THE BREAKTHROUGH EFFECT:
HOW TO TRIGGER A CASCADE OF TIPPING POINTS TO ACCELERATE THE NET ZERO TRANSITION
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 redefines 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 has 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 1.5°C. 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 past 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 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 the 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. Soeeds, 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

"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

"The Breakthrough Effect report is essential reading for leaders in government and business and sets out clearly the positive tipping points we need to prioritize 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"
The Breakthrough Effect report was produced by Systemiq, in partnership with the University of Exeter, Simon Sharpe and the Bezos Earth Fund, and is a contribution to Systems Change Lab. The team that developed this report comprised: Mark Meldrum, Lloyd Pinnell, Katya Brennan, Mattia Romani (Systemiq), Simon Sharpe (Climate Champions team) and Tim Lenlon (University of Exeter).

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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 Bezas 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 a 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 those goals. 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. The company 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
Contact: communications@systemiq.earth

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 2020 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 Bezas Earth Fund, Systems Change Lab is supported by the UK Climate Change High-Level Champions and works with key partners and funders including Climate Action Tracker (a project of NewClimateInstitute 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
Contact: contact@systemschangelab.org

AUTHORS & ACKNOWLEDGEMENTS

The University of Exeter
Section 3: Tipping cascades

Super-leverage point 1: Mandating zero-emissions vehicles

Super-leverage point 2: Mandating green ammonia use in fertiliser production

Super-leverage point 3: Redirecting public procurement to promote the uptake of alternative proteins

Section 4: Key actions to bring forward tipping points

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

Key risks and opportunities

Conclusion: Tipping points and net-zero
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. 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. 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.

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).

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. 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. 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.

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.

Please see figure 1 in supporting text and appendix A for references.
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 zero-carbon fuels. In other sectors, such as 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. 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 incentivize 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.

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. 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).

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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 set to dominate projected demand for batteries, with estimates suggesting that electric vehicles will account for ~70% of total installed battery capacity in 2030. The potential for this tipping cascade.

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 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. This trend could in turn significantly reduce the cost of electricity from renewables + storage solutions, where battery costs account for ~30% of the total cost of power. 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). Since green ammonia can be shipped at relatively low-cost (only adding <10% to the delivered cost), 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;

2. 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 electrolyzers required to reduce green hydrogen prices to $1.5/kg H2 in locations with cheap renewable electricity. This could in turn help unlock tipping points in green ammonia use for shipping and green hydrogen use in steel production, which is already used in fertiliser production, thereby reducing pressure for land conversion.

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). 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%-20% (alongside other interventions), 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 7-18% of agricultural land today, 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.

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

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. For example, recent evidence suggests that if the 3 largest car markets were 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. 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, 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

<table>
<thead>
<tr>
<th>Sector</th>
<th>Emissions</th>
<th>Solution Focus</th>
<th>Current state</th>
<th>Tipping point to reach ‘mass market’ state and unlock S-curve adoption</th>
<th>Confidence in tipping point</th>
<th>Progress headline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>Solar + Wind + Storage</td>
<td>Niche/Mass Market</td>
<td>• Levelised cost of electricity (LCOE) of new solar/wind + battery storage is &lt;30c/kWh.</td>
<td>High: Strong learning effects + battery production economies of scale</td>
<td>Battery cost declines 90% from 2010, now of $1.36/MWh, and expected to reach $1/MWh by 2023. LCOE of solar + battery already below $3/MWh and expected to be cheaper than gas power in the US by 2023. Strong policy support in many countries requires 25-30% of generation by 2030. Some by &gt;50%. Shorter planning + permitting timelines (all EU countries exceed legal permitting time limits, some by &gt;5x).</td>
<td></td>
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<tr>
<td>Light-Duty Road</td>
<td>Battery Electric Vehicles (BEVs)</td>
<td>Niche/Mass Market</td>
<td>• Lower price of BEVs from price of internal combustion vehicles.</td>
<td>High: Battery production economies of scale + charging infrastructure network effects</td>
<td>Cost parity is expected by 2035-36 in leading markets (US, EU, China). Subsidies are closing the gap in some markets, e.g., US IRA with $7,500 purchase credit + $3,500 credit for existing BEVs.</td>
<td>Battery electric vehicles are not close to price parity for mid/long-haul routes in most regions, although price parity almost achieved in markets with supportive policy (e.g., Germany). Key barriers to public charging infrastructure at major transport hubs. However, policy support is growing with the EU setting a target for high-speed trucking charging every 40km on core TEN-T networks.</td>
</tr>
<tr>
<td>Heavy-Duty Road</td>
<td>Battery Electric Trucks (BETs)</td>
<td>Niche</td>
<td>• Total cost of ownership (TCO) of BEV + fuel + ICT trucks are lower than diesel + fuel.</td>
<td>High: Battery production economies of scale + charging infrastructure network effects</td>
<td>Medium: Learning-by-doing + scale economies in VRE + electrolyser costs</td>
<td>Electric heavy-duty trucks are not close to price parity for mid/long-haul routes in most regions, although price parity almost achieved in markets with supportive policy (e.g., Germany). Key barriers to public charging infrastructure at major transport hubs. However, policy support is growing with the EU setting a target for high-speed trucking charging every 40km on core TEN-T networks.</td>
</tr>
<tr>
<td>Building Heating</td>
<td>Heat Pumps (Residential/Commercial)</td>
<td>Niche</td>
<td>• Heat pump CapEx + installation cost (gas vs. gas boiler CapEx) is lower.</td>
<td>Low: Some limited evidence of economies of scale in production</td>
<td>Heat pump CapEx (~3c) higher than gas boilers. However, economies of scale transitioning into lowering costs (e.g., Germany, Sweden, UK, Italy). Adoption is 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 couples with other tenets).</td>
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</tr>
<tr>
<td>Fertiliser</td>
<td>Green Ammonia</td>
<td>Solution Development</td>
<td>• Green ammonia cost per ton less than grey ammonia for nitrogen-based fertilisers.</td>
<td>Medium: Learning-by-doing + scale economies in VRE + electrolyser costs</td>
<td>Companies are implementing plans for large-scale fertiliser production from green ammonia, with full investment decision (FID) reached for first major production facilities and multiple in feasibility stage. Policy support shifting to move market – EU ETS fertiliser sectors (~60% CO2 today) + India is preparing domestic production targets.</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>Green Hydrogen (BH)</td>
<td>Solution Development</td>
<td>• Cost per ton of steel produced using green-H2 BH less than steel from fossil-based production (i.e., follow furnace-based oxygen technology, no CO2 emissions).</td>
<td>Medium: Learning-by-doing + scale economies in VRE + electrolyser costs</td>
<td>11 full-scale plants planned to be operational by 2030, relative to c. 400 fossil-based steel plants globally. Need to ramp up scale of R&amp;D. 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 2024.</td>
<td></td>
</tr>
<tr>
<td>Shipping</td>
<td>Green Ammonia</td>
<td>Solution Development</td>
<td>• Green ammonia fuel cost per ton less than fossil-based shipping fuel.</td>
<td>Medium: Learning-by-doing + scale economies in VRE + electrolyser costs</td>
<td>Clydebank declaration committed to support the development of at least 4 green corridors within this decade &amp; 9 more corridors committed to provide green hydrogen in which the EU is a major consumer and can thus benefit from the use of hydrogen for other purposes (e.g., agriculture, commodities, etc.). Large scale potential exists for hydrogen demand in other regions.</td>
<td>Whole supply chain is transitioning to green hydrogen, with production facilities in leading markets (US, Europe) and multiple more in feasibility stage. Policy support is crucial to move market – fuel carbon price or equivalent subsidy (~$100/tCO2 expected in 2024).</td>
</tr>
<tr>
<td>Aviation</td>
<td>Power to Liquid Fuels</td>
<td>Solution Development</td>
<td>• [F1]: total cost of ownership of electric plane (gas vs. fuel) [fuel: jet fuel jet fuel].</td>
<td>Medium: Learning-by-doing + scale economies in VRE + electrolyser costs</td>
<td>Production of Pt fuels remains at demonstration stage but proposed EU blending mandate (~2% of total fuel use from Pt by 2050) can drive initial scale that supports cost declines. Not major policy support emerging (e.g., US, China).可持续航空煤油价格, but lower cost premium remains: 3-9x more expensive than fossil jet fuel at present.</td>
<td></td>
</tr>
<tr>
<td>Food &amp; Agriculture</td>
<td>Alternative Proteins</td>
<td>Niche</td>
<td>• Cost of plant-based proteins less than meat products.</td>
<td>Medium: Scale-economies + economies of scale</td>
<td>Alternative proteins projected to reach ~10% of market share by 2025 (e.g., Technological innovation and policy could push to ~20%. Rapid upslope by early adopters in some regions (e.g., US, EU) with 5-7x price premium by 2025.</td>
<td>Production of Pt fuels remains at demonstration stage but proposed EU blending mandate (~2% of total fuel use from Pt by 2050) can drive initial scale that supports cost declines. Not major policy support emerging (e.g., US, China). Sustainable Aviation Fuel tax credits), but large cost premium remains: 3-9x more expensive than fossil jet fuel at present.</td>
</tr>
<tr>
<td>Avoiding Land Use Change</td>
<td>Volatile Nature-Based Solutions (VNB)</td>
<td>Niche</td>
<td>• Value of preserving land (e.g., through sales of nature-based carbon credits and other ecosystem services equivalent to ~$200/tCO2).</td>
<td>Low: Requires strong + continual regulations</td>
<td>Policy supports nature-based solutions can provide high returns. The EU has set an ambitious target of a 50% reduction in net deforestation by 2030, leveraging the potential of a suite of nature-based solutions (NBS). To address the EU’s 2030 climate target, a number of initiatives are being developed to support the deployment of NBS on a large scale.</td>
<td>Policy supports nature-based solutions can provide high returns. The EU has set an ambitious target of a 50% reduction in net deforestation by 2030, leveraging the potential of a suite of nature-based solutions (NBS). To address the EU’s 2030 climate target, a number of initiatives are being developed to support the deployment of NBS on a large scale.</td>
</tr>
<tr>
<td>Cement</td>
<td>CCUS</td>
<td>Solution Development</td>
<td>N/A</td>
<td>Low: No clear feedback loop, driven by policy</td>
<td>Positive feedback loop from the required level of investment and policy support – but some initial signs of progress on R&amp;D investment.</td>
<td></td>
</tr>
<tr>
<td>Chemicals</td>
<td>CO2/Green Hydrogen</td>
<td>Solution Development</td>
<td>N/A</td>
<td>Low: No clear feedback loop, driven by policy</td>
<td>Range of solutions depending on type of chemical – limited progress to date towards large-scale decarbonisation.</td>
<td></td>
</tr>
</tbody>
</table>
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

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. 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.

**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.

**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.
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 of 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.

![Image of a car]

**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:

- **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.
- **Network and coordination effects:** Where 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).
Incident 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. Further, companies in industries that shift into decline can see sharp financial devaluations as investors shift away, increasing the cost of capital.

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. 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. The number of new patents issued relating to fossil fuel technologies has fallen almost 20% since 2015, which could be one such example. 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%. Further work is required to identify these leading indicators to help identify signals of potentially imminent tipping points.

Further, companies in industries that shift into decline can see sharp financial devaluations as investors shift away, increasing the cost of capital.

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.

System change drivers

• Policy Support
• Market Development
• Buyer Preferences

The Breakthrough Effect
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. This has made renewable energy more competitive against fossil fuels, helping to close stranded asset risks for fossil fuels, and opening up stranded opportunities for alternative protein (displaces animal protein), precision agriculture (reduces fertilizer emissions), and growing cold chain storage capacity (reduces food losses and waste). Conversely, the cost of power from fossil fuels costs has remained broadly flat 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 energy transition proceeds, renewables are increasingly allowing for the bespoke synthesis of bio-pesticides.

Most projections have systematically underestimated the rate of cost reductions for these technologies, due primarily to an under-appreciation 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. Short-term factors such as supply chain bottlenecks can disrupt this trend, as seen with the 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.

Solar and Wind: These have now become the cheapest source of new bulk power in countries representing 90% of electricity generation. 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.

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. 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.

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 480 large-scale hydrogen project proposals now in place. 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.

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 fertilizer emissions), and growing cold chain storage capacity (reduces food loss and waste). 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. The cost per megabase of DNA sequencing has fallen by a factor of 100,000 since the year 2000. 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.

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 hydropower vs. renewable developments has widened by >10% over the last 5 years, equivalent to a global carbon tax of $80/ton CO₂. 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.

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, wind power LCOEs reaching parity with those of new gas fired power plants).

The Breakthrough Effect
Figure 4:  
Solar and wind – learning curves

Historical and projected LCOE vs. installed capacity for solar

Learning Rate: 34%

Installed Capacity (right axis)  LCOE  Tipping Point Range

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

Learning Rate: 23%

Installed Capacity  LCOE  Tipping Point Range

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%

Installed Capacity  Battery Pack Price  Tipping Point Range

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

Learning Rate: 18%

Installed Capacity  Capital Cost  Tipping Point Range

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); [4] (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.
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. 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 by 2-3 years. 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 by 2-3 years.

However, battery prices increased by 7% in 2022 as the result of higher material prices, especially in the case of li-ion. BloombergNEF predicts that if prices remain high for an extended period, this may slow the learning rate for li-ion batteries from 19% to 14%, 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. 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 <32/$kg, which is feasible before 2030 in favourable locations with cost renewables, as at this level green hydrogen becomes competitive with blue and some grey sources of hydrogen production. 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 off-take 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 in residential homes, 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 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.

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 14%, 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 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 about 40% and 60% of total space and water heating in advanced and emerging/developing economies, respectively.

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.

72 The Breakthrough Effect
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. 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. 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. 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.

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%. 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.
New CCGT

Existing CCGT

LCOE projections for solar PV + battery storage vs. current LCOE range for unsubsidised combined cycle gas-fired turbine; existing CCGT refers to marginal cost of operating fully depreciated plant.

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 unconstrained combined cycle gas-fired turbine, existing CCGT refers to marginal cost of operating fully depreciated plant.

Sources:


Solution status

Solutions for 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 (it is Europe). [8] 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/year, driven primarily by growth in China and the US. Latest forecasts expect there to be just over 40 GW installed globally by 2030 under current trends, compared to 585 GW required for net-zero alignment. [9]

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

Note:

LCOE – levelized cost energy. [3] 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 30 MW capacity; range shows moderate scenario minimum and maximum based on resources class by average capacity factor (from 20% to 33%). [4] LCOE for new combined cycle gas-turbine (CCGT) shows current global average benchmark range for unconstrained combined cycle gas-fired turbine, existing CCGT refers to marginal cost of operating fully depreciated plant.

Sources:


Confidence in existence of reinforcing feedback loops

- Learning curves & economies of scale: as solar/wind/batteries are deployed, we experience strong cost reductions (35%, 25% /19% respectively per doubling of output); lower costs in turn encourage more deployment.
- Not critical issue – batteries are highly effective at providing ancillary services to the grid. However, the complement of solutions 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.
- 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.
- In US, average utility scale power projects spend in interconnection queues doubled from 2010 to 4 years in 2021 – with 1.4 TW currently awaiting connection approval.

Target conditions to trigger tipping point

- 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 <$35/MWh)
- 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

Progress*:

- LCOE for solar/wind + battery storage (4-hour) tracking towards cost parity with new coal/gas by 2025 (US example), now at $55/MWh (range of $45-75/MWh by location)
- In US, IRA support pulls this further forward by providing tax credits of $35/kWh for battery cells and $10/kWh for modules
- Comparing only “peaking” assets; utility scale 4-hour battery storage global average LCOE marginally lower than gas peaker plants in 2021 at ~$150/MWh
- Not critical issue – batteries are highly effective at providing ancillary services to the grid, also a complement of solutions 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.
- 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. $1000bn p.a. by 2025 to support the pace of new connections for renewables at the expected timing of the tipping point and rise to ~$800bn by 2030 as adoption scales on the S-curve
- More research required to understand requirements by region and year

Accessiblity

- 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.
- In US, average utility scale power projects spend in interconnection queues doubled from 2010 to 4 years in 2021 – with 1.4 TW currently awaiting connection approval.
Tipping point
• Tipping point likely when BEV* hit sticker price parity with ICE vehicles. Greater deployment drives scale economies in battery production, further increasing cost advantages.
• Charging infrastructure roll-out key to overcome range anxiety and trigger coordination effects – 3x fast chargers per 1,000 electric vehicles key first step – more research required to understand size of effect.

Confidence in existence of reinforcing feedback loops
• Learning curves & economies of scale: as more BEVs are deployed, we experience 1.9% cost reduction per doubling of output; lower costs encourage greater deployment2
• Network effects: increase in charging infrastructure makes it easier to adopt BEVs, which encourages more charging infrastructure to be developed2

Target condition to trigger tipping point
• 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.

Forecast pre-tax retail prices for passenger vehicles by region*4,5

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

Sources:
Total cost of ownership for BETs vs. diesel trucks by region – long-haul

- 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).4
- 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).5 – more research required to understand potential for similar steps to bring forward cost parity in other regions.

Cost parity

BETs* remain in the early stage of adoption, representing 0.3% of total sales globally in 2021 (approx. 10,000 units sold).1, but are showing promising signs in some regions with leading companies starting to deploy these at scale1. 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%.2

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-charging6.

BETs* already at or near TCO cost parity with diesel trucks in regional and long-haul segments across key regions (EU, US, China, India) – at ~$0.5/pk km (currently 2-3x higher)7.

Sicker piece less important factor but support required in short-term to overcome high up-front costs (BETs currently ~3x diesel trucks pre-tax retail price).8

• Other measures will also be important for reducing total energy demand growth, including most importantly (a) encouraging 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

- Sector context

- The main pathway to decarbonising trucking will be 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.3

- 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 effect1 – more research required to understand size of effect.

- Confidence in existence of reinforcing feedback loops

- Learning curves & economies of scale: as more batteries are produced, we experience 19% cost reduction per doubling of output; lower costs encourage greater deployment1.
- Network effects: increase in charging infrastructure makes it easier to adopt BETs, which encourages more charging infrastructure to be developed.

- Target conditions to trigger tipping point

- Achieve TCO advantage for BETs vs diesel trucks in regions and long-haul segments across key regions (EU, US, China, India) – at ~$0.5/pk km (currently 2-3x higher).

- Sicker piece less important factor but support required in short-term to overcome high up-front costs (BETs currently ~3x diesel trucks pre-tax retail price).8

- 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).9

- 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.

- ACCESSIBILITY

- 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 CO2). Attractiveness: 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 (~2.5-3.5 million) and overnight depot (500,000-750,000).


SECTOR TIPPING POINT
BUILDING HEATING: HEAT PUMPS (RESIDENTIAL RETROFITS)

6% of total global GHG emissions

Section context

- Residential space heating accounts for the majority of building heating demand1. Residential buildings are inherently more decentralised than commercial buildings, meaning that the low-carbon transition relies on the decisions of a larger set of agents. 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 vary 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 today2. Low-carbon heating solutions must be implemented in parallel with levers to reduce demand (e.g., building fabric improvements). 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% respectively3.

- 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 3-4 less energy to deliver the same amount of heat as gas boilers require4.

Solution status

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

- Highest adoption in Norway, Sweden and Canada but fastest sales growth in Europe (33% growth in 2021 vs. 2020 year on year), US (15%), China and Japan (13%)5.

- Heat pumps (HPs) have replaced ~20% of boilers in Europe6.

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 of implementation 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:

Confidence in existence of reinforcing feedback loops

- 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. 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

- 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)7 vs. $4k (US) vs. €6–7.5k (EU)8 – 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.

- Yearly average efficiency (COP9) of >3 required for lower OpEx vs. gas boilers. A COP 3, HPs deliver 3 units of heat (kWth) for every 1 unit of electrical energy (kW) required to run the heat pump.

- Overcome installation time disadvantage + other practical challenges (e.g., changing radiators + legal challenges for shared buildings).

- HPs combined with heat storage systems (e.g., water tank) to smooth electrical load demands, reducing peak electricity demand from heating.

- Scale building energy efficiency retrofits to reduce domestic heat load and reduce volume of heat required, and thus ability for heat pumps to meet heating needs.

- Reskill + expand the workforce with accessible training facilities.

Progress*

- HP lifetime costs are cheaper than gas boilers in several countries (due to lower OpEx), but CapEx + installation still multiple times more expensive(UK - 1.7-1.3x, EU - 0.8-1x, US - 14x).9

- 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.

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 $20 per ton of CO2). Accessibility: green – no barrier to tipping point, amber – point but strong progress underway, red – currently impeding tipping point with limited progress to date. *CO2 of operation is performance of the ratio of heat generated from energy (kWh) required to run the heat pump.

Sources:
Projected cost per ton grey vs. green ammonia for fertiliser production

Cost Parity: requires green hydrogen price of $2.2/kg
$100/ton CO2 or equivalent subsidy

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<td>800</td>
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</tbody>
</table>

Note: * Last 10 years from 2011 to 2020 excluding 2021 and 2022 due to energy price spikes
** 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.
*** The point at which a technology is considered to reach maturity is the year in which it is estimated to reach 1% of 2050 GHG emissions.


The Breakthrough Effect
Steel production from green hydrogen DRI: Levelized cost of steel production from new continental blast furnace green hydrogen DRI steel:

**Solution status**

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).

**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. For example, scrap contribution to total steel expected to increase from 3% today to 45% by 2050.
- Given the large scale of existing infrastructure and infrastructure 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 2030.

**Levelized cost of steel production from new continental blast furnace vs. hydrogen DRI**

**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 the traditional blast furnace is replaced with DRI production (using green hydrogen) followed by a melter. Assumes utility scale dedicated renewables for hydrogen learning effects and economies of scale, which could drive S-curve outcomes.

**Confidence in existence of reinforcing feedback loops**

<table>
<thead>
<tr>
<th>Tipping point</th>
<th>Progress*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning curves &amp; economies of scale: as more electrolyser are deployed, we experience 18% cost reduction per doubling of output, and lower costs encourage greater deployment</td>
<td></td>
</tr>
<tr>
<td>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 equivalent form of support</td>
<td></td>
</tr>
</tbody>
</table>

**Target conditions to trigger tipping point**

- In absence of carbon price, green H2 DRI based steel 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)

**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/tCO2). Affordability + accessibility: green – no barrier to tipping point, amber – currently impending tipping point but strong progress underway, red – currently impending tipping point with limited progress to date. **(2)** 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.


**Note:** Absolute: green – zero carbon production, amber – pathway to green production (incl. policy support measures equivalent to $100/tCO2). Access to green hydrogen: amber – no barrier to tipping point, green – currently impending tipping point but strong progress underway, red – currently impending tipping point with limited progress to date. **(2)** 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.

Heavy Fuel Oil

Projected cost per ton green ammonia for shipping vs. heavy fuel oil

<table>
<thead>
<tr>
<th>Year</th>
<th>Historical average*</th>
<th>Historical range*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>2025</td>
<td>1,000</td>
<td>500</td>
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<tr>
<td>2030</td>
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<td>2050</td>
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</tbody>
</table>

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

Sources: (1) Energy Transition Commission (2020), The Petri Wave: A Blueprint for Commercial-Scale Zero-Emission Shipping Pitches, Final Report for the Getting to Zero Coalition; (2) IHS Markit (2020), A Strategy for the Transition to Zero-Emission Shipping, Special Report for the Getting to Zero Coalition; (3) IHS Markit and UN Climate Change High Level Champions (September 2021), Climate Action in Shipping – Progress Towards Shipping’s 2030 Breakthrough; (4) Making Mission Possible (2022); (5) 1.5-Aligned Ammonia Possible; (6) Data.

**Cost Parity:** requires green hydrogen price of $1.6/kg + $100/ton carbon price or equivalent subsidy

- Heavy Fuel Oil
- Carbon Price or Equivalent ($100/ton CO2)
- Green Ammonia (adjusted to volumes equivalent to 1 ton HFO)

- 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 +$1.4/kg H2 + carbon price or equivalent subsidy of ~$100/ton CO2

- 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

- Total cost of ownership of green ammonia powered container vessel expected to be ~70% higher than conventional equivalent in 2030 based on current trends
- 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 $1.4/kg

- 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)
- Recent announcements indicate retrofitting LNG ships to run on ammonia feasible by 2023

- 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
- 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 >15Y away (incl. policy support measures equivalent to ~$100/ton CO2). Accessibility: green – no barrier to bigger port, amber – currently impeding tipping point but strong progress underway, red – currently impeding tipping point with limited progress to date.

Sources: (1) REN A (2020), Green Hydrogen Cost Reduction: Scaling Up Electrolysers to meet the 1.5°C Climate Goal; (2) Making Mission Possible (2022); (3) 1.5-Aligned Ammonia Possible; (4) Maersk-McKinnon Moller Center for Zero Carbon Shipping (October 2021), Industry Transition Strategy; (5) Global Maritime Forum (2022), Mapping of Zero Emission Pitches and Demonstration Projects, Getting to Zero Coalition; (6) Getting to Zero Coalition (December 2021). A Strategy for the Transition to Zero-Emission Shipping; (4) Ammonia Energy Association (August 2022).
**Power-to-liquid production costs vs. fossil jet fuel prices**

- **Range of PtL costs (lower costs in regions with cheaper renewable power)**
- **Historical range**
- **Historical average**

**Multiple of Fossil Jet Fuel Price**

- **2020**
- **2025**
- **2030**
- **2035**
- **2040**
- **2045**
- **2050**

**Cost Parity:** requires green hydrogen price of $1/kg + $200/ton carbon price or equivalent subsidy

- **Average Jet Fuel Price + $200/ton CO2 Carbon Price or Equivalent Subsidy**

**Note:**
- *Range shows historical fossil jet fuel price (average over past two decades: $600–$650/t and historical fluctuations over past two decades: $135–$1,350/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 1,000 km and 2,500 km respectively. (3) This may increase if technological innovation + airframe redesign 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:**
- [2] ICAO – Tracker of SAF Offtake Agreements
- [3] IRENA (2020), Green Hydrogen Cost Reduction: Scaling Up Electrolysers to meet the 1.5°C Climate Goal

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**Tipping point**

- **Target conditions to trigger tipping point**
- **Progress**

**Affordability**

- **Niche: Current blending limit of 50% in existing jet engines (PtL – fossil jet fuel)**
- **Blending limit is expected to be lifted by 2030, the latest, with first engines already 100% SAF- compatible by 2025**
- **PtL significantly reduces production of contrails vs. fossil jet fuel – likely responsible for 2/3 of aviation’s total climate impact**

**Accessibility**

- **Niche: Limited additional downstream infrastructure needed – PtL can be blended into existing refuelling infrastructure at airports**
- **Mass Market: PtL production (e.g., biogenic or direct air capture)**
- **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). Attraciveness – 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 (2022), Green Hydrogen Cost Reduction: Scaling Up Electrolysers to meet the 1.5°C Climate Goal
**Sector context**
- A portfolio of solutions will be required across the food + agriculture sector to decarbonize the value chain in order to decarbonize agriculture.
- 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-curves outcomes. More research required to determine whether other solutions in this sector have the potential for S-curve outcomes e.g., regenerative agriculture.
- Three APIs 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)**.
- This content will focus on the nearest tipping point (PB protein) which may trigger acceleration in the parity of the other 2 key APIs as these share some common technologies with PB protein (e.g., extrusion and extrudable fat technologies).

**Solution status**
Globally, the solution is a niche market with APIs accounting for 2% of the animal protein market in 2020**. 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)**
- US sales increased by 72% (vs. 2019)**. 3x faster than total food sales**.
- China’s PB market ($91bn) was greater than the US’s ($84bn) in 2018 – forecast to grow 20-25% p.a.

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

BCC analysis finds APIs are on track to reach ~10% market share by 2035 but policy and technological step changes could drive adoption to ~20%**.

More research required to determine global adoption potential of PB foods.

**Projected cost of alternative proteins vs. conventional animal-based proteins**

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**Notes:**
- **“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 SECTOR TIPPING POINT framework.”**
- **“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 SECTOR TIPPING POINT framework.”**
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- **“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 SECTOR TIPPING POINT framework.”**

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**Sources:**
- [3] BCC (2021), *Food for Thought: The Protein Transformation*
- [4] European Commission (2021), *Europe’s First-Based Food Industry Shows Record-Level Growth*
- [6] Good Food Institute (2021), *Plant-based Source Gains World-Based Focus*
- [13] ProVeg International (2022), *How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products*
- [14] ProVeg International (2022), *How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products*
- [15] ProVeg International (2022), *How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products*
- [16] ProVeg International (2022), *How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products*
- [17] ProVeg International (2022), *How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products*
- [18] ProVeg International (2022), *How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products*
- [19] ProVeg International (2022), *How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products*
- [20] ProVeg International (2022), *How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products*
- [21] ProVeg International (2022), *How Lidl Became a One-Stop-Shop for Mainstream Consumers Buying Plant-Based Products*
AVOIDING LAND USE CHANGE: VALUING NATURE-BASED SOLUTIONS*

Solution status

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. 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, addiionality, 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 vs. carbon price for avoided deforestation

\[
\text{Deforestation Cost vs. Carbon Price} = \frac{\text{Deforestation Cost}}{\text{Carbon Price}}
\]

Confidence in existence of reinforcing feedback loops

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

Target conditions to trigger tipping point

- 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) More liquid market paying for avoiding land use change – (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/finances on buyers to reduce demand. More research required to understand key cost-related factors for land holders.
- Nature-based carbon credit buyer: N/A

Progress**

- Land holder: a) Higher market liquidity, with a >2x increase of nature-based carbon credits in the VCM; increasing examples of governments paying for ecosystem services as public goods.
  However, NBS only receives ~2% of total climate finance. To date, this has not generated sufficient revenues to ensure that 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.
  c) Price paid for nature-based carbon credits is still 1/3rd of price paid for AFOLU commodities on the international market.

More research required to determine required prices + climate finance to outweigh benefits of converting land.
- Nature-based carbon credit buyer: N/A

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, addiionality) and transparency to enable buyers to make credible reduction claims and reduce risk exposure, e.g., through the scaling of rating agencies + improved policies/regulations on corporate and government emissions reduction.
  1 SC alignment to enhance benefits of buying from the carbon markets + reduce appeal/feasibility of deforestation-linked production.

Note: *Nature-based solutions cover forests, coastal wetlands and peatlands. **AFOLU has been split into two categories with land use’s 10% share addressed in the Food + Agriculture sector tipping point. 

SECTOR TIPPING POINT

AVOIDING LAND USE CHANGE: VALUING NATURE-BASED SOLUTIONS*

Sector context

- To align with a 1.5-degree scenario globally, the land use sector will require both emissions reduction and carbon removal activities. The focus is on an 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 + degradation of coastal wetlands + peatland.
- This deep-dive focuses on deforestation, forests, peatlands and coastal wetlands because they are the world’s primary carbon sinks and stores.1,2
- 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 90-95% of tropical deforestation cases; 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 see be covered (e.g., payments for ecosystem services + ecosystem restoration, 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).

* (NBS) to solutions

• 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 90-95% of tropical deforestation cases; 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 see be covered (e.g., payments for ecosystem services + ecosystem restoration, 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).

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.

Orange text indicates uncertainties that require further investigation

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, addiionality, 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).
**ENABLING ENVIRONMENT**

- **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 curated to reduce relative appeal for land holders.

- **Nature-based carbon credit buyer:** Mature networks of trading, rating, and insurance companies offering solutions (e.g., standardized contracts) to facilitate scaled demand. Geospatial intelligence is widespread and 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. However, these only reach a fraction of land holders engaging in carbon markets; generally not accessible.

- **Nature-based carbon credit:** Increasing number of companies involved in trading, rating + insurance improving liquidity, processing time + implementing more effective products, e.g., standardized contracts.

- **Recent advances in forest monitoring (e.g., Sylvera + ctrees) 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 + more research required to understand application potential.

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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:**
SECTION 3  
TIPPING CASCADES

Super-leverage point 1: Mandating zero-emissions vehicles  
Super-leverage point 2: Mandating green ammonia use in fertilizer production  
Super-leverage point 3: Redirecting public procurement to promote the uptake of alternative proteins

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 electrolyzers 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.

These links create the possibility of tipping cascades, where crossing a tipping point in one sector accelerates progress towards tipping points in other sectors. This can happen by way of a shared technology such as hydrogen electrolyzers 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 discontinuous. 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. 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.

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. 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.

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

81 See 10 sector covered in sector slides above for reference.

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

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.
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 (60% more than expected under current trends). 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. 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 cost declines 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. Green ammonia can be shipped at a relatively low-cost (only adding <10% to the delivered cost) 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 adapt 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.

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.

Mandates for green ammonia use in fertiliser production should be considered in union 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). 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 disproportionately affect the most vulnerable populations who spend upward of 60% of their income on food.

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 electrolyser production, which would reduce capital costs by ~70% given current learning rates. This could unlock $1.5/kg green hydrogen costs if accompanied by continued falls in the cost of clean electricity—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).

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. For example, public institutions spend GBP 2.4 billion (USD 2.9 billion) on food annually in the UK alone, sufficient to have a material impact on plant-based protein market value, estimated at USD ~30 billion annually worldwide. 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. 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’ projectable market share in 2035 from ~10% to ~20%, 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. 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. 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 up to 90% fewer emissions than meat (including animal and associated land use emissions), reaching this level of adoption would result in an approx. 0.85-2.2 Gt cumulative of emissions savings by 2050.

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.

92 $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, fuels, synthetic jet fuel, methanol). Hydrogen itself does not transport economically, and this end-use that requires hydrogen gas (e.g., H2-trucks, refineries) will produce hydrogen locally, at local costs of hydrogen production based on local renewables resources.
Figure 5: Super-leverage points and tipping cascades

Greater battery/powertrain deployment in cars reduces cost for trucks & vice versa + shared charging infrastructure

SLP 1. MANDATING ZERO-EMISSION VEHICLES

Heavy-Duty Road: Electric Trucks 3%
- Cumulative deployment
- Battery prices + vehicle costs

Light-Duty Road: Electric Vehicles 9%
- Cumulative deployment
- Battery prices, vehicle + operation costs

Power: Solar, Wind + Storage 26%
- Cumulative deployment
- Cost of renewable energy + storage

Building Heating: Heat Pumps 6%
- Cumulative deployment
- Production, installation & capital + operation costs

SLP 2. MANDATING GREEN AMMONIA USE IN FERTILISER PRODUCTION

Fertiliser: Green Ammonia 2%
- Green H2 production costs
- Cumulative deployment

Agriculture: Alternative Proteins 13%
- Adoption rates
- Production costs and quality + consumer preference

Land Use: Nature-Based Solutions 10%
- Demand for land
- Value of land protection relative to value of land conversion

SLP 3. REDIRECTING PUBLIC PROCUREMENT TO PROMOTE THE UPTAKE OF ALTERNATIVE PROTEINS

Steel: Green Hydrogen DRI 7%
- Green H2 production costs
- Cumulative deployment

Aviation: Power-to-Liquids Fuels 2%
- Green H2 production costs
- Cumulative deployment

Key
- Transport
- Energy
- Industry
- Food and Land Use
- Buildings
- Reinforcing feedback loop
- Share of current global emissions by sector
- Super-leverage points

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

Cumulative installed electrolyser capacity vs. green hydrogen production cost

- Cost parity for green hydrogen-based production vs. fossil-based production

- Fossil-based fertiliser production: $2.2/kg
- Fossil-based shipping fuel: $1.6/kg
- Fossil-based steel production: $1.2/kg

Total Sector Demand
- Fertiliser: ~30 Mt. H2
- Shipping Fuel: ~140 Mt. H2
- Steel: ~90 Mt. H2
- Aviation: ~100 Mt. H2

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.

SECTION 4

KEY ACTIONS TO BRING FORWARD TIPPING POINTS

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

Key risks and opportunities

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. 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:104

- **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.
  - E.g., First mover coalition supporting development of green ammonia in shipping corridors.

- **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., US inflation reduction act provides green hydrogen credit of $3/kg H2 making green steel cost competitive in US.

- **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., early retirement of coal plants (Europe, USA).

- **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.

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

<table>
<thead>
<tr>
<th>Sector</th>
<th>Solution</th>
<th>Current state</th>
<th>Confidence in tipping point</th>
<th>Policy Support</th>
<th>Buyer Preferences</th>
<th>Market Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>Scale Wind + Storage</td>
<td>Niche / Major Market</td>
<td>High (Strong learning effect)</td>
<td>Target: Key short-term interventions: [1] power market relaxations (e.g. roll out of capacity markets); [2] reducing permitting and regulatory delays, particularly for transmission &amp; distribution, reduction in costs and auctioning and proper interconnection services. Progress: Permits being amended or other key barriers: e.g. all EU countries except the 2020-2021 permits; some by more than 1x (UK) or legislative action underway or plan.</td>
<td>Target: N/A – not the key driver of capacity additions (predominantly independent on policy); however, corporate purchase agreements can contribute to driving down production costs (e.g. Google, Apple, Facebook)</td>
<td>Target: Cumulative deployment of 400 GW battery storage in next decade needed to drive 50% reduction in production costs via learning curves economies of scale. Progress: Global battery storage investment expected to double in 2022 to $18.4bn but still 65% below net-zero trajectory requirement.</td>
</tr>
<tr>
<td>Light-Duty Road</td>
<td>Battery Electric Vehicles (BEV)</td>
<td>Niche</td>
<td>High (favorable production economies of scale + changing infrastructure network effect)</td>
<td>Target: [1] implement closer pricearker subsidies (e.g. purchase subsidies + tax breaks) (e.g. refer to [2], support for build-out of long-term charging networks) [3] accelerate deployment of VRE + electrolyser (e.g. to support for build-out of long-term charging networks) [4] in grid-connected battery storage, particularly in regions with low P2G potential (e.g. Asia) Progress: Demonstrate value in grid-connected battery storage, particularly in regions with low P2G potential (e.g. Asia)</td>
<td>Target: Clear market signal and voluntary demand partnerships targeting 100% by 2050</td>
<td>Progress: Volume of leading companies driving demand via process compliance partnerships: [1] 2020: 2/2; [2] 2020–2021: 1/4; [3] 2021–2022: 1/4; [4] 2022: 1/4, but committed to switching fuels to EVs and/or initial charging for staff/customers by 2023.</td>
</tr>
<tr>
<td>Rail</td>
<td>Green-Ammonia</td>
<td>Solution Development (medium-low to high viability: Niche to low viability: Niche)</td>
<td>High (favorable production economies of scale + changing infrastructure network effect)</td>
<td>Target: De-risk private investment for first-of-a-kind (FOAK) production facilities (e.g. grants, bonds, CBILS, CCUS) (e.g. Chinese, EU) (e.g. increasing competitiveness (e.g. carbon pricing + blending, mandated); [3] implement certification schemes to encourage sustainable production (e.g. for sustainable production output with carbon offset). Progress: Positive early stage signals wih [1] direct investment on projects (e.g. $1bn for H发生在 + Europe) and [2] Defra’s Hydrogen strategy (demand green hydrogen for rail freight by 2024/2025 + 2030/2035); [2] H2EQ requiring 45% emission reductions for hydrogen for rail freight.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>Green Hydrogen G2</td>
<td>Medium (learning-by-doing factor + scale economies of scope + changing infrastructure network effect)</td>
<td>Medium</td>
<td>Target: Continue to [1] move forward purchasing green steel from H2-2030 (at 20%+). Progress: Positive sign in 2021 (e.g. automotive firms see carbon neutrality goals (e.g. Mercedes-Benz with DAX to source H2-DRM) [2] steel) and (3) H2-based steelmaking initiatives increasing green hydrogen for steel.</td>
<td>Target: Cost to reach 2030 of +30% in cost (e.g. H2-2030). Progress: H2Eqs requiring 45% emission reductions for hydrogen for rail freight.</td>
<td></td>
</tr>
<tr>
<td>Shipping</td>
<td>Green-Ammonia</td>
<td>Solution Development (medium-low to high viability: Niche to low viability: Niche)</td>
<td>High (cost savings + carbon price)</td>
<td>Target: De-risk private investment in production facilities (e.g. CL5 CCM) (e.g. CCM + low carbon policy) (medium-low to high viability: Niche to low viability: Niche)</td>
<td>Target: H/A - impact on consumer prices not major barrier if policy support in place</td>
<td>Progress: Opportunities to integrate green hydrogen into shipping sector by 2030 to reduce ship emissions.</td>
</tr>
<tr>
<td>Aviation</td>
<td>Power-to-Liquids Fuels</td>
<td>Medium (learning-by-doing factor + scale economies of scope + changing infrastructure network effect)</td>
<td>Medium</td>
<td>Target: Reduce cost differential between SAFs and fossil jet fuel (e.g. SAF standards) (e.g. $5bn from 2022), [1] long-term government mandates (5%–10% by 2030). Progress: [3] US SAF tax credit of $1.25/gallon (SAF), [2] EU proposed mandate of 0.7% PtL (2030).</td>
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<td></td>
</tr>
<tr>
<td>Road &amp; Agriculture</td>
<td>Alternative Fuels</td>
<td>Medium</td>
<td>High (Social norm diffusion + economics of scale)</td>
<td>Target: Unlock large-scale production + adoption of alternative fuels by leveraging public procurement, stimulating open innovation &amp; R&amp;D funding and building strong demand signals, but strong competition with other low-carbon technologies.</td>
<td>Target: Sign-off from project partnerships reaching 1.4 Mt SAF by 2022 + 1.7 Mt by 2030 – long term acceptance of additional consumer costs of –10% final retail price for consumers. Progress: [1] 100% capacity (e.g. SAF), [2] 35% with green hydrogen technology. Platforms developing strong consumer bases to pay for SAF + Shell, Antwerp, AW18 trials launching global book-</td>
<td>Progress: Establish cross-industry value chains to drive commercialization and growth in sectors, e.g. SAFs + Shell, Accenture, Annex GBT launching first-time</td>
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<td>Vining, weather-</td>
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<td>Medium</td>
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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. 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). 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. 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.

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, electrolyzers, 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. 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. 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.

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.

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. 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.

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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.

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.
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.
- **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.

<table>
<thead>
<tr>
<th>Initial Change</th>
<th>Effect – Positive Feedback Loop</th>
<th>Accelerated Tipping Point</th>
<th>Data Relevant to Strength of Link</th>
<th>Data Relevant to Time Delay of Link</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power</strong>: greater deployment of solar and wind power + battery storage</td>
<td>Light-Duty Road: increase uptake of battery electric vehicles</td>
<td>Learning curves/economies of scale drive lower battery storage costs</td>
<td>Battery pack costs represent 20-30% total EV production costs</td>
<td>10-15 year average car lifespan</td>
</tr>
<tr>
<td><strong>Fertilisers</strong>: increase uptake of green ammonia</td>
<td>Heavy-Duty Road: increase uptake of battery electric trucks vs. diesel trucks</td>
<td></td>
<td>Battery pack costs represent 20-30% total BET production costs, electricity costs (10-20% TCO)</td>
<td>15 year average truck lifespan</td>
</tr>
<tr>
<td><strong>Batteries</strong>: reduce TCO of heat pumps</td>
<td>Bunkering/refuelling infrastructure</td>
<td></td>
<td>Battery pack costs represent 20-30% total BET production costs, electricity costs (10-20% TCO)</td>
<td>15 year average gas boiler lifespan (but retrofitting in existing buildings challenging)</td>
</tr>
<tr>
<td><strong>Steel</strong>: accelerate cost competitiveness of scrap + electric arc furnace production vs. conventional</td>
<td>Airports: accelerate cost parity for green H2 DRI based steel vs. conventional</td>
<td></td>
<td>Renewables account for ~40% of total investment requirement for net-zero trajectory in steel</td>
<td>20 year average lifespan for conventional steel plant</td>
</tr>
<tr>
<td><strong>Aviation</strong>: accelerate cost parity for short-haul electric vs. fossil jet fuel</td>
<td>Shipping: accelerate cost parity for green ammonia vs. heavy-fuel oil</td>
<td></td>
<td>~50-75% reduction in renewables LCOE required for cost parity</td>
<td>15-20 year average commercial aircraft lifespan</td>
</tr>
<tr>
<td><strong>Shipping</strong>: accelerate cost parity for green ammonia vs. heavy-fuel oil</td>
<td>Aviation: accelerate cost parity for green ammonia vs. heavy-fuel oil</td>
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</tr>
<tr>
<td><strong>Fertilisers</strong>: accelerate cost parity for green ammonia vs. nitrogen-based fertilisers</td>
<td><strong>Power</strong>: bring forward cost parity of renewables + battery storage vs. fossil-based generation (VRE grid penetration increases to 40-60%)</td>
<td></td>
<td>Majority of total installed battery capacity by 2030 projected to be for EVs + BETs (+800%)</td>
<td>~5 years to develop new solar, wind + battery power plants</td>
</tr>
<tr>
<td><strong>Power</strong>: bring forward cost parity of renewables + battery storage vs. fossil-based generation</td>
<td><strong>Power</strong>: increased demand for renewable generation supports further deployment</td>
<td></td>
<td>EV + BET electricity demand to increase 10x by 2030, accounting for ~15% total demand</td>
<td>~5 years to develop new solar, wind + battery power plants</td>
</tr>
<tr>
<td><strong>Power</strong>: increased demand for renewable generation supports further deployment</td>
<td><strong>Heavy-Duty Road</strong>: increase uptake of battery electric trucks</td>
<td></td>
<td>Battery pack costs represent ~20% total BET production costs</td>
<td>15 year average truck lifespan</td>
</tr>
<tr>
<td><strong>Aviation</strong>: accelerate cost parity for short-haul electric vs. fossil jet fuel</td>
<td><strong>Aviation</strong>: accelerate cost parity for short-haul electric vs. fossil jet fuel</td>
<td></td>
<td>4x increase in battery density required to reach 1000km range</td>
<td>15-20 year average commercial aircraft lifespan</td>
</tr>
<tr>
<td><strong>Shipping</strong>: accelerate cost parity for green ammonia vs. heavy-fuel oil</td>
<td><strong>Shipping</strong>: accelerate cost parity for green ammonia vs. heavy-fuel oil</td>
<td></td>
<td>4x decrease in battery density required to reach 1000km range</td>
<td>20-30 year average lifespan for cargo/container ships (but retrofitting possible)</td>
</tr>
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<td><strong>Power</strong>: bring forward cost parity of renewables + battery storage vs. fossil-based generation</td>
<td><strong>Power</strong>: bring forward cost parity of renewables + battery storage vs. fossil-based generation</td>
<td></td>
<td>Provides significantly lower cost option for flexibility that dedicated battery storage for power</td>
<td>10-15 year average car lifespan</td>
</tr>
<tr>
<td><strong>Power</strong>: increased demand for renewable generation supports further deployment</td>
<td><strong>Power</strong>: increased demand for renewable generation supports further deployment</td>
<td></td>
<td>EV + BET electricity demand to increase 10x by 2030, accounting for ~15% total demand</td>
<td>15 year average truck lifespan</td>
</tr>
<tr>
<td><strong>Aviation</strong>: accelerate cost parity for green H2 energy for seasonal balancing vs. fossil fuel (e.g. gas peaker plants)</td>
<td><strong>Aviation</strong>: accelerate cost parity for green H2 energy for seasonal balancing vs. fossil fuel (e.g. gas peaker plants)</td>
<td></td>
<td>Green H2 to play limited role in power system, accounting for ~5% generation share</td>
<td>Longer asset turnover times in industrial facilities</td>
</tr>
<tr>
<td><strong>Steel</strong>: accelerate cost parity for green H2 DRI based steel vs. conventional</td>
<td><strong>Steel</strong>: accelerate cost parity for green H2 DRI based steel vs. conventional</td>
<td></td>
<td>Green H2 price of $1.2-2.2/kg required for competitiveness (with carbon price equivalent of &gt;$200/ton)</td>
<td>10-15 years to build H2 compatible power plants</td>
</tr>
<tr>
<td><strong>Shipping</strong>: accelerate cost parity for green ammonia vs. heavy-fuel oil</td>
<td><strong>Shipping</strong>: accelerate cost parity for green ammonia vs. heavy-fuel oil</td>
<td></td>
<td>Green H2 price of ~$1.6/kg required for competitiveness (with carbon price equivalent of ~$100/ton)</td>
<td>20 year average lifespan for conventional steel plant</td>
</tr>
<tr>
<td><strong>Aviation</strong>: accelerate cost parity for hydrogen fuel cell aviation vs. fossil jet fuel</td>
<td><strong>Aviation</strong>: accelerate cost parity for hydrogen fuel cell aviation vs. fossil jet fuel</td>
<td></td>
<td>Green H2 price of ~$1/kg required for competitiveness (with carbon price equivalent of ~$100/ton)</td>
<td>20-30 year average lifespan for cargo/container ships (but retrofitting possible) + bunkering/refuelling infrastructure</td>
</tr>
<tr>
<td><strong>Aviation</strong>: accelerate cost parity for PL synthetics vs. fossil jet fuel</td>
<td><strong>Aviation</strong>: accelerate cost parity for PL synthetics vs. fossil jet fuel</td>
<td></td>
<td>Green H2 price of ~$1/kg required for competitiveness (with carbon price equivalent of ~$100/ton)</td>
<td>15-20 year average commercial aircraft lifespan</td>
</tr>
<tr>
<td><strong>Fertilisers</strong>: increase green ammonia adoption</td>
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<td></td>
<td>Green H2 price of ~$1/kg required for competitiveness (with carbon price equivalent of ~$100/ton)</td>
<td>15-20 year average commercial aircraft lifespan</td>
</tr>
<tr>
<td><strong>Power &amp; Agriculture</strong>: increase consumption of alternative protein</td>
<td><strong>Power &amp; Agriculture</strong>: increase consumption of alternative protein</td>
<td></td>
<td>Green H2 price of ~$1/kg required for competitiveness (with carbon price equivalent of ~$100/ton)</td>
<td>Potential to protect/restore natural land immediately</td>
</tr>
</tbody>
</table>

---

The Breakthrough Effect
Endnotes

53. Current projections refer to selection of optimistic scenarios from integrated assessment models (IAMs) and IEA studies. Ibid.

54. Bloomberg NEF (June 2022), Global LCOE Benchmarks 1H 2022


57. Benchmark Mineral Intelligence (2021), Global Battery Arms Race.


59. RMI (2021), Fuelling the Transition: Accelerating Cost-Competitive Green Hydrogen.

60. Ember Climate (2020), German State Awards €317 Million To Loss-Making Coal Plants


62. Rystad Energy (October 2022), Press release: Renewable projects payback time drops to under a year in some places – capital investments shoot up.

63. UNEP and FAO (2022), Sustainable Food Cold Chains.

64. Good Food Institute (2021), Reducing the Price of Alternative Proteins.

65. National Human Genome Research Institute; see – www.102genome.gov/sequencingcosts


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


69. BloombergNEF (2022), Lithium-Ion Battery Price Survey

70. Systemix analysis based on BloombergNEF (2022).

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.

72. Despite the fact that cooling presents a greater challenge than heating in many countries, its decarbonization pathway requires clean electrification (already taking place in the power sector) rather than a separate end-solution, as is the case with heating.

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.

74. Energy Transition Commission (September 2020), Making Mission Possible.

75. Mission Possible Partnership (July 2022), Making Net-Zero Aviation Possible.


78. Energy Transition Commission (September 2020), Making Mission Possible.


80. Sharpe & Lenton (2021), Upward scaling tipping cascades to meet climate goals: plausible grounds for hope


82. Calculations based on WRI Climate Watch database: all figures use 2019 data for total greenhouse gas emissions. Percentage share of top 10 highest emissions country by sector: Agriculture = 55%, Building Heating = 67%, Electricity and Heat = 75%, Manufacturing and Construction = 77%, Transportation = 62%, Land Use Change and Forestry = 70%.

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


86. Ibid.

87. Figures refer to solar PV power with 4-hour lithium-ion battery storage at 40% capacity of solar PV. NREL (2021), Annual Technology Baseline.

88. ETC (2021), Making the Hydrogen Economy Possible.

89. This datapoint is based on [1] USD 400-500/t NH3 being the target price for green ammonia and [2] example distances using routes from Brazil to Singapore at USD 29/t NH3 and the Middle East to Singapore at USD 15/t NH3


94. Assuming 18% learning rate. See: ETC (2021), Making the Hydrogen Economy Possible.

95. $2/kg H2 to be achieved in favourable locations with very good solar/wind resource. These locations are set to be 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.


97. The Environment, Food and Rural Affairs Committee (2021), Public Sector Procurement of Food. House of Commons.


100. BCG (2022), The Untapped Climate Opportunity in Alternative Proteins.


104. BCG (2022), The Untapped Climate Opportunity in Alternative Proteins.


106. RMI (2022), Harnessing the Power of S-Curves.

107. RMI (2022), Green Hydrogen on an S-curve: Fast, Beneficial, and Inevitable.


110. IEA (2021), World Energy Outlook: People-Centred Transition.


114. BNEF, 1H Battery Metals Outlook, 2022


116. BNEF, Global Copper Outlook 2022-40, 2022

117. WWF (2022), The Future is Circular: Circular Economy and Critical Minerals for the Green Transition, SINTEF.


Endnotes

Sources for references in the table in Section 4: ‘Key actions to accelerate enabling conditions to trigger tipping points by sector’

<table>
<thead>
<tr>
<th>Sector</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-Road Transport</td>
<td>n/a</td>
</tr>
<tr>
<td>Steel</td>
<td>n/a</td>
</tr>
<tr>
<td>Aviation</td>
<td>[18] ICAO – Tracker of SAF Offtake Agreements</td>
</tr>
</tbody>
</table>
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