks • 2 million chargers installed globally (including high-speed and overnight depot)	**High:** Battery production economies of scale + charging infrastructure network effects				**Battery electric trucks are not close to price parity for mid/long-haul routes in most regions** although price parity almost reached in markets with supportive policy (e.g., Germany). Key barrier is access to public charging infrastructure at major transport hubs. However, policy support is growing with the EU setting a target for high-speed trucking chargers every 60km on core TEN-T networks.
Building Heating	6%	Heat Pumps (Residential Retrofits)	Niche	• Heat pump CapEx + installation cost <u>less than</u> gas boiler CapEx (household retrofits), including subsidies • Average efficiency coefficient >300% • Installation time 1-3 days	**Low:** Some limited evidence of economies of scale in production				**Heat pump CapEx (~3x) higher than gas boilers. However, economies of scale translating into lowering costs** (e.g., Germany, Sweden, Italy, UK). Adoption beginning to increase (+13% in 2021 globally) as policy in major markets begins to favour heat pumps. More progress required on heat storage systems (e.g., water tanks) and increasing customer convenience (e.g., reduced installation time, or couple with other retrofit).
Fertiliser	2%	Green Ammonia	Solution Development	• Green ammonia cost per ton <u>less than</u> grey ammonia for nitrogen-based fertilisers ***Can occur when the below conditions are present:*** • Carbon price or equivalent subsidy/regulation (~$100/tCO2) • Green hydrogen price ~$2.2/kg H2	**High:** Learning-by-doing + scale economies in VRE + electrolyser costs				**Companies are implementing plans for large-scale fertiliser production from green ammonia,** with final investment decision (FID) status reached for first major production facilities and multiple more in feasibility stage. Policy support starting to move market – EU ETS covers fertilisers (~$80/ton CO2 today) + India has proposed production targets.
Steel	7%	Green Hydrogen DRI	Solution Development	• Cost per ton of steel produced using green H2 DRI <u>less than</u> steel from fossil-based production (i.e., blast furnace-basic oxygen furnace, no CCUS) ***Can occur when the below conditions are present:*** • Carbon price or equivalent subsidy/regulation (~$100/tCO2) • Green hydrogen price ~$1.2-2.2/kg H2 (depending on production region)	**Medium:** Learning-by-doing + scale economies in VRE + electrolyser costs				**11 full-scale plants planned to be operational by 2030, relative to c.400 fossil-based steel plants globally.** Need to ramp up rate of FID. Further policy support required, including two major consuming regions introducing carbon price or equivalent subsidies, including with Carbon Border Adjustment Mechanism (CBAM); EU likely to include steel in CBAM from 2026.
Shipping	3%	Green Ammonia	Solution Development	• Green ammonia fuel cost per ton <u>less than</u> fossil-based shipping fuel ***Can occur when the below conditions are present:*** • Carbon price or equivalent subsidy/regulation (~$100/tCO2) • Green hydrogen price ~$1.6/kg H2	**Medium:** Learning-by-doing + scale economies in VRE + electrolyser costs				**Clydebank declaration committed to support the development of at least 6 green corridors within this decade + first mover coalition committed to provide initial offtake volumes.** Multiplication of plans for green ammonia bunkering facilities (e.g., Port of Rotterdam). Hydrogen price of $2/kg possible by mid-2020s in favourable locations. However, there is a need to provide long-term policy certainty to bridge cost premium and increase rate of FID approval.
Aviation	2%	Power-to-Liquid Fuels	Solution Development	(TP1) Total cost of ownership of electric planes <u>less than</u> fossil jet plane (short-haul) (TP2) PtL fuel cost per ton <u>less than</u> fossil jet fuel (long-haul) ***Can occur when the below conditions are present:*** • Carbon price or equivalent subsidy/regulation of >$200/tCO2 • Green hydrogen price ~$1/kg H2 in favourable locations	**Medium:** Learning-by-doing + scale economies in VRE + electrolyser costs				**Production of PtL fuels remains at demonstration stage but proposed EU blending mandate (2% of total fuel use from PtL by 2030) can drive initial scale that supports cost declines.** First major policy support emerging (e.g. US IRA Sustainable Aviation Fuel tax credits), but large cost premium remains: 3-9x more expensive than fossil jet-fuel at present.
Food & Agriculture	12%	Alternative Proteins	Niche	• Cost of plant-based proteins <u>less than</u> meat products • Equivalent attractiveness (taste, texture, nutrition)	**Medium:** Social norm diffusion + economies of scale				**Alternative proteins projected to reach ~10% of market share by 2035** but technological innovation and policy could push to ~20%. Rapid up-take by early adopters in some regions (e.g., 50% + 73% increase EU + US sales respectively and size of China's plant-based market has been greater than US in recent years) indicate this could soon shift into mass market in these regions. Attractiveness (taste, texture + nutrition) remains a key barrier to accelerating adoption.
Avoiding Land Use Change	11%	Valuing Nature-Based Solutions (NBS)	Niche	Value of preserving land (e.g., through sales of nature-based carbon credits and ecosystem services payment) <u>greater than</u> value of converting land to other purposes (e.g., agriculture, commodities, forestry) *from the perspective of land holders (incl. consideration of penalties and regualtions)*	**Low:** Requires strong + continual regulations				**Payoff shifting marginally towards preserving land** – increase in traded volume (5x increase in VCM market share 2019–2021) and price (33% increase in VCM 2019–2021) of NBS in carbon markets; improving project verification is helping to bolster the market. However, challenges in regulatory enforcement and quality of credits (e.g., additionality + permanence) remain major barriers of adoption.
Cement	7%	CCUS	Solution Development	N/A	**Low:** No clear feedback loop, driven by policy				**Far from the required level of investment and policy support** – but some initial signs of progress in R&D investment.
Chemicals	4%	CCUS/Green Hydrogen	Solution Development	N/A	**Low:** No clear feedback loop, driven by policy				**Range of solutions depending on type of chemical** – limited progress to-date towards large-scale decarbonisation.

Highlights reinforcing loop between sectors that can lead to a cascade of tipping points. See figure 5 in Section 3 for further detail.

SECTION 1

HOW TIPPING POINTS WORK

Positive socio-economic tipping points can occur where new solutions cross a threshold in affordability, attractiveness or accessibility compared to incumbent solutions.

Progress towards tipping points is often driven by reinforcing feedback loops in the development and diffusion of new solutions, where increases in production lead to higher performance, lower cost, greater adoption, and further production. These include, for example, learning by doing effects, economies of scale, the emergence of complementary technologies, and the spread of new social norms. Once a tipping point is reached, these reinforcing feedbacks become more powerful than the balancing feedbacks (such as opposition from incumbents) that have been resisting change. Consumers, producers, and investors shift decisively towards the new technology, and do not look back. The transition acquires a self-accelerating momentum. When close to being reached, tipping points can be triggered by small interventions that alter the balance of competition between new technologies and incumbents.[34]

HISTORICAL AND RECENT EXAMPLES

History is rife with examples of rapid transitions that prove new solutions can take over a market in just a few decades.

There are numerous examples of new technologies that have scaled up from niche applications to virtually total adoption in the space of 20-30 years. Some complex manufactured goods, such as cars, refrigerators, and microwaves, have done so in this timeframe. Even in the case of major infrastructure or energy systems, similar patterns have been seen. In other cases, the transition to new solutions played out over longer periods, highlighting the need for concerted action to accelerate the pace of change for zero-emission solutions to scale in time to meet our global climate goals.

For many new solutions, there is evidence that rapid increase in deployment took place after some threshold of relative affordability was passed, often supported by improved availability or attractiveness. For example:

- **Affordability:** UK coal demand for heating fell sharply after 1960 when cheaper gas was discovered in the North Sea, with its use almost fully replaced within 30 years.[35]
- **Attractiveness:** Household central heating largely replaced traditional heating methods in the US over a 40-year period, in part due to its advantages in health and safety, efficiency, and flexibility. It offered consumers the ability to regulate temperatures and spread heat across households via a single system.
- **Accessibility:** Building out public charging stations was a key factor in promoting electric vehicle (EV) adoption in Norway, in addition to strong tax and subsidy policies.[36] Charger installation began in 2009, when EVs accounted for 0.1% of total car sales, contributing to a rapid market transformation, with EV's sales share rising to almost 90% by 2021.

See figure 1 and 2 below for US and UK data on the adoption curves for a sample of infrastructure and energy systems and manufactured goods – supporting explanations are provided in appendix A.[37]

Large-scale industrial and economic transitions often start with a disruptive technological innovation. New types of solutions initially find a use in a niche market, where they offer an improvement relative to the existing solution. After reaching a tipping point, these can break into mass market adoption and expand to other markets, radically reshaping the economy in the process. For example, the invention and refinement of the steam engine triggered a massive expansion of coal mining and the creation of a rail transport network in England. This helped propel the industrial revolution.[38] A similar phenomenon could be underway with the advent of low-cost renewables. These may bring forward a new era of electrification across the economy as more and more sectors reach their respective tipping points thanks to cheaper and more accessible zero-carbon power.

Figure 1: The historical adoption of a sample of infrastructure and energy systems

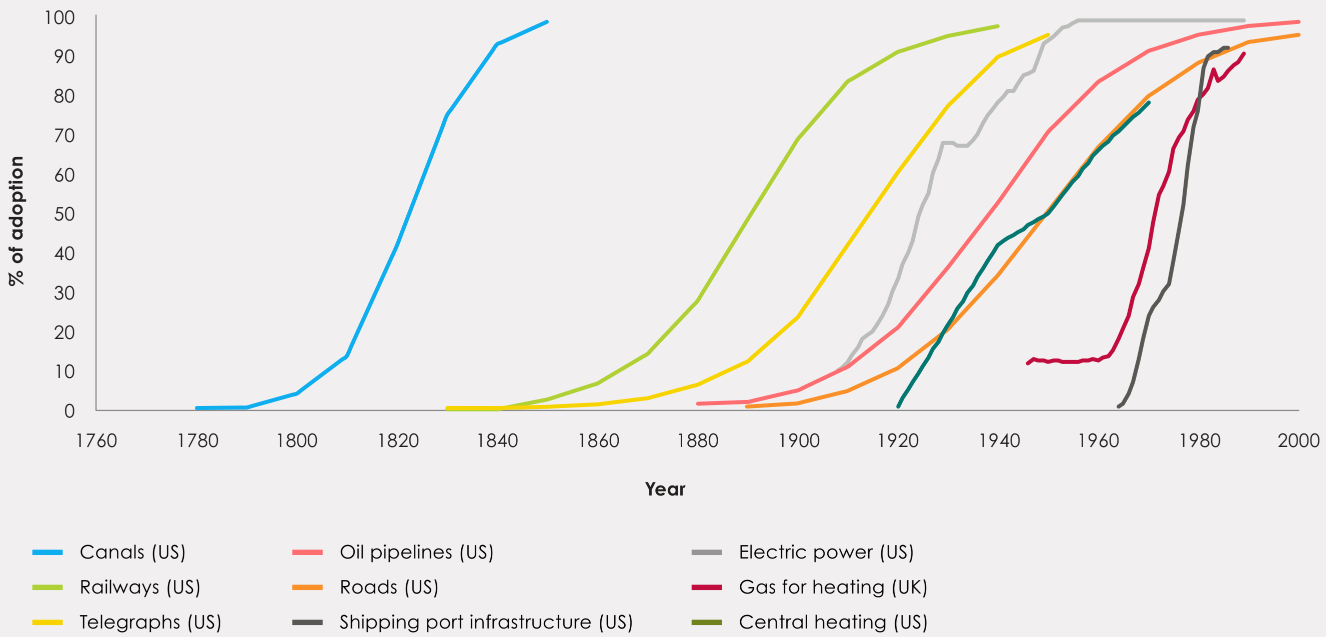
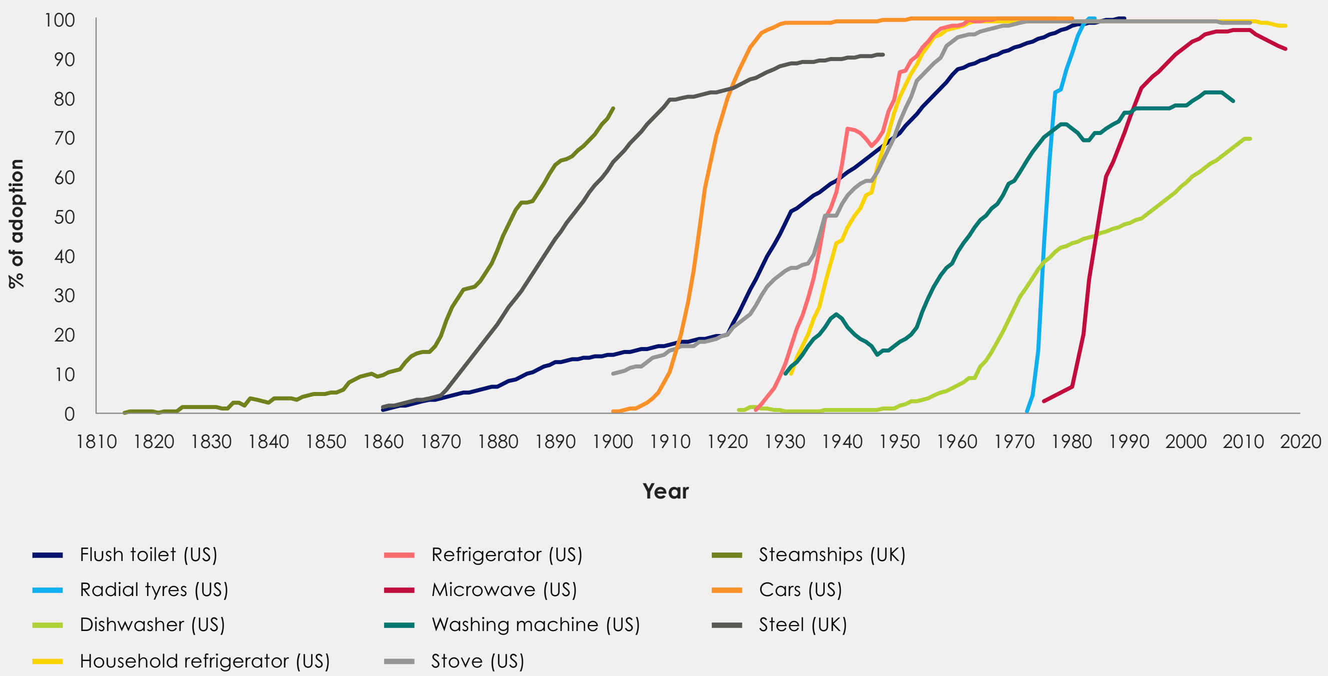


Figure 2: The historical adoption of a sample of manufactured goods



ENABLING CONDITIONS FOR TIPPING POINTS

Affordability

A critical variable in relation to tipping points is cost, which depends crucially on scale.

As new technologies or practices emerge, they often follow sharp cost declines as their production increases. This phenomenon, referred to as 'Wright's Law', predicts that costs fall as a function of cumulative production, driven by the reinforcing feedbacks of learning by doing and economies of scale. The net result is that less time and resource is needed for each subsequent unit of production. Further, as the new solutions approach cost parity with incumbent alternatives, incentives emerge to reallocate finance from the assets of the old system to those of the new. This can increase cost of capital for the old system and accelerate the shift from old to new.

The speed of cost declines depends crucially on the characteristics of the solution in question. The technologies that display the sharpest cost reductions as output increases tend to be those that are small in size and easily replicable. As these are less complex to manufacture and have shorter lifetimes, they typically see faster learning rates and knowledge diffusion with increased production. Companies have greater opportunity to improve production processes that are continuously repeated.[39]

Attractiveness

Cost is not always a sufficient condition alone for triggering tipping points. Improved performance relative to the existing solution is typically also necessary.

New solutions often need to possess certain attributes that set them apart from incumbents across dimensions other than cost, such as higher quality or reliability, or new capabilities. In early stages of deployment, this can be crucial for allowing new solutions to gain a foothold in the market. Niche market segments that place priority on these attributes may adopt the solution despite cost disadvantages present in the early stages. For example, early buyers of electric vehicles were in large part attracted by the novelty value and 'green credentials' these offered and were willing to accept the substantial price premium relative to conventional cars. In many cases, new technologies or practices emerge that fundamentally alter the service offered by the product category. For example, successive new generations of music players – from vinyl to tapes to CDs to online streaming – did not significantly reduce average retail prices but offered different functionality that transformed the product, eventually to unlimited on-the-go listening.[40]

The emergence of new laws and regulations can have a major influence on the attractiveness of new solutions. For example, there is evidence to suggest that new policies designed to improve public safety (e.g., licensing, speed limits, and traffic rules) strengthened the social acceptance of cars.[41] Broader socio-economic and cultural shifts can also cause certain products to gain relevance and appeal. For example, the rise in suburbanisation and associated home ownership in America in the post-WWII period, in conjunction with shifts in the social role of women, generated increased demand for mass-produced, energy-intensive products, including kitchen appliances, home entertainment devices and processed and frozen food.[42]

Accessibility

In addition, many types of new solutions require supporting infrastructure to be in place before adoption at large-scale can take off.

Following the establishment of a national electricity transmission and distribution system in the UK, households rapidly switched from gas lighting to cheaper electric lighting. As the new connection infrastructure was rolled out, gas demand for lighting peaked in the UK in 1920 and was almost entirely replaced within 40 years. Similarly, as telecommunication networks enabling access to the internet have spread across the world, a range of internet-enabled solutions have expanded and scaled up rapidly – from digital software to remote sensors and geo-spatial monitoring.[43] For technologies that enable multiple downstream uses, developing the required supporting infrastructure opens up the pathway to large-scale application, shifting the system into a new era. Building out renewable energy generation, and transmission and distribution networks, for example, is key to enabling electrification of multiple energy consuming sectors in transport, industry, and buildings.

Once the right enabling conditions are in place and reinforcing feedback loops are present, new solutions can reach their tipping point, leading to rapid growth in adoption along an S-curve. As the flow of products in markets changes in favour of zero-emission solutions, through the share of new sales or new builds (e.g., of houses, factories), the stock of products in the market will adjust with a certain time lag. For example, as the share electric vehicles in new passenger vehicles sold increases over time, the share of EVs in the global fleet of cars will follow the same trend with approximately a 10–15-year delay, given average car lifetimes. See figure 3 below for an illustration of this process.

REINFORCING FEEDBACK LOOPS

New solution scale-up

Tipping points depend on the feedback loops that determine the behaviour of all dynamic systems, including sectors of the economy.

A reinforcing feedback loop occurs when an increase in a variable leads to a further increase in the same variable. For example, greater deployment of a technology leads to lower costs, and lower costs lead to greater deployment. This dynamic can drive exponential growth in adoption of the new technology. A balancing feedback occurs when an increase in a variable leads to a decrease in the same variable. For example, policy to encourage the deployment of new solutions can result in a backlash from incumbents, leading to weaker policy.

The interaction of these two kinds of feedback loops creates the typical 'S-curve' shape of a technology transition. Early in the transition, reinforcing feedbacks can drive the development of new technologies but at the same time, balancing feedbacks dominate the behaviour of the sector as incumbent technologies and business models are resilient against attempts to disrupt them. At the tipping point, reinforcing feedbacks become dominant, driving exponential growth in adoption of the new solution, and decline in use of the old. Beyond this point, the transition is likely to be irreversible, and can stay on course despite short-term volatility (e.g., supply chain bottlenecks), although its pace can still be influenced by many factors. Towards the end of the transition, balancing feedbacks again become dominant as the new technology approaches market saturation.

There are several distinct types of reinforcing feedback loops. They will often exist simultaneously. The most important types include:[44]

- **Learning by doing:** Where the deployment of a technology leads to greater innovation that improves the product and lowers costs as production is optimized, this increases the net benefits and encourages further deployment.
- **Economies of scale:** Where increased scale of production spreads fixed costs across greater volumes, and leads to more effective division of labour, this lowers unit-costs of production and in turn encourages increased rate of output.
- **Technological reinforcement:** Where the more something is used, the more additional technologies or practices emerge that make it more useful.[45]
- **Network and coordination effects:** Where the more economic agents take a similar action, the greater the advantages to others of doing the same.
- **Self-reinforcing expectations:** Where expectations on future market size trigger investments that grow the market, therefore meeting/exceeding expectations and triggering further investment.
- **Contagion of social norms:** Where new solutions can spread rapidly through social communication after crossing into early majority adoption (also referred to as Roger's Law).

The presence of feedbacks helps create 'path dependence' in the economy: the options available at any point in time depend on what has happened before. When business models, consumer practices, and investment strategies have developed around mature technologies, they may all interact in a way that prevents change (a state that is known as 'system lock-in'). Identifying and dismantling such barriers to change can be an important role for policy. When competing new technologies are emerging, the reinforcing feedbacks mentioned above can quickly amplify the advantages and extend the lead of whichever is ahead. Since policy can (either deliberately or inadvertently) tip the balance, it can be important for governments to explicitly consider the risks and opportunities of different technology options, and in some cases to choose between them.

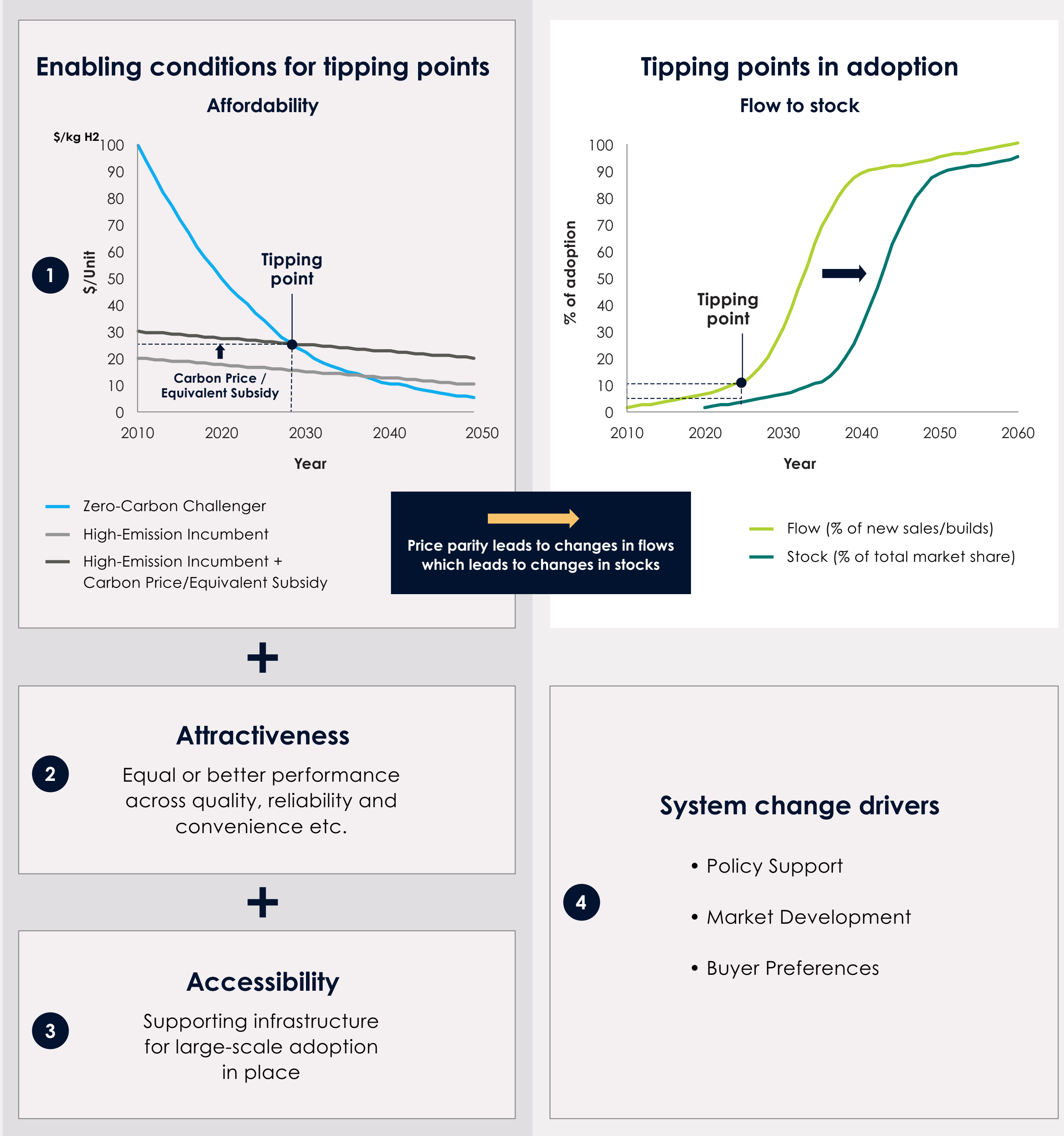
Incumbent solution decline

As a new solution scales up, the incumbent solution may face its own reinforcing feedback loops that accelerate decline. A tipping point that is positive for a new solution is a 'cliff moment' for the incumbent solution. Following this 'cliff moment', incumbent solutions lose their structural advantage and increasingly experience similar reinforcing dynamics, simply in reverse: diseconomies of scale as output falls, falling demand leading to cuts in production, and the economy increasingly considering the existing solution unfavourably as it embraces the new solution.[46] Further, companies in industries that shift into decline can see sharp financial devaluations as investors shift away, increasing the cost of capital.[47]

This last point is a particular challenge for capital intensive and highly leveraged sectors that can see under-utilised assets become economically stranded. This phenomenon can be seen in the US coal power industry, where demand peaked in 2012, followed by a sharp drop in profitability as utilisation rates of coal plants fell to below 50%. Shortly before this peak, stock prices fell dramatically and within 2 years half of the companies in the sector went bankrupt.[48] Total demand for coal for power generation in the US is now 60% lower than its peak.

Early warning signs are likely to be visible that indicate incumbents are on the brink of a sudden decline. Before a tipping point, as the incumbent technology or business model loses stability, it is likely to show greater variability (e.g., price volatility) and slower recovery from crises than previously observed. Slowing investment in research and development or the rate of innovation is another indicator of forthcoming decline.[49] The number of new patents issued relating to fossil fuel technologies has fallen almost 20% since 2015, which could be one such example.[50] In some cases, there may be a ramp up of political efforts to slow the transition before subsequent retrenchment. For example, the oil sector's lobbying CapEx peaked in 2009 and has since fallen by 36%.[51] Further work is required to identify these leading indicators to help identify signals of potentially imminent tipping points.

Figure 3: Illustration of tipping points process



BREAKTHROUGH TECHNOLOGIES

The reinforcing feedback effects described above are driving rapid cost reductions in several technologies that are core to the low carbon transition.

The cost of solar and wind has plummeted over the last 10 years, largely due to learning-by-doing and economies of scale effects made possible by market-creating policies and the replicable nature of these technologies. As prices have fallen, demand for renewables has increased, attracting more firms to enter the market and compete to drive costs even lower. The same phenomenon is underway for other modular technologies that leverage and enable low-cost renewable energy, most importantly including batteries and hydrogen electrolysers.

Most projections have systematically underestimated the rate of cost reductions for these technologies, due primarily to an underappreciation of strength of the reinforcing feedbacks. For example, the average projected annual cost reduction for solar PV from 2010-2020 was 2.6% (with a maximum of 6%), whereas realised figures over this period were in fact 15% per year.[52] Short-term factors such as supply chain bottlenecks can disrupt this trend, as seen with wind power from 2012-2014, but this provides a strong incentive for businesses to find solutions to these challenges and resume cost reductions. Some experts argue that most cost projections today continue to underestimate the potential cost reduction in future years relative to historical trends.[53]

Solar and Wind: These have now become the **cheapest source of new bulk power** in countries representing 90% of electricity generation.[54] If current trends continue, solar is set to become the cheapest form of power generation almost everywhere in the world within the next 5 years even when energy storage costs are added.[55]

Batteries: The cost of lithium-ion battery cells declined by 97% in the last three decades, with **costs halving in just four years** from 2014-2018.[56] Their cost is highly likely to continue to fall substantially as rising electric vehicle demand drives production at greater scale, with 150 giga-factories in operation globally today compared to just 1 five years ago.[57]

Electrolysers: The cost of electrolysers has fallen by 50% in the last 10 years. We are now seeing a rapid acceleration in deployment plans across the world, with **installed capacity increasing by ~80% in 2021**, and 680 large-scale hydrogen project proposals now in place.[58] The cost to produce green hydrogen is expected to fall 50–60% by 2030, meaning that achieving US$2/kg without subsidies is feasible within the next five years.[59]

Figure 4 below shows the historical and potential future trajectory for the costs of the four key energy transition technologies, as production increases in line with what would be required to achieve a net zero economy by 2050. A continuation of the historical learning rate suggests that substantial cost reductions are expected as output scales up. The figures also highlight the 'tipping point range' for these technologies, where their costs reach a level that makes them economically competitive against fossil-based incumbents (e.g., solar and wind power LCOEs reaching parity with those of new gas fired power plants).

Conversely, the cost of power from fossil fuels costs has remained broadly flat over the long-term (though highly volatile in the short-term) and is not expected to see reductions in the long run relative to historical pricing. The cost of producing electricity from coal, for example, has shown virtually no improvement over the last 10 years, as coal power plants cannot be made much more efficient. While renewables rely on free and limitless sources of energy, fossil energy relies on fuels that can be expensive to extract. In addition, as the penetration of renewables in the power mix has increased, the asset utilisation of fossil-based power sources has fallen, causing costs per unit of energy to rise for coal and gas power plants. For example, even before the COVID pandemic, the average utilisation rates of coal-fired power plants in Germany fell to ~20% in 2020, with >90% of plants running at a loss over the prior 2 years, collectively losing over €1 billion.[60]

The financial sector is increasingly factoring in stranded asset risks for fossil fuels, helping to close the green premium with zero-carbon alternatives. The spread in the cost of capital of hydrocarbon vs. renewable developments has widened by >10% over the last 5 years, equivalent to a global carbon tax of $80/ton CO2.[61] This has considerably increased project costs and is improving the competitiveness of clean alternatives. This is already being reflected in energy investments, with capital expenditure on renewable power set to overtake that for oil & gas developments for the first time in history this year.[62]

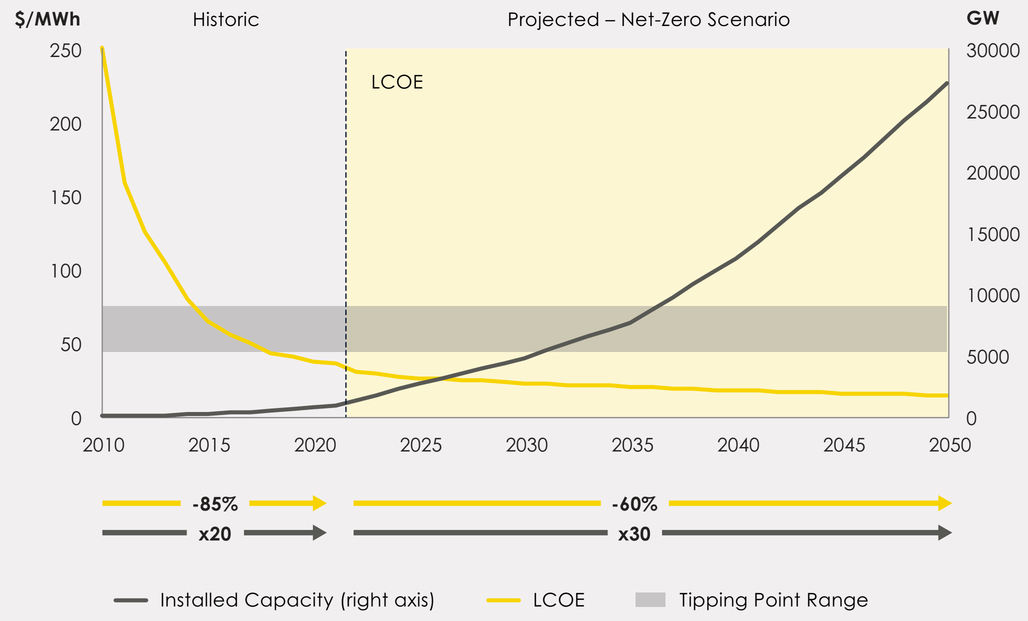
In parallel, the global food and agricultural system is increasingly discovering and deploying sustainable solutions that can cut its emissions without compromising food security. New technological and practical solutions are emerging with early indications that some could take off exponentially. Costs are falling and performance (e.g., taste, texture, productivity and nutrition) is improving for solutions across the global supply chain, including for alternative proteins (displaces animal protein), precision agriculture (reduces fertiliser emissions), and growing cold chain storage capacity (reduces food loss and waste).[63] For example, recent progress toward alternative protein cost parity has been driven by both lower plant-based protein production costs and rising meat prices. In 2021, conventional protein prices increased by 8-18% over the same week in 2020, while plant-based protein prices decreased (by up to 6%) or remained the same.[64] The cost per megabase of DNA sequencing has fallen by a factor of 100,000 since the year 2000.[65] This is supporting the genetic mapping of the microbiome, which combined with advanced technology platforms, is making the process for discovering novel bio-fertilisers quicker and cheaper. At the same time, genetic editing advances are increasingly allowing for the bespoke synthesis of bio-pesticides.[66]

Figure 4:

Solar and wind – learning curves

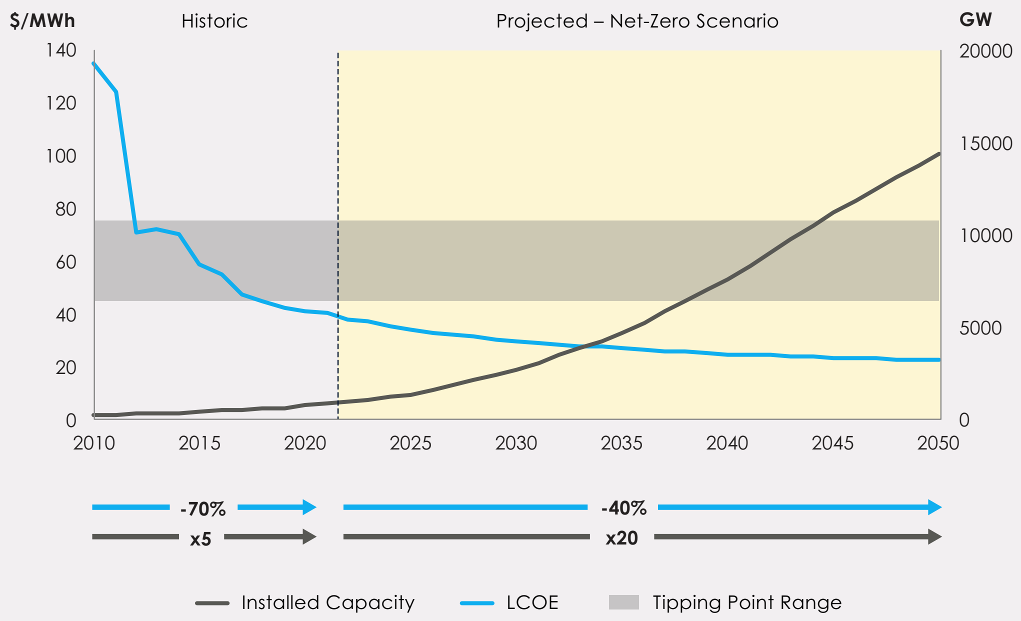
Historical and projected LCOE vs. installed capacity for solar

Learning Rate: 36%



Historical and projected LCOE vs. installed capacity for power from wind

Learning Rate: 23%



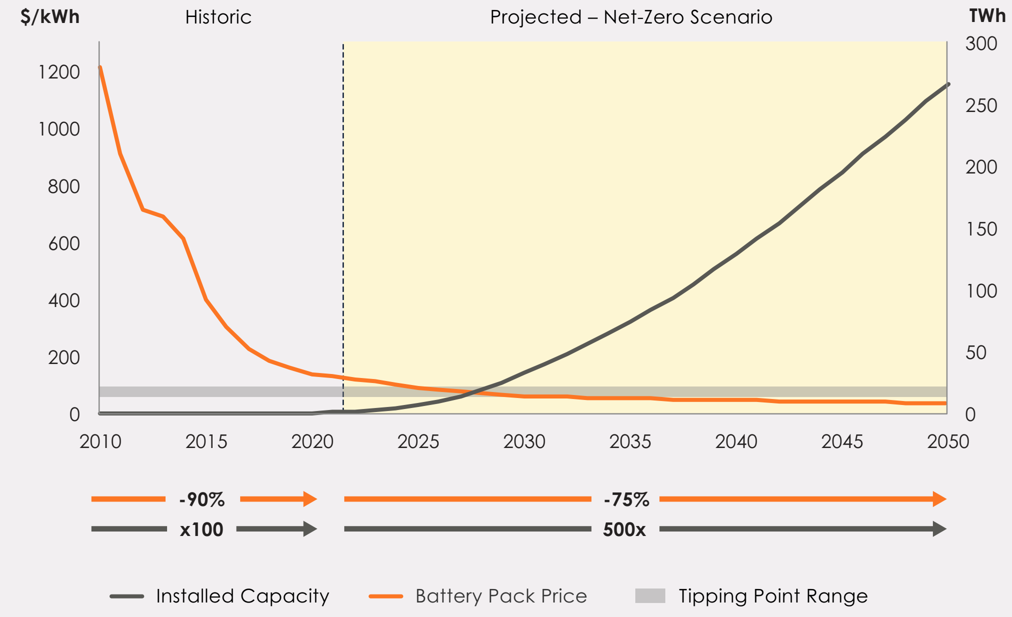
Note: Tipping point range shows current LCOE from new gas-based power (global average) – i.e., cost at which renewables become cheaper than fossil-based alternatives. Projections refer to deployment required for scenario in which net zero achieved globally by 2050, in slower transition scenarios cost reductions decrease by less over the same period due to more gradual capacity instalment. [1] Learning rate calculated as the percentage decrease in total cost following a doubling in installed capacity; refers to learning rate observed over 2010-2020. [2] Cost reduction for solar PV (utility-scale) and onshore wind refers to unsubsidized LCOE.

Sources: Our World in Data (2020); Lazard (2021) – Levelized Cost of Energy Analysis – v15; Mission Possible Partnership (2022); IEA (2020), Net-Zero by 2050; ETC (2021), Making Clean Electrification Possible.

Batteries and electrolysers – learning curves

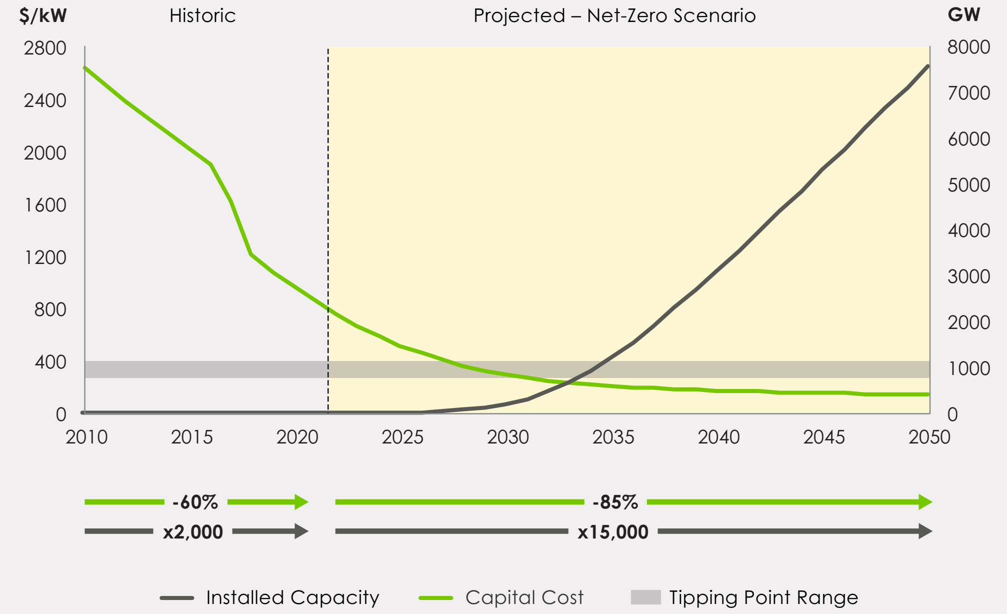
Historical and projected battery pack cost vs. installed capacity for li-ion batteries

Learning Rate: 19%



Historical and projected capital cost vs. installed capacity for P2X electrolysers

Learning Rate: 18%



Note: Tipping point range for li-ion batteries refers to level required for cost parity of BEVs with conventional passenger vehicles. Tipping point range for electrolysers refers to electrolyser capital costs supporting green hydrogen prices of $1.5-2.0/kg H2, where decarbonisation of hard-to-abate sectors becomes cost effective (excluding long-distance aviation). Increase in installed capacity for li-ion batteries refers to total change in global generation for battery packs in GWh across all sectors. Li-ion battery cost reductions refer to decreases in capital costs for 4-hour utility-scale storage, P2X electrolyser cost refers to CapEx for utility scale plants of >1GW.

Sources: Our World in Data (2020); IRENA (2020), Green Hydrogen Cost Reduction; Oxford INET (2022), Empirically Grounded Technology Forecasts and the Energy Transition; BloombergNEF (2022), New Energy Outlook [3] Mission Possible Partnership (2022); NREL (2021), Annual Technology Baseline, IEA (2020), Net-Zero by 2050; ETC (2021), Making the Hydrogen Economy Possible. BloombergNEF 2020 Electric Vehicle Outlook and 2020 Lithium-ion Battery Price Survey.

SECTION 2

IDENTIFYING TIPPING POINTS BY SECTOR

In the power and road transport sectors, cost advantages for zero-carbon solutions are here or close and short-term actions can significantly accelerate the transition.

Clear downwards trends in technology costs mean there is increasingly a strong economic motive to move away from high-emitting incumbents, without the need for a high carbon price or equivalent support.[67] As we reach a tipping point in the power sector, key actions can help make the S-curve steeper (i.e., accelerating adoption), e.g.: shortening planning and permitting timelines, evolving regulation to fully account for low-carbon solutions and building out electricity transmission and distribution (T+D) infrastructure ahead of generation build out (T+D has a longer lead time than generation). Similarly, in light road transport, electric vehicles are set to become cheaper than internal combustion engine vehicles in key countries within ~3-5 years (EU, US, China).[68] We are already seeing adoption accelerate just ahead of this tipping point. To bring forward the tipping point and achieve a steep S-curve, incline investments need to be made to increase access to charging infrastructure, especially in countries currently lagging in the transition.

However, battery prices increased by 7% in 2022 as the result of higher material prices, especially in the case of li-ion.[69] BloombergNEF predicts that if prices remain high for an extended period, this may slow the learning rate for li-ion batteries from 19% to 16%, resulting in 44% higher battery costs by 2030, which could delay the date of cost parity between BEVs and ICE vehicles by 2-3 years.[70]

In industry and long-distance transport, establishing the first wave of green hydrogen plants can drive scale economies in production and bring down costs, though continued regulatory support will be required for large-scale adoption.

The decarbonisation of fertiliser and steel production, long-haul shipping, and aviation, will depend heavily on the use of green hydrogen. Green hydrogen production remains primarily at the pilot stage at present. Creating the first set of commercial scale projects can set in motion learning-by-doing effects that continually drive down electrolyser costs. A key short-term target is delivering green hydrogen at <$2/kg, which is feasible before 2030 in favourable locations with low-cost renewables, as at this level green hydrogen becomes competitive with blue and some grey sources of hydrogen production.[71] For the first commercial-scale projects to be viable at today's higher prices of green hydrogen, policy support is required to de-risk investments and absorb some of today's "green premium" (e.g., via tax breaks, concessional loans, contracts for difference). Cross-value chain collaboration is also crucial to secure offtake and in some cases link through to a part of the value chain that can justify paying a green premium, e.g., electric vehicle manufacturers paying a premium for green steel, to produce and sell a car that has zero embodied emissions. Once the first wave of commercial-scale projects is in place, the next wave will benefit from lower electrolyser costs and an established and de-risked value chain. Even for the second wave and beyond, there will remain a (measurably smaller) cost premium relative to existing fossil-based solutions in these sectors. Therefore, longer-term policies coordinated across major producing regions are likely to be required to support large-scale deployment, which may be in the form of mandates (e.g., aviation fuel blending mandates), carbon pricing (e.g., $100/tCO2 on steel), or equivalent subsidies.

In some sectors, it is unclear if reinforcing feedback loops will be strong enough for tipping points to exist, meaning that growth of new solutions is more likely to be linear than exponential. In the buildings sector, for example, the bulk of energy demand comes from space and water heating[72] in residential homes,[73] where a significant cost differential exists between the up-front capital and installation costs of heat pumps versus gas boilers, particularly in cases where use of a heat pump requires the retrofitting of buildings for greater energy efficiency. It is currently unclear whether increasing deployment will trigger feedback loops that drive capital costs for heat pumps below of the cost of gas boilers for consumers. In relation to dietary shifts, while alternative proteins are on track to reach cost parity with meat relatively soon, it is unclear the extent to which changing social norms can lead to widespread change in consumer preferences supporting mass market adoption. Similarly, strict regulatory enforcement is likely to remain the key mechanism for preventing continued land conversion, as reinforcing feedback loops in the scaling up of finance for the preservation of forests or other policy measures are difficult to predict.

In such cases, the transition to low-carbon solutions may not benefit from a strong pull of reinforcing feedback loops. The transition to low-carbon solutions is likely to require even stronger and more consistent policy support than elsewhere, to continually push up and then maintain levels of adoption of solutions.

67 See infographics on following pages for supporting evidence by sector.

71 Grey hydrogen refers to production using unabated methane or coal. Blue hydrogen refers to production route deriving hydrogen from methane from natural gas with the application of carbon capture and storage.

73 Global energy demand for space and water heating amounted to 62 exajoules (EJ) in 2021, accounting for around half of energy consumption in buildings and directly emitting 2.5 gigatonnes (Gt) of CO2 – roughly 80% of direct buildings emissions. In 2021, residential buildings accounted for approx. 60% and 80% of total space and water heating in advanced and emerging/developing economies, respectively.

Energy & resource efficiency

Solutions that improve energy and resource efficiency are equally critical for sectoral decarbonisation and facilitate the task of zero-emission solutions.

While this analysis focuses primarily on supply-side tipping points for S-curve growth of zero-carbon solutions, technologies and practices that reduce overall energy and resource use across sectors also have a vital role to play in reducing emissions. The result of improved efficiency is reduction of the growth in energy and resource demand, meaning zero-carbon solutions have a smaller overall market to take over. This allows solutions to take-over the market and push out the high-carbon solution faster. Pulling all feasible levers to improve energy productivity globally is estimated to be able to reduce total global energy demand by 15% relative to current levels by 2050, and ~30% versus current trends.[74] It is difficult at this stage to establish with confidence potential S-curve dynamics across efficiency solutions, especially due to unpredictable changes in consumer behaviour. This is a topic that requires further consideration given the critical role it can play and uncertainty that remains over the potential to activate S-curves.

Gradual improvements in energy efficiency are vital but insufficient alone. In the aviation industry, for example, improving aircraft design, retrofitting new engines, operational improvements, and better air traffic management could make the global fleet 40% more fuel efficient in 2050 than in 2019.[75] In buildings, energy efficiency (e.g., from insulation, glazing and improved heating controls) is central to the transition, though progress has been slow in most regions to date. Cost-saving energy efficiency measures are currently often held back by long payback times, low rates of returns and inconvenience overheads.

More circular systems are a key lever in reducing primary production of energy-intensive materials. In the steel industry, for example, extending product lifetime, improving scrap collection and recycling, as well as strategies to reduce material inputs (e.g., 3D printing, minimising waste, or vehicle light-weighting) could reduce global steel demand by up to 40% in 2050 against current trends.[76] In the concrete/cement industry, lower demand from similar efficiency and circular solutions could reduce emissions for the sector by ~40% by 2050, with more than half the investments required leading to cost savings for producers.[77]

The application of digital technologies has the potential to radically improve efficiency. For example, improved analytics and operation of heating controls, e.g., via smart metering, could lower household energy demand by around 20%.[78] This will further be important for enabling demand-side flexibility in electricity grids through smart charging and vehicle-to-grid storage; these are resource efficient solutions. In agriculture, geo-spatial monitoring and predictive analytics could markedly improve the monitoring of crop, soil, and livestock, limiting the application of chemical inputs to only what is needed. The increasing power of artificial intelligence and machine learning is now also being used to accelerate the discovery of sustainable materials and chemicals, speeding up time to market.

SECTOR TIPPING POINT

POWER: SOLAR, WIND & STORAGE

26% of total global GHG emissions

Sector context

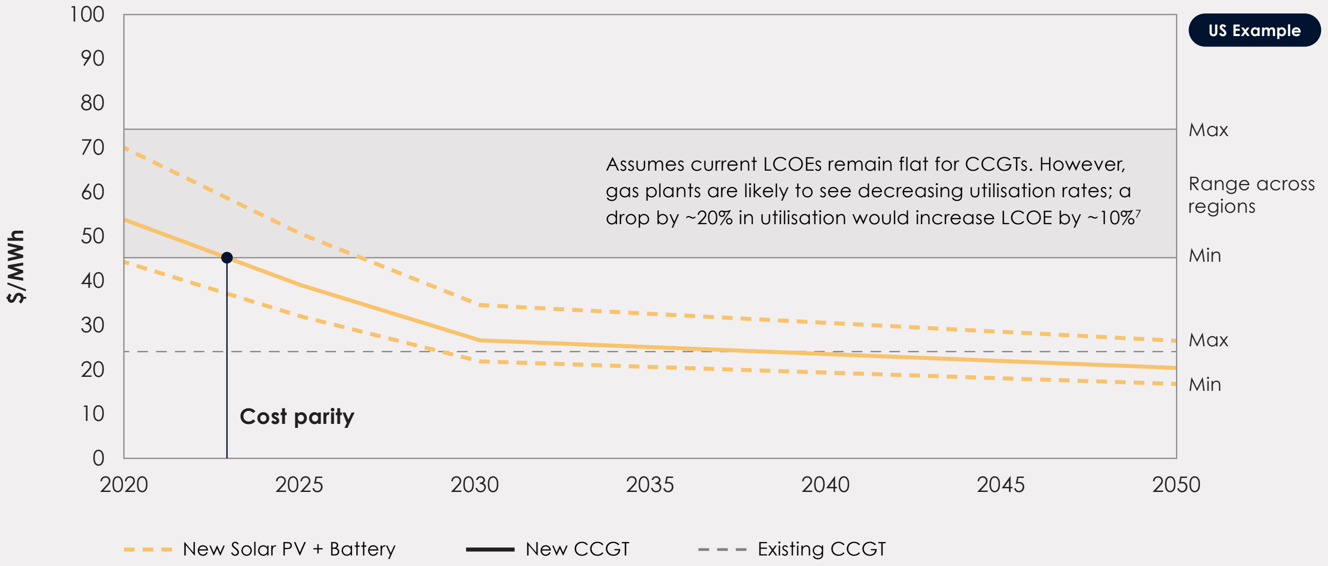
- Four tipping points exist in the power sector, where:
  1. The LCOE of new wind/solar < new coal/gas (reached for majority of the world in 2018)
  2. LCOE of new wind/solar + new storage < new coal/gas
  3. LCOE of new wind/solar < existing coal/gas
  4. LCOE of new wind/solar + new storage < existing coal/gas.
- The **first tipping point** (new wind/solar < new coal/gas) has **already been reached in most regions**, with existing flexibility in the power system (e.g., gas power plants, interconnectors + hydro resources) enabling penetration up to ~30% of total power generation.[1]
- The focus now is therefore on the **next tipping point which** requires the cost of **renewables coupled with flexibility** (e.g., battery storage) to be cheaper than cost of new coal/gas generation, to drive solar/wind + battery storage **penetration to a ~75–90% grid share**, the maximum level that can be served by renewables + daily balancing solutions such as battery storage, varies by geography.[2]
- There are a range of other **low-cost levers to provide flexibility** that should be maximised e.g., demand-side responses, but there remains a considerable requirement for battery storage to help renewables reach ~75–90% grid share.

Solution status

MASS MARKET — **Solar/wind:** jointly accounted for **>75% of total new capacity additions globally** last year, taking their **share in total generation above 10%** for the first time. In 2021, 10 nations met >25% electricity demand with wind and solar power (8 in Europe)[3]

NICHE MARKET — **Solar/wind + storage:** there is currently just ~30 GW of installed battery storage capacity for power globally. However, in 2021 the **rate of installation doubled to 7.1 GW/yr.** driven primarily by growth in China and the US. Latest forecasts expect there to be just over 400 GW installed globally by 2030 under current trends,[4] compared to 585 GW required for net-zero alignment.[5]

LCOE projections for solar PV + battery storage[6] vs. current LCOE range for power generation from natural gas[7]



Note: LCOE – levelized cost energy. [5] LCOE for solar PV + battery plant refers to representative plant in the US with single-axis tracking PV system of 130 MW capacity and 4-hour lithium-ion battery storage system with 50 MW capacity; range shows moderate scenario minimum and maximum based on resources class by average capacity factor (from 20% to 33%). [6] LCOE for new combined cycle gas turbine (CCGT) shows current global average benchmark range for unsubsidised combined cycle gas-fired turbine; existing CCGT refers to marginal cost of operating fully depreciated plant.

Sources: [1] Systemiq (December 2020), Paris Effect; [2] ETC (2021), Making Clean Electrification Possible. [3] EMBER (2022), Climate Data Explorer; [3] Bloomberg NEF (2022), H2 2022 Energy Storage Market Outlook; [4] IEA (2021), Net Zero by 2050; [5] NREL (2021), Annual Technology Baseline; [6] Lazard (2021), Levelized Cost of Energy Analysis; [7] Systemiq analysis based on Making Mission Possible (2022); Central LCOE Forecast.

Orange text indicates uncertainties that require further investigation

Tipping point

- The tipping point will be **primarily cost-driven** and achieved when new wind/solar + flexibility (4+ hours, 40%) – as per battery example in chart above – is cheaper than new coal/gas.
- However, **investment** into **electricity transmissions and distribution networks to enable renewables connections** will be a critical enabler in driving adoption.

Confidence in existence of reinforcing feedback loops

HIGH — **Learning curves & economies of scale:** as more solar/wind/batteries are deployed; we experience strong cost reductions (36% /23% /19% respectively per doubling of output); lower costs in turn encourage more deployment[1]

	Target conditions to trigger tipping point	Progress*
AFFORDABILITY	• **Levelized cost of energy (LCOE) from new solar and wind generation + utility-scale battery storage** (4+ hours, 40%) < LCOE of new coal or gas power plants, majority of countries – at <$50/MWh[2]	• LCOE for solar/wind + battery storage (4-hour) **tracking towards cost parity** with new coal/gas by 2023 (US example), **now at $55/MWh** (range of $45-70/MWh by location)[2] • In **US, IRA support** pulls this further forward by providing tax credits of $35/kWh for battery cells and $10/kWh for modules[3] • Comparing only "peaking" assets: utility scale 4-hour battery storage global **average LCOE marginally lower than gas peaker** plants in 2021 at ~$150/MWh[4]
ATTRACTIVENESS	• N/A (not a major driver or inhibitor of tipping points) • Renewables offer better air quality • However renewables are **subject to intermittency** and **provide less inertia** into the system; **storage is important** for balancing and can contribute to responsiveness needed in systems with less inertia	• **Not critical issue** – batteries are highly effective at providing ancillary services to the grid, also a complement of solutions are being deployed in countries with high renewables penetration to tackle inertia • Increased deployment of offshore wind in certain geographies is also reducing the intermittency challenges given **higher load factors**
ACCESSIBILITY	• The **build out of electricity networks** is a fundamental enabler of additional renewable electricity connections • **Annual global investment in transmission and distribution infrastructure** needs to reach approx. **$500 bn p.a. by 2025** to support the pace of new connections for renewables at the expected timing of the tipping point and rise to ~$800 bn by 2030 as adoption scales on the S-curve[5] *– more research required to understand requirements by region and year*	• Need to scale investment into transmission and distribution from total expected investment in 2022 at ~$300bn up to **~$500bn by 2025** + there has been **no clear upward trends** over the last 5 years[6] • In US, average time utility scale power projects spend in **interconnection queues** doubled from 2010 to 4 years in 2021 – with 1.4 TW currently awaiting connection approval[7]

Note: *Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date; [2] LCOE for solar PV + battery plant refers to representative plant in the US with single-axis tracking PV system of 130 MW capacity and 4-hour lithium-ion battery storage system with 50 MW capacity; range shows moderate scenario minimum and maximum based on resources class by average capacity factor (from 20% to 33%).

Sources: [1] Solar and Wind: Our World in Data; based on IRENA (2020); Li-Ion Batteries: Our World in Data based on Ziegler & Trancik (2021); [2] NREL (2021), Annual Technology Baseline; [3] ClimateTech VC (2022), 'IRA and the New Capital Cots of Climate'; [4] Bloomberg NEF (June 2022), Global LCOE Benchmarks 1H 2022; [5] IEA (2021), Net-Zero by 2050; [6] IEA (2022), World Energy Investment 2022; [7] Lawrence Berkeley National Laboratory (2021), 'Queued Up'

SECTOR TIPPING POINT

LIGHT-DUTY ROAD: BATTERY ELECTRIC VEHICLES

9% of total global GHG emissions

Sector context

- **Demand reduction and behavioural change** will be important for reducing total emissions from the road transport sector, e.g. via modal shift to public transport and denser urban design. However, a **rapid shift towards electric vehicles** is nonetheless required for full decarbonisation.
- **Lifetime emissions** for average medium-size BEVs today are already lower than comparable gasoline cars by 60-70% in the EU and US, and 20-45% in China and India (due primarily to different grid carbon intensities).[1]
- To be on track for a **net-zero global fleet by 2050, electric vehicles must account for ~60% of total global new passenger sales by 2030** and 100% by just before 2040 given average car lifetimes.[2]
- Electrification is advancing much more quickly in **buses and 2/3-wheelers than cars**, where sales of BEVs already accounted for 44% and 42% of new sales last year, respectively.[2]

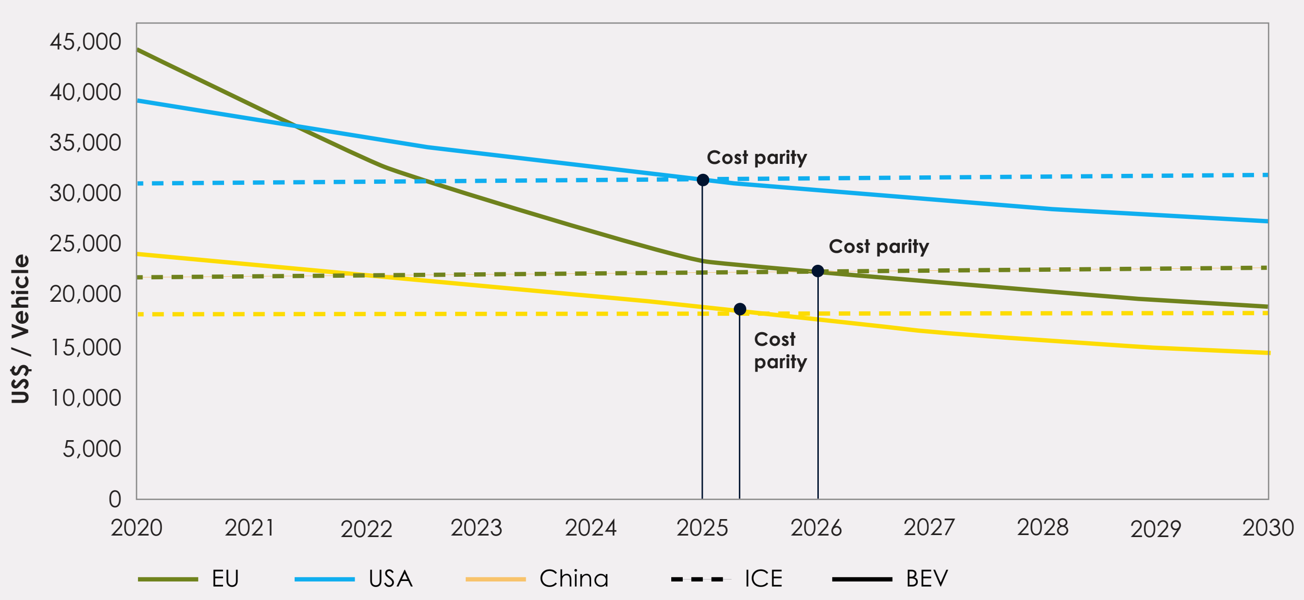
Solution status

NICHE/ MASS MARKET

This sector is on the **border of niche to mass market** with numerous countries implementing purchase subsidies that are already **closing the price parity gap to reach a tipping point**. We are now reaching a tipping frontier where mass market adoption is being triggered slightly ahead of the subsidy-free tipping point.

Global passenger EV sales doubled in 2021 to ~6.6 million units, accounting for **9% of total new sales** (excl. PHEVs), further rising to 13.2% in H1 2022. **China and Europe** are major drivers of the momentum, with **EV sales reaching above 20% of total sales in Q2 2022** in both markets[2]

Forecast pre-tax retail prices for passenger vehicles by region[3,4,5]



Note: Average car lifetime expectancy between 10-15 years depending on segment type and region.

Sources: [1] ICCT (2021), A Global Comparison of the Life-cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars; [2] Bloomberg NEF (2022), Electric Vehicle Outlook; [3] Bloomberg NEF (May 2021), Hitting the EV Inflection Point; [4] ICCT (2019), Update on Electric Vehicle Costs in the United States through 2030; [5] ICCT (2021), Evaluating Electric Vehicle Costs and Benefits In China in the 2020–2035 Time Frame.

Orange text indicates uncertainties that require further investigation

Tipping point

- Tipping point likely **when BEVs* hit sticker price parity with ICE vehicles**. Greater deployment drives **scale economies in battery production**, further increasing cost advantage
- **Charging infrastructure** roll out key to overcome range anxiety and trigger coordination effects – **3+ fast chargers per 1,000 electric vehicles** key first step[2] *– more research required to understand size of effect*

Confidence in existence of reinforcing feedback loops

HIGH

- **Learning curves & economies of scale:** as more BEVs are deployed; we experience 19% cost reduction per doubling of output; lower costs encourage greater deployment[1]
- **Network effects:** increase in charging infrastructure makes it easier to adopt BEVs, which encourages more charging infrastructure to de developed[2]

	Target conditions to trigger tipping point	Progress**
AFFORDABILITY	• Reaching **cost parity for sticker prices** (i.e., pre-tax retail prices) for passenger vehicles across all major regions – primarily dependent on battery density and production costs	• Forecasts suggest BEV prices will reach **cost parity** with ICE vehicles in all light vehicle segments by **2025–2026** in major regions (EU, US, China)[4] – but later in lagging regions *– more research required to understand cost parity timing in lagging markets (e.g. India etc.)* • However, high critical mineral prices (e.g., lithium) for an extended period risks delaying point of cost parity by slowing cost decline for li-ion batteries
ATTRACTIVENESS	• BEVs required **average driving range of 300–500 km** to overcome range adoption barrier, if adequate supporting charging infrastructure in place[5] • **Equivalent number of available models** relative to ICE vehicles to cover all forms of consumer preference	• The **average range of new BEVs** (sales-weighted) has increased by 9% per year from 2015-2021, reaching **350km** (vs. median of ~650km for average gas ICE vehicle), with some new models exceeding 600km[5] • Globally, **>450 electric car models** available in 2021, >2x number in 2018[4] – in the US, **60% of models** available expected to be hybrid or electric between 2022–2025[6]
ACCESSIBILITY	• Public Chargers: The volume of BEVs required for tipping point to take hold at cost parity with ICE vehicles is **~80 million BEVs globally** – this would need **~5 million public chargers** to support deployment[7] • Public Fast Chargers: **Approx. 3 public fast chargers per 1,000 electric vehicles** is a critical component in addressing charging anxiety[1] (US example) *– more research required to validate fast chargers as key customer criteria varies considerably by country[8]*	• Installation is still lagging in many key markets – as of 2021, there were just **1.8 million public EV charging connectors installed** globally[7] • Deployment of public chargers is growing rapidly in leading countries at **20–30% per year**[7]

Note: *BEV – battery-electric vehicle; ICE – internal combustion engine. **Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date; [6] At present there are between 5-20 public chargers per EV on average – this is estimated to increase to 30-45 EVs/charger as adoption increases, as many mass-market EV drivers will not have access to home charging. Public charger availability requirements differ substantially between regions based on housing stock, average distance travelled and population density (e.g., Norway and the US have high reliance on home charging); [8] Figure refers to minimum level required to support BEV adoption for long distance travel in the US in rural areas (1.5 per EV required in cities) – in addition, 400 fast charging stations are estimated to be required to cover all US inter-city transport on interstate highways (i.e., approx. 1 every 110km)

Sources: Our World in Data based on Ziegler & Trancik (2021); [2] US Department of Energy (2017), National Plug-in Electric Vehicle Infrastructure Analysis; [3] See for example: Wolbertus et al (2021), 'Charging infrastructure roll-out strategies for large scale introduction of electric vehicles in urban areas: An agent-based simulation study', Transportation Research Part A 148, 262–285; [4] See previous page for sources; [5] IEA (2022), Global Electric Vehicle Outlook; [6] Bank of America (2021), US Automotive Product Pipeline, Car Wars 2022-2025; [7] Bloomberg NEF (2022), Electric Vehicle Outlook

SECTOR TIPPING POINT

HEAVY-DUTY ROAD: BATTERY ELECTRIC TRUCKS

3% of total global GHG emissions

Sector context

- The main pathway to decarbonising trucking will be developing and using new vehicles and drivetrains: **battery electric trucks (BETs) and hydrogen electric trucks**, powered with fuel cells.
- Hydrogen electric trucks are expected to play an important role in decarbonising the long-haul trucking sector, however, BETs are expected to reach cost parity earlier across all segments and make up a measurably greater share of total final energy demand.[1]
- Other measures will also be important for reducing total energy demand growth, including most importantly (a) encouraging a **modal shift** from long-haul trucking to rail; (b) increasing **supply chain efficiency** to reduce distances travelled, and, (c) improving **logistical efficiency** by increasing fleet utilisation and net load factors.

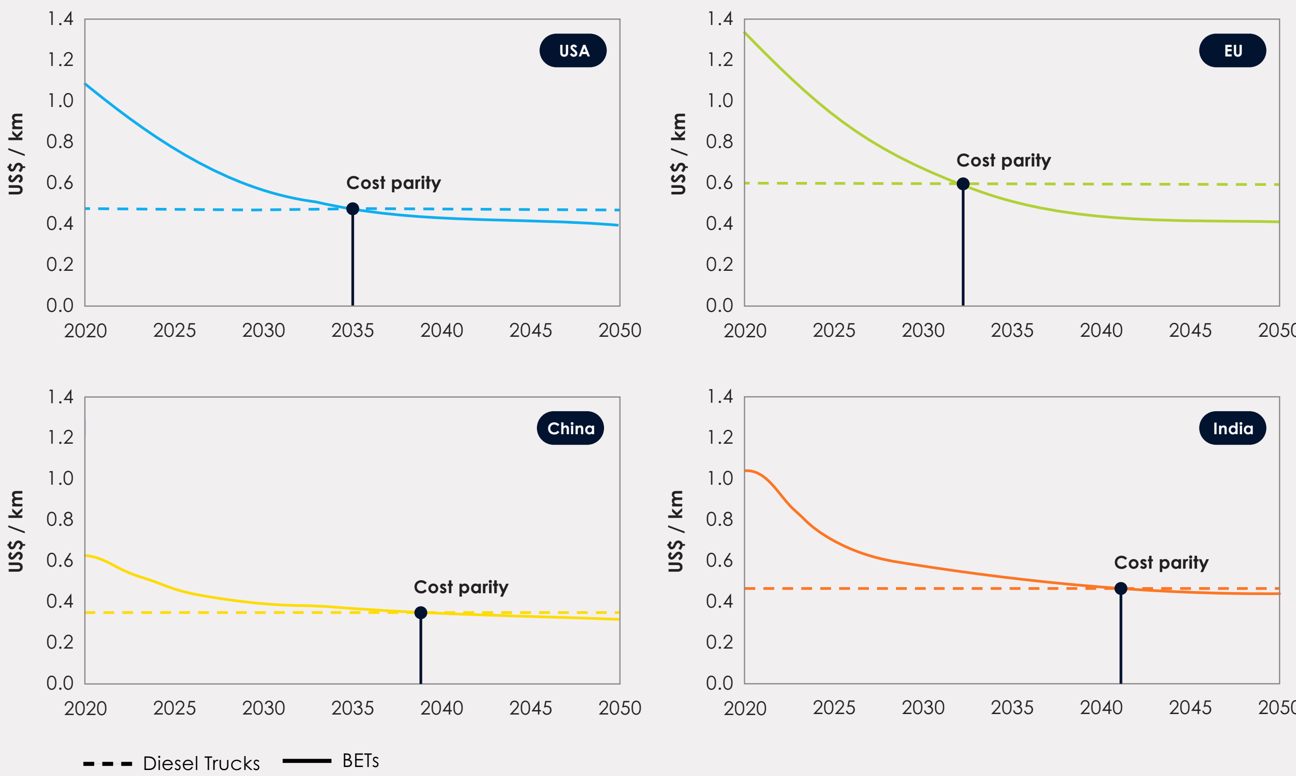
Solution status

NICHE MARKET

BETs* remain in the **early stage of adoption**, representing **0.3% of total sales globally** in 2021 (approx. 10,000 units sold),[2] but are showing promising signs in some regions with leading companies starting to deploy these at scale[3]

Significant increase in **light commercial electric trucks sales in China**, with penetration reaching 10% this year, with medium/heavy-duty electric trucks further behind at 2–3%[3]

Total cost of ownership for BETs vs. diesel trucks by region – long-haul[1]



Note: Battery Electric Trucks (BETs)

Sources: [1] Mission Possible Partnership (July 2022), Making Zero-Emissions Trucking Possible; [2] IEA (September 2022), Tracking Report – Transport. [3] Bloomberg NEF (2022), Electric Vehicle Outlook 2022.

Orange text indicates uncertainties that require further investigation

Tipping point

- Tipping point possible when BETs reach **total cost of ownership (TCO) advantage** vs. diesel trucks, as **reinforcing feedback loops in battery costs** take effect
- **~2 million chargers** (incl. public high-speed + overnight depot) installed globally to support the volumes of BETs required to reach the tipping point; **network effects in charging infrastructure** at major hubs take effect[2] *– more research required to understand size of effect*

Confidence in existence of reinforcing feedback loops

HIGH

- **Learning curves & economies of scale:** as more batteries are produced; we experience 19% cost reduction per doubling of output; lower costs encourage greater deployment[1]
- **Network effects:** increase in charging infrastructure makes it easier to adopt BETs, which encourages more charging infrastructure to de developed

	Target conditions to trigger tipping point	Progress*
AFFORDABILITY	• Achieve **TCO advantage** for BETs vs diesel trucks in **regional and long-hauls segments** across key regions (EU, US, China, India) – at **~$0.5/per km (currently 2-3x higher)**[1] • Sticker price less important factor but support required in short-term to **overcome high up-front costs** (BETs currently ~3x diesel trucks pre-tax retail price)[3]	• BETs already at or **near TCO cost parity** with diesel trucks in **urban segments in key regions** (EU, US, China), but not expected for **long-haul segments before 2030–2035** depending on the region (excluding India)[2] • However, TCO cost parity closer in countries with **low-cost power and supportive policy** – e.g. ~2025 in Germany (lower road taxes and highway fees)[4] *– more research required to understand potential for similar steps to bring forward cost parity in other regions*
ATTRACTIVENESS	• **Not major barrier for much of sector** – current range ~500km (3x less than diesel trucks) suited to current practice/regulation requiring frequent stops every 4~5 hours as allows for re-charging[5] • BETs **eliminate tailpipe emissions and noise pollution**, have high torque, and are able to recover energy lost in braking – making them attractive in urban environments	• Limitations in the **quantity** and **variety of vehicles** available continue to inhibit fleet adoption, but large range of new products under development • Battery packs add **~1 ton per truck** but majority of trucks **not weight constrained** (volume limit more important factor)
ACCESSIBILITY	• Volume of BETs required to reach tipping point is ~7 million. To support this volume requires **~2 million chargers** (incl. public high-speed + overnight depot)** – with focus first on electrifying **heavy-duty transport hubs + high-traffic routes** (e.g., large harbours, large industrial areas)[2] • Develop **ultra-fast charging stations on key highway routes** with up to 1MW power (~ 3x faster than public charging stations today) connected to ultra-high voltage cables	• A **gradual build-out** of **public charging** is already happening in urban areas. • Progress remains limited on longer-range segments where **public charging infrastructure** build-out is differentially important *– more research required on key locations and numbers required* • **EU** recently set **target** for **high-speed trucking chargers every 60km** on core TEN-T networks

Note: BET – battery-electric trucks. *Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO_2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date; **Split between public high-speed (1.4–1.8 million) and overnight depot (400,000–700,000).

Sources: [1] Our World in Data based on Ziegler & Trancik (2021); [2] Mission Possible Partnership (2022), Making Zero-Emissions Trucking Possible; [3] ICCT (2022), 'How Much Does an Electric Semi Really Cost?'; [4] Transport & Environment (2021), How to Decarbonise Long Haul Trucking in Germany; [5] Transport & Environment (2021), Analysis of Long-Haul Battery-Electric Trucking in the EU.

SECTOR TIPPING POINT

BUILDING HEATING: HEAT PUMPS (RESIDENTIAL RETROFITS)

6% of total global GHG emissions

Sector context

- **Residential space heating accounts for the majority of building heating demand[1].** Residential buildings are inherently more decentralised than commercial buildings, meaning that the low-carbon transition relies on the decisions of a larger set of actors. Residential property owners have a range of possible clean heating solutions (e.g., heat pumps, electric resistive and radiant solutions, district heating schemes, etc.). The optimal solution will differ based on a country's existing infrastructure, the local context (e.g., district heating networks are better suited to dense areas) and building type (e.g., inefficiency and space constraints make heat pumps more challenging).
- **Installing low-carbon heating solutions in existing buildings and improving fabric will be the most critical actions to transition the sector.** 80% of buildings that will exist in 2050 are those present today[2]. Low-carbon heating solutions must be implemented in parallel with levers to reduce demand (e.g., building fabric assessments). For example, in the UK, constructing new buildings and retrofitting existing buildings to the highest standard of efficiency has the potential to reduce their heating demand by 65% and 80% respectively[3].
- **Heat pumps (HPs) are expected to be a key lever in decarbonising building heating.** The core technology behind HPs (Vapour Compression Refrigeration Cycle) is used for cooling all over the world and is now emerging as a low-carbon heating solution. HPs can be powered by renewable electricity and require 3-4x less energy to deliver the same amount of heat as gas boilers require[4]. HPs are categorised by where they extract heat from (i.e., ground, water and air-source) coupled with the building's heat distribution systems (i.e., via air or water).
- **Air-source HPs will likely deliver the greatest contribution to building heating decarbonisation due to purchase cost and installation advantages over other HPs.** Air-source HPs currently make up 60% of the global heat pump market[5]. These can take the form of air-to-air and air-to-water. Air-to-air systems can deliver both cooling and heating making them often more cost-effective than installing both a gas boiler and separate air conditioning, which is especially relevant in temperate climate zones. Air-to-water systems do not provide cooling and also require additional supporting infrastructure (e.g., water tanks) but deliver domestic hot water and have noise and comfort advantages. Recent technology developments mean HPs that are suitable as a 'one-for-one' replacement for existing boilers are now available and can provide the 70°C flow temperatures needed in many poorly insulated buildings.[5] Continued policy support (e.g., subsidies) may be required on an enduring basis to close the cost differential between HPs and fossil solutions (e.g., gas boilers). It is also unclear the extent to which reinforcing feedback loops can drive down capital and installation costs, implying adoption may grow linearly rather than following an S-curve.
- **Strong policy support is proving effective in reducing the cost differential and scaling adoption of HPs.** Europe is providing proof points that other countries can draw upon with carbon taxes and subsidies encouraging 25% sales growth in 2021[6]. ~20% of gas boilers across the EU have now been replaced by HPs, saving consumers upwards of $100 bn in fuel costs[7]. Today's cost of living and energy crises make the case for HPs particularly attractive to policymakers, as they reduce Europe's largest source of gas demand, building heating, and total energy demand for households[4].

Solution status

NICHE MARKET

Heat pumps meet 10% of global heating need in buildings today[5] – with steady growth to date.

Highest adoption in Norway, Sweden and Canada but **fastest sales growth in Europe** (35% growth in 2021 vs. 2020 year on year), US (15%), China and Japan (13%)[5]

Heat pumps (HPs) have replaced ~20% of boilers in Europe[6].

Tipping point

- Tipping point for deployment of heat pumps in existing residential buildings once heat pumps (HPs) reach **price parity on upfront costs** with gas boilers; this requires policy support (e.g., subsidies) to lower up-front costs
- **Solutions found to overcome practical and time disadvantages in installation of HPs**
- Enabling assets developed and built out: **heat storage as part of HP systems (i.e., water tanks)**; electricity network infrastructure to support increased electrical loads + 'smart' grids to manage peak electrical demand

Sources: [1] IEA (2022), Buildings; [2] McKinsey (2021) Call for Action: Seizing the Decarbonisation Opportunity in Construction; [3] Energy Research Partnership (2016), Heating Buildings; [4] IEA (2022) The Future of Heat Pumps; [5] IRENA (2022), Heat Pump Costs and Markets; [6] IEA (2022), Heat Pumps; [7] Bloomberg (2022) Clean Energy Has A Tipping Point

Orange text indicates uncertainties that require further investigation

Confidence in existence of reinforcing feedback loops

MID

- Some limited evidence of **economies of scale in heat pump production**, though data is limited to small sample of countries over last 5–10 years.[1]
  More research required to understand economies of scale in production and effect of developing larger global supply chains + potential cost savings from pre-fabrication of systems and integrating installations into other renovation processes

	Target conditions to trigger tipping point	Progress*
AFFORDABILITY	• **Price parity in CapEx + installation cost** of HPs vs. gas boilers. Reached through standardised production and subsidies. Target upfront cost (to be on par with gas boilers): ~£1–5k per unit(UK)[2] $6k (US)[3] + €0.7–3k (EU)[4] *– more research required to understand potential scale economies in production* • **Alternative financing models** available, allowing upfront costs to be distributed over time, and balanced against possibly lower operating costs for customers	• **HP lifetime costs are cheaper than gas boilers** in several countries (due to lower OpEx) but CapEx + installation still multiple times more expensive(UK- £7-13k[5], EU – €8-10k[6], US – $14k[7]). • CapEx + installation costs are reducing, accelerated by subsidies + economies of scale (e.g., Germany, Italy, UK, France). **UK** government forecasts **cost parity in 2030** *– more research required on global progress.* • **Alternative financing models** are being piloted (e.g., 'heat as a service') but not enough proof points or deployment yet to trigger mass roll-out.
ATTRACTIVENESS	• Yearly average efficiency **(COP[8])** of **>3 required for lower OpEx vs. gas boilers**. At COP 3, HPs deliver 3 units of heat (kWh_{th}) for every 1 unit of electrical energy (kWh) required to run the heat pump. • Overcome **installation time disadvantage** + other **practical challenges** (e.g., changing radiators + legal challenges for shared buildings)	• **OpEx already favors HPs in many markets**. While cost of energy is cheaper for gas vs. electricity (e.g., $0.04/kWh gas vs. $0.14/kWh elec. in UK pre-crisis [9]), HPs are **300–500% energy efficient**[10] **vs. gas boilers which are c.90% energy efficient** [11] • Yearly average **HP efficiency improving** at **2% p.a**[12]. Technological improvements, system optimisation/design and advanced control systems have notably improved COP in Germany + Italy[10]. • Current **installation time ~3–8 days** vs. 1–3 days for gas boilers *– more research required on reduction potential*
ACCESSIBILITY	• HPs combined with **heat storage systems** (e.g., water tank) to smooth electrical load demands, reducing peak electricity demand from heating • Investments into **electricity network capacity** to support increased electrical loads from heat pumps • Scale **building energy efficiency** retrofits to **minimise heat loss** and reduce volume of heat required, and thus ability for heat pumps to meet heating needs. • **Reskill + expand the workforce** with accessible training facilities.	• Manufacturers **developing combined HPs + storage systems to absorb energy fluctuations + reduce peak energy demand,** but remain at niche market. • Average global energy **retrofit rate for buildings is 1%**[13] **vs required 3%**[14] • Significant **deficit in trained HP engineers** (3000 in UK) vs number needed to meet 2030 demand (27,000 in UK)[15] but strong incentive to reskill once market develops *– more research required on size of workforce needed*

Note: *Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date; [8] Coefficient of performance is the ratio of heat generated from energy used; [14] Landlords and tenants will share the cost of carbon, with landlords bearing a greater share of the burden for properties with poor energy efficiency. Households will benefit as revenue is redistributed through lower electricity costs. – Building Performance Institute Europe (2021) Introducing a Carbon Price on Heating Fuels

Sources: [1] IEA (2022), Heat Pumps; [2] Greenwatch (2022), Boiler Costs in the UK; [3] HomeAdvisor (2022) Install a Boiler; [4] Energy Price (2022) How Much Does a Gas Boiler Cost; [5] Heat Pump Chooser (2022) How Much Does A Heat Pump Cost; [6] Daikin(2022) What are Heat Pump Subsidies; [7] Carbon Switch (2022) How Much Does a Heat Pump Cost; [9] UK Power (2022), Compare Energy Prices; [10] IRENA (2022), Heat Pump Costs and Markets; [11] The Heating Hub (2020) Boiler Efficiency Guide; [12] McKinsey & Company (2022), Building Decarbonization; [13] IEA (2020), Sustainable Recovery [14] World Economic Forum (2022), To Create Net-Zero Cities, we Need to Look Hard at our Older Buildings;[15] Nesta (2022) How to Scale a Highly Skilled Heat Pump Industry

SECTOR TIPPING POINT

FERTILISER: GREEN AMMONIA

Sector context

- **Demand levers, blue ammonia** and **green ammonia** are all key contributors to decarbonising the fertiliser industry.
- **Optimising fertiliser use** through **improved nitrogen efficiency** use has the potential to reduce the sector's emissions by 70% through measures such as improved crop rotation (e.g., adding legumes), matching fertiliser with crop needs (e.g., through timing and quantities) and dietary shifts[1].
- **Blue ammonia offers a transitional abatement option**, expected to produce 2–27% of ammonia due to its lower cost than green ammonia in the short-term[2].
- However, **green ammonia is the focus of this content as it will deliver the greatest emissions intensity reduction for ammonia production** both due to its emissions profile and share of clean ammonia production which is expected to reach >90%[2].

Solution status

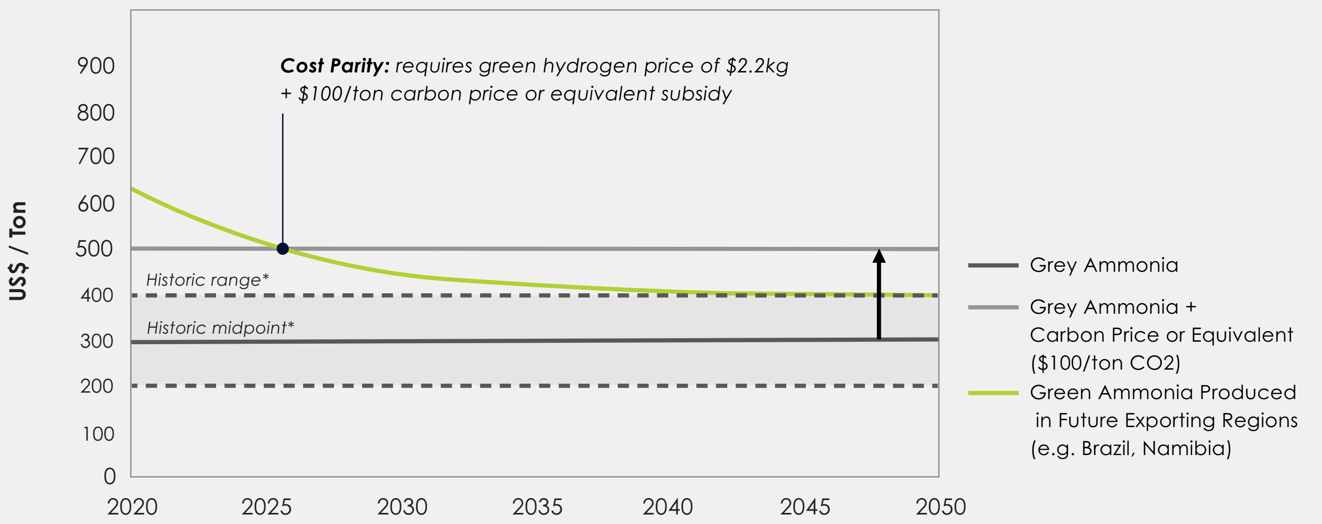
SOLUTION DEVELOPMENT

Major fertilizer producers such as Yara, CF Industries, Unigel have begun construction on green ammonia plants, with **commercial launch scheduled for 2023**

Three green ammonia **projects are operational** (up to 20 MW electrolysers) with seven more **reaching the final investment decision** stage[2]

Green ammonia production projected to be both **economically viable and technologically mature** within the decade[3]

Projected cost per ton grey vs. green ammonia for fertiliser production[2]



Note: * Last 10 years from 2011 to 2020 excluding 2021 and 2022 due to energy price spikes [2] Refers to project range for green ammonia production from electrolysis with dedicated VREs and pipeline H2 storage plus ammonia synthesis (lowest cost scenario); Grey ammonia production cost assumes natural gas via steam methane reforming taking historic average gas price of $5/MMBtu. [3] The point at which a technology is considered to reach maturity is the year in which it is estimated to reach TRL 9 and thus commercial scale, which is 2025 for electrolysis-based ammonia production.

Sources: [1] IFA (2022), Reducing Emissions From Fertiliser Use; [2] Mission Possible Partnership (2022), Making 1.5-Aligned Ammonia Possible

Orange text indicates uncertainties that require further investigation

Tipping point

- Tipping point possible after **1st wave of greens ammonia plants for fertilisers developed** (~50 plants, ~45–50 Mt production p.a.*) to kick-off large-scale adoption – 2nd wave to benefit from de-risked investment.
- This can close the **initial cost premium** for green ammonia vs. grey ammonia through scale economies in H2 production, targeting **<$500/ton green ammonia with hydrogen price of <$2.2/kg H2**. $500/t is competitive with grey ammonia under pre-crisis natural gas prices **+ carbon price or equivalent of ~$100/ton CO2** applied.

Confidence in existence of reinforcing feedback loops

HIGH

- **Learning curves & economies of scale:** as more electrolysers are deployed; we experience 18% cost reduction per doubling of output, and lower costs encourage greater deployment[1]

	Target conditions to trigger tipping point	Progress**
AFFORDABILITY	• Achieve **cost parity for green ammonia** vs conventional grey ammonia – at **$200–400/ton**[2] (20-year long-term average: currently $1,000 –$1,500/ton[2] due to current high gas prices)	• Current green ammonia production costs of **>$600–900/ton uncompetitive with grey ammonia**[3] • **Cost parity of green ammonia vs. grey ammonia** within reach by 2024 (year of project entering feasibility stage) in favourable locations through combination of **green H2 price <$2.2/kg** (vs. ~$2.5-4.5/kg today) and subject to carbon price or equivalent subsidy of **$100/ton CO2 across several major producing regions**[2]
ATTRACTIVENESS	• N/A – grey and green ammonia are **chemically identical**. There is **no difference in downstream use** of grey or green ammonia for fertiliser input.	• N/A
ACCESSIBILITY	• Mass Market: Large **expansion in renewables and hydrogen production** capacity to drive down costs; focussing on favourable locations with very good renewable resource • Scale **trading infrastructure** required to transport from **new producers** to demand centres*** i.e., more ammonia storage at ports + more ammonia-carrying ships.	• Can be **transported and stored** relatively cheaply and easily, but infrastructure expansion required in new producing regions (e.g., Namibia, Mauritania) and expanded infrastructure in importing regions (e.g., Europe)

Note: *Mtpa plants, running at ~95% CUF; **Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date; *** Grey ammonia is currently produced near to points of use with only 10% of global production being exported[4]. As new supply chains emerge in low-cost producer regions that do not always equate to demand centers, greater quantities of green ammonia will need to be shipped to fertiliser manufacturing plants. Supporting trade flows from new producers (e.g., Namibia + Mauritania) to consumer markets (e.g., Europe) requires a scale up in infrastructure such as storage tanks and import infrastructure.

Sources: [1] IRENA (2020), Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5°c Climate Goal; [2] Mission Possible Partnership (2022), Making 1.5-Aligned Ammonia Possible; [3] Argus (2021), Inside Fertiliser Analytics: Green Ammonia; [4] Yara (2021), Renewable Hydrogen and Ammonia Production; [5] IEA (2021), Ammonia Technology Roadmap

SECTOR TIPPING POINT

STEEL: GREEN HYDROGEN DRI

7% of total global GHG emissions

Sector context

- A portfolio of solutions will be needed to decarbonise steelmaking dependent on the cost-competitiveness in various locations, including **scrap** and **material efficiency, blast furnace** and **direct reduced iron-based (DRI)** steelmaking[1]. For example, scrap contribution to total steel expected to increase from 34% today to 45% by 2050[1].
- Given the large scale of **existing infrastructure** and infrastructural **timelines, blast furnaces** with carbon capture, utilization, and storage **(CCUS)** are expected to play a significant role. Current blast furnace capital stock is unlikely to be completely replaced before 2050 + hydrogen (H2) DRI solutions are not expected to scale at the rate required to become the primary solution for most steel plants before 2030.
- This content focuses on hydrogen DRI because it has the largest mitigation potential (compared to CCS solutions) and has a greater potential for (albeit still challenging) **reinforcing feedback loops** from **green hydrogen learning effects** and **economies of scale**, which could drive **S-curve** outcomes.

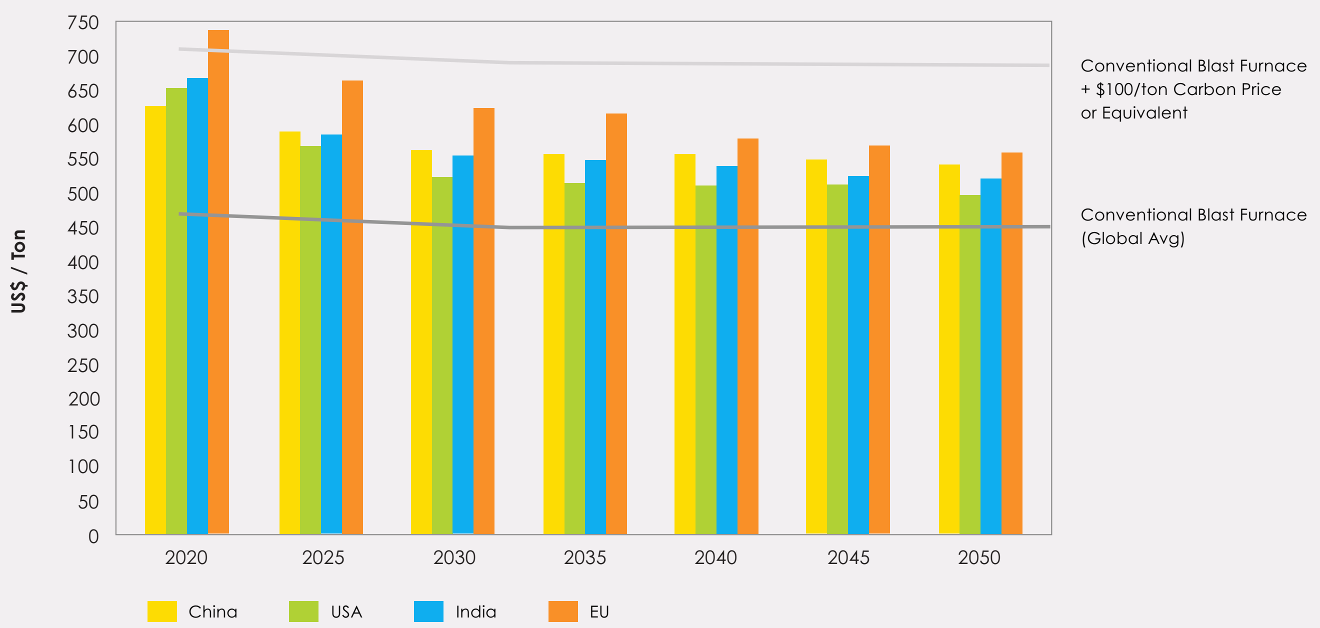
Solution status

SOLUTION DEVELOPMENT

Steel production from green hydrogen is still at the **demonstration stage**, with the HYBRIT project in Sweden producing the first ever batch last year. However, the foundations of larger-scale adoption are emerging, with a steadily growing volume of **feasibility studies, risk-sharing partnerships, and pilot projects**

According to announced projects, **11 full-scale green hydrogen DRI steel projects plants are planned to operational by 2030** (vs. 400 existing fossil-based steel plants) globally, with some now achieving **final investment decision status** (e.g., Thyssenkrupp Duisburg and Salzgitter Salcos projects)[2]

Levelized cost of steel production from new continental blast furnace vs. hydrogen DRI[1]



Note: Figures refer to new steel plants assuming 2.5 Mt annual production capacity and 80% utilisation. [2] Conventional blast furnace range refers to Blast Furnace-Basic Oxygen Furnace (currently accounts for 70% of global steel production). Green H2 DRI (direct reduced iron) refers to production route where the traditional blast furnace is replaced with DRI production (using green hydrogen) followed by a melter. Assumes utility scale dedicated renewables for hydrogen production. Alternative production route with electric arc furnace also possible, where coal is replaced as carbon source with green hydrogen in shaft furnace rather than blast furnace.

Sources: [1] Making Mission Possible (2022), MPP Steel Net-Zero Explorer; [2] Leadership Group for Industry Transition – Green Steel Tracker; [3] Systems Change Lab (2022), Commercialise New Solutions for Cement, Steel and Plastics.

Orange text indicates uncertainties that require further investigation

Tipping point

- Tipping point possible after **1st wave of greens steel plants developed** (~25 plants, ~50 Mt production p.a.) to kick-off large-scale adoption – 2nd wave to benefit from de-risked investment[2]
- This can close the **initial cost premium** for green hydrogen vs. grey hydrogen through scale economies in H2 production, targeting <$1.2–2.2/kg H2 (depending on production region) + carbon price or equivalent subsidy of ~$100/ton CO2[2]

Confidence in existence of reinforcing feedback loops

MID

- **Learning curves & economies of scale:** as more electrolysers are deployed; we experience 18% cost reduction per doubling of output, and lower costs encourage greater deployment[1]

	Target conditions to trigger tipping point	Progress*
AFFORDABILITY	• Achieve parity in the **levelized cost of steel production (LCOP)** for steel from **DRI made with 100% green hydrogen** vs. unabated fossil fuel-based production routes (with carbon price or equivalent form of support)**	• In absence of carbon price, green H2 DRI based steel not competitive until **price of hydrogen reaches <$0.65/kg**, not expected by 2050[2] • 100% green hydrogen steelmaking expected to be competitive with average BF-BOF by 2025 with **carbon price or equivalent subsidy of $100/tCO2 and green H2 price of <$1.2–2.2/kg** (depending on the region)[2]
ATTRACTIVENESS	• N/A: No significant difference with conventional steel production routes	• N/A
ACCESSIBILITY	• N/A: Hydrogen production and electricity generation likely to be on site and part of green steel projects in most cases • Mass Market: Develop new **higher-grade iron ore deposits** and greater pre-processing capacity to enable lower-grade ores be utilised in DRI-EAF steelmaking	• Only 13% of iron ore shipped today is of a suitable grade to use in DRI-EAF steelmaking – increasing share requires **cross-value-chain implications**, creating opportunities and challenges in upstream **iron mining activities**[2]

Note: *Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date; **DRI – Direct Reduced Iron. Conventional unabated fossil-based production refers to average Blast Furnace-Basic Oxygen Furnace (BF-BOF). Steel produced using zero-carbon hydrogen accounts for 35%–45% of primary steel production in 2050 in net-zero scenarios.

Sources: [1] IRENA (2020), Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5°c Climate Goal; [2] Making Mission Possible (September 2022), Net-Zero Steel: Steel Transition Strategy; [3] IEA (September 2022), Steel Tracking Report.

SECTOR TIPPING POINT

SHIPPING: GREEN AMMONIA

3% of total global GHG emissions

Sector context

- A combination of efficiency strategies will be required to reduce emissions growth in the sector, including most importantly (1) **system efficiency improvements** from modal shift to train and improving operational efficiency through **logistics optimisation**, (2) **energy efficiency improvements** of existing ships and engines through improved **ship designs and propulsion systems**.[1]
- Beyond this, **short-haul shipping** can be decarbonised via **electric engines with battery or hydrogen fuel cells**, but limits on energy density mean that **alternative liquid fuels** will be needed for **deep-sea long-haul shipping**, with largely unchanged engines (accounting for ~80% of final energy demand in net-zero scenarios).[2]
- While a range of options exist, **green ammonia and methanol** are expected to play the largest role, given constraints on sustainable biomass availability and low volumetric density of hydrogen as a fuel. We focus on ammonia as this does not require an additional supply of CO2 for production

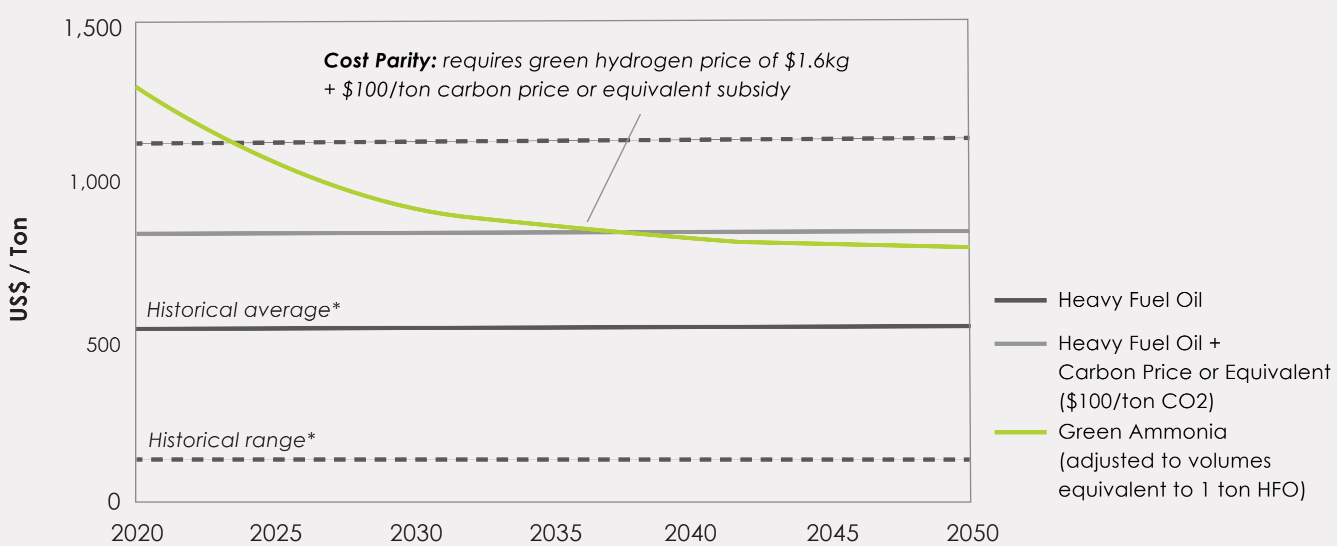
Solution status

SOLUTION DEVELOPMENT

Green ammonia for shipping remains at **solution development stage with ~80 pilot technology projects** currently underway globally[3]

However, niche market stage is approaching, with the NoGAPs project is developing **green ammonia-powered ships** targeting **operation by 2025**, Maersk aims to put 12 green methanol-powered ships into service by same year[3]

Projected cost per ton green ammonia for shipping[4] vs. heavy fuel oil[5]



Note: * Last 10 years, excluding recent energy price spikes [1] Refers to projected production cost of green ammonia production from electrolysis with dedicated renewables and pipeline H2 storage plus ammonia synthesis (lowest cost scenario); [2] Refers to monthly average international price of heavy fuel oil at Port of Rotterdam.

Sources: [1] Energy Transition Commission (2020), The First Wave: A Blueprint for Commercial-Scale Zero-Emission Shipping Pilots, Special Report for the Getting to Zero Coalition; [2] UMAS (2020), A Strategy for the Transition to Zero-Emission Shipping, Special Report for the Getting to Zero Coalition; [3] UMAS and UN Climate Change High Level Champions (September 2021), Climate Action in Shipping – Progress towards Shipping's 2030 Breakthrough. [4] Making Mission Possible (2022), Making 1.5-Aligned Ammonia Possible; [5] INSEE Data.

Orange text indicates uncertainties that require further investigation

Tipping point

- Tipping point possible after **1st wave of 'green shipping corridors' developed** (5% global fuel consumption, ~30 Mt production p.a.) to kick-off large-scale adoption – 2nd wave to benefit from de-risked investment **+ network effect** between ports and ships *– more research required on potential size of effect*
- This can close the **initial cost premium for** green ammonia vs. grey ammonia through scale economies in H2 production, targeting <$1.6/kg H2 + carbon price or equivalent subsidy of ~$100/ton CO2[2]

Confidence in existence of reinforcing feedback loops

MID

- **Learning curves & economies of scale:** as more electrolysers are deployed; we experience 18% cost reduction per doubling of output, and lower costs encourage greater deployment[1]

	Target conditions to trigger tipping point	Progress*
AFFORDABILITY	• Niche: N/A – driven by regulatory push and/or corporate decarbonisation plans • Mass Market: Cost parity for **green ammonia as shipping fuel vs. HFO** achieved at green ammonia production cost of $420/t-NH3 (produced from H2 at $1.6/kg) and HFO at $850/t (reached with carbon price or equivalent of $100/tCO2)[2]	• **Total cost of ownership** of green ammonia powered container vessel expected to be ~70% higher than conventional equivalent in 2030 based on current trends[3] • Production cost of green ammonia expected to fall rapidly as green hydrogen production scales – with **cost parity possible by 2035** in favourable locations with carbon price or equivalent subsidy of ~$100/ton CO2 and hydrogen price of $1.6/kg[2]
ATTRACTIVENESS	• Niche: Develop high-quality **ammonia engines for large commercial shipping** & overcome **handling issues caused by toxicity of ammonia**	• Acceleration of timelines for producing ammonia engines, with **first models expected to become available by 2024** for small ships and 2026 for larger ships (e.g. Maersk placed order of 12 ships with Hyundai heavy Industries this year)[4] • Recent announcements indicate **retrofitting LNG ships** to run on ammonia feasible by 2023[5]
ACCESSIBILITY	• Niche: Multiple large ports with **charging and bunkering infrastructure**, focussed in major hubs (e.g., Port of Rotterdam/Shanghai etc.) • Mass Market: Develop shipyards with the capacity to **build or retrofit ships running on ammonia**	• Multiplication of **plans for new facilities** – e.g. 8 import terminals planned at Port of Rotterdam, feasibility study underway at Port of Hamburg for imports from UAE[6] • **Pipeline for shipyards** remains major hurdle as these remain overburdened, with 2–3 year waiting time for new output at present

Note: *Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date.

Sources: [1] IRENA (2020), Green Hydrogen Cost Reduction: Scaling Up Electrolysers to meet the 1.5°c Climate Goal; [2] Making Mission Possible (2022), Making 1.5-Aligned Ammonia Possible; [3] Maersk- McKinney Moller Center for Zero Carbon Shipping (October 2021), Industry Transition Strategy; [4] Global Maritime Forum (2022), Mapping of Zero Emission Pilots and Demonstration Projects, Getting to Zero Coalition; [5] Getting to Zero Coalition (October 2021), A Strategy for the Transition to Zero-Emission Shipping; [6] Ammonia Energy Association (August 2022).

SECTOR TIPPING POINT

AVIATION: POWER-TO-LIQUID FUELS

Sector context

- The decarbonisation of the aviation sector will be driven by 3 key solutions: [1] **energy efficiency** [2] **hydrogen and battery electric planes** and [3] **sustainable aviation fuels.**
  - **Improved efficiency via aircraft design and other operational measures** is expected to reduce emissions by approx. 1/3rd vs. projected baseline growth.[1]
  - **Hydrogen and battery-electric aircraft** are expected to account for 35% final energy demand by 2050 in a net-zero scenario, limited by technical constraints on potential flight distances.[2]
- The remaining 65% of energy demand will therefore come from **sustainable aviation fuels (SAFs)** – while biofuels are the cheapest option, volumes are limited by availability of sustainable biomass, so the bulk of this (~75% of final energy) is likely to come from **power-to-liquid fuels (PtL)**

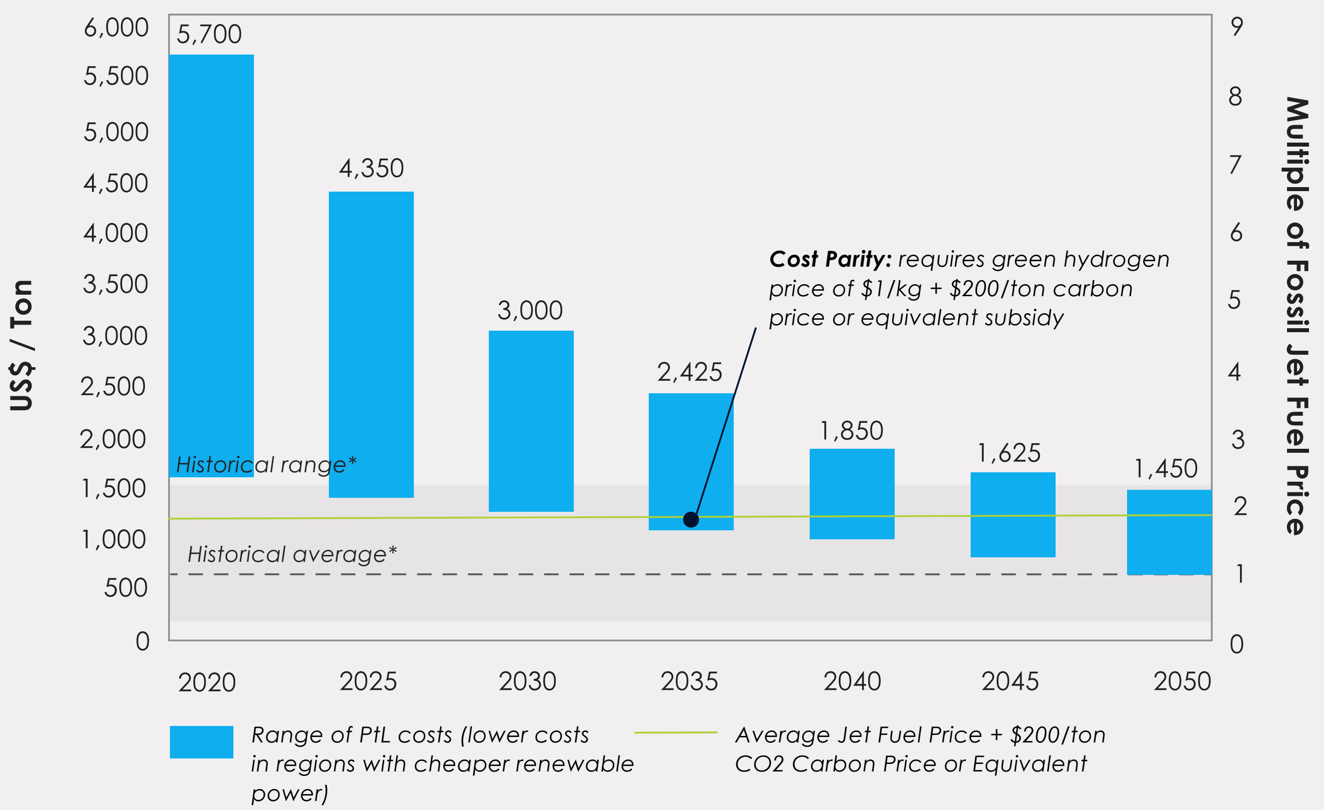
Solution status

SOLUTION DEVELOPMENT

PtL remains at **demonstration stage**, current production pipeline set to bring online 120 kt output per year by 2025 and 560 kt by 2030 – with 5 major projects publicly announced[2]

PtL currently has a technical readiness level of 5-6, meaning it is insufficiently advanced to ramp up immediately, but **large-scale market entry is feasible by 2025**[1]

Power-to-liquid production costs vs. fossil jet fuel prices[1]



Note: * Range shows historical fossil jet fuel price (average over past two decades: $600–$650/t and historical fluctuations over past two decades: $135–$1,590/t). [1] Refers to optimistic renewables scenario assuming aggressive cost reduction in renewable electricity prices driven by large scale deployment. [2] Assumes battery-electric and hydrogen aircraft range limited to maximum of 1000 km and 2500 km respectively, this may increase if technological innovation + airframe redesigns enable hydrogen-based aviation to unlock longer ranges. N.B. Remaining 5%–10% of residual emissions must be neutralised by carbon dioxide removals to achieve net-zero by 2050.

Sources: [1] Mission Possible Partnership (2022), Aviation: Pathways to Net-Zero – Net-Zero Aviation Explorer; [2] ICAO – Tracker of SAF Offtake Agreements

Orange text indicates uncertainties that require further investigation

Tipping point

- Tipping point possible after **1st wave of plants developed in multiple geographies** (25–50 plants, ~7.5–15 Mt PtL production p.a.) to kick-off large-scale roll-out of PtL – 2nd wave of plants to benefit from de-risked investment[2]
- This can close the **initial cost premium** for PtL vs. fossil jet fuel through scale economies in H2 production in lowest cost regions (e.g., Brazil), targeting $1/kg H2 + carbon price or equivalent subsidy of at least $200/ton CO2[2]

Confidence in existence of reinforcing feedback loops

MID

- **Learning curves & economies of scale:** as more electrolysers are deployed; we experience 18% cost reduction per doubling of output, and lower costs encourage greater deployment[1]

	Target conditions to trigger tipping point	Progress*
AFFORDABILITY	• Mass Market: PtL most likely **never cheaper than historical average price of fossil jet fuel** without carbon price/other forms of intervention – cost parity requiring **carbon price of >$200/tCO2 and green H2 price of ~$1/kg** in favourable locations	• Currently **3–9x more expensive than fossil jet fuel** – key factors in achieving cost parity = cost of renewable electricity (for H2 production and DAC) expected to fall rapidly in the mid-term[2] • Expected to remain **1–2.5x more expensive than fossil jet fuel by 2050** without any form of carbon price of equivalent subsidy to bridge green premium[2]
ATTRACTIVENESS	• Niche: Current **blending limit of 50%** in existing jet engines (PtL – fossil jet fuel)[3]	• Blending limit is expected to be lifted by 2030 the latest, with first **engines already 100% SAF-compatible by 2023**[3] • PtL significantly reduces **production of contrails** vs. fossil jet fuel – likely responsible for 2/3 of aviation's total climate impact[2]
ACCESSIBILITY	• Niche: Limited additional downstream infrastructure needed – PtL can be blended into **existing refuelling infrastructure at airports** • Mass Market: **CO2 transport network** may be needed if point-source-CO2 is not at the PtL production site	• Source of **sustainable CO2** required for large-scale PtL production (e.g., biogenic or direct air capture)

Note: **Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date; [1] Figures assume green hydrogen production from on-site renewable electricity generation.

Sources: [1] IRENA (2020), Green Hydrogen Cost Reduction: Scaling Up Electrolysers to meet the 1.5°c Climate Goal; [2] Mission Possible Partnership (July 2022), Making Net-Zero Aviation Possible; [3] EASA(2022) Sustainable Aviation Fuels

SECTOR TIPPING POINT

FOOD & AGRICULTURE: ALTERNATIVE PROTEINS

Sector context

- A **portfolio of solutions will be required across the food + agriculture value** chain in order to decarbonize the sector.
- This content **focuses on alternative proteins (APs)** because there is a potential for (albeit not certain) **reinforcing feedback loops** from learning effects, economies of scale + social norms which could drive S-curve outcomes. *More research required to determine whether other solutions in this sector have the potential for S-curve outcomes e.g., regenerative agriculture.*
- Three APs have potential to follow S-curves in the food + agriculture sector: **plant-based** (PB), **microorganism** and **animal-cell based protein**. Forecasts predict each to reach tipping points at different stages: PB protein (2023); microorganism protein (2025); animal-cell based protein (2032)*[2]
- This content will **focus on the nearest tipping point (PB protein)** which may trigger acceleration in the parity of the other 2 key APs as these share some common technologies with PB protein (e.g., extrusion and extrudable fat technologies).

Solution status

NICHE MARKET

Globally, the solution is a **niche market**, with APs accounting for **2%** of the animal protein market in 2020[3]**

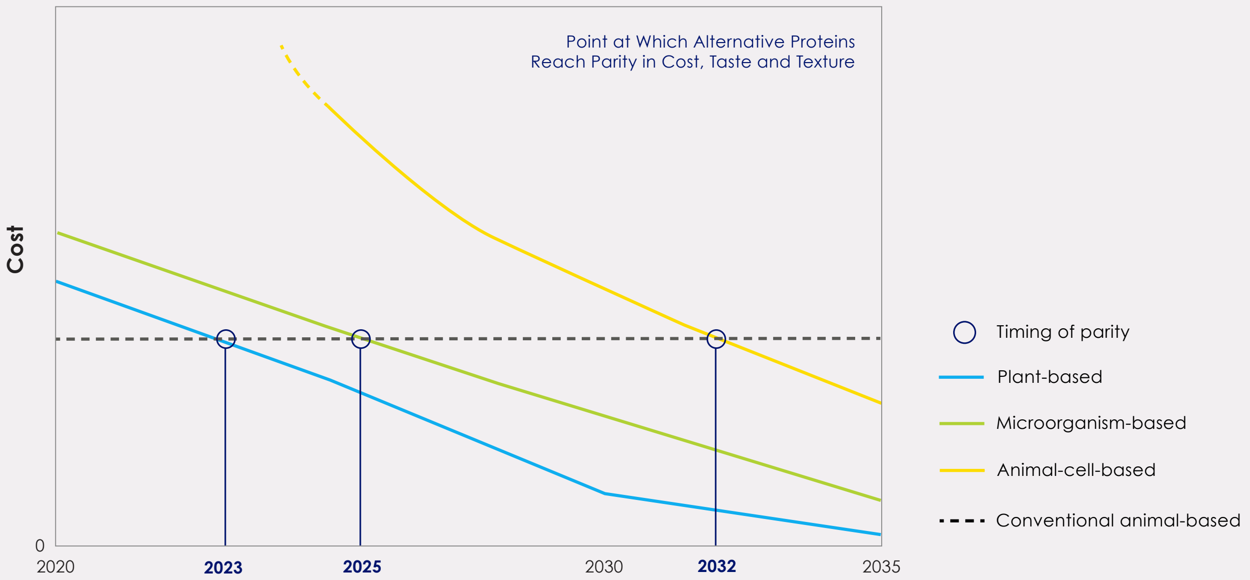
In some regions (e.g., Europe + US), the solution has advanced to the early adopter stage.
- European sales increased by ~50% in 2 years (2018-2020)[4]
- US sales increased by 72% (vs. 2019)[5], 3x faster than total food sales[6]
- China's PB market ($910m) was greater than the US's ($684m) in 2018 – forecast to grow 20–25% p.a.

– More research required on recent progress in China and other key markets

BCG analysis finds APs are on track to reach **~10% market share by 2035** but **policy** and **technological** step changes could drive adoption to ~20%[2]

More research required to determine global adoption potential of PB foods

Projected cost of alternative proteins vs. conventional animal-based proteins[3]



Note: **We have split AFOLU into two categories with food + agriculture's 13% share addressed here and land use's 10% share addressed in the Avoiding Land Use Change sector deep-dive; ** Plant-based: incl. but not limited to burgers, sausages, chicken, dairy, and egg substitutes made from soy, pea, and other proteins; *** It should be noted that very recent sales of PB products have slowed. For example, Beyond Meat's share price has significantly decreased in recent months. This is caused by a variety of factors incl. but not limited to inflationary pressures, COVID-19 affecting supply chains (higher input costs) and greater competition reducing the market share held by key actors (e.g., Beyond Meat)

Sources: [1] IPCC (2019), Climate Change and Lands; [2] BCG (2022), The Untapped Climate Opportunity in Alternative Proteins; [3] BCG (2021), Food for Thought the Protein Transformation; [4] European Commission (2021), 'Europe's Plant Based Food Industry Shows Record-Level Growth'; [5] Good Food Institute (2022) Reducing the Price of Alternative Proteins; [6] Good Food Institute (2021), U.S. Retail Market Insights Plant-Based Foods

Orange text indicates uncertainties that require further investigation

Tipping point

- A tipping point may be triggered once plant-based (PB) alternatives reach **cost parity** with animal protein + equivalent **attractiveness (taste, texture, nutrition)**
  - This will be influenced by a number of factors particularly social and cultural norms (e.g., gender identities related to meat, religious customs etc.) meaning tipping-points are likely to be context-specific.

Confidence in existence of reinforcing feedback loops

MID

- Preliminary evidence from other research suggests **early adoption between 10–40% of the population (some identifying 25%)** would **trigger a tipping point** that could rapidly scale up adoption[1]
- This is **not a well evidenced tipping point** and will likely vary significantly by local context and culture *– more research required to increase confidence in its existence, particularly at a global scale*
- **Social contagion:** Positive experiences from trying APs that effectively mimick meat coupled with word of mouth and changing social norms could trigger reinforcing feedback loops[1]
- **Increasing returns on adoption: Economies of scale** and **learning effects** are beginning to lower prices and improve quality + attractiveness of APs

	Target conditions to trigger tipping point	Progress*
AFFORDABILITY	• Achieve **cost parity** for **PB vs animal protein**, in **high-consumption markets** (US, EU, China) • Falling PB protein costs may trigger acceleration in cost reduction for the other 2 key APs (alternative proteins): **microorganism + animal-cell based protein** as these share some common technologies with PB protein *– more research required on relationship between APs*	• **Cost parity** for PB meats expected next year (2023), **some products competitive today** – microorganism (2025) and animal-cell based protein (2032)[2]; requires rapid scale up of **manufacturing and processing capacity** *– more research required to provide greater confidence in these forecasts* • APs price fell in 2021 whilst **conventional meat prices rose by double digits**, reducing cost gap from both curves[3]
ATTRACTIVENESS	• Achieve **taste and texture that mimic** animal protein and overcome **health and nutrition concerns** to appeal to average mass market consumers	• **13% of consumers** surveyed in key consumer markets** currently (nearly or) exclusively consume APs, but 27% state they would if 3 key inhibitors were overcome (health, nutrition, taste)[2] *– more detailed research required to understand effect on consumer behaviour* • Taste and texture significantly improved but still not on par with animal protein – new technologies in development could radically improve (e.g., **cultured fats** to **mimic meat flavour**)
ACCESSIBILITY	• PB protein to be **easy to purchase in stores, online, and in restaurants**	• PB proteins are **present in most prominent fast food chains e.g., Burger King sells PB burgers all over the world**, Subway with PB options globally*** and McDonald's McPlant is sold across Europe[1] • **Grocery stores increasingly positioning PBs in prominent areas to promote sales** with chains like Tesco[4], Lidl[5] + Carrefour[6] making PB targets + ranges for certain markets *– more research required to understand role of supermarkets/ hospitality in shifting to APs*

Notes: *Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date; * BCG survey of 3,700 respondents across China, US, UAE, UK, France, Spain and Germany; ** Geographies incl. but not limited to South Africa, Morocco, Brazil, Argentina, Bahamas, Nicaragua, Dominican Republic, Saint Martin, Saint Kitts, Mexico, Costa Rica, Morocco, Philippines, Indonesia, China, Japan, Thailand, South Korea, Australia, New Zealand, UAE, Oman, Saudi Arabia, US, Canada, Europe *** Geographies incl. but not limited to Asian outlets, Brazil and Europe

Sources: [1] FOLU (2021), Positive Tipping Points for Food and Land Use Systems Transformation; [2] BCG (2022), The Untapped Climate Opportunity in Alternative Proteins; [3] Good Food Institute (2022) Reducing the Price of Alternative Proteins; [4] The Guardian (2020), Tesco Sets 300% Sales Target for Plant-Based Alternatives to Meat; [5] ProVeg International (2022) How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products; [6] Businesswire (2021), Carrefour Sets Itself Some New Targets for its CSR and Food Transition Index

SECTOR TIPPING POINT

AVOIDING LAND USE CHANGE: VALUING NATURE-BASED SOLUTIONS*

10**% of total global GHG emissions

Sector context

- To align with a 1.5-degree scenario globally, the land use sector will require both **emissions reduction** and **carbon removal activities**.[2] The focus here is on emission reduction by avoiding land-use change alone, in line with the broader report.
- **Land-based emission reduction activities** can be divided into: a) reducing emissions from agricultural production; b) shifting to plant-based diets; c) reducing food loss + waste; d) **reducing emissions from deforestation** + the conversion/degradation of coastal **wetlands + peatland**
- This deep-dive focuses on d) forests, peatlands and coastal wetlands because they are the world's primary carbon sinks and stores.[2,3]
- **This centres on reducing direct drivers of ecosystem loss, primarily by: i) reducing conversion of land for agriculture + aquaculture** (i.e., reducing deforestation-linked commodities); one study finds that it is the dominant driver of tree cover loss in an estimated 90–99% of tropical deforestation cases[4]; ii) leveraging mechanisms to place a value on **nature-based solutions*** (NBS) to **promote land protection** across forests, peatlands and coastal wetlands by offering an alternative to converting land for agriculture
- Whilst there are other effective solutions that we will be cover (e.g., payments for ecosystem services + ecotourism), buying credible, high-quality **nature-based credits on the carbon market** is a mechanism for scaling NBS where positive signals are emerging across solution + market development and policy. These are therefore the focus of this analysis, alongside reference to complementary measures to reduce the relative appeal of land conversion versus protection.

Solution status

NICHE MARKET

Traded volume of nature-based credits in carbon markets is **scaling rapidly** e.g., a **5x increase on the VCM** with market share growing from 28-45% between 2019 and 2021[5].

Early adopters are valuing NBS which is providing initial scale, as evidence by carbon markets' traded volume growth. **NBS require greater consumer appeal/ competitiveness** (e.g., through transparency, additionality, permanence to enhance credibility + mechanisms to value additional biodiversity and social impacts) coupled with continued **buyer growth** (e.g., corporate commitments that can translate into greater demand for nature-based carbon credits, as part of science-based reduction pathways).

Marginal cost of avoiding deforestation[6] vs. carbon price for avoided deforestation[7]

Note: *Nature-based solutions cover forests, coastal wetlands and peatlands; **AFOLU has been split into two categories with land use's 10% share addressed here and food + agriculture's 13% share addressed in the Food + Agriculture sector tipping point [6] LCCA – life-cycle cost analysis: refers to average price of basket of commodities most commonly linked to deforestation; [7] NGEO – nature-based global emissions offset: refers to price for nature-based projects traded on CBL Global Emissions Offset Futures, verified by Verra and Climate Community and Biodiversity (CCB) accredited – majority of credits included are REDD+ avoided deforestation projects (minimum vintage year of 2016).

Sources: [1] IPCC (2019), Climate Change and Lands; [2] Roe et al (2019) Contribution of the land sector to a 1.5C world; [3] Goldstein et al (2020), Protecting Irrecoverable Carbon in Earth's Ecosystems [4] Pendrill et al (2022), Disentangling the Numbers Behind Agriculture-Driven Tropical Deforestation; [5] Ecosystem Marketplace (2022), State of the Voluntary Carbon Markets; [6, 7] Vertree Analysis based on World Bank, Bloomberg.;

Orange text indicates uncertainties that require further investigation

Tipping point

- A tipping point may be possible when land holders* see a **financial benefit from preserving rather than converting land** (including forests, coastal wetlands and peatlands).
- This outcome is influenced by many elements, incl. (but not limited to) **revenues from the sale of nature-based carbon credits**, reduced/eliminated value of commodities linked to deforestation, peatland degradation, and coastal wetland conversion, etc.
- This can be simplified in the following equation:
  - **Value** of **preserving land (e.g., through sales of nature-based carbon credits or ecosystem service payments)** > value of converting land to other purposes (e.g., agriculture/commodities/forestry)
  - **Value** is correlated to **costs and benefits** of action, incl. **economic and non-economic** outcomes e.g., legal penalties.

Confidence in existence of reinforcing feedback loops

LOW

- **No clear market-based reinforcing feedback loop identified** – likely to be **driven by policy** along l**inear trajectory.** *More research required to verify this hypothesis.*

	Target conditions to trigger tipping point	Progress**
AFFORDABILITY	• Land holder: Here, affordability relates to the relative cost/ value of the low-carbon option – i.e., a greater value for preserving than converting land. This requires: a) A more liquid market paying for **avoiding land use change**[1] – (e.g., via the VCM) b) **Higher prices** in carbon markets or other environmental service markets c) Lower **value from selling products linked to deforestation/ nature degradation** – e.g. through the use of taxes/fines on buyers to reduce demand. *More research required to understand key cost-related factors for land holders* • Nature-based carbon credit buyer: N/A	• Land holder: a) **Higher market liquidity,** with a >2x increase of nature-based carbon credits in the VCM[2]; increasing examples of governments paying for ecosystem services as public goods[3] However, NBS **only receives ~2% of total climate finance**[4]. To date, this has not generated sufficient revenues to ensure that benefits of preserving land outweigh those of converting it b) **Rapid average price increase** per unit of nature-based credits on carbon markets e.g., **33% increase in VCM** 2019-2021[2] c) Price paid for nature-based carbon credits is still 1/3rd of price paid for AFOLU commodities on the international market[2] *More research required to determine required prices + climate finance to outweigh benefits of converting land* • Nature-based carbon credit buyer: N/A
ATTRACTIVENESS	• Land holder: Protecting land provides a more **stable revenue stream** than converting it • Nature-based carbon credit buyer: Continuation of improved **carbon markets standardization/ quality** (e.g., permanence, additionality) and **transparency** to enable buyers to make credible reduction claims and reduce risk exposure, e.g., through the scaling of rating agencies[5] + **improved policies/regulation on corporate and government** emissions reduction/ 1.5C alignment **claims** to enhance benefits of buying from the carbon markets + **reduce appeal/ feasibility** of deforestation-linked production	• Land holder: The **price of nature-based carbon credits** on carbon markets continues to **fluctuate,** but **brokers** are gradually emerging as a middle entity to **provide stability by taking on the risk of price volatility** e.g., Goldman Sachs + Revalue[6].*More research required to determine what is considered stable revenue stream by various land holders* • Nature-based carbon credit buyer: Standardisation/ quality of credits, regulation, governance, transparency on pricing and data **remain inhibitor of scaling adoption**[7], organisations are working to fill this gap. Interesting new models are being explored e.g., **offset reserve banks as insurance** against permanence issues. *More research required to establish the determining inhibitors for different buyers*

- Land holder: **Knowledge** is **accessible** to land holders on how to **engage in nature-based carbon credits/ payments for ecosystem services** (e.g., comply with methodologies + calculate the carbon stock of their land) + the **process of engaging** is simplified. **Markets for deforestation-linked commodities are curtailed** to reduce relative appeal for land holders
- Nature-based carbon credit buyer: Mature network of **trading, rating** and **insurance** companies offering solutions (e.g., standardised contracts) to facilitate scaled demand. **Geo-spatial intelligence** is widespread + applied across key regions, allowing businesses to **trace their entire supply chain** back to the source

- Land holder: Multiple projects supporting communities to ensure their land is investment ready (e.g., **workplans, budgets + cash project projections**) e.g., Terra Global Capital's Rural Development Tool in Colombia[8]. However, these **only reach a fraction of land holders** + engaging in carbon markets is **generally not accessible**
- Nature-based carbon credit:
  - Increasing number of companies involved in trading, rating + insurance are **improving liquidity, processing time** + implementing more effective products, e.g., standardised contracts
  - Recent advances in **forest monitoring** (e.g., Sylvera [9] + ctrees [10] using ratings + geospatial data to measure carbon stock to **increase the validity of nature-based credits + thus value in protecting land**). However, scaling up geospatial monitoring inhibited by barriers e.g., lack of awareness + capacity to use spatial data + **significant investment still required for deployment**[11] *– more research required to understand application potential*

Note: *Land holders refer to all communities who hold land, including indigenous communities who may not legally own the land; ** Affordability: green – no cost disadvantage, amber – point of parity is <5Y away, red – point of parity is >5Y away (incl. policy support measures equivalent to <$100/ton CO2). Attractiveness + accessibility: green – no barrier to tipping point, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date.

Sources: [1] Mckinsey (2021), A Blueprint for Scaling Voluntary Carbon Markets to Meet the Climate Challenge; IEMA (2020), Accelerating Private Investment in Nature-Based Solutions; FlowCarbon (2022), GNT and the Importance of Liquidity; [2] Ecosystem Marketplace (2022), State of the Voluntary Carbon Markets; [3] Price (2020); [4] Climate policy Initiative (2021), Global Landscape of Climate Finance 2021; [5] Carbon Pulse (2022), The Voluntary Carbon Market Needs Ratings Agencies; [6] Revalue (2022) Revaluer; [7] Kotsialou, Kuralbayeva & Lainging (2021), Blockchain's Potential in Forest Offsets, The Voluntary Carbon Markets and REDD+; Compensate (2021), Reforming the Voluntary Carbon Market; Climate Trade (2022), Building Integrity and Transparency in Carbon Markets; [8] Terra Global Capital (2021), Colombia's Carbon Market Revolutionising Rural Development; [9] Sylvera (2022); [10] ctrees (2022); [11] World Economic Forum (2022), Location Matters Using Spatial Intelligence for Business Action on Nature and Climate

SECTION 3

TIPPING CASCADES

Many zero-carbon solutions can support transitions in multiple different sectors.

Low-cost renewable power combined with cheaper and longer-duration battery storage is now making direct electrification more feasible across many sectors of the economy (e.g., heavy-duty transport, short-haul shipping and aviation). At the same time, cheaper and more powerful electrolysers create new avenues for industries to decarbonise using green hydrogen and its derivatives (e.g., green ammonia for fertilisers, shipping fuel and synthetic jet fuel in aviation). This progress is continuously expanding the frontier of the energy transition. In 2021, the estimated cost for decarbonising 70% of global emissions was 40% lower than 2 years prior, as the decarbonisation of previously 'hard-to-abate' sectors had become more feasible thanks to underpinning technologies that cut across sectors.[79]

These links create the possibility of *tipping cascades*, where crossing a tipping point in one sector accelerates progress towards tipping points in other sectors.[80] This can happen by way of a shared technology such as hydrogen electrolysers being driven down the cost curve in one sector and used in others, or by the output of one sector (such as clean electricity) providing a low-cost input to others (e.g., road transport).

Figure 5 below highlights some of the key interactions between sectors and their low-carbon solutions. As shown, reinforcing feedback loops are present both within and *between* sectors, such that accelerating one feedback loop will have knock-on effects on several high-emitting sectors.

In the climate system, the presence of reinforcing feedbacks that create links between tipping points is a source of danger. In the global economy, these links are a source of opportunity: activation of a tipping cascade could greatly increase our chances of limiting global temperature increase.

Leverage points

In dynamic systems, cause and effect are usually disproportionate. Sometimes much effort can be expended without having much effect. A leverage point is a place where a small intervention can achieve a large effect.[81]

In the context of low carbon transitions, we can think of a leverage point as a policy or action that has relatively low cost or difficulty and a relatively large effect on the development or deployment of zero-emission solutions. In any emitting sector, many complementary policies are needed to support a transition. Nevertheless, at any given moment in time, there may be one policy that stands out for its unusual degree of leverage. For example, in the power sector at its current stage of transition, contracts for difference (CfDs) can be highly effective in reducing the financing costs of renewables. In some countries this is helping to grow renewables deployment even when the CfDs strike price is less than the expected market price of electricity, implying negative subsidy. While other policies (such as planning permissions and grid connections) are needed too, the ability to support deployment at low or negative cost means that CfDs stand out as a point of leverage.

Super-leverage points

The potential for tipping cascades between sectors suggests the existence of what could be called *'super-leverage points'* – opportunities for actions that have relatively low cost or difficulty, and a relatively high chance of catalysing a tipping cascade. Here we define super-leverage points as having the following attributes:

- Being the highest-leverage action within their own sector, based on combining low cost or difficulty with large effect on the development or deployment of zero emission solutions;
- Having an influence on at least one other major-emitting sector that is: a) positive in direction, i.e. it supports the transition; b) high in impact; and c) reasonably high in probability.

While the economy-wide transition to net zero emissions will require countless interventions, it may be useful to identify and focus effort on super-leverage points to increase the chances of rapid progress.

The actions of just one country acting alone, however well targeted, are unlikely to catalyse a tipping cascade in the global economy. If countries act together and jointly focus efforts on a super-leverage point, they may well be able to do so. In most emitting sectors, the ten largest countries account for 55–75% of global production or consumption.[82] Forty-five countries accounting for over 70% of global GDP have already committed to the Breakthrough Agenda, with a joint aim of working together to cross tipping points in each of the emitting sectors.

WE SUGGEST HERE THREE CANDIDATE SUPER-LEVERAGE POINTS THAT COULD POTENTIALLY ACCELERATE TIPPING CASCADES ACROSS 10 SECTORS REPRESENTING 70% OF GLOBAL EMISSIONS.[83]

1. Mandating zero-emission vehicles

Within the light road transport transition, there is evidence that zero emission vehicle (ZEV) mandates are a strong leverage point. By requiring manufacturers to ensure ZEVs account for rising proportion of their car sales, they overcome a constraint on supply, and ensure increasing volumes of production – which in turn lead to falling costs and rising demand. Versions of this policy have proved highly effective in California, China, and the Canadian provinces of Quebec and British Columbia.[84] The ZEV mandate involves no government expenditure, but instead relies on the reallocation of industrial capital to drive investment and innovation in the new solution. The ZEV mandate is insufficient alone – charging infrastructure investment and many other policies are important – but it has particularly high leverage for accelerating the transition to electric vehicles in light road transport. This can help to accelerate low carbon transitions in at least two other sectors, in significant ways:

i) **The power sector:** Passenger EVs represent the majority of projected demand for batteries, with estimates suggesting that they will account for ~70% of total installed battery capacity by 2030.[85]

83 See 10 sectors covered in sector slides above for reference.

Boosting EV adoption to 60% of total global passenger vehicle sales by 2030, aligning with net zero trajectories, would increase the total volume of battery production by 10 times from current levels (50% more than expected under current trends).[86] Given current learning rates, this could drive a 60% reduction in battery costs by 2030. This would in turn reduce the cost of solar/wind + storage solutions in the power sector; as battery costs account for ~30% of the total cost of power for these solutions.[87] The faster battery cost decline could bring forward cost parity of solar/wind + storage with gas (or coal) power generation. In addition, electric vehicle batteries can provide zero-marginal cost flexibility in the power system through 'smart charging', enabling a faster, smoother, and lower cost integration of high levels of solar and wind generation.

ii) **Heavy road transport:** Cheaper and better-performing batteries achieved through the scale-up of electric cars would increase the competitiveness of battery-electric trucks, bringing forward the point where they outcompete petrol or diesel trucks. There are also likely to be advances in electric drivetrain technology that are transferable from cars to trucks.

Just as with tipping cascades, confidence in the existence and effectiveness of super leverage points varies across sectors. Evidence of ZEV mandates proving effective in bringing forward EV tipping points mentioned above, combined with the importance of battery costs in bringing forward power and heavy road transport tipping points, means there is high confidence in this super leverage point.

2. Mandating green ammonia use in fertiliser production

Fertiliser production with green ammonia (produced from green hydrogen) has one of the lowest green premia in the emerging hydrogen economy.[88] Green ammonia can be shipped at a relatively low-cost (only adding <10% to the delivered cost[89]) meaning it can be produced in the regions with the lowest hydrogen production costs, and then transported to fertiliser production sites. Further, there is no end-sector conversion required since fertiliser plants already consume ammonia, unlike steel or shipping which need new steel plants and ship engines respectively to adopt hydrogen solutions. The shift of fertiliser manufacturing to green ammonia may therefore be achievable with policies that are *relatively* low cost and low difficulty.

Mandates that require an increasing proportion of green ammonia in fertiliser production (or consumption) could be particularly effective in establishing this as a first large-scale market.[90] Requirements for a rising percentage of fuel to come from non-fossil fuel sources can help overcome the 'chicken-and-egg' barrier to achieving economies of scale to reduce costs. This idea is starting to gain traction politically in some regions. For example, India's draft hydrogen strategy requires 5% minimum green ammonia production for the domestic fertiliser sector by 2023–24 and 20% by 2027–28.[91]

Mandates for green ammonia use in fertiliser production should be considered in unison with other policies (e.g., subsidies, tax breaks) to avoid increasing the cost of food production. Fertiliser costs historically represent 15%–40% of crop production costs (according to figures from North America).[92] Cost impacts could be minimized in part through optimizations in fertiliser application or savings through other efficiencies in farm management, but appropriate policy and financing mechanisms will be needed to ensure the transition to green ammonia use does not result in higher crop prices, which would disproportionally affect the most vulnerable populations who spend upward of 60% of their income on food.[93]

Progress in green ammonia use for fertilisers could scale up the supply chains of green hydrogen production and bring down the cost of green hydrogen for use in several other sectors. For example, implementing a 25% green ammonia blending mandate in fertiliser manufacturing could create demand for almost 100 GW of hydrogen electrolysers, which would reduce capital costs by ~70% given current learning rates.[94] This could unlock $1.5/kg green hydrogen costs if accompanied by continued falls in the cost of clean electricity[95] – helping to close the gap to cost parity or increase the economic viability of zero emission solutions in other sectors including steel production and shipping (see figure 6 below).

95 $2/kg H2 to be achieved in favourable locations with very good solar/wind resource. These locations are set to become exporters of hydrogen-products (e.g., green ammonia). Other regions will benefit from production in these low-cost regions, specifically for hydrogen-products (ammonia, steel, synthetic jet fuel, methanol). Hydrogen itself does not transport economically, and thus end-uses that require hydrogen gas (e.g., H2-trucks, refineries) will produce hydrogen locally, at local costs of hydrogen production based on local renewables resource.

The evidence supporting the potential for rapid cost reductions in green hydrogen production is relatively strong, but this remains a nascent industry with limited historical data across its use cases, giving us moderate confidence in the existence of this super leverage point.

3. Redirecting public procurement to promote the uptake of alternative proteins

Favouring alternative proteins in public procurement policies globally could help to bring forward tipping points in their adoption. Using public institutions (e.g., government offices, hospitals, prisons, schools) to purchase alternative proteins in large quantities would rapidly increase demand and help producers to achieve economies of scale, thereby lowering costs. Public procurement accounts for between 5-6% of food sales in the UK and EU.[96] For example, public institutions spend GBP 2.4 billion (USD 2.9 billion) on food annually in the UK alone,[97] sufficient to have a material impact on plant-based protein market value, estimated at USD ~30 billion annually worldwide.[98] By introducing large numbers of consumers to these products, public procurement can also enhance accessibility and help to shift social norms around meat consumption.

Shifting public procurement would not require significant additional government expenditure but can instead focus on redirecting existing budgets away from animal proteins and towards alternative proteins. Nor would it require significant technological advances, given plant-based proteins are already well advanced technologically.

This can help to accelerate low carbon transitions in two key sectors:

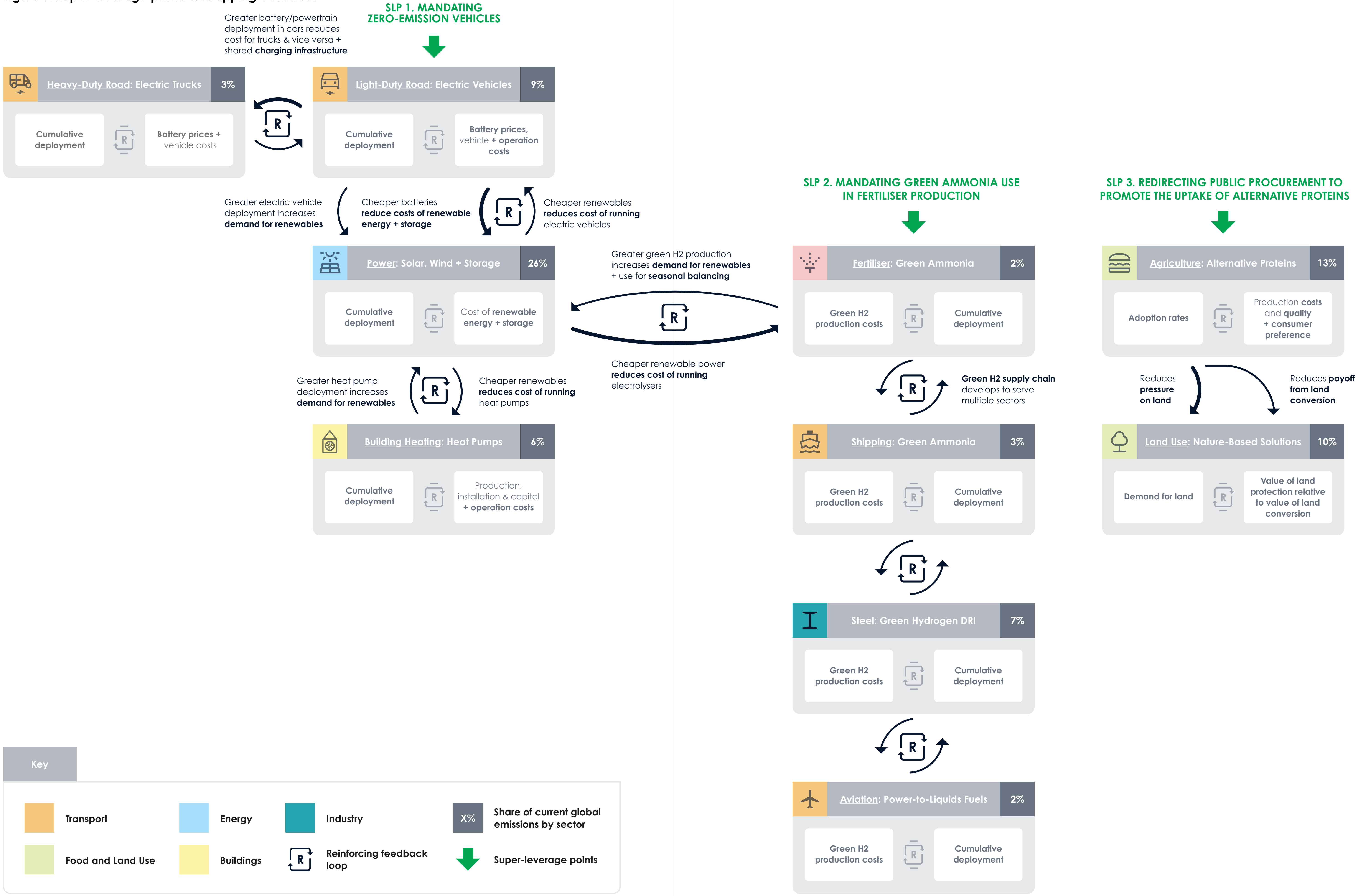
- In agriculture, by reducing emissions from livestock farming. Livestock farming alone (excluding associated land use change) accounts for 8% of anthropogenic GHG emissions.[99] Bringing forward the tipping point in alternative proteins, by achieving parity with animal-based proteins across price, taste and texture, could help to increase alternative proteins' projected market share in 2035 from ~10% to ~20%[100], significantly reducing global demand for meat.
- Of the 7.1 Gt CO2e emissions from livestock farming, approx. 20% is estimated to be related to land use change.[101] **If a tipping point for alternative proteins is reached, and alternative proteins achieve 20% market share, this would free up an estimated ~400-800 million hectares of land from use for meat production, equivalent to 7-15% of total land currently dedicated to agriculture.**[102] By reducing pressure on land conversion, this could help to reduce the value of converting land relative to the value of protecting land. Since alternative proteins emit <u>up to</u> 90% fewer emissions than meat (including animal and associated land use emissions)[103], reaching this level of adoption would result in an approx. 0.85-2.2Gt cumulative of emissions savings by 2030.[104]

While it is clear that redirecting public procurement towards alternative proteins would significantly increase demand, in the absence of significant attempts to use this lever at scale, there is little evidence yet to assess its effectiveness. Additionally, as a nascent industry, there is a lack of historical data to determine the relationship between increased alternative protein production/consumption and decreased animal protein production/consumption and associated land use change. This gives us relatively low confidence in the existence of this super leverage point, although, for the reasons we have set out, we believe its existence is a strong possibility.

The scale and pace of the economic transitions required to meet climate change goals are unprecedented in human history. The past will not provide a full guide to the future, and decisions will have to be taken in the face of uncertainty. While we aim to highlight where further evidence would be helpful, we also urge policymakers to take decisions on the balance of probabilities, and to act without delay.

Figure 5 illustrates how these 3 super-leverage points can trigger reinforcing feedback loops for zero-emission solutions both within and across sectors, causing a tipping cascade across the system. A more exhaustive list of interactions between tipping points across sectors is provided in appendix B.

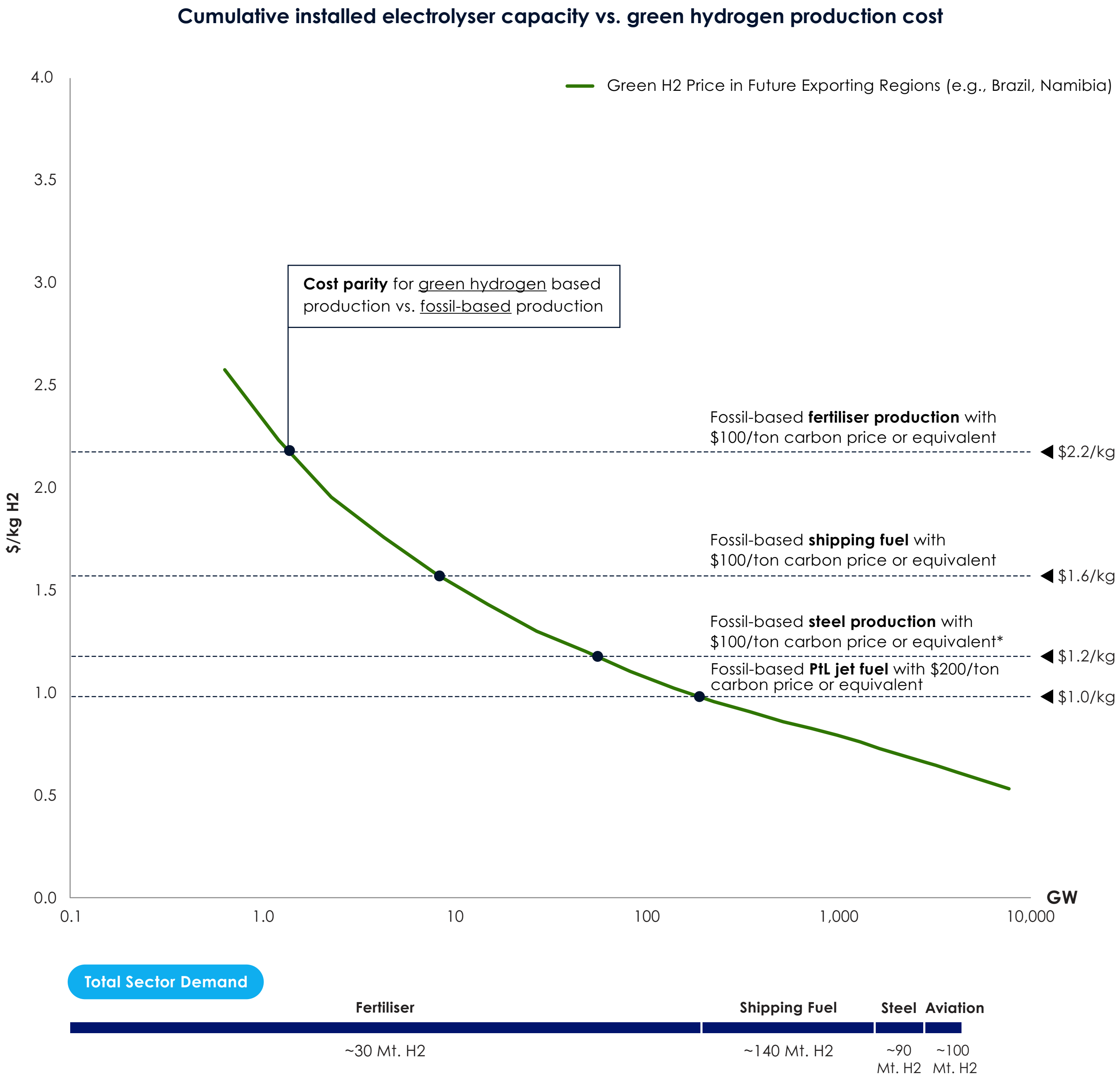
Figure 5: Super-leverage points and tipping cascades



Note: GHG emissions represent the whole sector NOT the percentage of emissions that can be abated from the selected solution – more research required to model this latter indicator.

The Appendix contains a complete list of all identified interactions between sectors, along with data points that support our hypotheses regarding the strength and timing of cross-sector links.

Figure 6: Impact of scaling green hydrogen production by sector on production costs



Note: * Across all major producing regions (EU, US, China India). Green hydrogen production – i) favourable scenario assumes average LCOE of PV and onshore wind of lowest 33% locations (falling from $22/MWh in 2020 to $10/MWh in 2050) and average scenarios assumes median LCOE from lowest 75% locations (falling from $39/MWh in 2020 to $17/MWh in 2050) from BloombergNEF forecasts, ii) additional 20% (favourable) and 10% (average) LCOE savings included due to directly connecting dedicated renewables to electrolyser, iii) 18 % learning rate for favourable & 13 % for average scenario. Electrolyser capacity utilization factor: 45%. Comparison to BloombergNEF most favourable ($0.55/kg) and average ($0.86/kg) and Hydrogen Council favourable (ca. $0.85/kg) and average (ca. $1.45/kg) in 2050.

Source: Systemiq Analysis based on [1] BloombergNEF (2021), Natural Gas Price Database; [2] BloombergNEF (2020), 2H 2020 LCOE Data Viewer; [3] BloombergNEF (2021), 1H2021 Hydrogen Levelized Cost Update; [4] Hydrogen Council (2021), Hydrogen Insights.

SECTION 4

KEY ACTIONS TO BRING FORWARD TIPPING POINTS

For new solutions to reach tipping points, many actors in the system need to adapt and coordinate to support the new solution.

Further, when new technologies or practices emerge, they often face strong initial resistance from incumbents who favour the status quo. In road transport, for example, the use of internal combustion engine vehicles is embedded within larger structures that make rapid change difficult, such as co-dependent industries across the supply chain (e.g., component parts manufacturers, car maintenance/ repair firms, dealerships etc.), existing physical assets (e.g., refuelling networks and stations), or legal and regulatory frameworks (e.g., revenues from fuel taxes). However, once the advantage of the new solution becomes apparent, actors increasingly shift to support it and drive its adoption.[105] In practice, this means that there is often a long lead-in period for new solutions when overall market share remains small, before rapid growth kicks in.

Different types of actions are required across different stages of adoption.

As new technologies and practices develop, they go through a series of transition phases which call for different interventions and strategies from policymakers, corporates, consumers, and financiers. These can broadly be categorised as follows:[106]

- **Concept:** Early-stage innovation drives the development of new solutions. This stage requires trial periods to explore different possibilities before a viable option is identified, where publicly funded research and development programmes complement private sector experimentation.
  - E.g., the US CHIPS and Science Act supports nuclear fusion and bio-technology research and development.
- **Solution development:** Solutions are being piloted at demonstration scale to show proof of concept, often through public-private partnerships. This stage requires strong public financial support to de-risk investment in first-of-a-kind (FOAK) commercial projects (e.g., via concessional loans and grants, early market support, etc.). Key role for voluntary corporate demand coalitions to provide guaranteed offtake for initial output, covering large initial cost premiums relative to incumbent solution.
  - E.g., First mover coalition supporting development of green ammonia in shipping corridors.
- **Niche market:** The solution is taken up by early adopters, connecting supply and demand to provide initial scale. This stage requires establishing and growing the consumer base and improving solution competitiveness; buyer coalitions and blended/green finance are crucial to increase deployment. Policy shifts focus to first wave of large-scale production (e.g., via subsidies and tax breaks) and building out supporting public (or PPP) infrastructure.
  - E.g., US inflation reduction act provides green hydrogen credit of \$3/kg H2 making green steel cost competitive in US[107].
- **Mass market:** The solution reaches early majority adoption as it outcompetes the incumbent (start of the steep part of the S-curve). Demonstration of profit generation drives broader market participation, supported by expanded access to capital as financing is reallocated from old to new solutions. This stage requires re-designing markets in favour of the new solutions through new regulatory frameworks and schemes to initiate the phase-out of the incumbent solution.
  - E.g., carbon pricing programmes, zero emission solution mandates, bans on gas boiler/ICE vehicles, creation of capacity/flexibility power markets to support solar/wind integration.
- **Late market:** The solution reaches large-scale adoption. At this stage the focus shifts to institutionalisation, such as setting and enforcing new standards and managing the implications of declining industries (e.g., providing social safety nets and workforce retraining). This stage also includes expansion of the solution to new markets as incumbents are pushed out of remaining niches.
  - E.g., early retirement of coal plants (Europe, USA).

In the following table, we set out a selection of key actions required for accelerating the transition to zero-carbon solutions, which reflects their current stage of adoption. As shown, most sectors are now at the solutions development or niche market stage, which calls for a strong focus on targeted policy to support and de-risk corporate investment into early-stage solutions. There has been significant progress in recent years across a number of sectors. However, we are behind on the transition overall, compared to what is needed to avoid dangerous climate change. Stronger and more targeted action can help to trigger tipping points sooner and accelerate the transition to a low-carbon economy.

CASE STUDY

The German energy transition in the context of global advances in solar and wind

An example of the importance of different actions by stage of development for new solutions can be seen in the German electricity transition over the last 50 years. In this case, solar and wind power technologies first emerged via research and development programmes initiated following the 1970s oil crisis – concentrated in certain countries e.g., the US, Japan, and Germany. These subsequently found a niche amongst a small group of environmentally focused citizen groups, farmers, and smaller utilities nationally, and were taken up for various niche applications globally, such as satellites, offshore oil rigs and consumer electronics.[108] In Germany, positive attitudes towards these initially spread slowly as their benefits became clearer, then changed abruptly following the shock of the 1986 Chernobyl nuclear accident, after which point alternative forms of energy gained prominence in social discourse.

Subsequently, German government policy in the form of the feed-in-tariff programme made renewables economically feasible, stimulating significant deployment in the 1990s. Production expanded across the world, particularly in China for solar PV manufacturing, driving learning-by-doing effects and economies of scale. This led to the emergence of several highly successful German businesses (e.g., Enercon producing wind turbines, SolarWorld AG for photovoltaic manufacturing), which eventually motivated other companies to re-direct investment towards renewables, including oil and gas majors. In parallel, political support increasingly shifted in favour of renewables as their economic contribution became obvious, e.g., through employment and tax revenues.

This was not a smooth process, with major setbacks along the way, including political opposition following increased prices and the collapse of German solar PV manufacturers in the face of Chinese competition. Major disruptions created volatility, including policy U-turns following the Fukushima incident and re-design of power markets to account for the intermittency of renewables. However, the overall trend nevertheless remained relatively steady, with renewables increasing from 5% to over 40% of total power generation in Germany from 2000-2020, highlighting the power of S-curves once they take hold.[109]

Key actions to accelerate enabling conditions to trigger tipping points by sector

Sector	Solution	Current state	Confidence in tipping point	Policy Support	Buyer Preferences	Market Development
Power	Solar, Wind + Storage	Niche / Mass Market	**High** (Strong learning effects)	**Target:** Key short-term interventions: [1] **power market reform** (e.g., roll out of capacity markets) [2] **reducing planning and permitting timelines**, particularly for transmission + distribution, reduce grid congestion and shorten interconnection queues. **Progress: Permitting timelines remain a key barrier**, e.g. all EU countries exceed the legal 2-year permitting time limit , some by more than 5x – but legislative efforts underway to shorten.	**Target: N/A – not the key driver of capacity additions** (primarily dependent on utilities), but corporate power purchase agreements can contribute to accelerated deployment. **Progress: Corporations driving new demand**, with 140 companies signing PPAs in 2021, equivalent to >10% new capacity – driven by growth in the US, especially technology firms.	**Target: Cumulative deployment of ~600 GW battery storage** in next decade needed to drive 50% reduction in production cost via learning curves/economies of scale. **Progress:** Global battery storage **investment expected to >double in 2022 to ~$18 bn**– but still **~80% below net-zero trajectory requirement**.
Light-Duty Road	Battery Electric Vehicles (BEVs)	Niche	**High** (Battery production economies of scale + charging infrastructure network effects)	**Target:** [1] **Implement sticker price subsidies** (e.g., purchase subsidies + tax rebates) [2] enforce **preferential treatment for EV drivers** (i.e, free access to bus lanes, parking + toll roads) [3] combine **banning all ICE light-duty vehicle sales (by 2035)** with city-based action to restrict existing usage. **Progress:** [2] EU member states (20% increase from 2021) offer incentives for purchase. **Countries with ICE phase-out goal accounted for ~20% of 2020 passenger vehicle sales**, reaching 40% (up from 8% in 2019) when interim adoption targets are included (China, USA).	**Target:** Clear market signal sent via **voluntary demand partnerships targeting 100% EV purchases** by 2030/2035, depending on the region. **Progress:** Number of **leading companies driving demand via procurement policies/ partnerships** e.g., EV100 (129 multinationals committed to switching fleets to EVs and/or install charging for staff/ customers by 2030)	**Target:** End **ICE investment** and commit to **phasing out sales of ICE vehicles** by 2030/2035 – depending on the region, while scaling EV investment. **Progress: 4 automakers committed to ending ICE vehicle investments + 13 committed to phasing out production** between 2025-2040. Automakers collectively announced $526 billion in EV investment before 2026.
Heavy-Duty Road	Battery Electric Trucks (BETs)	Niche	**High** (Battery production economies of scale + charging infrastructure network effects)	**Target:** Incentivise adoption by [1] **overcoming upfront costs** (e.g., accelerating depreciation via temporary tax reductions) , [2] supporting the **build-out of long-range charging networks** [3] preferential **highway rates** [4] subsiding **green electricity** [5] long-term **diesel phase outs**. **Progress:** Key markets implementing initial policies, e.g., the **EU's mandatory sales target for zero-emission trucks** (15% in 2025 – 30% in 2030) + UK committed to 100% zero- emission heavy goods vehicles by 2040.	**Target:** Corporates with large fleets send strong signals via **voluntary demand commitments** **Progress:** Major companies (incl. **IKEA, Unilever, DPD via Climate Group EV100+ Initiative**) **committed to 100% zero-emission fleet** (2040) + establishment of **'First Movers Coalition'** aiming for >30% heavy-duty + 100% medium-duty truck purchases to be zero-emission (2030).	**Target: >30% BET sales as share of total (2030)** by developing transition plans, investing in new models + adopting new business models to overcome initial technological risks (e.g., leasing). **Progress:** Several **large manufacturers targeting 35-60% sales** (2030) + major firms (e.g., Tesla, Daimler, Volvo) presenting plans for zero-emission medium+long-haul trucks in 2023.)
Building Heating	Heat Pumps	Niche	**Low** (No clear feedback loop, driven by policy)	**Target:** Overcome **high CapEx up-front costs barrier** using [1] financial instruments (e.g., subsidies, lower tax rate on electricity vs. gas for heating) [2] mechanisms to integrate installation into building works (e.g., retrofits as part of renovations) [3] carbon pricing + gas boiler bans. **Progress:** [1] **Subsidies present in key markets** (China, US, France, Italy, UK) [2] **policy support for retrofit** (UK's 13% energy demand reduction target incl. subsidising retrofits), [3] staged fossil fuel bans in leading markets (Norway, France and UK) + Germany implemented carbon price in 2021. However, historically, success has been limited by fragmented market + low uptake.	**Target:** Increase **public awareness** of **energy** and **cost saving** potential. **Progress: Sales increased by 13% (globally), ~35% (Europe)** in 2021 *– more research required on buyer preferences.*	**Target: Investment** and **manufacturing capacity** rapidly scaled and **installation improved** through standardisation and upskilling the workforce. **Progress: Global investment grew by record 25% in 2021** and 10% **CAGR forecast** until 2027 + production capacity growing notably in Europe.
Fertiliser	Green Ammonia	Solution Development	**High** (Learning-by-doing + scale economies in VRE + electrolyser costs)	**Target:**[1] **De-risk private investment for first-of-a-kind** (FOAK) production facilities (e.g., grants, tax breaks, CfDs), [2] increase **competitiveness** (e.g., carbon pricing + blending mandates), [3] implement certification schemes to encourage sustainable premium (e.g., for sustainable crop production with green ammonia). **Progress:** Positive early stage signals with [1] direct production grants (e.g., $31m for Yara + Engine) and [2] **India's draft hydrogen strategy** mandating green ammonia for fertiliser (5% production by 2023/24 – 20% 2027/28), **EU's ETS requiring 43% emission reduction** for fertiliser (2030).	**Target:** N/A – impact on **consumer prices not major barrier if policy support in place** **Progress:** Price difference of high fertiliser crops account for 8-9% final product cost (if all cost passed to consumer)	**Target: Demonstrate profit generation** from green ammonia production for fertiliser use + major producers **commit to blending grey and green ammonia**, building out infrastructure. **Progress: Yara + CF industries** (world's largest producers) **committed to blending** grey and green; number of projects planned e.g., **NEOM $5bn, HØST $1bn**.
Steel	Green Hydrogen DRI	Solution Development	**Medium** (Learning-by-doing + scale economies in VRE + electrolyser costs)	**Target:** Scale finance via [1] combining concessional + blended finance, [2] credit + loan guarantees to de-risk investment, [3] **CapEx grants for FOAK commericial projects.** Additionally, apply **carbon prices of >$50/ton and green public procurement** commitments for zero-emission steel. **Progress:** Positive signals from key consumers, including **EU's carbon border adjustment mechanism** to include steel from 2026 + **China** (50% of global output) announced **carbon price for 2023**.	**Target:** Commit to **~90 Mt./yr forward purchasing of green steel from H2 DRI** (~350 Mt./yr.) **Progress:** Positive signs from off-taking sectors, e.g. **automotive firms set carbon neutrality pledges** (incl. Mercedes Benz partnering with SSAB to source H2-DRI steel when solution is market fit) + initiatives (e.g., SteelZero + First Movers Coalition) increasing demand – but **first-mover disadvantage in wholesale markets remains**.	**Target: Demonstrate profit generation** of operational plants + in the long term, develop **joint definition of low-carbon steel** + support creation of **regulatory body**. **Progress:** Companies representing **20% of global steel production set net-zero compatible targets**, translating into planned pilot + demonstration facilities and **Responsible Steel Standard** recently established.
Shipping	Green Ammonia	Solution Development	**Medium** (Learning-by-doing + scale economies in VRE + electrolyser costs)"	**Target:** [1] **De-risk private investment in production facilities** (e.g., CfD schemes + loan guarantees), [2] **stimulate uptake** (fuel tax breaks + blending mandates), [3] introduce carbon price or equivalent subsidy rising to $150/ton by 2030. **Progress: US IRA tax credit** provides $3/kg for H2, reducing prices to $1.5-2.0/kg + EU ETS is considering **carbon pricing + carbon intensity limits** for on-board energy.	**Target: Large freight purchasers** commit to **forward offtake agreement** + accept potential double average transport costs (equivalent to <1% increase in final product cost for consumers). **Progress:** Initial steps via **voluntary demand initiatives** (e.g., **First Mover Coalition**) + customers (mining + retail firms) setting **supply-chain emission reduction targets (increasing demand for low-carbon solution to deliver on targets)**. However, more action required.	**Target:** Demonstrate **profit generation** from shipping routes + production with long-term goal of **200 zero-carbon deep-sea ships** and **30 'green corridor' routes** in operation. **Progress:** Clydebank Declaration committed to support development of at least **6 green corridors** this decade + multiple feasibility studies underway (e.g. Australia – East Asia corridor + Los Angeles- Shanghai).
Aviation	Power-to-Liquid-Fuels	Solution Development	**Medium** (Learning-by-doing + scale economies in VRE + electrolyser costs)	**Target:** [1] **Reduce cost differential** between SAFs vs fossil jet fuel (e.g., SAF blender's tax credit), [2] long-term **blending mandates** (5-7% by 2025), [3] **supply 20% of public-sector air travel with SAFs** (2030). **Progress:** [1] US IRA tax credit of $1.25/gallon (SAF), [2] EU proposed mandate of 0.7% PtL (2030) + Norway/Sweden existing 30% SAF mandate (2030) + SAF Grand Challenge target of supplying 16-18% of US demand with SAF.	**Target:** Signal demand via **offtake agreements reaching ~5 Mt. SAF by 2025** & ~15 Mt. by 2030 + long-term **acceptance of additional consumer costs** of ~10-20% final price. **Progress: 100 producers** (via CST ambition statement) **committing to 10% SAF** by 2030 + 35 airlines with carbon neutrality targets and **platforms developed allowing consumers to pay** for SAFs + Shell, Accenture, Annex GBT launching **global book-and-claim system** for SAFs.	**Target:** Establish cross-value chain cosortia to de-risk PtL production pathways + **bring FOAK PtL plants to market (2025)**. **Progress:** SAF consortium bringing PtL to market in N.America **(2025-26) with FOAK plant** + 28 Mt SAF currently under offtake agreements from airlines (but limited share of PtL).
Food & Agriculture	Alternative Proteins	Niche	**Medium** (Social norm diffusion + economies of scale)	**Target:** Unlock large-scale production + adoption of alternative proteins by leveraging **public procurement**, stimulating **open access innovation + R&D funding and banning meat advertisements** + applying **carbon price.** **Progress:** Recently announced funding from key consumers (EU, US, UK), Dutch City of Haarlem first to ban public meat advertisements but no country planning meat taxes.	**Target:** Reach ~25% global population regularly consuming APs to potentially trigger rapid diffusion in consumer preferences. *More research required on potential contagion effect.* **Progress:** Rapid increase in demand for sustainable + healthy food (61% Europeans choose sustainable options + 54% more people care about health than in 2010). However, demand slowing in line with inflation.	**Target:** Global plant-based protein **investment** reaches **$11 billion**, with a shift from venture capital to **debt financing** in order to fund **large processing + manufacturing plants**. **Progress: Sharp increase in private investment at 124% annual growth rate, reaching $5 billion** in 2021, driven by North America but increasingly global with rapid rises in Asia (up 92% 2020–2021) + Middle East (11% of global investment in 2021).
Avoiding Land Use Change	Valuing Nature-Based Solutions	Niche	**Low** (Requires strong + continual regulation)	**Target:** [1] Improve **tenure security**, governance and legal enforcement to prevent deforestation, [2] support **internalisation of deforestation-linked carbon emissions into the price** of products to lower **value of converting land relative to protecting land**, e.g., via carbon border adjustment mechanisms + due diligence laws + supply-chain transparency to detect damage, [3] introduce **compliance markets** in regions with major NBS potential (e.g., Brazil). **Progress:** Nature-based **compliance markets** in **Colombia, Indonesia**, Singapore, California + the EU's **Corporate Sustainability Reporting Directive will be first legally binding disclosure standard** on corporate use of VCM.	**Target:** N/A limited evidence buyers are willing to pay premium for non-deforestation-linked products. However, could target increase in consumer pressure on policymakers to regulate, for which there is evidence of willingness – see Policy Support. **Progress:** N/A	**Target:** Total tropical forest protection **investment** reaches **$1.3-6.4tn*** by 2030 + **VCM contributes $5-50bn (2030) by growing 15x by 2030**; 100x by 2050. **Growth in carbon markets accompanied by increased demand + supply-side** integrity (i.e., buyers do not substitute credits for reducing their emissions + issues on additionality, permanence + accounting etc. are managed.) *More research required on financing requirements.* **Progress: VCM market value quadrupled in a year** (2020–2021) from ~$500m to **~$2bn** + value of land expected to significantly increase as the GHG protocol (most widely used accounting standard) **pilot tests a land sector methodology**, increasing the standardisation, integrity + reducing the risk associated with NBS credits.
Cement	CCUS	Solution Development	**Low** (No clear feedback loop, driven by policy)	**Target:** Close price differential by [1] **de-risking private investment** (e.g., capital grants + tax breaks), [2] leveraging **public procurement to stimulate demand**, [3] **carbon pricing/ carbon border adjustment mechanisms**. **Progress:** Few positive signals but EU innovation fund is supporting first cement CCUS pilot + EU plans to integrate cement into the **carbon border adjustment mechanism from 2026**.	**Target:** Value chain collaboration to provide **voluntary demand signals** and increase **public awareness** + acceptance of CO2 storage. **Progress: First steps** taken via initiatives **e.g., Climate Group's 'Concrete Zero'** initiative with 17 members commiting to **procure 30% low-emission concrete by 2025 + 50% by 2030**.	**Target: Annual investment of $30 billion** + ~**10 major cement plants with CCUS** in operation by 2030, capturing ~0.3 Gt. CO2 per year. **Progress: Limited investment to date** but sector's **R&D budget targeting decarbonisation** – in 2021 cement companies spent $2.3 bn ~2x higher than 2015. **7 full-scale H2-DRI projects announced (in operation by 2030)** + 8 projects initially using natural gas-based DRI planning to switch to hydrogen + 2 planning to use H2-DRI and electric air furnace.

KEY TRANSITION RISKS AND OPPORTUNITIES

The transition to a low-carbon economy has the potential to create a more prosperous and just global economy on multiple fronts.

Clean energy offers an opportunity to expand the number of middle-income jobs around the world and reduce inequality. The IEA projects that the transition to clean energy would generate over 4x more new jobs by 2030 than would be lost in fossil fuel sectors.[110] In the US, recent evidence shows that clean energy jobs offer 10-20% higher wages than the national average and are widely available to workers without university degrees (accounting for 45% of current roles).[111] This has the added benefit of reducing the impacts of air pollution from burning fossil fuels, which is responsible for 1 every 5 deaths globally and disproportionally impact lower-income communities.[112,113] The shift away from a high-carbon economy can also reduce other harms to the environment and public health, including plastic pollution and biodiversity loss. Maximising the potential benefits of the transition calls for a focus on scaling low-carbon industries responsibly, for example by developing low-impact mining solutions, significantly increasing material circularity, and investing to enable employees of fossil industries a route into new jobs.

Critical mineral supply chain risk must be carefully managed to avoid bottlenecks in the deployment of many zero-carbon energy solutions. As the energy transition accelerates, the production of renewables, batteries, electrolysers, and power grids will lead to a substantial rise in demand for critical minerals, for example with li-ion demand set to increase ~7x by 2030.[114] There are sufficient reserves to meet the demands of the energy transition for all critical minerals (e.g., steel, cobalt, copper, nickel, li-ion). These have historically expanded in line with greater demand as rising prices have incentivised further exploration. The estimated global reserves of li-ion and nickel, for example, have doubled in recent years as electric vehicle adoption has increased.[115] However, reserves are often located in ecologically and socially sensitive areas (e.g., cobalt is highly concentrated in the DR Congo), meaning that potential exploitation in these sites requires considered assessment and mitigation of potential negative impacts. In addition, long project timescales (e.g., 15-20 years for copper mines) mean that expanding supply at the pace required for the transition could be a challenge without efforts to reduce these or other innovations.[116]

Improving material recovery and recycling systems will be crucial to ensure that supply keeps pace with rising demand and to manage resource intensity of the transition over the long-term. It will be crucial to create a much more effective recovery and recycling system to reduce demand growth as clean energy technology stock reaches end-of-life. This can be achieved with the right system of policies and incentives, and a build-out of logistics and infrastructure. If these are successfully introduced, this could lead to falling primary demand requirements by 2040s, mitigating many of the impacts from mining over the mid-to-long term.[117]

It will also be crucial to re-train the workforce for new jobs in the low-carbon transition to ensure skills shortages do not become a bottleneck and to ensure a just transition. It has been estimated that building towards net zero economies by 2030 stands to add over 35 million net new jobs globally, with growth in sectors like renewable power, energy-efficient buildings, local food economies and land restoration.[118] The new jobs generated by the transition to a zero-carbon economy considerably outnumber those that will be displaced as old industries decline. It will be crucial to support workers to move into growing industries to ensure the transition delivers on its opportunity to reduce inequality as well as emissions. Governments are beginning to demonstrate how a just transition can be assured. These strategies centre on investment in the development of new industries in regions where the economy has been most dependent on fossil fuel industries, workforce retraining and relocation support, and the provision of social safety nets.

CONCLUSION

TIPPING POINTS AND NET-ZERO

Action to bring forward in time the triggering of positive socio-economic tipping points will be critical to limit global temperature increases and will unlock new economic value.

We know from historical experience that the adoption of new solutions can increase dramatically when tipping points are crossed, such that incumbent solutions are replaced and decline at an accelerated pace. In addition, the strong reinforcing feedback loops that exist within and between sectors for zero-carbon solutions mean that tipping cascades can spread change rapidly across sectors and make it less reversible. A focus on joint international action to activate tipping points and cascades could have an outsized impact on global emissions and contribute materially to reducing the risks of dangerous climate change.

APPENDIX A

Historical examples

Infrastructure and energy systems

- **Canals** (US) – growth of canals in the United States as a percentage of their maximum network size from 1780 to 1850.
- **Railways** (US) – growth of railways in the United States as a percentage of their maximum network size from 1830 to 1940.
- **Telegraphs** (US) – growth of telegraphs in the United States as a percentage of their maximum network size from 1830 to 1950.
- **Oil pipelines** (US) – growth of oil pipelines in the United States as a percentage of their maximum network size from 1880 to 2000.
- **Roads** (US) – growth of roads in the United States as a percentage of their maximum network size from 1890 to 2000.
- **Shipping port infrastructure** (US) – calculated as a percentage adoption of port infrastructure in the US from 1964 to 1986.
- **Electric power** (US) – calculated as a percentage of American households with electric power from 1908 to 1989.
- **Gas for heating** (UK) – because coal and gas dominated the market during this time period, this figure calculated the share of gas as a percentage of coal and gas combined from 1946 to 1989.
- **Central heating** (US) – calculated as a percentage of American housing units with central heating installed between 1920 and 1970.

Manufactured goods

- **Flush toilet** (US) – calculated as a percentage of all American households with access to a flush toilet from 1860 to 1989.
- **Radial tyres** (US) – calculated as a proportion of cars with radial tyres compared to car output from 1972 to 1984.
- **Dishwasher** (US) – adoption rates of dishwashers in American households from 1948 to 2011.
- **Household refrigerator** (US) – calculated as a percentage of American households with a refrigerator from 1931 to 2017.
- **Refrigerator** (US) – diffusion rates of refrigerators in the US economy from 1925 to 1977.
- **Microwave** (US) – diffusion rates of microwaves in the US economy from 1980 to 2017.
- **Washing machine** (US) – calculated as a percentage of American households with a washing machine from 1930-2008.
- **Stove** (US) – calculated as a percentage of American households with a stove from 1900-2011.
- **Steamships** (UK) – because sail ships and steamships dominated the market during this time period, this figure calculated the share of steamships as a percentage of ships and steamships combined from 1815 to 1900.
- **Cars** (US) – because the alternative/incumbent was predominantly horses, this calculation determined the share of cars as a percentage of horses and cars combined from 1900 to 1980.
- **Steel** (UK) – because the alternative/incumbent was predominantly cast iron, this calculation determined the share of cars as a percentage of horses and cars combined from 1860 to 1947.

APPENDIX B

List of interactions between reinforcing feedback loops across sectors

Further research would be valuable to more thoroughly assess the strength and timing of each of these links and to identify other links. This could support the identification of further super-leverage points.

Initial Change	Effect – Positive Feedback Loop	Accelerated Tipping Point	Data Relevant to Strength of Link	Data Relevant to Time Delay of Link
Power: greater deployment of **solar and wind power + battery storage**	Learning curves/economies of scale drive lower **renewables + battery LCOE**	Light-Duty Road: bring forward **sticker price parity of EVs** vs. ICE vehicles	Battery pack costs represent 20-30% total EV production costs	**10-15 year** average car lifespan
		Heavy-Duty Road: reduce TCO of battery-**electric trucks** vs diesel trucks	Battery pack costs represent 20-30% total BET production costs, electricity costs 10-20% TCO	**15 year** average truck lifespan
		Buildings: reduce TCO of **heat pumps**	CAPEX key barrier, represents ~40% current TCO of heat pumps	**15 year** average gas boiler lifespan (but retrofits in existing buildings challenging)
		Steel: accelerate cost competitiveness of **scrap + electric arc furnace** production vs. conventional	Renewables account for ~40% of total investment requirement for net-zero trajectory in steel	**20 year** average lifespan for conventional steel plant
		Aviation: accelerate cost parity for **short-haul electric** vs. fossil jet fuel	~50% reduction in renewables LCOE required for cost parity	**15-20 year** average commercial aircraft lifespan
		Steel: accelerate cost parity for **green H2 DRI based steel** vs. conventional	Renewables account for ~40% of total investment requirement for net-zero trajectory in steel	**20 year** average lifespan for conventional steel plant
		Shipping: accelerate cost parity for **green ammonia** vs. heavy-fuel oil	Renewables account for ~50-75% of cost of green ammonia production	**20-30 year** average lifespan for cargo/container ships (but retrofitting possible)
		Aviation: accelerate cost parity for **PtL synfuels** vs. fossil jet fuel	Renewable electricity generation represent 60-70% PtL production costs	**~5 years** to build new SAF plants (drop-in fuel – limited retrofits required on existing aircraft)
		Fertiliser: accelerate cost parity for **green ammonia vs. nitrogen-based fertilisers**	Renewables account for ~50-75% of cost of green ammonia production	**5-10 years** to develop large-scale green ammonia production plant
Light-Duty Road: increase uptake of **battery electric vehicles**	Learning curves/economies of scale drive lower **battery storage costs**	Power: bring forward cost parity of **renewables + battery storage** vs. fossil-based generation (VRE grid pentration increases to 30-80%)	Majority of total installed battery capacity by 2030 projected to be for EVs + BETs (>80%)	**~5 years** to develop new solar, wind + battery power plants
		Power: increased demand for renewable generation supports **further deployment**	EV + BET electricity demand to increase 10x by 2030, accounting for ~15% total demand	**~5 years** to develop new solar, wind + battery power plants
		Heavy-Duty Road: increase uptake of **battery electric trucks**	Battery pack costs represent ~20% total BET production costs	**15 year** average truck lifespan
		Aviation: accelerate cost parity for **short-haul electric** vs. fossil jet fuel	4x increase in battery density required to reach 1000km range	**15-20 year** average commercial aircraft lifespan
		Shipping: accelerate cost parity for **short-haul electric** vs. heavy-fuel oil	4x decrease in battery density required to reach 1500km range	**20-30 year** average lifespan for cargo/container ships (but retrofitting possible)
Heavy-Duty Road: increase uptake of **battery electric trucks**	Learning curves/economies of scale drive lower **battery storage costs**	Power: bring forward cost parity of **renewables + battery storage** vs. fossil-based generation	Majority of total installed battery capacity by 2030 projected to be for EVs + BETs (>80%)	**~5 years** to develop new solar, wind + battery power plants
		Power: increased demand for renewable generation supports **further deployment**	EV + BET electricity demand to increase 10x by 2030, accounting for ~15% total demand	**~5 years** to develop new solar, wind + battery power plants
Light-Duty Road: increase uptake of **battery electric vehicles**	Learning curves/economies of scale drive lower **battery storage costs**	Power: battery capacity in electric vehicle fleet provides demand side response assets in power grid delivering **low-cost flexibility**, increasing penetration for solar/wind deployment	Provides significantly lower cost option for flexibility that dedicated battery storage for power	**10-15 year** average car lifespan
Heavy-Duty Road: increase uptake of **battery electric trucks**	Learning curves/economies of scale drive lower **battery storage costs**			**15 year** average truck lifespan
Industry: increased uptake of **batteries** for on-site power storage	Learning curves/economies of scale drive lower **battery storage costs**			Longer asset turnover times in industrial facilities
Fertilisers: increase **green ammonia** adoption	Learning curves/economies of scale drive lower **green H2 production costs**	Power: accelerate cost parity for **green H2 energy for seasonal balancing** vs. fossil fuels (e.g. gas peaker plants)	Green H2 to play limited role in power system, accounting for <5% generation	**10-15 years** to build H2 compatible power plants
		Steel: accelerate cost parity for **green H2 DRI based steel** vs. conventional	Green H2 price of $1.2-2.2/kg required for competitiveness (with carbon price or equivalent of $100/ton)	**20 year** average lifespan for conventional steel plant
		Shipping: accelerate cost parity for **green ammonia** vs. heavy-fuel oil	Green H2 price of <$1.6/kg required for competitiveness (with carbon price equivalent of <$100/ton)	**20-30 year** average lifespan for cargo/container ships (but retrofitting possible) + **bunkering/refuelling infrastructure**
		Aviation: accelerate cost parity for **hydrogen fuel cell aviation** vs. fossil jet fuel	Green H2 price of <$1/kg required for competitiveness (with carbon price equivalent of <$200/ton)	**15-20 year** average commercial aircraft lifespan
		Aviation: accelerate cost parity for **PtL synfuels** vs. fossil jet fuel	Green H2 price of <$1/kg required for competitiveness (with carbon price equivalent of >$200/ton)	**15-20 year** average commercial aircraft lifespan
Food & Agriculture: increase consumption of **alternative protein**s	Shift in **social norms** as early majority changes consumption patters	Avoiding Land Use Change: reduced demand for meat decreases **pressure on land**	~25% of emissions from livestock related to land use change (e.g. deforestation)	Potential to protect/restore natural land immediate

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Steel	n/a
Shipping	[15] RMI (2022), How the New Climate Bill Promises to Cut Inflation, Upgrade the Economy, and Slash Emissions; [16] European Parliament (2022) Sustainable maritime fuels – Fit for 55 package: the FuelEU Maritime Proposal [17] Global Maritime Forum (2022), Climate Action in Shipping – Progress Towards Shipping's 2030 Breakthrough
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