

First build, then break. A policy framework for accelerating zero-carbon transitions

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Anna Murphy, Simon Sharpe, Frank Geels,
Johan Lilliestam, Anthony Patt



ETH zürich



FAU Friedrich-Alexander-Universität
Erlangen-Nürnberg

MANCHESTER
1824
The University of Manchester

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About this report

‘First build, then break: a policy framework for accelerating zero-carbon transitions’ builds on a previous report ‘Analytical tools for innovation and competitiveness in the low carbon transition’, which outlined key policy questions facing ministries of finance in addressing decarbonisation, low-carbon growth, and competitiveness. It proposed a set of conceptual frameworks, decision-making frameworks, and analytical tools that can support policymakers to navigate low-carbon transitions, working with structural change, path-dependency, and uncertainty.

This report brings an empirical perspective to low-carbon transition policy instruments, packages and sequences. It explains how technology transitions, including low-carbon transitions, occur in four stages: Emergence I: Invention, Emergence II: Market Introduction, Diffusion, and Reconfiguration, and how, because each stage has different aims and challenges, different policies are required. The framework is illustrated by nearly 20 case studies of policy-enabled technological change from history and present-day low-carbon transitions.

About S-Curve Economics

S-Curve Economics CIC is a non-profit research organisation focused on advancing the understanding of the economics and diplomacy of the energy transition. Our analysis focuses on the power, road transport, and steel sectors, and cross-cutting issues of economics, policy appraisal, and diplomacy. We are based in London. Find out more at www.scurveeconomics.org.

About the authors

Anna Murphy is Head of Policy Appraisal at S-Curve Economics CIC. Anna has a background in climate strategy consulting. She has delivered climate-related strategy and research projects for start-up, industry, government and development finance clients with the Economics of Energy Innovation and System Transition (EEIST) project, as a Research Fellow at Exeter University, a Research Analyst at the Institute for Innovation and Public Purpose, and Senior Consultant at Nordic Sustainability. Anna holds a Master's in Public Administration from the Institute for Innovation and Public Purpose, University College London. She also works at the World Bank, engaging with ministries of finance on policymaking for low-carbon innovation and competitiveness.

Simon Sharpe is Managing Director of S-Curve Economics CIC. He was previously Deputy Director of the UK Government's COP26 Unit, and his other roles in government included leading international climate change strategy, developing the approach to clean growth in the UK's industrial strategy, and serving as head of private office to Ministers of State for Energy and Climate Change. He also served on diplomatic postings to China and India. He has published academic papers and policy reports on climate change science, economics, and diplomacy. His book, 'Five Times Faster: Rethinking the Science, Economics, and Diplomacy of Climate Change', was listed by the Times and Financial Times as one of the best environment books of the year 2023. He was recently awarded the title of Honorary Professor at the University of Manchester.

Frank Geels is Eddie Davies Professor of Sustainability Transitions at the Alliance Manchester Business School at the University of Manchester. Geels is a world-leading scholar on sustainability transitions in energy, mobility, buildings, and agri-food systems. He has published 7 books and 117 peer-reviewed journal articles, received multiple awards and honours, and was selected in the 2014 and 2019–2024 Highly Cited Researchers lists. He was a lead author of the Working Group III contribution to the 2022 The Intergovernmental Panel on Climate Change (IPCC) report, was a member of the Scientific Committee of the European Environment Agency (2016–2024), and has written invited reports for the European Commission, OECD, World Bank, European Environment Agency, and UK Department for Business, Energy and Industrial Strategy.

Johan Lilliestam is Professor of Sustainability Transition Policy at the School of Business, Economics and Society at Friedrich Alexander University Erlangen–Nürnberg, Germany. His research focus is policies, government strategies and instruments for a transition to a completely renewable energy system, including the effects of interactions between different energy policies. Much of his recent work focuses on empirical evaluation of policy effects, as the scientific background for designing appropriate policy mixes. His work is strongly interdisciplinary and problem-driven, drawing on insights and methods especially from political science and transition studies. He is a European Research Council grantee. Johan serves as Lead Author in the seventh assessment report of the IPCC.

Anthony Patt is Professor of Climate Policy at ETH Zurich, the Swiss Federal Institute of Technology. He and the research group he leads have published extensively both on the technological pathways to achieve net zero emissions by mid-century and on the policy instruments that appear most successful at accelerating change in this direction. He is a member of numerous advisory bodies in Switzerland, where he supports policymaking at the federal, state, and municipal levels, and has worked as a consultant to the World Bank, the Food and Agriculture Organisation, and multiple national governments. He has served as Coordinating Lead Author, Lead Author, and Review Editor on the fifth and sixth assessment reports of the IPCC.



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EXECUTIVE SUMMARY

The majority of governments have set goals for their economies to reach net zero emissions. Meeting these goals requires transitions from fossil fuels to zero-emission systems in each greenhouse-gas-emitting sector: power, transport, buildings, industry, and agriculture. Whether the aim is to avoid dangerous climate change or to take advantage of zero-carbon¹ technologies for reasons of cost, quality, or competitiveness, it is useful for governments to know what kinds of policies and strategies are likely to be effective in advancing these transitions. This report provides a guiding framework to inform those choices.

First build, then break

First build the new zero-carbon technology systems, then break the old polluting ones. This is the overarching principle. It is not only a political necessity, but also a practical one. People can only stop using an old technology when a new one is available and affordable. New solutions must be invented, introduced into the market, and scaled up, before old systems can be phased out. Crucially, policies that focus on developing new solutions and constructing new systems benefit from self-amplifying feedback effects, early in the transition.

A transition is not the same as decarbonisation. Emissions can be reduced by policies that make fossil fuel systems operate more efficiently, but can only be eliminated by the development of zero- or near-zero-carbon technologies and systems.

Match the policy to the stage of transition

There are distinct stages in the process of building new technologies, and the infrastructure and social systems they need, and dismantling the old systems. Each stage involves different problems, which different policies can help to address.

- During the **Emergence stage**, policymakers must first support the **Invention** of new solutions by setting out a vision for the future, directing publicly funded research and development (R&D), and connecting key stakeholders. They can then enable the **Market Introduction** of new technologies with policies that simultaneously create demand and support supply, such as public procurement, targeted subsidies for production or consumption, and concessional lending.



- **Diffusion** requires scale-up and cost reduction, which policymakers can support with subsidies and public communications campaigns, financial support for manufacturing and deployment, technology mandates and standards, and support for infrastructure, skills, and trade. Measures to put pressure on the old technology, such as taxes, can begin to play a role here too.
- Finally, the **Reconfiguration** of broader infrastructure, markets, social norms, and governance is achieved through a range of measures. Only at this stage can old technologies be phased out, with bans and taxes on their sale and use.

In sum, there is no single most appropriate policy to drive a transition, but rather a sequence of policies whose importance changes as the transition progresses.

Technology transitions happen both globally and nationally, and the process is largely the same for countries leading and following in global transitions. However, ‘follower’ countries can start at the Market Introduction stage and are typically able to move into the Diffusion stage more quickly by drawing on international experience. Although followers may progress faster, first movers may capture most of the new industry and jobs.

There are examples of effective policies to drive transitions throughout history, and in the present. Technology transitions (more properly described as ‘socio-technical transitions’) have taken place many times in the past, providing opportunities to learn what works. In the examples of transitions from horses to cars, from wells to piped water, from coal to gas, and many more, we can see how government policies have enabled and accelerated progress. Similarly, we can see which policies have been successful in driving transitions from fossil fuels to zero-carbon technologies. This report draws on case studies to illustrate which policies have worked at certain stages, and why.

A framework to identify policies needed now and in future. This report outlines the goals of policy, and common challenges, at each stage of the transition. This can help policymakers to identify which stage a given sector is at, in their country. We then identify the policies typically able to address those challenges, and we explain their rationale. We provide a series of case studies that illustrate how those policies have worked in historical technology transitions and in zero-carbon transitions over the past few years. At each stage, we suggest principles to inform policy design.

This framework can be used by policymakers to quickly identify policies needed now, foresee those likely to be needed in future, and design them effectively. It can also be used to inform strategies for the transition.

¹ The term ‘zero carbon’ is used interchangeably with ‘zero emissions’ throughout the report, and refers to zero or near-zero carbon emissions, or greenhouse gas emissions, arising from the use of a product or production process.



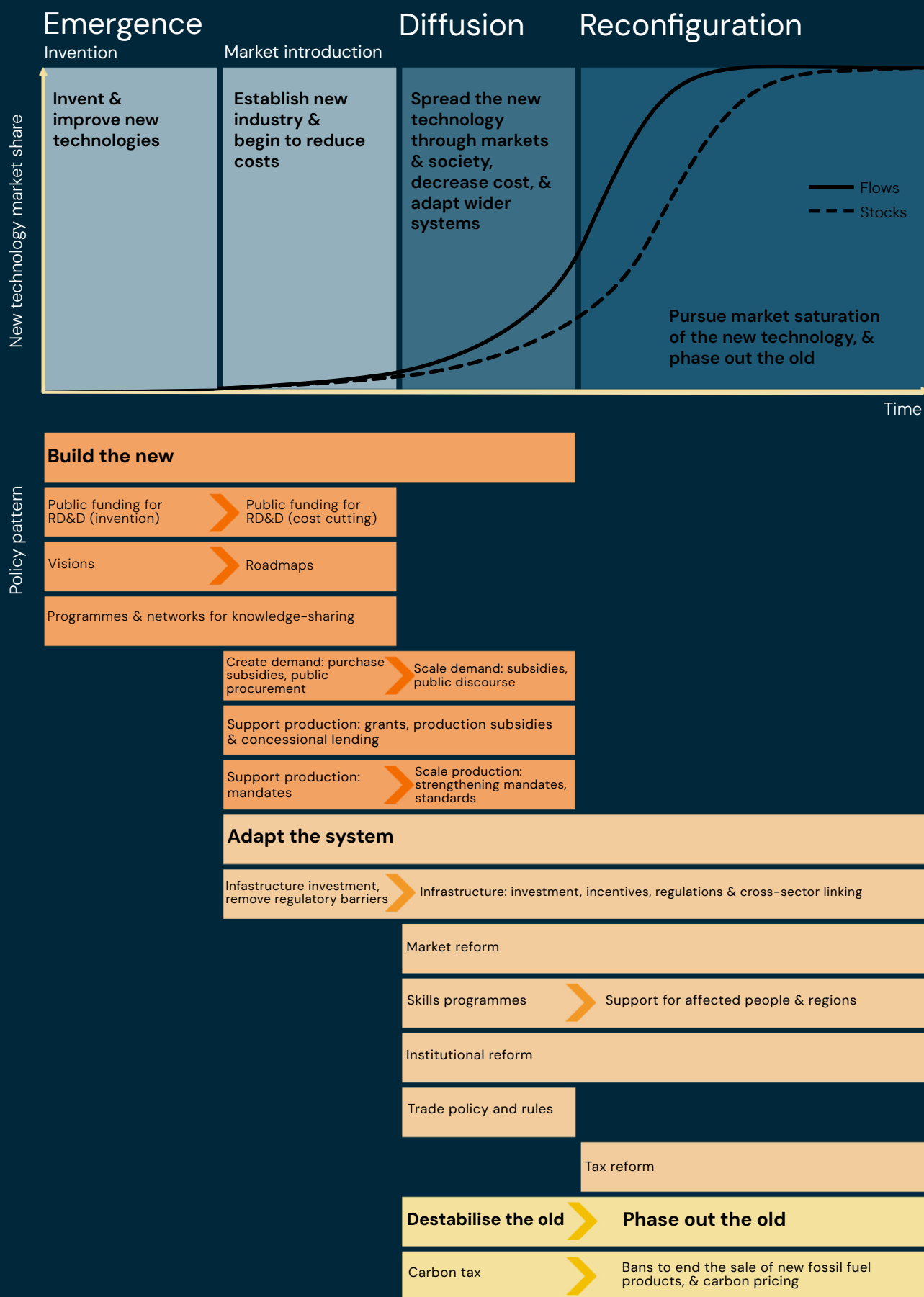


Figure i. The Accelerating Transitions Framework for policy. Note: the figure illustrates the stages of the transition in a given sector, the policy aims at each stage, and the policies likely to be effective at each stage. The market share of the new technology follows an s-curve, first growing slowly, then accelerating, before plateauing as the transition nears completion. The solid s-curve represents flows (sales or investment, such as annual car sales). The dashed s-curve represents stocks (products or assets in use, such as total car fleet). Once flows change, a shift in stocks becomes inevitable, but it has a time lag which is longer in sectors where assets have longer lifetimes. This is a generalised framework: the specifics will differ across sectors and countries. Source: authors.



1. Emergence I: Invention

At the start of the transition, policymakers must support innovators to invent and test new technologies, identify which of these might meet society's needs, and eventually consolidate around one or more viable designs. Their aim is to ensure that zero-carbon innovations which may accelerate decarbonisation are discovered, and that the most promising design options progress from research and development to pilots and demonstration projects. Once the new technologies prove viable at the demonstration stage, they are ready for market introduction.

Problems to solve include the reality that nurturing the invention of viable solutions is fundamentally difficult, time-consuming, and involves failure. The high uncertainty in this process can undermine private sector involvement, and isolation of innovators from industry, policymakers, and other researchers can slow progress.

Policies

- **Public funding for research, development and demonstration (RD&D)** can help innovators to develop technically viable, high-performance, and low-cost zero-carbon solutions. This reduces private sector reluctance to invest in high-risk solutions.
- **Policy objectives** clarify desired technology capabilities, characteristics, or outcomes, and help to align innovators and financiers around specific goals.
- **Knowledge-sharing programmes and network-building** enable innovators to exchange information, collaborate on solutions and connect to industry, investors, and policymakers, potentially enabling co-design, commercialisation, and supportive policy.

Case studies from the UK, Germany, Austria and Sweden, from the aviation, heating, power, and steel sectors, illustrate how these policies have been used effectively during this stage of the transition.

The stage ends when one or more technology options for the sector have been invented, and their designs have been tested, validated, and stabilised sufficiently to be introduced into a commercial market setting.

Principles for policymaking during the Invention stage

Principle	Explanation
Additionality in the global context	No country can or must invent every clean technology itself; it can import or adapt innovations while focusing its own invention efforts on sectors where it has strong potential to succeed.
Stable commitment	A clear vision for the future direction of technological development will only galvanise innovators and reassure investors if underpinned by stable political commitment, even as specific policy instruments evolve.
Adaptive portfolio approach	When technological uncertainty is high, supporting diverse options, evaluating progress, and adjusting support can help to avoid premature commitment to certain technologies or designs.



2. Emergence II: Market Introduction

At this stage, the goal for policymakers is to help companies to **introduce the new technologies into the market for the first time**, despite high costs and uncertainties. The aims are to achieve the first deployment of new technologies, establish new industries (which may be new to the country or new to the world, if the country is leading), and create early market demand. At this stage, the new technology remains immature and is unlikely to be able to compete successfully against incumbents. Demand-creating and supply-enabling policies can kickstart positive feedback effects such as economies of scale and learning-by-doing, which drive cost reductions and increase uptake. Small differences in the uptake of different technologies can be quickly amplified, leading some options to succeed and others to fail. Through this process, it becomes clear which of the technology options may be viable to deploy at a scale that could meet the demand of the whole sector.

Problems to solve include high costs and performance-related issues of the new technologies. New technologies are typically more expensive than existing technologies and would not survive competition without support. There is still uncertainty about which technologies and designs will have most potential and should be scaled up. This uncertainty can cause a lack of investment, and high financing costs. Regulatory barriers or lack of infrastructure can also prevent first deployment in a market context.

Policies

- **Creating demand: purchase subsidies and public procurement.** Purchase subsidies improve the new technology's affordability and attractiveness to consumers, creating demand and enabling introduction into the market.² Subsidies can be funded through taxes on the sale of fossil fuel products.³ (These have a different purpose from the carbon taxes used during Diffusion and Reconfiguration, which aim to disincentivise the use of polluting technologies – an aim that can be realised once alternatives are available.) Demand can also be created by public procurement: a government's purchasing power is often large enough to create a meaningful market niche.
- **Supporting production: grants, subsidies, concessional lending and mandates.** Grants or subsidies decrease upfront costs and risks of early production. Concessional lending similarly can reduce the cost of capital and catalyse business investment. Mandates can force an initial investment into new technologies.
- **Adapting the wider system: initial infrastructure investment and removing regulatory barriers.** For some technologies, new infrastructure or regulatory change may be needed for a technology to reach the market at all. The government can invest directly or incentivise the private sector to invest in infrastructure (with the most appropriate choice depending on the sector), and can adapt regulation to make new technologies legal and viable.

Case studies from France, India, Uruguay, the UK, and the US, from the public transport, power, aviation, and food sectors, show how these policies have been used effectively.

This stage ends when it is clear which of the technologies introduced to the market are most likely to diffuse at scale and have the potential to compete with the incumbents in the mainstream market. This is likely to be due to those technologies' cost reduction or potential for it, or their better performance than other options.

² The distributional effects of technology-specific subsidies depend on the sector and on policy design. The first beneficiaries are sometimes wealthy consumers, who can afford to buy more expensive products. This increases deployment, brings the technology down the learning curve, and helps the technology to become more affordable for all consumers. Alternatively, subsidies can be designed to exclude high-income earners, or to target low-income households or low-cost segments of a market. In other sectors, subsidies for production using the new technologies may have no direct distributional effects.

³ These are different from carbon taxes in practice and intent, because the tax level is set based on the revenue needed and is not proportionate to emissions.

Principles for policymaking during the Market Introduction stage

Principle	Explanation
Focus on zero-carbon technologies	Support the early deployment and improvement of zero-carbon technologies that have the long-term potential to eliminate emissions from the sector, rather than supporting lower-carbon technologies, even if the latter achieve emission reductions at lower cost.
Back winning technologies	Early-stage technologies are likely to face a disadvantage compared with more mature technologies. Policies can be tailored to support more than one viable option, with the strongest support given to those that emerge as most successful and suited to the long-term needs of the sector.
Match supply push with demand pull	Producers and consumers often wait for each other to move to the new technology, preventing momentum. Governments can simultaneously stimulate supply and demand to overcome this problem.



3. Diffusion

The goal at this stage is to spread the new technology rapidly through markets and society. This can be helped by crossing thresholds where the new technology begins to outperform the old in cost, performance, profitability, or desirability, making it the 'common-sense' choice for a growing share of producers and consumers. Positive feedbacks of learning-by-doing and economies of scale – where the more the technology is deployed, the more it improves and the less it costs – can drive rapid progress.

Problems to solve still include cost reduction, and improving attractiveness of the zero-carbon technology to consumers who make up the majority of the market. Widespread deployment requires industry to reallocate investment from the old to the new technology. In addition, infrastructure, market, regulatory, and other systems must be transformed at scale, so they no longer favour incumbent technologies and are adapted to the new. There can be competitiveness challenges in trade-exposed sectors, and fierce resistance from incumbents.

Policies

- **Scale up demand: subsidies and positive public discourse.** Deployment subsidies are often still important to enable new technologies to compete against incumbents, though policymakers can taper them as costs fall. Subsidies can be complemented with taxes on the old technologies, to maintain revenue neutrality, or to further shift the cost advantage towards the new technologies, or to signal the start of a transition away from incumbent industries. Public communications campaigns can advertise the benefits of zero-carbon technologies, and the policy support available to consumers.
- **Scale up supply and reallocate investment: mandates and standards.** Mandates that require a rising proportion of sales or production to have a given characteristic (such as zero emissions) can at this stage reallocate private sector investment from the old to the new technologies on a large scale, increasing economies of scale and accelerating cost reduction. Performance standards, when sufficiently stringent, can also incentivise or force a switch to the new technologies. These policy tools both support the growth of the new technologies and begin to disincentivise and destabilise the old technologies and systems.
- **Adapt the system: infrastructure, markets, skills, institutions and trade.** As the new technology grows, it will start causing friction within the existing system. Market reforms can rewire existing markets built for and favouring incumbent technologies. Skills programmes, funding, incentives and partnerships can help to develop needed capabilities. Infrastructure investment at scale may be necessary. New institutions can be created to govern markets that did not previously exist. In trade-exposed sectors where the new technologies are higher cost, international agreements on standards, tariffs, or taxes can enable the new technologies to be produced, sold, and adopted more effectively across borders.

Case studies from the heating, water, power, and passenger transport sectors in Denmark, the Netherlands, China, and the UK show effective use of these policies at this stage.

This stage ends after critical thresholds in the attractiveness of the new technologies to consumers or its profitability to producers have been crossed, and the new technology accounts for the majority of sales or new investments.

Principles for policymaking during the Diffusion stage

Principle	Explanation
Focus on positive feedbacks	Policies that grow the new technologies' market share can drive investment, innovation, cost reduction, and demand, changing the political economy and expanding future policy options. The priority is to support the growth of new industries first, enabling the decline of the old industries later.
Target tipping points	Target policies to make zero-carbon technologies lower cost and more attractive than fossil fuel technologies. This makes zero-carbon technologies the default choice for producers and consumers and locks in rapid, long-term change.
Remove barriers	Removing regulatory, administrative and societal barriers is critical to enable the rapid diffusion of zero-carbon technologies.



4: Reconfiguration

The aims for policymakers at this stage are to enable the new technology to reach a full share of the market, to phase out the old technology with a minimum of disruption, and to adapt the rest of the system. There are three different but related processes. First, the new technology must reach market saturation in new inputs into the system, such as electric vehicles (EVs) as a percentage of new car sales (this is the solid line in Figure i and represents ‘flows’); then it must reach saturation across the whole system, such as EVs as the percentage of all cars on the road (this is the dashed line in Figure i and represents ‘stocks’). The second process is that the old technology and its infrastructure must be wound down and retired. Third, the wider social and economic system must be adapted, to avoid problems arising either from the final stage of growth of the new technology or from the wind-down of the old.

Problems to solve include difficulties associated with completing the diffusion of the new technology to the last market segments or geographical areas. Winding down the old technology must be attempted without disrupting services to users. The significant political, social, and economic risks of this stage must be carefully managed to prevent backlash against the transition, or long-term adverse social and economic consequences.

Policies

- **Complete system adaptation: infrastructure extension and adaptation with public investment and regulation, market reforms, and tax reforms.** The new infrastructure must be extended to cover all users and uses, which may involve regulation requiring coverage in remote locations. Deeper market reforms can support the deployment of complementary technologies that support the functioning of systems built around the new ‘core’ technologies; for example, energy storage and flexible grid technologies will be important to power systems dominated by solar and wind. Tax reforms need to replace decreasing revenues from taxes on the old technology with new sources.
- **Carbon prices and regulations to limit and end the sale of fossil fuel products.** In the zero-carbon transition, carbon pricing can change the relative costs of technology options, pushing the most carbon-intensive technologies and assets out of the market first, but only when alternatives are in place to take over. In any transition, regulations (explicit bans on the old technology, or mandates requiring the new technologies to reach 100% of sales) are likely to be the most effective way to phase out the old technology, since banning a product or technology is stronger than merely disincentivising it.
- **Support for affected workers, communities and regions.** Regional development programmes to support workers, communities, and regions that stand to lose from the decline of the old industries may be desirable for many reasons, and may help to avoid strong social opposition to the transition. This may need to start during the Diffusion stage, but it becomes even more critical in Reconfiguration. (During the Invention and Market Introduction stages, most workers, communities, and regions are unlikely to be strongly affected by the transition.).

Case studies from the road transport, aviation, power, and heating sectors in the US, Germany, and Switzerland show the effective use of these policies at this stage.

Principles for policymaking during the Reconfiguration stage

Principle	Explanation
Create positive cross-sector links	Linking transitions across sectors at this stage can enable progress and overcome challenges. Positive cross-sector interdependencies can be created through sharing infrastructure, sharing technologies, and aligning standards and market designs.
Integrate the transition into broader strategies	To help policies for the transition and policies with other objectives to reinforce rather than undermine one another, coordination across government can integrate policies for the transition into skills, industrial, infrastructure, housing, development, trade, national security, and other strategies.
Deal deliberately with distributional issues	Effective policy must be politically embedded, not just economically rational. It may require institutional reform, broad-based coalitions, and combining technical policy with legitimacy-building measures.

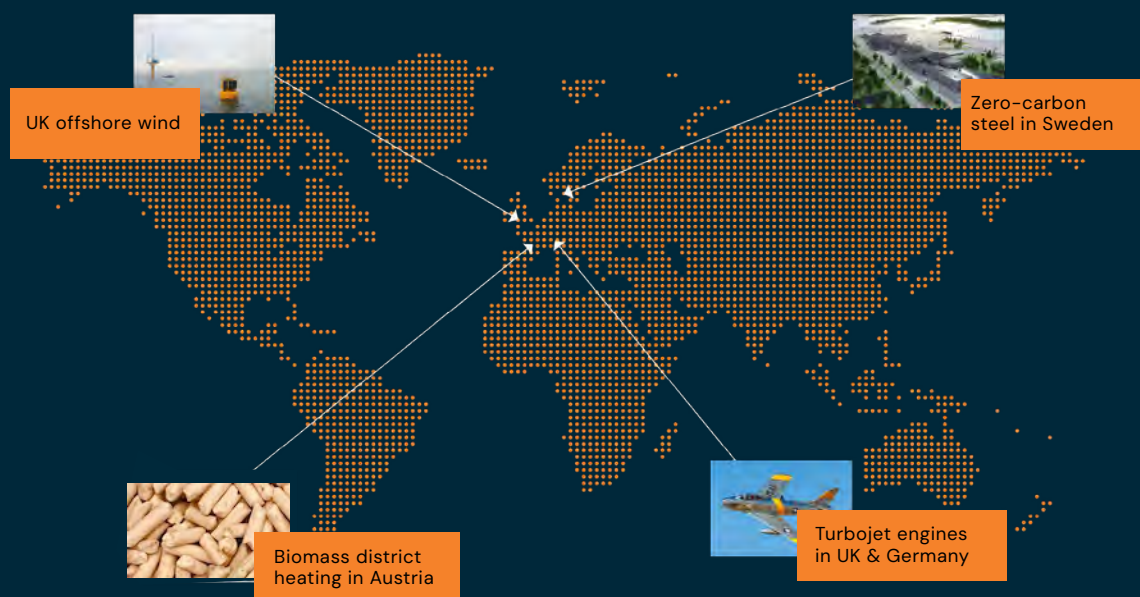


The case studies

The case studies include examples of historical technology system transitions, as well as recent and current examples of transitions to zero- or near-zero-carbon technologies. They cross time-periods, countries, and sectors. While each is unique, together they illustrate the pattern in the process of transitions and the policies that typically contribute to progress at each stage.

Key: **C:** Context and challenge. **P:** Policy solution. **R:** Result. **I:** Longer-term impact.





Invention case studies

1. Turbojet engines in UK & Germany (1930–45)

- C.** Turbojet innovators struggled for investment
- P.** Publicly funded RD&D (military interest)
- R.** Successful demonstrations drove public and private sector investment
- I.** Faster planes (up to 8x thrust of early demonstrations)

2. Biomass district heating (BMDH) in Austria (1970–2013)

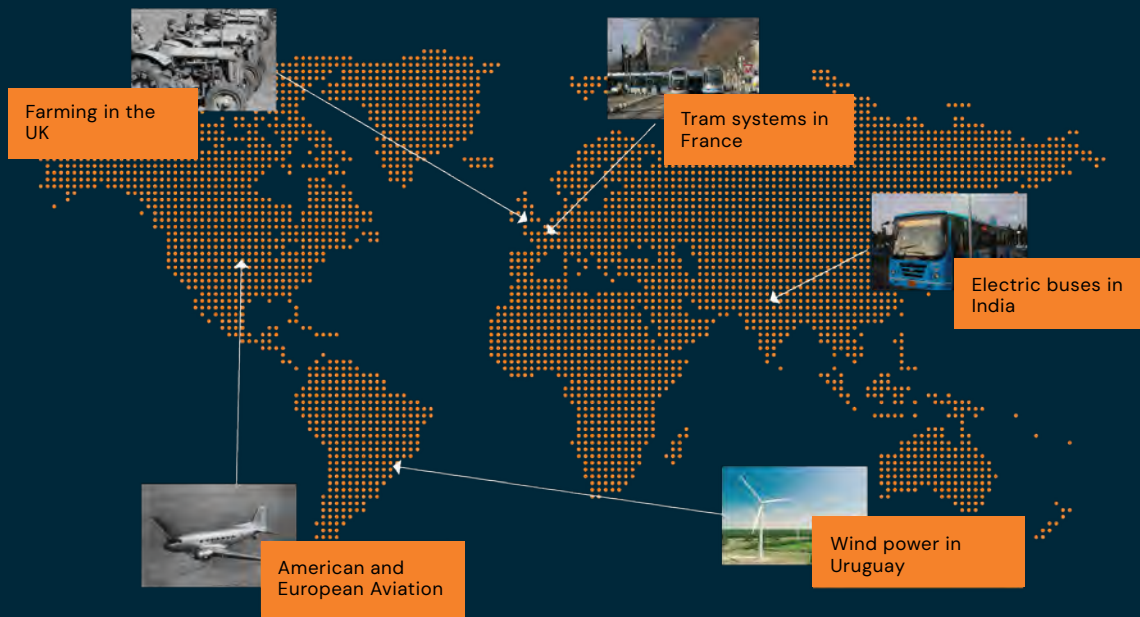
- C.** Rural innovators were isolated
- P.** Network building and knowledge sharing in 1980s by public energy agencies
- R.** Systems improved and costs reduced
- I.** Laid foundations for Austrian exporter industry of pellet boilers

3. Offshore wind in the UK (2008 to present)

- C.** Offshore wind expensive and untested
- P.** Public–private innovation accelerator was created
- R.** 150 joint R&D projects cut costs by 15% in 10 years
- I.** Accelerator was expanded and replicated internationally

4. Zero-carbon steel in Sweden (2015 to present)

- C.** History of steel innovation, cheap renewables to produce hydrogen
- P.** Government commitment to zero-carbon steel, joint venture and public finance
- R.** Successful and evolving demonstration project(s)
- I.** Other countries followed, and global transition beginning



Market Introduction case studies

5. Tram systems in France (1970–2000)

- C.** Urban congestion and accidents
- P.** Public procurement
- R.** First tram systems were replicated to 15 of 19 major French cities
- I.** From late 1990s, declining car use in many French cities

6. Electric buses in India (2015–2024)

- C.** Air pollution, oil imports, insufficient public transport
- P.** Public procurement – aggregated bus purchasing
- R.** Higher electric bus deployment at lower costs
- I.** Policy being replicated internationally

7. Wind power in Uruguay (2005–2016)

- C.** Energy insecurity and drought undermining hydropower
- P.** Reverse auctions for large-scale capacity, feed-in tariffs for small-scale
- R.** Fastest-growing wind share of all countries globally 2014–2016
- I.** Improved power system stability and increased export revenue

8. American and European aviation (1890–1930)

- C.** Post-war airline companies failing to create commercial niche
- P.** Grants and subsidies to create postal niche
- R.** Demand spurred manufacturer investment
- I.** Dominant design for commercial aviation popular by 1930s

9. From mixed to specialised wheat farming in the UK (1930–1970)

- C.** Bread/food insecurity due to war
- P.** Guaranteed prices to farmers, grants and cheap loans, knowledge sharing
- R.** Tractor and machinery diffusion, more land used for food
- I.** Long-term transition to mass-production systems



Diffusion case studies

10. From oil to district heating in Denmark (1950–1980)

- C.** 1973 oil crisis and debate on alternative heating
- P.** Plans, mandates and building codes for district heating
- R.** Diffusion of district heating in 1980s
- I.** Complementary policies and financing further lowered costs

11. From wells to pumped indoor water in the Netherlands (1870–1945)

- C.** Concerns about working-class living conditions
- P.** Public health campaigns on hygiene, and subsidies to water companies
- R.** Improved modern waterworks but challenges expanding to rural areas

12. From coal to natural gas in Dutch heating (1960–1980)

- C.** Discovery of easy-to-exploit natural gas field
- P.** New institutions for pricing, construction and transmission; campaign to change appliances; compensation to negatively affected people and businesses
- R.** Rapid transition from coal to natural gas in heating

13. Road transport shift to EVs in China (early 2000s to 2024)

- C.** High air pollution, high oil imports, R&D into zero-emission cars
- P.** Demand-side subsidies, charging infrastructure investment, supply-side regulation
- R.** Rapid EV sales growth especially after regulation introduced
- I.** China became largest car exporter in the world, made EVs cheap

14. Coal phase-out in the UK (2000s to present)

- C.** Weakened economics of coal, decreasing gas prices, climate concerns
- P.** Small carbon price floor on coal finance
- R.** Coal power made generally more expensive than gas
- I.** Coal rapidly pushed out of market



Reconfiguration case studies

15. Horse-and-carriages to automobiles in the US (1900–1992)

- C.** Increasing car popularity
- P.** Infrastructure subsidies and investments, particularly roads
- R.** Huge infrastructure system completed in 1992

16. From propeller aircraft to jetliners, US (1945–1980)

- C.** Expansion of air travel created safety and noise issues
- P.** New regulatory agency, long-range radar to improve safety, noise regulations
- R.** Ongoing social acceptance challenges for airport expansion
- I.** Funds beginning to be allocated

17. Coal phase-out in Germany (2019 to present day)

- C.** Aim to phase out coal
- P.** Coal Commission, recommended 2038 phase-out and funding for those affected
- R.** Recommendations adopted and widely accepted; coal plants being closed

18. Heat reconfiguration in Zurich, Switzerland (2023 to present)

- C.** 2040 net zero target, 50% of the city's emissions from heating buildings
- P.** Ban on new fossil fuel heating systems, district heating expansion, subsidies for renewable heating, coupled plan to end gas delivery and expand district heating, public information finance
- R.** Plans are on track, no visible opposition



INTRODUCTION

Governments covering over 80% of global emissions have committed to reach net zero national emissions around the middle of this century.⁴ This raises the question: which policies are best suited to make progress towards that goal?

Given the benefits of zero-carbon technologies such as reduced air pollution, energy independence, and advances in economic development, even where emissions reduction is not a priority, governments are interested in understanding how to navigate the global transition.⁵

The Intergovernmental Panel on Climate Change (IPCC) has described what is needed to meet climate change goals as ‘rapid and far-reaching system transitions’ in each of the greenhouse-gas-emitting sectors of the economy, ‘unprecedented in terms of scale, but not necessarily in terms of speed.’⁶ A system transition is a process in which one set of technologies, and its associated infrastructure, businesses, consumption patterns, and institutions, is replaced with another.⁷

System transitions, or technology transitions, have taken place many times in the past. All technology systems around us have transitioned at least once – progressing from pre-industrial to industrial technologies – and several have gone through multiple transitions. From horses to cars, from sailing ships to steamships to diesel ships, from wells to piped water, from letter-writing and encyclopaedias to emails, the internet, and mobile banking: shifts in dominant technologies have completely reshaped many sectors of the economy.⁸ In nearly all cases, the transition has enabled improvements in and expansion of service provision within the corresponding sector, creating new opportunities for economic development and improved living standards.⁹ By studying these past examples, we can see the types of policies that are most effective in advancing transitions, alongside the other forces of entrepreneurial innovation, private sector investment, and civil society activism.

The zero-carbon transition is underway. In sectors ranging from energy provision to transport to heating, carbon-intensive technologies are being replaced with zero-carbon technologies, even as the sectors themselves continue to expand and improve. Government policies are a main driver of these changes.¹⁰ It is possible to survey progress across countries and sectors, and see what is working. There are many examples of success, from which governments can usefully learn.

This report sets out a framework for policymaking to advance the zero-carbon transition. We aim to show which kinds of policies are likely to be effective at each stage of the transition and illustrate this with cases in which these kinds of policies have been effective. The report can be used by government departments with responsibilities for sectors where transitions must take place – power, transport, industry, buildings, and agriculture – and by ministries of finance, to inform strategic thinking and policy planning.

4 As of June 2024, 107 countries covering about 82% of global greenhouse gas emissions had adopted pledges of net zero greenhouse gas emissions in law, in a policy document, or in an announcement by a high-level government official. See United Nations Environment Programme (2024). Executive summary. In *Emissions Gap Report 2024: No more hot air ... please!* UNEP.

5 Bond, K. & Butler-Sloss, S. (2022). *The Energy Transition Narrative*. RMI.

6 Lee, H., Calvin, K., Dasgupta, D. et al. (2023). *Summary for Policymakers*. In: Climate Change 2023: Synthesis Report. IPCC.

7 Geels, F. W. & Schot, J. (2007). Typology of sociotechnical transition pathways, *Research Policy*, 36, pp.399–417.

8 For example, see Geels, F. W. (2002). *Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study*, *Research Policy*, 31, pp.1257–1274; Perez, C. (2002). *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages*. Edward Elgar Publishing; or Numata, Y., Speelman, L. & Gantman, M. (2023). *The Energy Transition Is a Technological Revolution — with a Deadline*. RMI.

9 Perez, C. (2002).

10 For example, see Díaz Anadon, L., Jones, A., Peñasco, C. et al. (2022). *Ten Principles for Policymaking in the Energy Transition*. Economics of Energy Innovation and System Transition (EEIST). University of Exeter.

It provides a guiding framework for strategies, and the rationales for particular policies. We do not give detailed policy recommendations for specific sectors or countries, at the transition stage each is in at present; there are other reports for that purpose.

The framework is designed to work with the political dynamics of the transition, not against them or regardless of them, but we do not aim to provide a guide to the political process itself. Our focus is on identifying effective policies to advance the transitions, and we do not go into depth on policies for building industrial competitiveness, a related but different discussion.

We focus on the development of systems that can lead to and sustain a zero-carbon economy, with a high quality of life, in the long term – not on short-term emissions reductions. This is an important distinction. Countries have set net zero emissions targets collectively and individually for a good reason: this is the only goal consistent with stopping the rise in atmospheric concentrations of greenhouse gases, limiting the risks of climate change, and meeting the temperature targets of the Paris Agreement. These net zero targets can only be met by developing zero- or near-zero-carbon¹¹ systems to replace fossil fuel systems, in each of the greenhouse-gas-emitting sectors of the economy.¹² We aim to support governments' thinking about that essential process. We do not focus on measures such as increasing the efficiency of fossil fuel systems, reducing demand, or deploying lower-emission technologies, which can contribute to reducing emissions, but do not generally contribute to progress towards the goal of eliminating emissions.

This report builds on a shift in experts' understanding of how transitions to zero-carbon technologies and systems happen. Previously, this understanding was rooted in theory that emphasised how market failures – such as a failure to price in the societal costs of climate impacts – could lead towards higher levels of carbon pollution than would be socially optimal, given the current state of technologies, their relative costs, and the infrastructure networks that enable them to work.¹³ There has been a shift over the past two decades towards a more dynamic understanding, which emphasises the potential for technological innovation and the construction of new systems to achieve a complete transformation of many markets, and the elimination of carbon emissions.¹⁴ Rapid cost declines of solar and wind power, and the critical role that deployment subsidies and regulation played in this process, have provoked an appreciation of non-linear technology dynamics and the role of policy in enabling them.¹⁵

This new understanding is relevant to the change that must take place in each of the emitting sectors. A caveat is that the problem of ending emissions from agriculture and land use, which we do not discuss in detail in this report, is more complex. While this necessarily involves technology transitions (in fertiliser production, for example), and [Case Study 9](#) shows how policy supported a transition in agriculture in the past, it also involves preserving the natural ecosystems within which these sectors are embedded – a qualitatively different challenge.

11 There are some industries where transformative clean solutions may be near-zero rather than completely zero carbon (green ammonia, used for clean shipping fuel, can still leak and create fugitive nitrous oxide emissions, as do other types of ammonia). The term 'zero carbon' is used interchangeably with 'zero emissions' throughout the report, and refers to zero or near-zero carbon emissions, or greenhouse gas emissions, arising from the use of a product or a production process.

12 Sharpe, S., Lilliestam, J. & Worthington, B. (2025). *Carbon budgets are not enough – the case for transition milestones*. S Curve Economics CIC.

13 Meckling, J. & Allan, B. (2020). *The evolution of ideas in global climate policy*. *Nature Climate Change*. 10. pp.434–438.

14 Ibid. See also: Díaz Anadon, L., Jones, A., Peñasco, C. et al. (2022).

15 See for example: Díaz Anadon, L., Jones, A., Peñasco, C. et al. (2022); Nemet, G. F. (2019). *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation*. Routledge. See also: Chapter 3 in Hallegatte, S., Godhino, C., Rentschler, J. et al. (2024). *Within Reach: Navigating the Political Economy of Decarbonization*. World Bank; and Grubb, M., Arima, J., Bosetti, V. et al. (2022). *1.7.1.2. Dynamic efficiency and uncertainty*. In: *Climate Change 2022: Mitigation of Climate Change*. IPCC.

The nature and stages of a transition

Technology transitions are also social and institutional transitions.¹⁶ They involve not only the spread of technologies, but also deep changes in the systems of production, infrastructure, consumption, and governance that produce and sustain them. This means that the challenge for policy is not simple: there are many dimensions of change, and many possibilities for intervention.

The challenge can be made less complex by recognising that transitions typically progress through several distinct stages. Each stage involves different problems, which different policies can address. There is no single most appropriate policy, but rather a sequence of policies whose usefulness changes as the transition progresses. A critical principle for this policy sequence is to first phase in new technologies, before starting to phase out the old ones.

The stages of a transition¹⁷ can be understood as follows:

- **Emergence:** In the Emergence stage, new technologies are invented, developed, and introduced into markets. During early emergence, **'Invention'**, the aim is to invent and improve new technologies, establish which may be able to meet society's needs, and consolidate their key design elements. There is high uncertainty in this process, and often many technologies (e.g. solar and wind) and technology designs (e.g. two- or three-blade wind turbines), are explored and tested. Policies that support research, development, and demonstration (RD&D) of new technologies and designs, set a clear direction for research efforts, and establish networks between researchers and innovators can help to advance this stage. The Invention stage ends when one or more technology options have been discovered, and the design of each of those technologies has stabilised enough for it to be introduced into markets.
- During the later part of the Emergence stage, **'Market Introduction'**, the aims are to deploy new technologies for the first time in a commercial setting, establish the new industries, create early market demand, and learn which of the technology options introduced so far may be viable at scale. A critical challenge is to achieve sufficient early cost reduction to make commercial production feasible. The Emergence stage ends when it is clear which of the technologies introduced to the market are most likely to diffuse at scale, with the potential to shoulder much, or all, of the mainstream market demand. This is likely to be because of their potential for cost reduction over time, or better technical performance than other options.
- **Diffusion:** During the 'Diffusion' stage, the aim is to spread the new technology rapidly through markets and society. This can be helped by crossing thresholds where the new technology begins to outperform the old in cost, performance, profitability or accessibility, making it the 'common-sense' choice for a growing share of producers and consumers. Positive feedbacks of learning-by-doing and economies of scale – where the more the technology is made, the more it improves and the less it costs – can drive rapid progress. One emerging challenge at this stage is managing resistance from incumbents who, increasingly seeing the competitiveness of new technologies, engage in economic, business, and political struggles against them. Policies such as subsidies and regulations for new technologies, and taxes on fossil fuel products, can reduce the cost difference, if one still exists, and give the new technologies an advantage over the old. Another challenge is to embed the new technology system while maintaining the goods or services that define the sector. This may require new infrastructure, or market reforms.

¹⁶ Geels, F. W., Sovacool, B. K., Schwanen, T. & Sorrell, S. (2017). *Sociotechnical transitions for deep decarbonization*. Science. 357. pp.1242–1244.

¹⁷ Builds on Victor, D., Sharpe, S. & Geels, F. (2019). *Accelerating the low-carbon transition*. Energy Transitions Commission.

- **Reconfiguration:** During the 'Reconfiguration' stage, the aim is to enable the new technology to reach the largest possible share of the market, in some sectors and segments reaching 100%, and to ensure wider social and economic structures are well adapted to it. The challenges can include ensuring that the sector can function effectively without the old technology, including during the transition period; supporting workers and communities that have lost jobs associated with the old technology; and finding new sources of tax revenues to replace any that depended on the old technology. Policies that can be helpful at this stage include extending market reforms and new infrastructure; supporting complementary technologies (those that help integrate the 'core' new technologies of the transition); skills policies; and regional development policies.

18 McNerney, J., Farmer, J. D., Redner, S. & Trancik, J. E. (2011). *The role of design complexity in technology improvement*. Proceedings of the National Academy of Sciences. 108. pp.9008–9013.

19 Lenton, T. M., Benson, S., Smith, T. et al. (2022). *Operationalising positive tipping points towards global sustainability*. Global Sustainability. doi:10.1017/sus.2021.30

Key concepts

- **Positive feedbacks** are self-reinforcing dynamics where initial changes – such as technology uptake or investment – make further change faster and easier.
- **Learning-by-doing** is a positive feedback. It is the process by which firms reduce costs and enhance performance through experience gained from repeated production or deployment of a technology. Some technologies have stronger learning-by-doing than others.¹⁸
- **Economies of scale** are another positive feedback. There are cost advantages that arise when producing at larger volumes, as fixed costs are spread over more units and inputs can be used more efficiently. Cost reductions tend to lead to increased demand, in turn driving higher volumes of production.
- A tipping point is the critical moment when a system shifts from one state to another, with reinforcing feedbacks (those that amplify change) becoming dominant over balancing feedbacks (those that maintain stability). In transitions, it marks the stage where change is self-sustaining and accelerates without continued external pressure, and is likely to have become irreversible.¹⁹



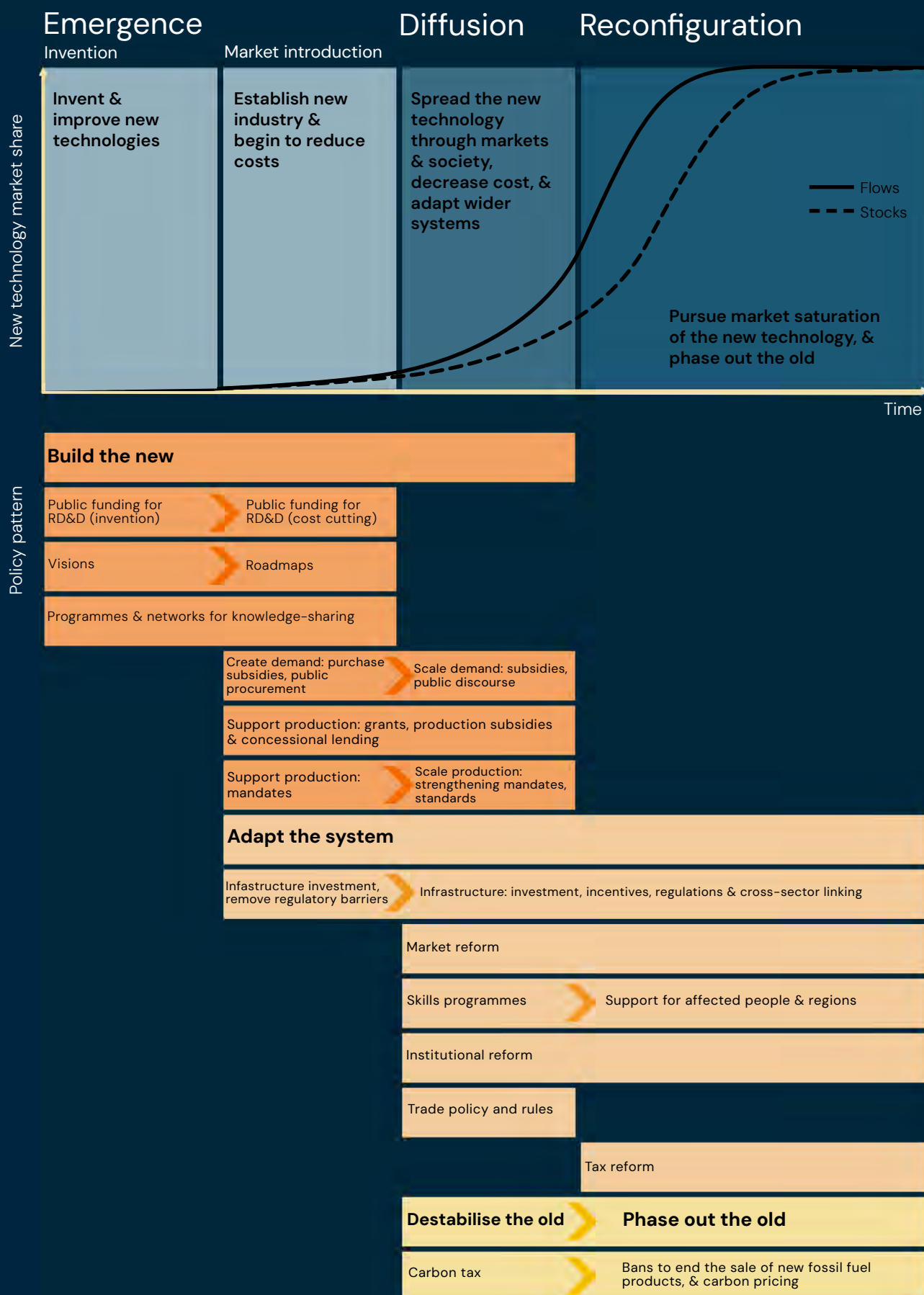


Figure 1. The Accelerating Transitions Framework for policy. Note: The figure illustrates the stages of the transition in a given sector, the policy aims at each stage, and the policies likely to be effective at each stage. The market share of the new technology follows an s-curve, first growing slowly, then accelerating, before plateauing as the transition nears completion. The solid s-curve represents flows (sales or investment, such as annual car sales). The dashed s-curve represents stocks (products or assets in use, such as total car fleet). Once flows change, a shift in stocks becomes inevitable, but it has a time lag which is longer in sectors where assets have longer lifetimes. The 'new technology market share' numbers shown are only roughly illustrative. This is a generalised framework: the specifics will differ across sectors and countries. Source: authors.

Figure 1 illustrates these stages of the transition, and the policies that are typically able to advance the transition at each stage. Of course, each transition is unique, and the specific policies that will be effective depend on the sector, and on local circumstances. The boundaries between stages of a transition are not precisely defined, and often a policy can be helpful in carrying the transition from one stage to another. The 'new technology market share' numbers shown in this figure are only roughly illustrative; the distinctions between stages are far better understood qualitatively than quantitatively.

Leaders and followers

This process of transition occurs at both global and national levels.²⁰ In each sector, leader countries drive technology innovation and cost reductions, from which all other countries can benefit.²¹ This creates the conditions for follower countries to start transitions at the Market Introduction stage, with their initial challenge being to make the new technology work in their national contexts. Not every country must invent each technology, but ultimately every country must deploy the new technology and adapt its systems to accommodate it. Technology is mainly global, but deployment and on-the-ground solutions are generally national.

Most countries respond to the global transition in each sector, rather than leading it. System transitions in 'follower' countries to a large degree involve similar processes to those in leader countries from the Market Introduction stage onwards. The focus of Market Introduction nationally after it has already taken place globally is likely to be on making the technology work in context, for example by adapting materials (e.g. heat-resistant solar photovoltaics (PV) in desert countries, or batteries that can function in low temperatures for electric vehicles (EVs) in cold countries) or business models (e.g. truck leasing instead of purchasing) to cater to different geographical or consumer sensitivities. By drawing on experiences from other countries, a follower country may be able to move from Market Introduction to Diffusion faster than global leaders did.

Structure of this report

This report is organised according to the stages of the transition. For each stage, we first discuss in general terms the challenges faced and the policies that are likely to be helpful. We illustrate these with case studies from historical technology transitions, and from current progress in the zero-carbon transition.

²⁰ Nemet, G. F. (2019).

²¹ Ibid. See also Beise, M. (2004). *Lead markets: Country-specific drivers of the global diffusion of innovations*. Research Policy. 33. pp.997–1018.

How to fund transition policies

The transition to zero-carbon systems in power, heating, transport, and industry may represent a net saving over the long run, rather than a net cost, if the costs of clean technologies continue to fall. However, even if that is the case, there will be short-term costs associated with many of the policies discussed in this report, such as those aimed at developing and deploying new technologies, or building new infrastructure. How should these costs be funded, in a context of fiscal constraints and competition with other spending priorities?

The funding needs and options vary according to the stage of the transition.

Emergence I: Invention

Public funding in the Invention stage is needed for research, development, and demonstration of new technologies. Public grants concessional lending, and private equity investment may also be needed to bring new technologies to first commercialization.

Most countries do not need to undergo the Invention stage in most transitions; instead, they can use solutions invented elsewhere and begin at the Market Introduction stage. In the countries that do lead the Invention stage, governments are likely to have existing budgets and programmes for public RD&D funding. Using these to support the zero-carbon transition can be a choice of priorities, rather than necessarily involving additional spending.

Private sector investment in research and development can also contribute to progress in the transition. More such investment is likely to be aligned with the transition if the government has indicated a clear political commitment to this direction of travel.

Emergence II: Market Introduction

At the Market Introduction stage, the major need for public funding is for targeted subsidies to enable the first deployment of the new technologies. Well-designed policies of this kind can mobilise private investment, by making the new technologies commercially viable.

One option is to raise funding within the sector, from a levy on the end-product or service (such as a levy on electricity to pay for renewable subsidies), or from a tax on the sale of fossil fuel products (for example, a tax on sales of petrol cars to fund a subsidy on electric vehicles). We discuss this option further in section [2.3 Policy design principles for Market Introduction](#). Targeted funding can also come from the reorientation of existing budgets of sectoral ministries, but this means that other sectoral priorities receive less funding, which may be politically contested. An alternative approach is to draw on government funds raised through general taxation. The first approach can be justified by the principle that the consumers of a given product or service should pay its full costs; the latter can be justified by the public interest in reducing the risks of climate change. In practice, the differences to consider are distributional, political, and in some sectors, related to international competitiveness. In many countries, the government's ability to borrow to fund investment will also be a consideration.

Diffusion

As the transition enters the Diffusion stage, the main challenge for policy is to reallocate private sector investment from the old technology to the new technology and its infrastructure. This can be achieved through incentives and regulations, as described in [3.2 Policies to accelerate the Diffusion stage](#).

To the extent that public funding is still needed, the sources of funding are largely the same as in the previous stage, but the actual instruments tend to focus on reducing risks for private investors (e.g. concessional lending, loan guarantees). The difference is that in Diffusion, public investment is likely to be a far small proportion of the total investment in the new technologies.

In principle, carbon pricing presents a third option to generate funding, although difficulties may arise if the carbon price is designed to achieve a policy goal rather than to raise the necessary amount of revenue. We discuss the role of carbon pricing as a policy lever for the transition in sections [3.2 Policies to accelerate the Diffusion stage – Scale up demand](#) and [4.2 Policies to accelerate the Reconfiguration stage – Carbon prices and regulations](#).

Reconfiguration

In the Reconfiguration stage of the transition, public funding may be most needed for providing support to workers who have lost jobs in declining industries, or for supporting economic diversification and development in regions where the old industries were located. These needs are not unique to the zero-carbon transition and can be financed using existing social security funds and regional development programmes that mitigate the effects of structural change in the economy. The issue for governments (or providers of international development assistance) to consider in the allocation of these funds is which workers and which places are at highest risk, at any given time.

A problem that governments may need to consider in parallel during the Reconfiguration stage is how to replace any lost tax revenues from declining industries. Options include taxing the new technologies or industries, the service provided, or the use of public infrastructure (for example road taxes to replace fuel taxes).

1. EMERGENCE 1: INVENTION

1.1 Overview

Invent and improve new technologies

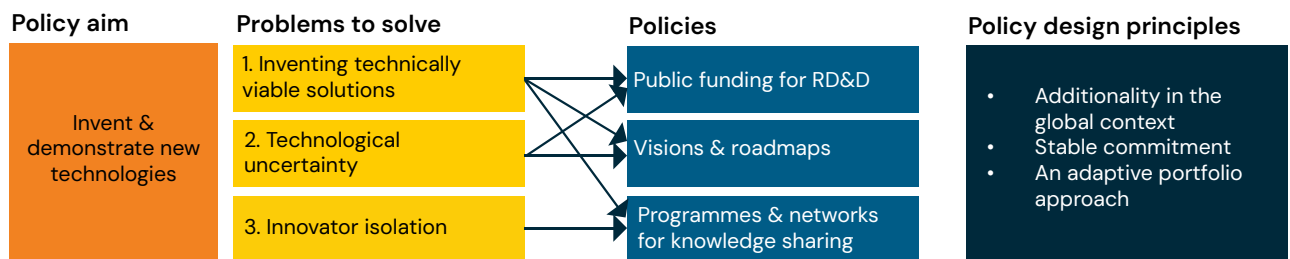
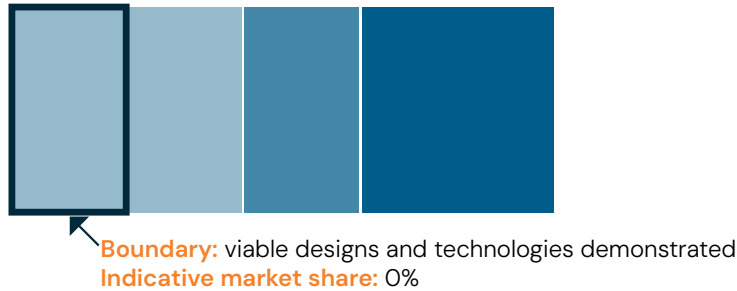
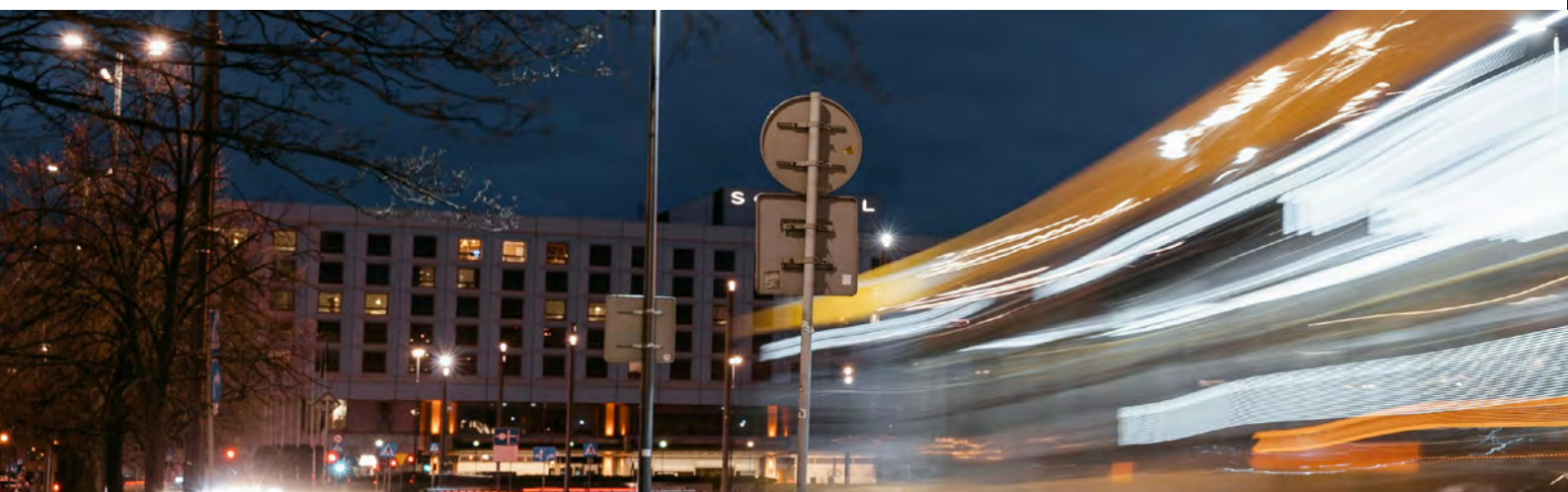


Figure 2. Emergence I: Invention – Overview of aims, problems to solve, policies, and policy principles.
Source: authors' own.

Aim: Policymakers' aims at this stage of the transition in a given sector are to stimulate the invention, identification, and development of viable zero-emission technology solutions. The focus during Invention is to establish basic technical functionality and to explore the pros and cons of different designs (as technologies usually emerge as a variety of designs, based on how sub-systems and components are combined).

The process: Important inventions can come from government-funded research labs, from the research and development programmes of businesses active in the sector, and from independent entrepreneurs and start-up companies. Initially, the inventions are low-performing, expensive, and unproven in their ability to solve a problem. Continued improvement and testing can take place in demonstration projects, or in small application domains for niche customers. In past transitions, these have often included the military, and wealthy enthusiasts.



Early applications enable learning on how to improve performance. This is an evolutionary process, in which many technologies, and design variations within them, compete. During the Invention stage for zero-emission passenger transport, there was innovation in biofuels, electric vehicles, and hydrogen fuel cell vehicles, and in different biofuel types, battery chemistries, and hydrogen storage options.

Eventually, a technology will reach the stage where learning from production and use becomes important and possible. Typically, a 'dominant design' (e.g. wind turbine), or various design options (e.g. two- and three-spoked wind turbines), must emerge for businesses and investors to have sufficient certainty to introduce the new technology into the market.²² This indicates the end of this stage. Innovation has not ended. Experimentation with alternative technologies and designs can persist for some time, but from now on, the space for competition broadens to include markets as well as labs.

Problems to solve

1. Inventing technically viable solutions

Inventing viable technological solutions is a high-risk process, with high rates of failure. Most inventions never reach commercial viability, making 'waste' an inherent part of the discovery process. Successful innovation demands tolerance for risk and political pressure, as visible failures can be misinterpreted as policy failure, rather than a necessary step towards success.²³

2. Technological uncertainty

Early on, new technologies tend to have low performance, high costs, and many teething problems in application. Businesses may be reluctant to make deep investments in developing new zero-carbon technologies, as it is unclear whether these new technologies will ever be able to compete with existing technologies, and also unclear which technology variation will prove most viable. Future performance, cost, customers, and market size are all uncertain. Businesses and investors do not want to bet on the wrong option, and therefore they often adopt a 'wait-and-see' attitude in the early stage, or invest small amounts of seed money.²⁴

3. Innovator isolation²⁵

Innovators are often isolated from one another, from industry stakeholders, and from policymakers or regulators. This can lead to ideas being underdeveloped, under-resourced, or undervalued, owing to lack of exposure or complementary knowledge, or lead to failure through the absence of necessary regulatory change.

22 Utterback, J. M. & Abernathy, W. J. (1975). *A dynamic model of process and product innovation*. Omega. 3. pp.639–656.

23 Rosenberg, N. (2009). *Uncertainty and Technological Change*. In: Nathan Rosenberg (ed.), *Studies on Science and the Innovation Process*. Selected Works of Nathan Rosenberg, Chapter 8, pp.153–172, World Scientific Publishing.

24 Mazzucato, M. (2013). *The Entrepreneurial State*. Anthem Press; Perez, C. (2002).

25 Schot, J. W. & Geels, F. W. (2008). *Strategic niche management and sustainable innovation journeys: Theory, findings, re-search agenda, and policy*. Technology Analysis & Strategic Management. 20. pp.537–554.



Example: Cement

The cement industry is responsible for about 8% of global CO₂ emissions. CO₂ is produced in two ways: 40% from burning fossil fuels to generate the high temperatures needed to produce cement from limestone; and 60% as a chemical by-product from converting limestone (calcium carbonate) into calcium oxide (an input into clinker). Decarbonisation can be achieved through carbon capture and storage (CCS), and by using an alternative input to limestone that does not produce CO₂ when processed.²⁶ While CCS is in principle already viable, the search for alternatives to limestone continues, and uncertainty around all options means that the transition remains at the Invention stage.

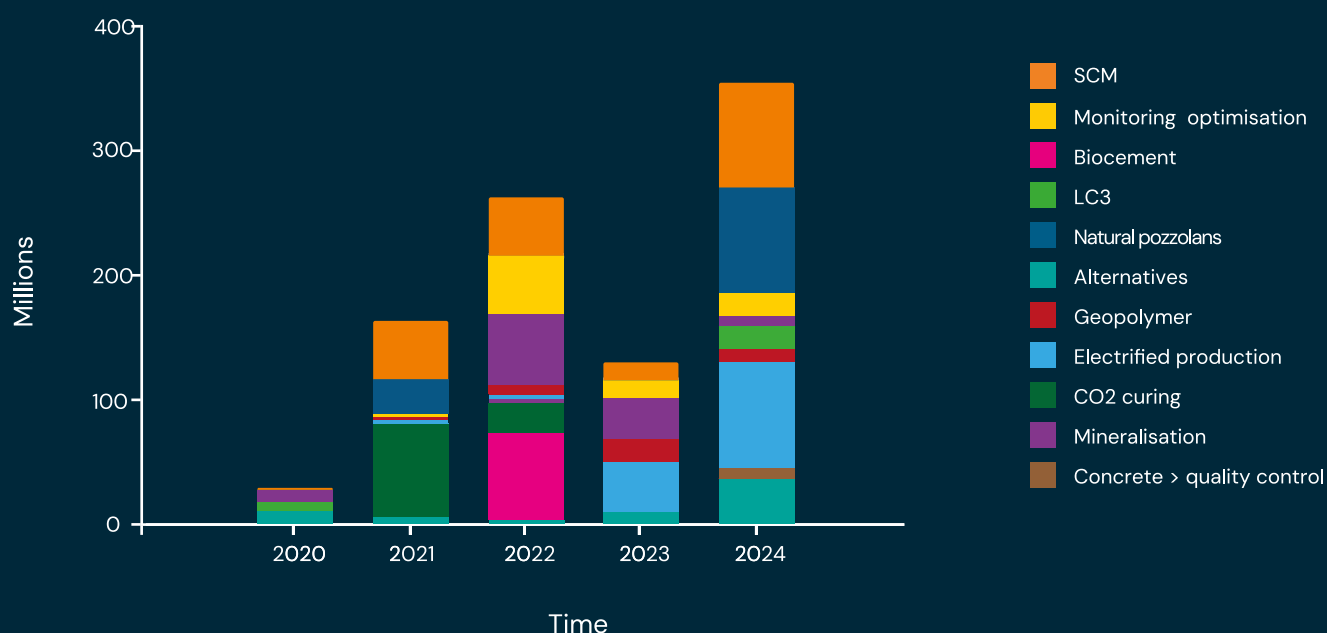


Figure 3. Cement and concrete innovation attracted \$371.9m in 2024, a record high – and innovation is going into a range of solutions.²⁷ Source: Lopez, B. (2025).

Inventing technically viable solutions: Existing novel technologies for cement production (such as using basalt, a carbon-free calcium silicate rock, instead of limestone) are reaching the stage of demonstration and planning for first commercialisation, and have been estimated to be 5–10 years from commercial deployment.²⁸ Industry continues to seek new solutions from the start-up community, as the viability of existing innovations for limestone substitutes or alternative clinker chemistries is uncertain. Options identified so far are relatively high cost. For example, the use of CCS is estimated to add 40–140% to the cost of cement.²⁹

26 Ritchie, H. (2024). [How to decarbonise the world's cement](#). Sustainability by numbers.

27 The '\$' sign refers to USD throughout the report.

28 Slaybaugh, P. (2023). [Brimstone's \\$189 million federal award is a game-changer for cement decarbonization](#). DCVC; WBCSD (2024). [Business Breakthrough Barometer Concrete & Cement](#).

29 A summary of different research and estimates is available at Ritchie, H. (2024). [Could low-carbon cement and steel be cheaper than we think?](#) Sustainability by numbers.



Uncertainty: The cement industry is responding to uncertainty about viable zero-carbon technologies and future revenues by focusing on improving material efficiencies and deploying carbon capture, use, and storage (CCUS), as short- to medium-term solutions. Investment in innovation remains low relative to the sector's emissions profile.³⁰ This lack of investment risks holding back the transition: even after new cement types for deep decarbonisation are developed, it will be necessary to gather performance data over years, or perhaps decades, before these become appropriate for many high-risk uses, such as bridges. The global cement association is asking for public R&D support, and other risk-sharing investment mechanisms.³¹

Isolation: The Global Cement and Concrete Association has recognised the need for collaboration between innovators, and has established an entrepreneur network providing mentorship, networking and other opportunities. In 2024, leading start-up companies working on decarbonising cement in North America launched an alliance to engage the public sector, which is responsible for over half of concrete purchases in the US, in creating policies supporting the use of low-carbon cement in public infrastructure.³²

In summary, the cement sector faces challenges that are typical of the Invention stage of the transition. Policies of the kind set out below may be appropriate to address these challenges.

30 WBCSD (2024).

31 GGCA (2021). [Concrete Future – The GGCA 2050 cement and concrete industry roadmap for net zero concrete.](#)

32 BusinessWire (2024). [leading climate startups launch alliance to engage public sector in reducing emissions from cement and concrete.](#)

1.2 Policies to accelerate the Invention stage

1. Public funding for Research, Development, and Demonstration

Public funding for research, development and demonstration (RD&D), typically in the form of grants and subsidies, can stimulate the development of technically viable, high-performance, and low-cost zero-emission solutions. Public support can overcome private sector reluctance to invest in high-risk solutions, and increase the overall resources for RD&D activities.

The development and testing of a wider range of technologies can help to identify technologies that may be able to compete successfully against incumbents over time. Many can be expected to fail, but with sustained investment in a portfolio of options, there is an increased chance of at least one successful option emerging.

2. Visions

A clear policy objective (often called a 'vision' or 'mission'), signalling desired technology capabilities, characteristics, or outcomes, can build a collective sense of where solutions are needed, helping to align the activities of innovators.³³

Vision documents can be developed collaboratively between government, industry, and researchers, and can mobilise diverse actors in pursuit of shared goals.³⁴ This can help attract resources, attention and collaboration. The increased clarity of collective intent can enhance business and investor confidence, attracting more capital into technology development.

At the next stage of the transition, Market Introduction, when the direction of innovation has become more clearly established, these initial mission statements or vision documents can be developed into more detailed technology roadmaps. Roadmaps can set goals and timelines for experimentation, market entry, and scale. They can support policy coherence as a framework for planning the use of various policy instruments in a strategy spanning the innovation cycle. Roadmaps can be adapted as a technology develops and uncertainty reduces.³⁵

3. Programmes and networks for knowledge-sharing

Knowledge-sharing programmes and networks enable innovators to discuss and exchange information, and to collaborate on the development of new solutions. These can take the forms of multilateral innovation programmes, national and regional innovation networks, open-access knowledge platforms and databases, cluster-based industrial innovation hubs, challenge-based and prize programmes, and regional knowledge exchanges. Their use reduces the risk of isolation of innovators and stagnation in technological progress.

As well as connecting innovators with each other, network-building programmes can also connect inventors with industry and policymakers, potentially enabling access to co-design and commercialisation opportunities, and allowing policy and regulation to be informed by technological developments. They may also increase access to otherwise inaccessible funding opportunities, technical infrastructure, and mentorship.

33 Mazzucato, M. & Dibb, G. (2019). *Missions: A beginner's guide*. (IIPP Policy Brief 09). UCL Institute for Innovation and Public Purpose.

34 Ibid.

35 For example, see the US Department of Energy's [ARPA-E Strategic Vision Roadmap](#), and the specific [Hydrogen Program Plan](#), which provided more sector-specific details. and concrete.

1.3 Policy design principles for Invention

1. Additionality in the global context

No country needs to invent all the technologies for its own zero-carbon transition. Often invention is done elsewhere in the world, and a country can either import the technologies or its industries can develop their own versions to be sold domestically or internationally.

A country is most likely to contribute to advancing the Invention stage of a global transition if it concentrates effort in areas where it has relevant industrial strengths. These can be identified through analysis of export data,³⁶ industrial consultation, and assessments of relevant national skills and resources.

For example, the government of South Korea's decision to develop industrial competitiveness in hydrogen fuel cells and battery technology leveraged existing industrial capabilities in semiconductors, chemicals, advanced materials, and precision manufacturing, enabling companies to make use of extensive experience. The government introduced a policy framework in 2005 for green hydrogen, which outlined a vision and high-level approach, a second strategy was announced in 2015, and its 2019 Hydrogen Economy Roadmap expanded ambition from world-class technology in utilisation towards production, storage, and transportation.³⁷ Both plans emphasised government-led R&D,³⁸ and the latter put a major focus on leading on domestic and overseas clean hydrogen production.³⁹ R&D projects led by the private sector and supported by public research institutes and government departments focused on areas including hydrogen extraction from ammonia, hydrogen gas turbine demonstration, liquefied hydrogen storage for rail transport, and hydrogen port demonstration projects.⁴⁰ South Korean companies including LG Energy Solution, SK On, and Samsung SDI now play a major role in the global market for batteries, and the country accounts for nearly half the world's supply of fuel cells.

2. Stable commitment

Setting out a clear vision for a future direction of technology development will only have its desired effects – aligning activities of innovators, and building confidence of investors – if the government remains committed to this vision over a sufficient period of time. While the specific policies used to transform the vision into reality may change, stability of political commitment and policy intent is important to realising policy objectives.

For example, from the early 2000s, China pursued a strategic vision to develop competitiveness in 'new energy vehicles', motivated by energy security, the potential to increase competitiveness in automotive manufacturing, and reducing air pollution. This vision was maintained through successive five-year national development plans, and supported with funding of R&D, and other policies. Two decades later, China now produces over 60% of the world's electric vehicles as well as most of the batteries that power them. China achieved this both by increasing its research and innovation capacity in the electric vehicle industry, and by building innovation capacity in related industries. This included increasing the number of engineering graduates from 360,000 per year in 2000 to 1.8m per year in 2018.⁴¹

36 Economic complexity analysis (with tools such as [Greenplexity](#) or [Green Transition Navigator](#)) can be used to identify products where a country may have potential to develop comparative advantage, but this needs to be interpreted with caution and should be complemented with qualitative assessment.

37 Sung, J. & Sergeeva, Z. (2024). Role of hydrogen in meeting South Korea's economic, environmental, and strategic targets. In: Shabaneh, R. et al. (eds.) *The Clean Hydrogen Economy and Saudi Arabia*. Routledge; Cho, A., Kim, H. & Park, S. (2024). *Resurgence of the hydrogen energy in South Korea's government strategies from 2005 to 2019*. *International Journal of Hydrogen Energy*. 6. pp.844–854.

38 Cho, A., Kim, H. & Park, S. (2024).

39 Shin, J.-E. (2022). *Hydrogen technology development and policy status by value chain in South Korea*. *Energies*. 15(23).

40 CSIRO (2022). *Hydrogen RD&D Collaboration Opportunities: The Republic of Korea*.

41 Statista (2025). *Number of bachelor's degrees* awarded in science and engineering (S&E) fields in selected countries world-wide from 2000 to 2018*.

In the wind sector, Denmark provided consistent, long-term investment in R&D and coordinated policy support. In Denmark, R&D support in the late 1970s helped to identify the three-bladed wind turbine as a standard design, and consistent financial support and priority grid access backed by clear political commitment provided security to private investors. This early technology support and experience in large-scale installations provided Danish manufacturers with a first-mover advantage over competitors in foreign countries, and in the 1980s, Danish companies formed an international reputation which continues today.

At the same time, there is a tension between the stability of commitment needed to succeed, and the flexibility to adapt and adjust when circumstances change or knowledge of particular technologies increases – potentially discovering that some are not as viable as previously thought, or that better options exist. This leads to the next principle: an adaptive portfolio approach.

3. An adaptive portfolio approach

Technology uncertainty is highest at the Invention stage of the transition. A portfolio approach enables multiple options to be explored simultaneously. Then, through monitoring, evaluation, and competition, the most promising technologies can be identified and scaled up. This mitigates the risks of potentially promising technologies being ignored, or of premature commitment to technologies that are later discovered to be flawed. Policies designed to be adaptive can more easily respond to unforeseen changes, exploit opportunities, and manage risks (including by discontinuing investment in a certain technology). While there should be policy commitment to solve a challenge, flexibility about which technologies will solve that challenge can allow adaptation in response to emerging information. The tension between the need for sustained commitment to a technology to enable it to succeed, and the need to remain flexible and open to new options, can never be entirely resolved: it is a dilemma, requiring careful navigation.

The US's ARPA-E agency was created in 2009 to fund a diversified portfolio of high-risk, high-reward clean technology RD&D projects.⁴² The agency monitors progress and reallocates funding based on companies' performance and technology success. Funding of \$4bn supported around 1,700 projects and over 160 companies with 32 exits worth \$22.2bn in value at the time the deals were made.⁴³ These projects supported advancement in battery chemistries, grid-scale energy storage, next-generation nuclear power, CCUS, and high-efficiency solar and wind power technology.

42 Azoulay, P., Fuchs, E., Goldstein, A. & Kearney, M. (2019). *Funding breakthrough research: Promises and challenges of the ARPA model*. Innovation Policy and the Economy. 19. pp.69–96; IEA (2021). *Advanced Research Projects Agency for Energy (ARPA-E)*.

43 ARPA-E (2025). *ARPA-E at a glance – Impact*.

Matching policies to the stage of the transition – Germany's hydrogen trains

There are many instances in which governments have used policies appropriate to one stage of the transition during another stage, and where those policies have not achieved the desired objective. One example may be a local German government's focus on the market introduction of hydrogen powered trains, before it became clear whether hydrogen or battery-electric would be most viable. In 2018, the first two hydrogen trains ever were put into commercial operation by a company owned by the government of Lower Saxony, and the government invested more than €93m in 14 trains between 2018 and 2022. But in November 2022, a study concluded that line electrification or battery hybrid⁴⁴ trains would be far cheaper over 30 years, and in the same year, the public transport company that had introduced them ruled out their further use and announced the replacement of remaining diesel trains with battery-electric.⁴⁵ The government had attempted market introduction with insufficient evidence on technological viability, particularly cost reduction potential. This is an inevitably challenging balancing act given the urgency of decarbonisation, particularly in sectors that are off-track for a transition in line with climate change goals.

44 Battery hybrid trains are powered by a battery that is recharged on sections of track with overhead power lines.

45 Baden-Württemberg Ministerium für Verkehr (2022). *Klimaneutral auch ohne Oberleitung* (summary translation at London Reconnections, 2022: *German state no longer considering hydrogen trains*); Hydrogen Insight (2023). *No more hydrogen trains – rail company that launched world's first H2 line last year opts for all-electric future*.

1.4 Case studies for Invention

The case studies in each section include examples of historical technology system transitions, as well as recent and current examples of transitions to zero- or near-zero-carbon technologies. They cross time-periods, countries, and sectors. While each is unique, together they illustrate the pattern in the process of transitions and the policies that typically contribute to progress at each stage.



CASE STUDY 1

The historical use of R&D policies: The invention and early development of turbojet engines (1930–1945)

The emergence of turbojet engines (Figure 4) is a good example of the importance of R&D policies in stimulating radical innovation, albeit in wartime context.⁴⁶ It shows how stable commitment to the vision of higher-performance planes, with innovation policies sustained over time, drove dramatic technological improvement.

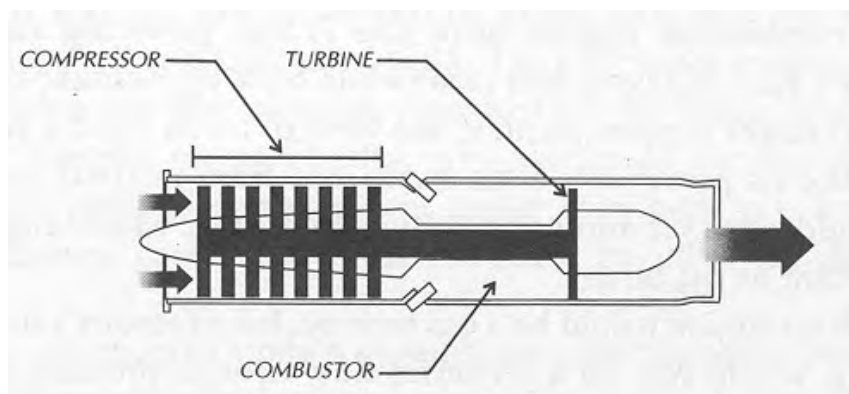


Figure 4. Schematic representation of turbojet engine. Source: Heppenheimer (1995).⁴⁷

Context

The propeller aircraft of the early twentieth century were limited in the speed and altitude that they could reach. Traditional propellers did not work well at high altitudes or high speeds because of thin air and physical limits on how fast propellers could spin.

In the early 1930s, three relative outsiders in the emerging aerodynamic science field (Whittle in the UK, von Ohain and Wagner in Germany) came up with a new engine design to solve these problems: the turbojet engine. It worked by sucking in air, compressing it, mixing it with fuel, igniting it to create hot, expanding gases, and then using that force to create thrust and move the plane forward.

The turbojet pioneers struggled to gain funding and interest from aeronautic firms, researchers, and policymakers.⁴⁸ One reason was the belief that technical progress in piston engine-propeller aircraft would continue, negating the need for alternatives. Another reason was that earlier research into turboprop engines (using gas turbines rather than piston engines to power propellers) had failed, leading to negative views on gas turbines.

46 Geels, F. W. (2006). *Co-evolutionary and multi-level dynamics in transitions: the transformation of aviation systems and the shift from propeller to turbojet (1930–1970)*. *Technovation*. 26. pp.999–1016.

47 Heppenheimer, T. A. (1995). *Turbulent Skies: The History of Commercial Aviation*. John Wiley & Sons.

48 Constant, E. W. (1980). *The Origins of the Turbojet Revolution*. John Hopkins University Press.

Whittle acquired a patent on jet engines in 1930 and spoke with the Air Ministry and several aero-engine firms who showed no interest. He formed a company and ran a prototype which faced technical challenges – as did the others in their own experiments.⁴⁹

R&D policy in response to a changing context

Increasing geo-political tensions in the late 1930s spurred public military R&D funding, including for alternative aero engines. Whittle got a small R&D contract to further develop the jet engine, and by mid-1939 successfully demonstrated its potential to the UK Air Ministry. In Germany, Wagner and von Ohain linked up with existing firms and successfully ran jet aircraft prototypes in 1937 and 1939.⁵⁰

While the technical feasibility of jet engines was demonstrated by the late 1930s, increased government funding for R&D projects enabled researchers to address many bottlenecks, venturing into unknown areas of high temperatures, high airflow speeds, supersonic aerodynamics, and high tensile material stress. R&D focused on combustion (chamber design, fuel injection methods, and the mixing of air and fuel), turbine design (blade shape and ability to withstand high temperatures and shockwaves),⁵¹ compressor designs, and thrust (heat-resistant materials such as nickel–chromium alloys).

Results



Figure 5. The 1942 Messerschmitt Me 262 Schwalbe (left), 1944 Gloster Meteor (middle), and 1947 F-86 Sabre (right). Sources: AsisBiz; Gloster Meteor Centenary of Military Aviation (2014); Wikipedia (n.d.).

Increased funding and successive R&D projects generated impressive performance improvements, so that jet engines by the end of the war produced between 2,000 and 4,000 lb of thrust (four to eight times that of the 1939 prototypes). Early jet engines were powerful but had high fuel consumption, limiting their range. Jet engines were therefore first deployed as interceptor fighters.

America, whose engineers developed jet engines during the war building on a knowledge-sharing arrangement with Britain in 1941, built some of the most powerful jet engines, which in 1947 powered the F-86 Sabre jet fighter (Figure 5), reaching a speed of up to 1,225 km/h.

⁴⁹ Ibid

⁵⁰ Gunston, B. (1997). *The Development of Jet and Turbine Aero Engines*. J. H. Haynes & Co Ltd.

⁵¹ Ibid

CASE STUDY 2

Public support for network building and knowledge-sharing: Austrian biomass district heating systems (1970–2013)

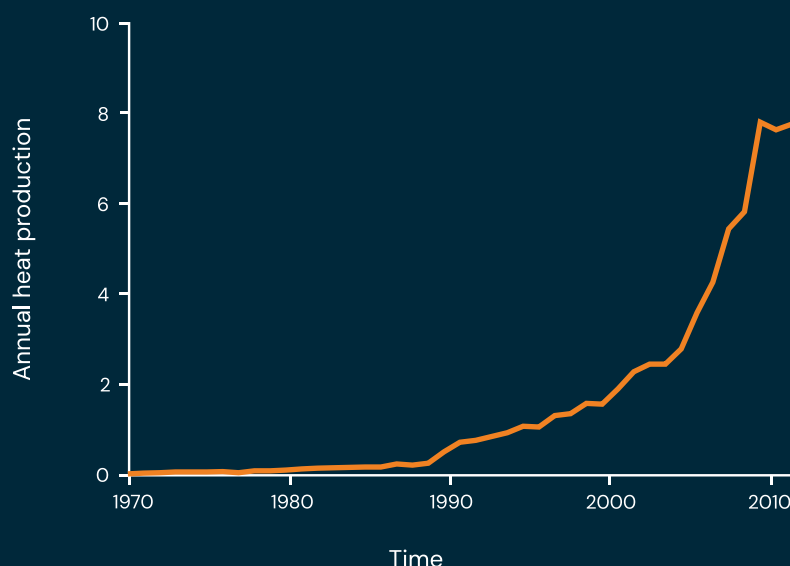


Figure 6. Annual heat production (in TWh) from Austrian biomass district heating. Source: Statistik Austria (2015).⁵²



Figure 7. The chain of custody for bioenergy. Source: Klimaaktiv (2020).

Network building and knowledge-sharing were important in the emergence of biomass district heating (BMDH) systems in Austria in the 1970s and 1980s, which subsequently diffused slowly in the 1990s and expanded rapidly in the 2000s (Figure 6). Once the technology had been identified as an economic opportunity, stable commitment to the industry over several decades laid the foundations for Austrian manufacturers to become leading exporters of pellet boilers (a technology closely related to BMDH).

BMDH systems were pioneered in the 1970s by sawmill owners, carpenters, monasteries, and agricultural cooperatives, who used surplus wood to generate heat in a boiler and sell this to nearby households or public buildings (e.g. schools, hospitals, town halls) in rural villages (Figure 7). Early plant operators operated independently, did not share information, and were secretive about operational problems.⁵³

The early 1980s were characterised by ‘spontaneous’, word-of-mouth information sharing between neighbouring villages and site-visits from entrepreneurs who were keen to replicate successful BMDH-schemes in their own village.⁵⁴

⁵² Statistik Austria (2015). *Energy Balances, Austria 1970–2013 detailed information*.

⁵³ Geels, F. W. & Johnson, V. (2018). *Towards a modular and temporal understanding of system diffusion: Adoption models and socio-technical theories applied to Austrian biomass district-heating (1979–2013)*. *Energy Research & Social Science*. 38. pp.138–153.

⁵⁴ Madlener, R. (2007). *Innovation diffusion, public policy, and local initiative: The case of wood-fuelled district heating systems in Austria*. *Energy Policy* 35. pp.1992–2008.

From the mid-1980s onwards, dedicated network-building and knowledge-sharing activities were undertaken. Provincial policymakers, who perceived BMDH systems as providing opportunities for the socio-economic revitalisation of rural areas with unemployment, declining industrial base, and depopulation, created energy agencies that provided technical advice, training, and financial support for BMDH developers, and improved communication between BMDH operators and component suppliers to reduce operational problems.⁵⁵ BMDH-related actors created the Austrian Biomass Association, which organised workshops, compared local experiences, and formulated generic lessons that were disseminated through workshops or brochures. Although early BMDH systems often experienced operational problems such as technical over-dimensioning or connecting too many dispersed buildings (lowering techno-economic performance), problems gradually diminished during the 1980s (Figure 8) as a result of learning processes and knowledge sharing.

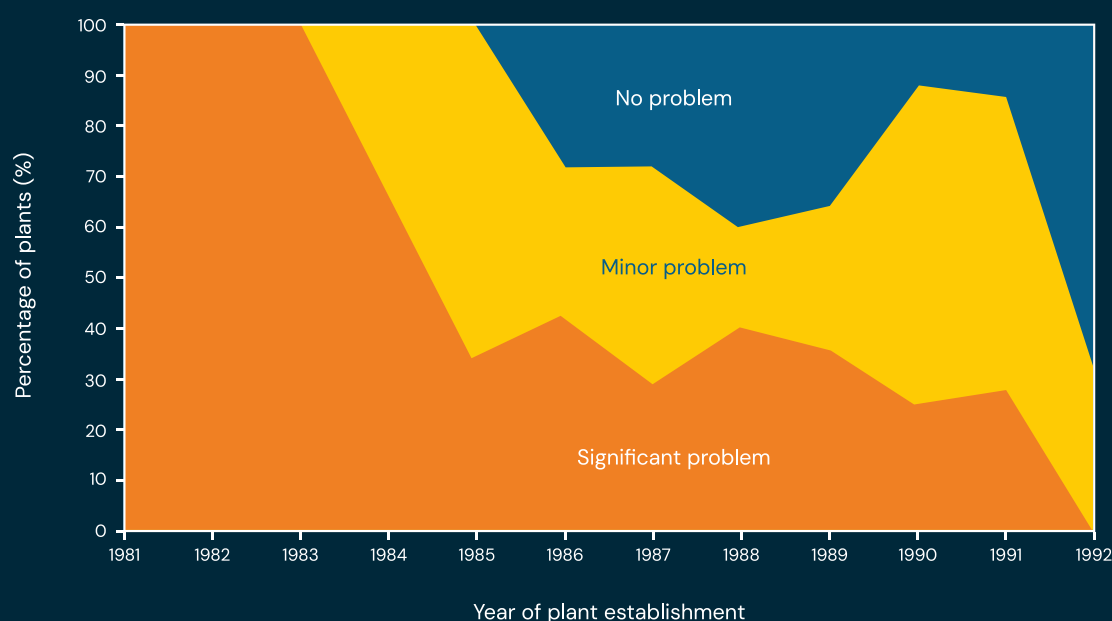


Figure 8. Operational problems in early BMDH plants, 1981–1992. Source: Rakos (2005)⁵⁶.

Performance improvements and cost reductions prepared the ground for the increasing use of village-scale BMDH systems from the 1990s onwards. This was supported by the federal Ministry of Agriculture, which in the early 1990s introduced additional financial support. This led to total subsidies and capital grants that could amount to 60% of investment costs,⁵⁷ significantly reducing the commercial risks. By the mid-1990s, policymakers began to see BMDH as a potential response option to climate change, leading to its inclusion in the 1995 Environmental Promotion Fund. The Green Electricity Act (2002) introduced a feed-in tariff for combined heat and power (CHP) plants that used BMDH systems to generate both electricity and heat. This enhanced the interest from energy utilities, who came to see BMDH-CHP plants as offering attractive business opportunities and as a way to meet renewable electricity targets. Increased investment from these powerful incumbent firms boosted the diffusion of this new BMDH option, which operated at much larger scale from the mid-2000s.

BMDH diffusion in the 1990s and 2000s stimulated complementary innovations in biomass collection and processing, prefabricated heat pipes (which reduced infrastructure installation costs and increased system efficiencies), and pellet boilers (which became easier to handle and more fuel-efficient). The creation of specialised clusters and supply chains made Austrian manufacturers world-leading exporters of pellet boilers.⁵⁸

⁵⁵ Rakos, C. (2005). Dissemination of biomass district heating systems in Austria: Lessons learned. In: Silveira, S. (ed.) *Bioenergy – Realizing the Potential*. Elsevier, pp.138–153.

⁵⁶ Rakos, C. (2005). pp.47–58.

⁵⁷ Geels, F. W. & Johnson, V. (2018).

⁵⁸ Ibid.

CASE STUDY 3

Network-building & knowledge-sharing: UK Offshore Wind (2008–present day)

Publicly funded network building and knowledge-sharing played a role, together with R&D, in cutting the costs of offshore wind in the UK, and making projects commercially viable. The UK had good natural conditions for offshore wind, high-quality research capabilities, and relevant industrial expertise in onshore wind and offshore oil and gas engineering. These conditions enabled innovation in the UK to be additional to global efforts, significantly advancing the development of offshore wind and making it available for use by other countries.

Context

Offshore wind was identified early as an attractive energy source for the UK, owing to a mixture of natural and political factors: a long and windy coastline, a broad and shallow continental shelf, a commitment to decarbonisation, not much sunlight, and opposition among some constituencies to onshore wind. In 2006, when only 1.5% of the UK's energy came from renewable sources but the government had a provisional target to reach 15% by 2020⁵⁹ (later raised to 20%), offshore wind was seen as one of the most important parts of the solution,⁶⁰ and a challenge the UK could rise to given existing industrial expertise.

Subsidies for renewable power had been introduced in 2002 (in the form of a portfolio standard with tradeable green certificates, known as the Renewables Obligation), but the 'technology-neutral' design of this policy meant that it only supported more mature technologies such as onshore wind, and not offshore wind. The UK's first offshore wind demonstration project had opened in the year 2000, and the first commercial project was launched in 2003 off the North Wales coast,⁶¹ with a £10m grant from the Department of Trade and Industry,⁶² but at this stage the technology was prohibitively expensive, relatively untested, and had close to zero market share.

The Carbon Trust and the Offshore Wind Accelerator

The Carbon Trust was established by the UK Government in 2001 as a publicly funded, business-led institution, to enable collaborative RD&D and to facilitate knowledge-sharing for decarbonisation.

In 2008, the Carbon Trust created the Offshore Wind Accelerator (OWA), which brought together nine leading offshore wind developers to collaborate on R&D, with the aims of solving technical challenges, commercialising solutions, and reducing costs. The OWA was funded by large industry players including ScottishPower Renewables, SSE, Equinor, and Orsted, as well as indirectly supported by the government through its funding of the Carbon Trust.⁶³ Before this, the offshore wind industry had no established process for knowledge-sharing on technical issues, or even for sharing basic health and safety information as was obligatory in the oil and gas industry.⁶⁴

The OWA identified key technological challenges for the industry, and prioritised them based on their expected contributions to reducing costs.⁶⁵ It brought innovators and supply chain businesses together to solve these challenges, often by inviting them to submit proposed solutions in competitions. It then provided financial and strategic support to develop, de-risk, and commercialise the winning innovations. The OWA also commissioned joint research from industry and university partners to investigate collective challenges holding back the whole industry.

59 Smith, L. (2008). *The Renewable Energy Strategy*. Standard Note SN/SC/4831. House of Commons Library.

60 Ibid.

61 Catapult Offshore Renewable Energy & BVG Associates. (n.d.). *UK offshore wind history*.

62 Total project costs were £80m, all bar £10m of which was financed by the company's balance sheet. Commercial viability was enabled by the location, which had relatively shallow waters, strong wind speeds, and proximity to the national grid.

63 Later, the OWA also received direct funding from the Scottish government. See: Carbon Trust (2017). *The Scottish Government invests £1.5million into OWA to drive cost reduction in offshore wind*.

64 Jennings, T., Tipper, H., Daglish, J. et al. (2020). *Policy, innovation and cost reduction in UK offshore wind*. UCL & Carbon Trust.

65 Nguyen, B. (2020). *Innovation in UK Offshore Wind: how government can improve public-private collaborative R&D*. Kleinmanenergy.

Examples of the OWA's activities include:

- **Competitions:** In 2009, the OWA called for new designs for wind turbine foundations that would be better able to cope with conditions offshore. From 104 applications, four technologies were chosen and awarded funding.⁶⁶ Other competitions focused on vessels and access systems to facilitate access to offshore wind plants by technicians.⁶⁷
- **Research:** The OWA funded a project that investigated how monopiles (vertical, cylindrical steel foundations for offshore wind turbines, driven into the seabed) behave in different soil and environmental conditions. This enabled design methodologies to be refined, reduced fabrication costs, and provided insight on how to effectively develop larger monopiles in deep waters.⁶⁸
- **Technology validation:** The OWA led independent validation of floating LiDAR (light detection and ranging) systems to build confidence in the technology's reliability, developed guidelines for its use, funded trials, and coordinated an industry roadmap to pave the way towards full commercial acceptance.⁶⁹ LiDAR is used to measure wind profiles, which are crucial for understanding how much energy a wind turbine at a proposed site could generate. Reliable wind data reduces the risks for investors, and helps projects to secure financing. Floating LiDAR was an improvement over LiDAR on fixed platforms, which could not be used in deep waters.

In this way, the OWA took an integrated approach to coordinating knowledge development and knowledge-sharing, connecting industry, innovators, and researchers to solve common challenges.

Complementary policies

During the early years of the OWA's operation, other policies supported the UK offshore wind sector's transition from the Invention stage to Market Introduction. In 2008, the Crown Estate launched its third seabed leasing round, offering nine large zones for offshore wind development with a combined potential capacity of around 30 GW.⁷⁰ In 2009, technology banding was introduced into the Renewables Obligation subsidy scheme, resulting in a doubling of support for offshore wind.⁷¹ In 2013, this scheme was replaced by contracts-for-difference, allocated through auctions.

Results

The OWA's work increased the chances of innovations progressing to commercial deployment. As its industry members saw the advantages of sharing the costs of specific R&D projects, they became increasingly motivated to participate.⁷² Eleven years after the formation of the OWA, the cost of offshore wind in the UK had fallen dramatically – from around £170/MWh in 2008, to around £40/MWh for contracts struck in 2018.⁷³ Analysis estimated that in 2018, the levelised cost of electricity (LCOE) from an offshore wind plant using technologies commercialised by the programme would be 15% lower than that of an equivalent site not using those technologies.

66 Carbon Trust (2018a). [10 years of accelerating innovation](#).

67 Ibid.

68 Ibid.

69 Carbon Trust (2018b). [Carbon Trust Offshore Wind Accelerator Roadmap for the commercial acceptance of floating LiDAR technology](#).

70 Catapult Offshore Renewable Energy & BVG Associates (n.d.). [UK offshore wind history](#).

71 Alongside price support, an essential step for developing offshore wind projects was coordinating permissions to access the seabed. As owner of the British coastline, the Crown Estate began awarding leases for areas of the seabed from 2001, granting developers the right to install wind projects offshore. In accordance with a 2001 European directive, from 2003 the government conducted offshore energy strategic environmental assessments to guide the location of leasing sites. The Energy Act 2004 created a renewable energy zone adjacent to UK territorial waters, expanding the area eligible to be leased.

72 Jennings, T., Tipper, H., Daglish, J. et al. (2020).

73 Carbon Trust (2019). [Record-low price for UK offshore wind cheaper than existing gas plants by 2023](#).

This implied that the government and industry's £100m investment in the OWA could be recouped in the first few years of a single project. The same cost reduction was estimated to equate to savings of £34bn across Europe, based on European governments' offshore wind deployment targets for 2030.⁷⁴ Beyond R&D collaboration, subsidy policies contributed substantially to cost reduction by supporting large-scale deployment, enabling learning, the realization of economies of scale, and lower financing costs, meaning that investors changed their perception of the sector's risks.⁷⁵

Later developments

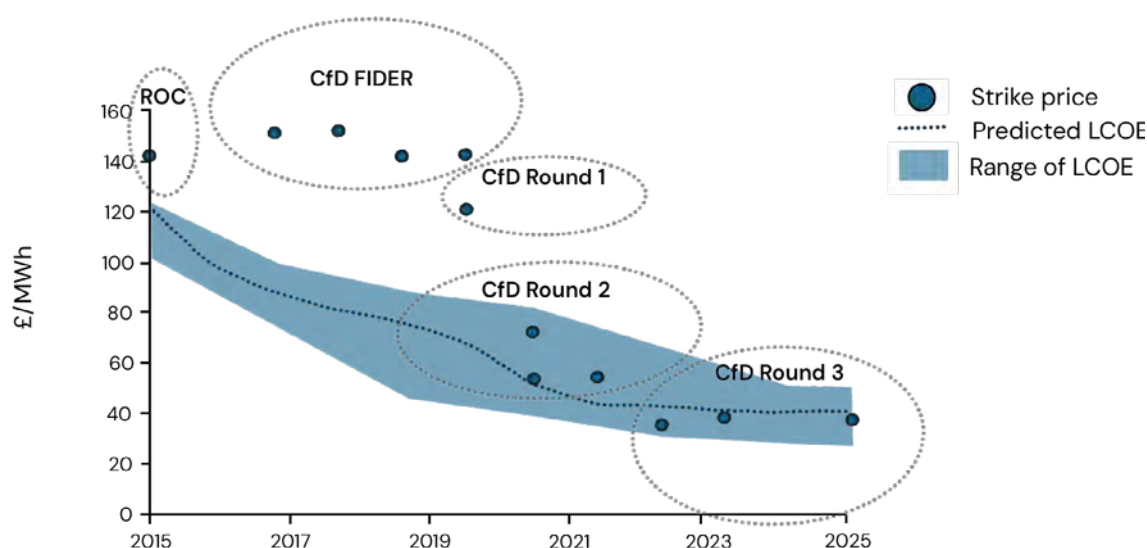


Figure 9. Strike price and estimated LCOE of operational wind farms (dark blue), and predicted average LCOE for Round 3 offshore zones (light blue). Note: 2012 prices for comparability with the early contracts. CfD stands for Contracts for Difference. ROC stands for Renewables Obligation Certificates. FIDER was an early form of the CfD scheme, and stands for Final Investment Decision Enabling for Renewables. Source: [Jennings et al. \(2020\)](#).

Whereas the Renewables Obligation had provided a fixed subsidy for each unit of renewable power output, the Contracts for Difference policy that replaced it in 2013 required project developers to compete for contracts in auctions with limited budgets. This sharpened competition within the sector, driving further cost reduction (see Figure 9). It also to some extent reduced openness to knowledge-sharing, which might anyway have become less necessary as the sector moved from Market Introduction to Diffusion. Despite this, collaboration through the OWA continued, supported by a shared interest in fending off competition from nuclear power.⁷⁶ Recent knowledge-sharing has focused on the streamlining of permitting and processes, and component recyclability, reflecting the shifting challenges as the industry matures.

The Carbon Trust now operates internationally – for example delivering projects on seismic interactions with wind turbine foundations (relevant to Japan and the West Coast of North America) – and has helped to create replications of the OWA in Vietnam and the Philippines. Although the OWA was initially set up and funded by the UK Government, it now has international influence and momentum.

⁷⁴ Nguyen, B. (2020); Carbon Trust (2018a).

⁷⁵ Jennings, T., Tipper, H., Daglish, J. et al. (2020).

⁷⁶ Ibid.

CASE STUDY 4

Inventing and demonstrating zero-carbon steel in Sweden: Government signalling, and financial support for RD&D (2015 to present)

The context and challenge

The steel industry accounts for about 8% of global CO₂ emissions, making it the single largest industrial source. The steel transition is split between primary and secondary steel production. The main technology for secondary steel production, electric arc furnaces (EAFs), can be near zero carbon, but primary steel production is the major emitter.⁷⁷ Global steel demand requires decarbonised primary production as well.⁷⁸

Primary steel production converts iron ore into molten steel, in a coke-based blast furnace.⁷⁹ By the early 2010s, two technology options had emerged to decarbonise this process. The first was to retrofit steel plants with carbon capture and storage (CCS) technology. CCS could capture 60–90% of the CO₂ emissions, but remaining emissions would need to be offset with additional measures.⁸⁰

The other option was to use a carbon-neutral alternative to the traditional blast furnace, building on an existing process known as DRI-EAF. This combined a direct reduced iron (DRI) furnace with the EAF process. The DRI furnace heats syngas (a mixture of hydrogen and carbon monoxide derived from natural gas) and reacts it with iron ore pellets. DRI reactors produce ‘sponge’ iron (iron produced from ore, without being melted), which like scrap becomes molten steel in an EAF. DRI reactors have existed for centuries, and some steel plants use the DRI-EAF process in countries without coal reserves, such as Iran and Saudi Arabia. They generate lower emissions than coke-fired blast furnaces, but the carbon monoxide in the syngas produces CO₂ emissions, and comes from fossil fuels. Pilot studies showed that with minor modification to the DRI reactor it would be possible to use pure hydrogen, instead of syngas.⁸¹ The innovation was to link the DRI reactor to a source of green hydrogen. Both DRI reactors and electrolyzers function best when operated continuously, so need an uninterrupted source of clean electricity. H₂-DRI-EAF steel plants would generate close to zero CO₂ emissions (Figure 10).⁸²

The CCS option offered lower short-run costs, because existing blast furnaces could be retrofitted, instead of needing new, untested H₂-DRI-EAF steel plants plus green electricity. Analysts estimated that CCS would add \$100–200 per tonne to steel costs and reduce emissions by about 60%. H₂-DRI-EAF would add at least double that to reduce emissions nearly completely.⁸³ But in the long run, blast furnaces with CCS would be more expensive to build and operate than blast furnaces without CCS, and remaining emissions would need to be offset with expensive direct air carbon capture and storage (DACCS). By contrast, the H₂-DRI-EAF pathway offered cost-saving features, meaning that if it could be pushed down the learning curve, its costs could fall to those of conventional steel and potentially further.

77 World Steel (2024). *World Steel in Figures*.

78 Mission Possible Partnership (2022). *Making Net-Zero Steel Possible*.

79 Coke – essentially pure carbon – reacts with oxygen to produce heat which melts the ore, and it reacts with the ore itself, turning iron oxide into iron. Both sets of reactions create CO₂ emissions.

80 Zhang, T., Zhang, M., Ling, J. et al. (2024). *Advancing carbon capture in hard-to-abate industries: Technology, cost, and policy insights*. *Clean Technologies and Environmental Policy*. 26. pp.2077–2094.

81 Wagner, D., Devisme, O., Patisson, F. et al. (2008). *A Laboratory Study of the Reduction of Iron Oxides by Hydrogen*. Cornell University.

82 Suer, J., Traverso, M. & Jäger, N. (2022). *Carbon footprint assessment of hydrogen and steel*. *Energies*. 15. pp.9468.

83 Zhang, T., Zhang, M., Ling, J. et al. (2024); Choi, W. & Kang, S. (2023). *Greenhouse gas reduction and economic cost of technologies using green hydrogen in the steel industry*. *Journal of Environmental Management*. 335. pp.117569.

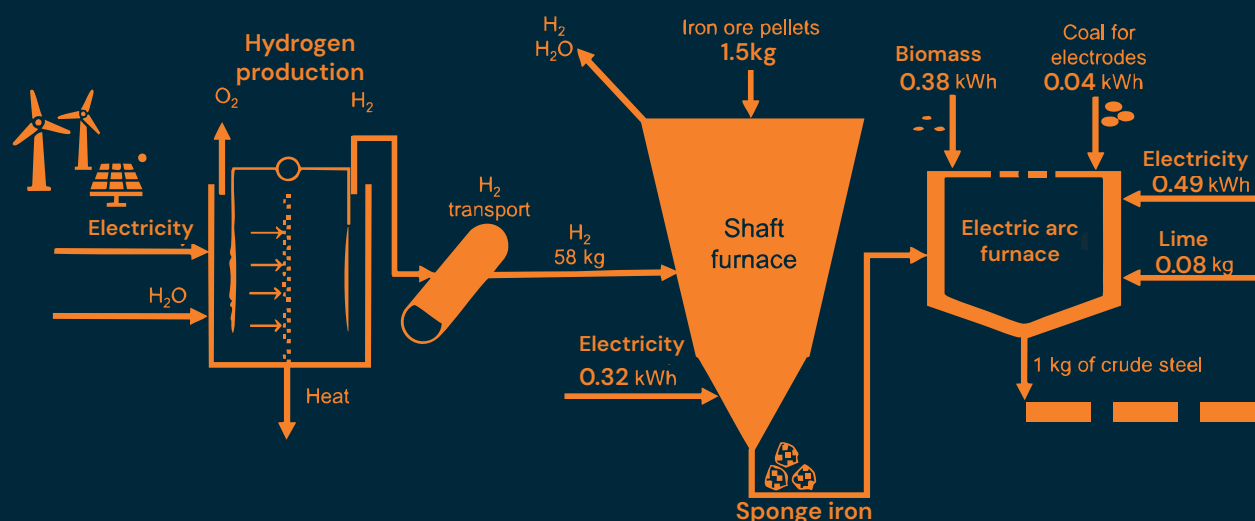


Figure 10. H2-DRI-EAF steel production. Source: Lipiäinen et al. (2024).

The long-run challenge was for a country to lead in driving the H2-DRI-EAF production pathway from theory into reality, and then scale it sufficiently to bring costs down. Sweden rose to that challenge. Sweden is a medium-sized steel producer, which exports and feeds its own industry, including the automobile manufacturer Volvo. It had a history of steel innovation, especially in the use of EAFs to produce high-quality steel. And it had abundant, low-cost, and uninterrupted renewable electricity (underutilised hydropower and wind power capacity). Especially this low-cost electricity would position H2-DRI-EAF steel made in Sweden favourably compared with that from other countries lacking the hydropower resource.

Policy approach

Sweden led the Invention stage of H2-DRI-EAF steel by working with industry to form the HYBRIT (Hydrogen Breakthrough Ironmaking Technology) project. It was launched in 2016. HYBRIT is a joint venture of three companies: LKAB, a 100% state-owned producer of iron ore; Vattenfall, a 100% state-owned supplier of fossil-free electricity; and SSAB, a publicly traded steel producer. The policies that have led to the success of the HBRIT project include:

- A clear government commitment to full decarbonisation in the steel industry, providing investors with confidence in the direction of travel; Financial support in the form of direct grants;
- Priority-setting within government to support the project through the initiation of negotiations, technical support, and streamlining of permitting processes;
- Financial support in the form of direct grants;
- To a more limited extent, state-ownership of key industrial actors.

The government's first steps towards the creation of HYBRIT were taken in 2015, with the development and later adoption of a climate policy framework with a 2045 net zero target.⁸⁴ It had clear signals that hard-to-abate sectors, including steel, had to reach this target. This framework created a clear direction of travel, and long-term commitment important to investors.⁸⁵ It built on Sweden's membership in the EU and hence participation in the Emissions Trading System (ETS), which also signalled the need for hard-to-abate sector decarbonisation by mid-century.

⁸⁴ Naturvårdsverket (2025). *Sweden's Climate Act and Climate Policy Framework*.

⁸⁵ This and subsequent opinions as to policy effectiveness rely on stakeholder interviews conducted February–May 2023, overseen by the author Anthony Patt during a student research project. Full informed consent, including for the opinions to be cited anonymously, was obtained from all interview partners.

Second, the government signalled that the state would publicly back the venture. The Swedish Energy Agency provided in-kind support to the feasibility study, while government-supported research institutes contributed to analysis. When the HYBRIT project was announced in 2016, the government publicly announced its support.⁸⁶ Later, the government worked to streamline the environmental permitting processes for the construction of HYBRIT plants and associated electricity supply.⁸⁷

Third, once the joint venture was formed and the feasibility studies were completed, the Swedish Energy Agency awarded a grant of \$60 million in 2018 for the construction of the first HYBRIT demonstration plant, which began producing H₂-DRI-EAF steel in 2021. In the next phase, HYBRIT is building the first full-sized production facility. In 2023, the Swedish Energy Agency provided a grant of \$300 million, and the EU a grant of \$150 million, for the construction of that facility.⁸⁸

Finally, research suggests that the state-ownership of two of the three HYBRIT partners – LKAB and Vattenfall – also played a role.⁸⁹ These companies see their own mission as being aligned with that of the government. State-ownership enables close cooperation between the leadership of these companies and the government: they provided fertile ground for the government's effort to launch an industrial coalition to take the lead on green steel development. Other stakeholders suggested that HYBRIT could have also succeeded without state-ownership, given the government's broader support.

Outcomes and implications

The first HYBRIT plant was constructed in the city of Luleå, near ample surplus supply of hydropower and wind energy. The plant entered operation in 2020. The Luleå plant integrates hydrogen production and storage with a hydrogen DRI reactor, and has tested various methods of integrating the two, but does not directly integrate these with the EAF process. In 2021, an EAF plant operated by SSAB used sponge iron from the HYBRIT Luleå plant to supply zero-carbon steel to Volvo, which was used in the manufacturing of prototype cars.⁹⁰ This demonstrated the feasibility of using such steel in manufacturing.

Based on the success of the first HYBRIT plant, the joint venture has commenced construction of its second, much larger facility. This is underway in the city of Gällivare, also in the north of Sweden and proximate to both iron ore and abundant hydropower and wind energy. While it will contain several innovations moving forward from Luleå, the Gällivare facility will still not completely integrate the full H₂-DRI-EAF process, but rather deliver sponge iron from the DRI reactor to a dedicated EAF facility operated separately by SSAB. Together they will initially supply 1.3 million tonnes of H₂-DRI-EAF steel in 2026, projected to rise to 2.7 million tonnes by 2030.⁹¹ This would represent a major increase in Sweden's current steel output of 4 million tonnes annually. The anticipated electricity demand from the Gällivare plant will be 5 TWh per year, roughly 40% that of the city of Stockholm.⁹² This, however, represents a small fraction of the surplus generation capacity of the region's existing wind and hydropower facilities.

86 LKAB (2018). [HYBRIT's world-first pilot plant wins Energy Agency's backing.](#)

87 CMS (2024). [Hydrogen law, regulations & strategy in Sweden.](#)

88 Swedish Energy Agency (n.d.). [Hybrit is granted SEK 3.1 billion.](#)

89 Stakeholder interviews 2023.

90 Chemical Processing (2021). [Hybrit delivers 'green steel' to Volvo for prototype vehicles.](#)

91 HYBRIT (2021). [HYBRIT: SSAB, LKAB and Vattenfall to begin industrialisation of future fossil-free steelmaking by establishing the world's first production plant for Wfossil-free sponge iron in Gallivare.](#)

92 Chen, H. [Sweden's HYBRIT secures funding to build first fossil fuel-free demonstration plant in Gallivare.](#)

Current estimates are that the cost of H₂-DRI-EAF steel from the Gällivare plant will exceed those of conventional steel by about \$150 per tonne, or 20%, although this benefits from the investment subsidies that the plant received.⁹³ As of 2023, the extremely limited quantities of green steel were selling for a \$200–300 per tonne premium on the European market, driven primarily by automakers wishing to reduce their Scope 3 emissions.⁹⁴ Several car manufacturers have signalled their commitment to incorporate at least 10% H₂-DRI-EAF steel into their production by 2030.⁹⁵ For perspective, a typical passenger car contains about one tonne of steel, so incorporating 10% green steel would increase the price of a car by just \$20–30. In the longer run, analysts expect the price premium of green steel to decline, owing to falling costs for renewable electricity and electrolyzers.⁹⁶ By the time the market uses 100% green steel, the price premium may have vanished.

Sweden pursued the demonstration and commercialisation of H₂-DRI-EAF steel both because it appeared to be the cost-effective technology for eliminating emissions, and because the country had a comparative advantage given its renewable electricity supply. The HYBRIT plant became the first to produce zero-carbon steel, and it spawned similar efforts elsewhere. In Germany, major steelmakers such as Salzgitter and Thyssenkrupp are developing hydrogen DRI-EAF facilities with significant public funding, including carbon contracts for difference. France, the Netherlands, Austria, and Spain are also providing state support for demonstration and commercial projects. There continues to be R&D on alternative technological pathways, including injection of hydrogen plasma into blast furnaces, and the complete electrification of the iron ore reduction process.⁹⁷ It is still too soon to tell whether these other technologies may eventually supplant the H₂-DRI-EAF in the production of green steel. But, in large part owing to Swedish action in the early stage, the steel transition is underway.

93 Lipiäinen, S., Sillman, J., Vakkilainen, E. et al. (2024). Hydrogen transport options for a large industrial user: Analysis on costs, efficiency, and GHG emissions in steel mills. *Sustainable Production and Consumption*. 44. pp.1–13.

94 Fastmarkets (2023). [Green premium for flat steel stable in first European assessment.](#)

95 Volvo Cars (2022). [Volvo Cars is first car maker to join SteelZero initiative in support of fossil-free steel ambitions.](#)

96 Peplow, M. (2021). [The race for green steel.](#) C&EN Global Enterprise.

97 Ibid.





2. EMERGENCE II: MARKET INTRODUCTION

2.1 Overview

Establish the new industry and begin to reduce costs

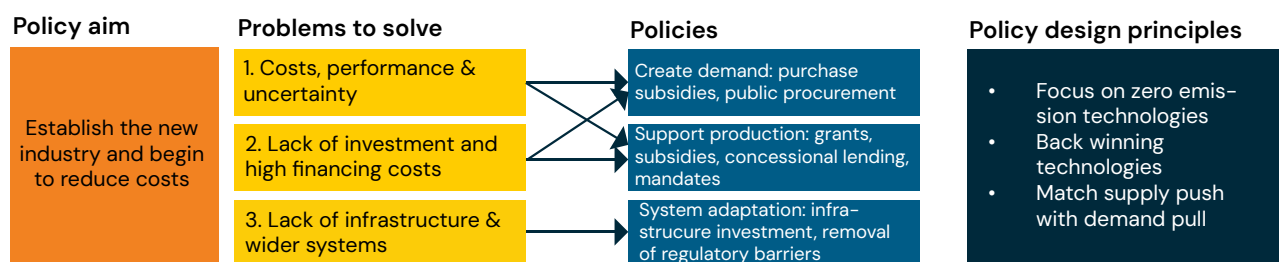


Figure 11. Emergence II: Market Introduction – Overview of aims, problems to solve, policies, and policy principles.
Source: authors' own.

Aim: The aims for policymakers at this stage are to achieve the first deployment of the zero-emission technology, to establish the new industries that produce it, and to begin reducing costs and improving performance through initial deployment and learning.

The process: After the Invention stage has produced at least one viable technology, the next challenge is to introduce the new technology (or technologies – there may be more than one) to the market. The new technology is still early in its development and is unlikely to be able to compete successfully against incumbents. Policy can help to create demand ('market pull') which incentivises firms to produce and sell the technology. Niche markets are needed, where the new technology can be deployed first while being protected against competition with incumbents. These can be in specific applications, such as the military, space industry, or high-end luxury segments where costs matter less, or they can be technology-specific niches created by policy within larger markets.

Early deployment nurtured by policies can activate positive feedback effects: learning-by-doing leads to improvements in quality; economies of scale lead to falling costs; these lead in turn to rising demand for the new technology, incentivising further investment in its production. Increasing returns to scale mean that small increases in deployment – such as a doubling from 1% to 2% market share – have a disproportionate impact. Small differences in the uptake of different technologies can be quickly amplified, leading to rapidly diverging trajectories, with lagging technologies failing entirely.

The creation of a market that supports the technology's first deployment enables entrepreneurs, firms, investors, and public agencies to better coordinate their efforts around the technology – building production capacity, supply chains, and distribution systems. Policymakers, regulators, and standard-setting bodies can begin to embed the new technology within relevant institutional frameworks as the market emerges, helping to build public legitimacy and user trust. If early deployment drives cost reductions and growing demand, the new technology will be able to enter the next stage of the transition: Diffusion across markets and society.

Often, multiple competing technology designs are introduced into the market, and it is only through competition that it becomes clear which is most viable to be deployed at scale. Sometimes, competition persists for years before the global industry convenes around a dominant technology (for example, battery-electric vehicles in preference to hydrogen fuel cell vehicles). Experimentation with alternative designs for a given technology can also persist (for example, silicon and thin film for solar PV, and different electric vehicle battery chemistries). Some countries may choose a different route entirely from that which is dominant globally, to make use of unique natural resources or preserve domestic industries.

Problems to solve

1. Costs, performance, and uncertainty

New technologies at the Market Introduction stage typically cost substantially more and underperform in many respects compared with the incumbent technologies. Designs are immature, manufacturing processes are being worked out, and they face difficulties of integration into market and technology systems, which were built for the status quo technology. This makes the private sector reluctant to invest, particularly because it remains unclear which technologies may prove most viable in the long run.

2. Lack of investment and high financing costs

Investment is critical at this stage to start a virtuous cycle of deployment, improving performance and falling costs, in turn attracting more investment. Starting the initial investment is a central task at this stage. Companies are often unwilling to invest in the assets needed to produce the new technology while demand for it is highly uncertain. Uncertainty means that whatever finance is available is likely to come at a high cost, making investment more difficult. Without investment, innovations can remain confined to small niches for a long time.

3. Lack of infrastructure, and regulatory barriers

In some cases, early production and adoption of the new technology can be held back by the absence of infrastructure, enabling regulations, institutions, or other elements of the economic system needed for it to function effectively – or by mismatches with the existing system built for incumbent technologies. The challenge depends on sector specificities and the extent to which the new technology can function within the existing system. Electric trucks do not need new roads, but do need charging infrastructure and exemptions to weight limits. Construction companies cannot use clinker alternatives for cement in load-bearing contexts without appropriate certification. Finding initial solutions to such system challenges may often be a task of Market Introduction.

Example: Heavy road transport

Consensus is emerging that battery-electric trucks are the most likely technology to decarbonise heavy road freight. Across the world, the sector is now in or entering the Market Introduction stage. Globally in 2024, medium and heavy electric trucks reached 4.4% of new sales in China and 2.2% in Europe.⁹⁸ In many other markets, the EV share of truck sales is still close to zero, but is expected to rise quickly as new and improved electric truck models are developed for European and Chinese markets.⁹⁹

High costs and low performance: The total cost of ownership of electric trucks has already fallen below that of diesel trucks in China in the heavy and medium-duty truck segments,¹⁰⁰ and in India for the heavy-duty segment and vans.¹⁰¹ In other leading markets, electric trucks are projected to reach cost parity with diesel or petrol trucks later this decade.¹⁰² However, the high purchase price of electric trucks remains a barrier to demand, particularly because most freight businesses are small, often single-vehicle operations, with price-sensitive owners.¹⁰³ Performance barriers still include lower payloads compared with diesel trucks.¹⁰⁴

Lack of investment: Truck manufacturers are increasing investment into electric vehicle (EV) technology, but not yet at the same scale as car manufacturers, where the transition is further ahead. Manufacturers face uncertainty about demand, given limited incentives for freight customers and operators to switch to EVs. Potential customers face their own risks, with uncertainty around resale values due to battery degradation, changing technology, charging infrastructure, and uncertain future demand (important for resale). Vehicle manufacturers are calling for stable regulatory timelines for the transition, to reduce these uncertainties.¹⁰⁵

System Barriers: Charging infrastructure is a critical need for electric trucks, but investors in charging infrastructure are hesitant in the face of uncertain demand, creating a 'chicken-and-egg' problem. In some countries, regulatory limits on gross vehicle weight put electric trucks at a disadvantage compared with diesel trucks – with the extra weight of batteries resulting in a smaller legal payload. The EU, UK, and US have changed regulations to allowing higher weight limits for zero-emission vehicles to offset the battery weight and enable electric trucks to carry the same payload as diesel trucks.

In summary, the heavy road transport sector in many countries is at the Market Introduction stage, suggesting that policies of the kinds described below may support its progress.

98 IEA (2025). *Global EV Outlook 2025. Trends in heavy-duty electric vehicles*.

99 These numbers come from the IEA, which defines trucks as medium- and heavy-duty freight trucks. The US data is from 2022 not 2023. See: IEA (2024a). *Electric truck registrations and sales share by region, 2015–2023*.

100 Akther, A., Polisetty, M., Lynch, C. et al. (2025). *Driving the Transition to Zero-Emission Trucks*. Economics of Energy Innovation and System Transition (EEIST), University of Exeter & ICCT.

101 Ibid.

102 IEA (2024b). *Global EV Outlook 2024: Moving towards increased affordability*; Akther, A., Polisetty, M., Lynch, C. et al. (2025).

103 Mission Possible Partnership (2022). *Making Zero-Emissions Trucking Possible: An industry-backed, 1.5 °C-aligned transition strategy*. Energy Transitions Commission.

104 Payloads are lower because battery-electric vehicles (BEVs) are typically heavier than diesel trucks as a result of their large battery packs, and gross vehicle weight is often subject to legal limits. Akther, A., Polisetty, M., Lynch, C. et al. (2025); Suneson, A., Herlt, A., Hans, M. et al. (2024). *The bumpy road to zero-emission trucks*. McKinsey & Company, Automotive & Assembly Practice, and McKinsey Center for Future Mobility; Spiller, B., Lohawala, N. & DeAngeli, E. (2023). *Medium- and heavy-duty vehicle electrification: Challenges, policy solutions, and open research questions*. Resources for the Future.

105 WBCSD (2024). *Business Breakthrough Barometer 2024*.



2.2 Policies to accelerate the Market Introduction stage

Policies from the Invention stage (public funding for R&D, visions, and programmes and networks for knowledge-sharing) remain relevant at this stage, though their focus can increasingly be on improving technologies and reducing their costs, rather than on inventing new technologies. As technology expectations stabilise and the direction of innovation becomes clearer, visions can be replaced with technology roadmaps that set goals and timelines for experimentation, market entry, and expansion of production. These can be used as a framework for policy planning.

1. Creating demand: purchase subsidies and public procurement

Subsidies for the purchase or use of the new technology can improve its affordability and attractiveness to consumers, creating demand and enabling its introduction to the market. Countries with leading rates of adoption of electric vehicles and heat pumps generally used purchase subsidies, as part of wider policy packages. In the power sector, deployment subsidies have primarily taken the form of fixed price contracts (feed-in tariffs and contracts for difference), which have guaranteed a price for clean power generated commercially or on residential rooftops that was above the market price.¹⁰⁶

Public procurement can be used to create demand for the new technology directly. The government's purchasing power is often large enough to create a substantial market niche. For example, up to 25% of steel, and up to 40% of cement and concrete, is bought by governments in some countries.¹⁰⁷ This use case of public procurement typically relies on standards or definitions which clarify the supported technology characteristics that will be supported. Quality and performance standards can be set high or raised over time, incentivising innovation.

By creating demand for the new technology, these policies increase business confidence and incentivise investment in technology production and its supply chain development. The deployment enabled by demand creation policies (and those that support production) can activate the positive feedback effects mentioned above: learning-by-doing leads to improvements in quality; economies of scale lead to falling costs; these lead in turn to rising demand for the new technology, incentivising further investment in its production.

2. Supporting production: grants, subsidies, concessional lending, and mandates

Grants or subsidies for the production of the new technology decrease the upfront costs and risks of early-stage production, and improve its commercial viability. Concessional lending can have a similar effect, reducing the cost of capital and catalysing business investment.

Mandates (sometimes referred to as quotas) require a minimum share of production in the sector to be met by the new technology, or by technologies with a particular characteristic such as 'zero emissions', forcing a reallocation of investment from the old to the new. These may be particularly useful when industries enjoy high profits from incumbent technologies and are unwilling to invest in new alternatives. They have been particularly successful at driving deployment of zero-emission vehicles. Renewable Portfolio Standards have been similarly successful in the power sector.

¹⁰⁶ More recently, as the power-sector transition has entered the Diffusion stage, there have been examples of contracts for difference being signed at levels below the market price, such as for offshore wind in the UK. In these examples, the primary function of the contracts for difference is no longer to provide a subsidy, but to reduce revenue uncertainty, which can help to reduce the cost of capital and incentivise investment.

¹⁰⁷ United Nations Industrial Development Organization (2021). [IDDI Infographic](#). UNIDO.

Public funding support for R&D, a central policy of the Invention stage of the transition, may continue to be useful at the Market Introduction stage. While the new technology has a small share of the market, industry investment in its development may be limited. Public support for R&D at this stage can drive innovation in production processes or in the product itself, helping to reduce costs and improve performance.

3. Adapting the system: initial infrastructure investment, and removal of regulatory barriers sharing

The most appropriate ‘niches’ for the Market Introduction of new technologies may be those for which no new infrastructure is required. However, for some technologies new infrastructure may be needed from the outset, and for others it will be needed as the transition progresses. The incentives for private investment in new infrastructure early in a transition are often weak, and it may not be clear exactly what is needed (for example, what kind of charging technology is needed by electric vehicles). Not only is the future market share of the new technology uncertain, but the revenues to infrastructure providers may be even more so. This creates a ‘chicken-and-egg’ problem: there will be little deployment of new technology without the needed infrastructure, and no investment in infrastructure without the new technology being deployed. Governments can overcome this during Market Introduction by investing directly in the necessary infrastructure for the market niche, or by co-investing with the private sector in a way that reduces perceived risks. This can clarify what works best at a small scale, laying foundations for larger-scale investment in new infrastructure during the Diffusion stage.

Regulatory changes can be important to remove barriers to a technology’s deployment. For example, cultivated meat faces unclear food safety regulations in many countries, ammonia as a marine fuel is penalised under some regulations because of toxicity, and battery-electric heavy trucks are limited by weight restrictions. Adjustments to regulations that were designed before the emergence of a new technology can ensure that their objectives are met without disadvantaging that technology unnecessarily.

2.3 Policy design principles for Market Introduction

1. Focus on zero-carbon technologies

The aim at this stage of the transition is not to introduce technologies so that they immediately reduce emissions, but to introduce and support market-driven improvement of zero-carbon technologies that have the potential to be deployed widely, consistent with the goal of eventually eliminating emissions from the sector. From this perspective, it is more useful to begin the deployment of zero-carbon technologies at a very small scale than to reduce emissions in other ways that are cheaper now but inconsistent with the goal of a zero-emissions sector in the long run. The support that may be needed to deploy zero-carbon technologies at this stage can be difficult for governments facing fiscal constraints, even if the small scale of deployment limits the total policy cost.

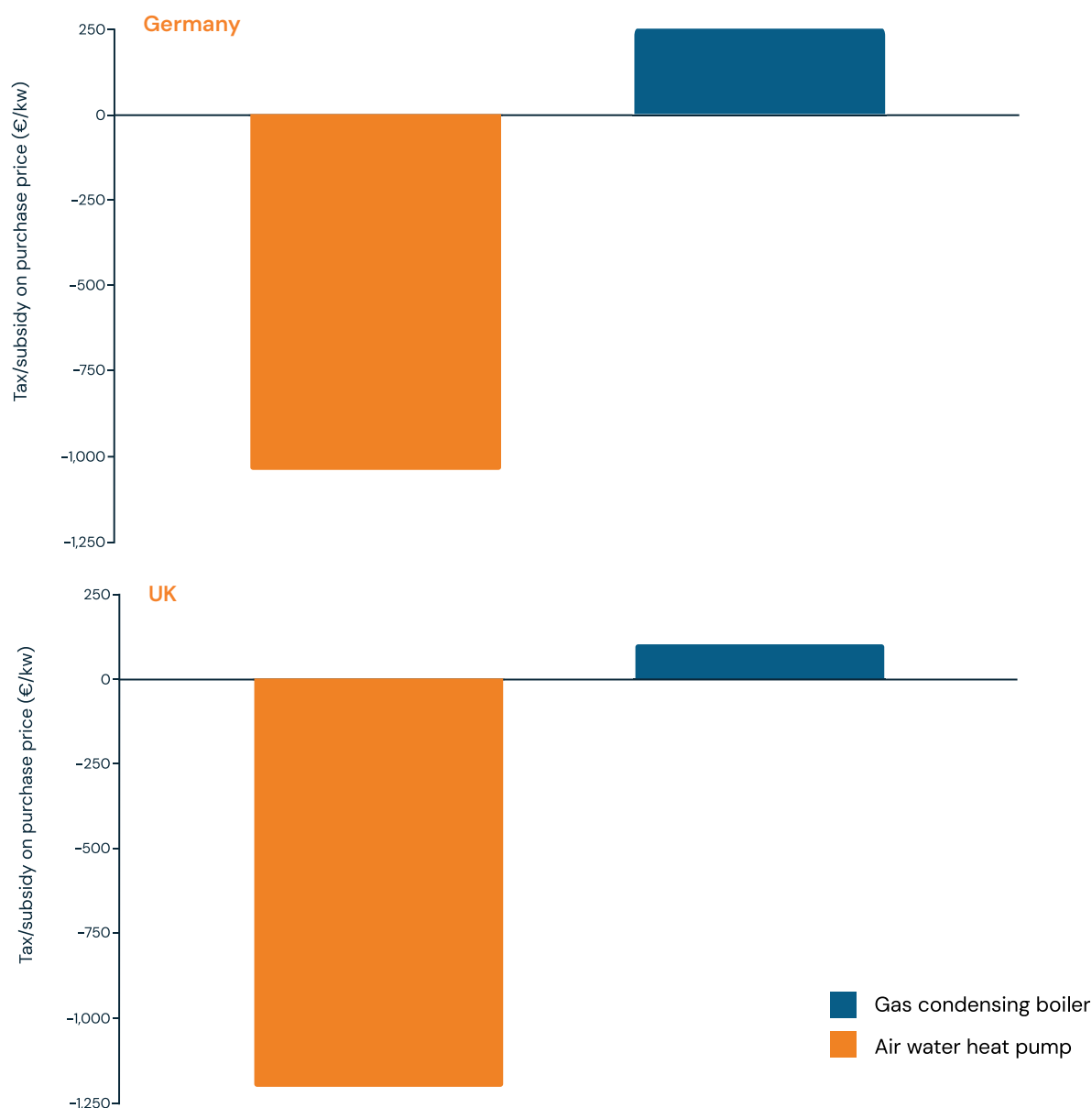


Figure 12. Small, revenue-neutral feebates on gas condensing boilers can make heat pumps cheaper to buy than gas boilers. This makes heat pumps more attractive to consumers without placing additional financial pressure on governments. Source: [Lynch et al. \(2024\)](#).

An option that should not be overlooked is the combination of a subsidy for clean technology with a tax on the fossil fuel product.¹⁰⁸ Sometimes known as a ‘feebate’, this can be designed to be revenue-neutral. Feebates have been used to stimulate the EV markets in France, Singapore, Sweden, and New Zealand.¹⁰⁹ An equivalent policy for heat decarbonisation is to fund heat pump subsidies through a tax on sales of gas boilers (see Figure 12). Early in the transition, a large subsidy on the purchase of each unit of clean technology can be funded by a small tax on each unit of fossil fuel technology, since the latter has a much larger market share.

¹⁰⁸ Lilliestam, J., Eckardt, J. & Bersalli, G. (forthcoming). Sequencing, spending and symbolism: low carbon taxes primarily serve purposes other than emissions reduction. Accepted for publication in *One Earth*.

¹⁰⁹ Wappelhorst, S. (2022). *Incentivizing zero- and low-emission vehicles: The magic of feebate programs*. ICCT.

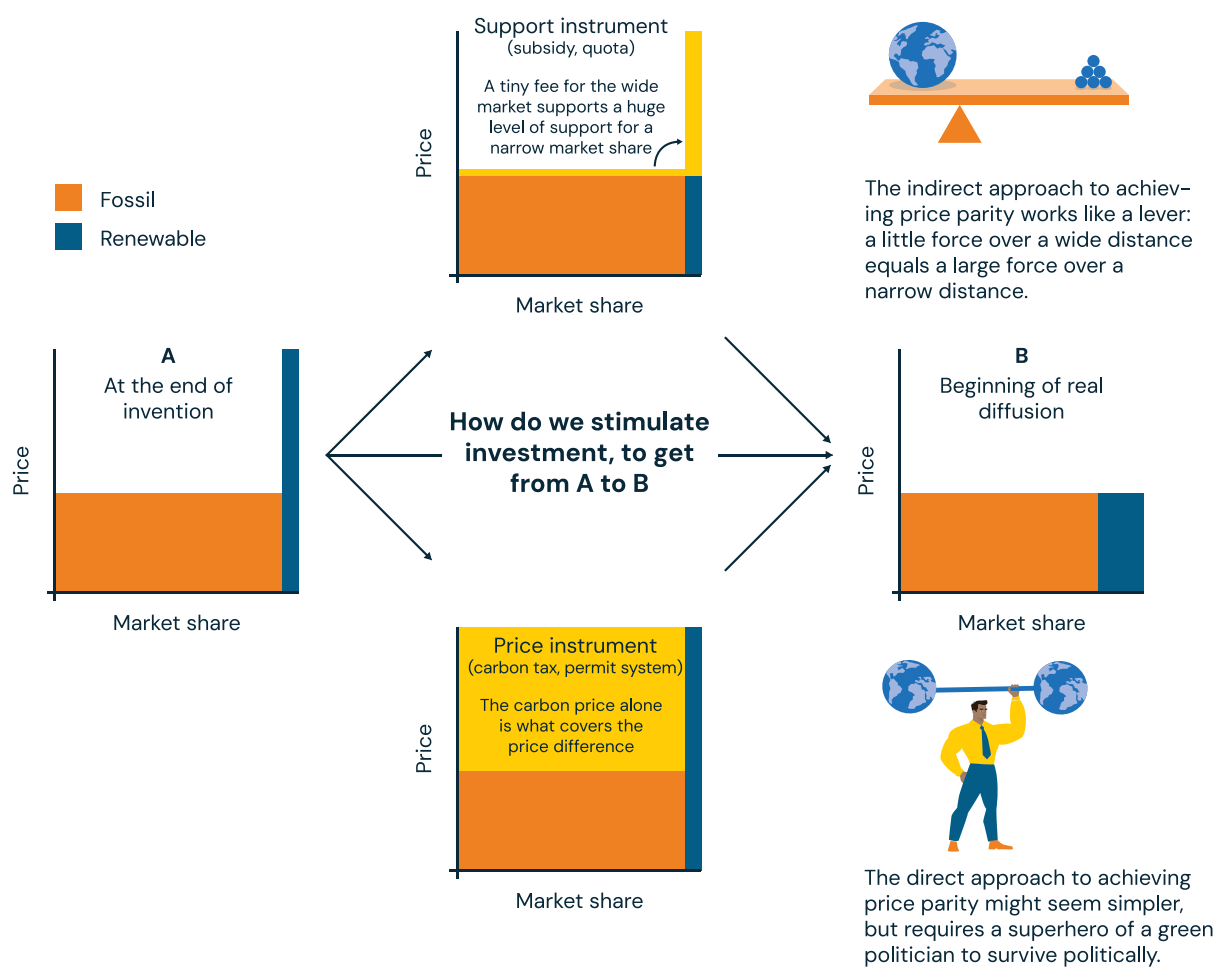


Figure 13. Large per-unit subsidies for clean technology during the Market Introduction stage can be funded by a very small tax on the much larger market of fossil fuel products. Source: Patt (2019) – Climate Policy teaching materials, ETH Zurich.

This ‘feebate’ approach is distinct from that of carbon pricing, in important ways. A carbon price may or may not be high enough to offset the difference in cost between a clean technology and a fossil fuel product, depending on how it is set, making its effectiveness uncertain. To be effective, a carbon price must substantially raise the cost of the fossil fuel product, which, at this stage in the transition, accounts for a large share of the market. This is likely to substantially increase costs for consumers. The feebate approach, in contrast, involves setting a subsidy at a level that will achieve (at least) cost parity between the clean technology and the fossil fuel product, ensuring a degree of effectiveness. Since the subsidy is applied to only a small share of the market but funded by a tax spread across the whole market, the additional cost to consumers can be much lower. This can be understood as a ‘high leverage’ way to use fiscal policy tools to advance the transition (see Figure 13).

2. Back winning technologies

For the Invention stage of the transition, when technology uncertainty is at its highest, we highlighted the benefits of a portfolio approach, allowing multiple technology options to be explored. In the Market Introduction stage, there may still be benefits to encouraging competition between technologies that have the desired characteristics. However, since technologies differ in their maturity, any given policy – even one intended to be technology-neutral – is likely to benefit some technologies more than others. Early-stage technologies are likely to face a disadvantage (given higher costs, lack of infrastructure, and higher costs of capital) compared with more mature technologies, unless policies actively redress this imbalance. Having different kinds, or different levels, of support, adapted to the specific characteristics and maturity of several promising technologies, is often important to avoid picking losers too early in the development process.

For example, when the UK introduced a technology-neutral Renewables Obligation (RO) in 2002, a tradable green certificate mechanism providing a subsidy in addition to the market price of electricity, the policy favoured onshore wind, which was more mature, and failed to incentivise investments into riskier and more expensive offshore wind projects. It was only through introducing technology 'banding' which provided a differentiated subsidy to technologies at different levels of maturity, in combination with other complementary policies, that offshore wind was introduced to the UK market.¹¹⁰ Offshore wind has since proved a useful addition to the UK's power generation mix, providing about 18%¹¹¹ of generation in 2024, with costs now typically below those of new gas plants.

When Germany introduced its feed-in tariff (FIT) system under the Renewable Energy Sources Act (EEG) in 2000, it offered technology-specific tariffs – fixed prices guaranteed over 20 years – for a range of renewable electricity sources. This differentiated support structure recognised the different maturity and costs of each technology, and adjusted tariffs accordingly to reduce risk for investors while avoiding overcompensation.¹¹² Over time, tariff levels were revised downward as technologies matured and costs fell, creating a dynamic incentive structure that tracked technological progress.¹¹³ Some technologies, such as geothermal, gradually fell away as they failed to scale up or prove cost-effective within the German context.¹¹⁴ By 2024, wind and solar together accounted for over 50% of Germany's electricity generation, with average costs well below those of fossil-based alternatives.¹¹⁵

The potential to maintain a portfolio approach may be limited by infrastructure requirements. For example, public procurement and subsidies for zero-emission buses were used to support both battery-electric and hydrogen fuel cell vehicles in multiple countries, until battery-electric buses emerged as the preferable technology.¹¹⁶ Establishing national networks of both electric charging stations and hydrogen refuelling stations would be costly and impractical. At this point, it makes sense for a government to recognise a winning technology, and support its progress towards the next stage of the transition.

One way to judge whether a technology is or has the potential to be a winning technology is to compare its rate of cost reduction over time to those of alternatives. Analysis of historical cost data shows that solar PV, wind power, and battery technologies have experienced exponential cost reduction consistently over recent decades (Figure 14). In contrast, there has been no demonstrated trend of cost reduction in nuclear or bioenergy technologies.¹¹⁷ Another way to judge is to compare technologies' rates of growth in the global market. For example, battery-electric vehicles and plug-in hybrid EVs together accounted for over a fifth of global car sales in 2024, whereas the number of fuel cell EVs sold remains vanishingly small.

110 Wang et al. (2024). [Banding: A game changer in the Renewables Obligation scheme in the United Kingdom](#). Energy Economics.

111 Wind power generated approximately 29.5% of the UK's electricity, and offshore wind about 60% of that. See Mayo, F. (2024). [UK low-carbon renewable power set to overtake fossil fuels for first time](#); and Renewable UK (2024). [Wind energy facts and figures](#).

112 Hoppmann, J., Huenteler, J. & Girod, B. (2014). [Compulsive policy-making – The evolution of the German feed-in tariff system for solar photovoltaic power](#). Research Policy. 43. pp.1422–1441.

113 Ibid.

114 Geothermal was not included in the reform from FIT to auctions. See Agora (2016). [Energiewende: What do the new laws mean? Ten questions and answers about EEG 2017, the Electricity Market Act, and the Digitisation Act](#). Study by Agora Energiewende.

115 Enerdata (2025). [Renewables accounted for nearly 60% of Germany's power generation in 2024](#). Enerdata Daily Energy News.

116 Díaz Anadon, L., Jones, A., Peñasco, C. et al. (2022); Barnard, M. (2024). [Brampton Transit Study's \\$360M gap: Hydrogen misrepresented as budget-friendly](#). The Future is Electric.

117 Way, R., Ives, M. C., Mealy, P. & Farmer, J. D. (2022). [Empirically grounded technology forecasts and the energy transition](#). Joule. 6. pp.2057–2082.

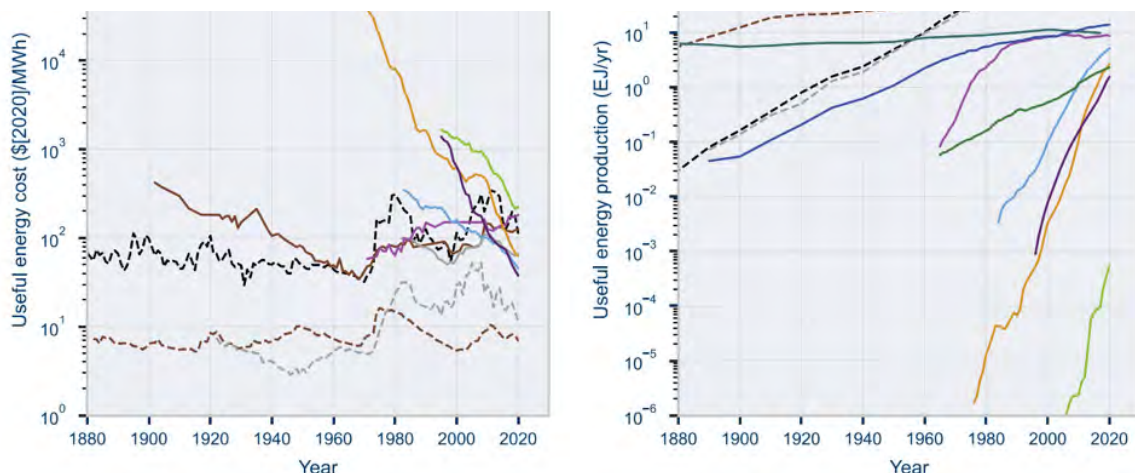
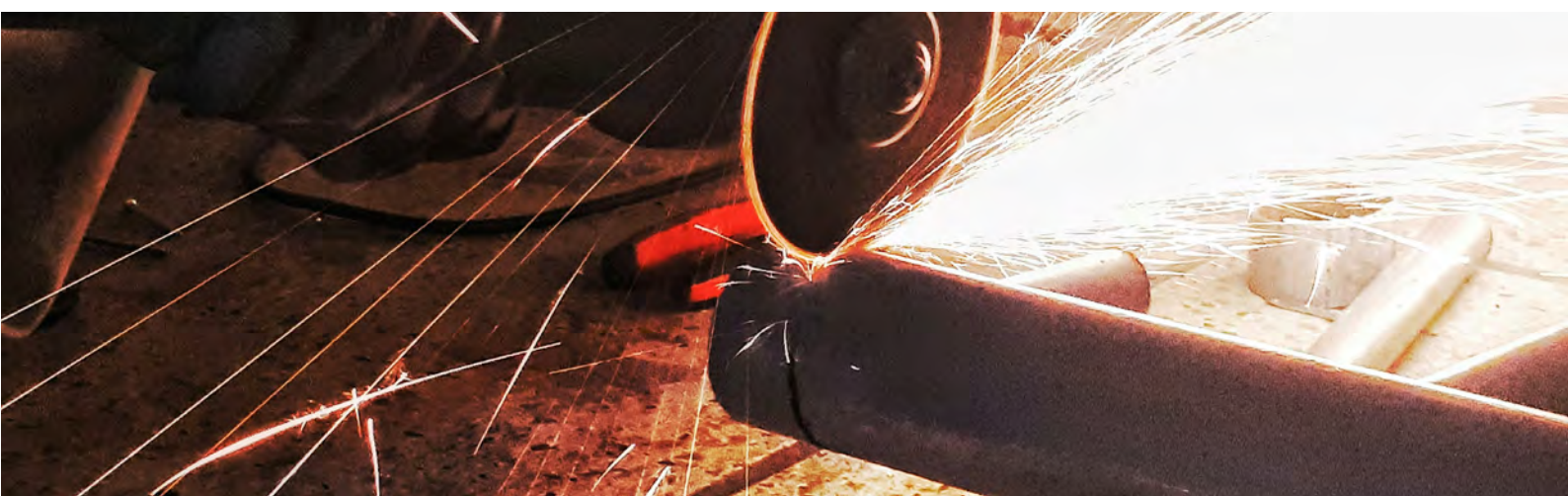


Figure 14. Historical costs and production of energy supply technologies. In A, note the difference in historical costs between coal/gas, and renewables such as solar, wind, and hydropower. In B, deployment shows the exponential rise in the production of oil and natural gas over a century, the rise and plateauing of nuclear energy, and the more dramatic exponential rise in the deployment of solar PV, wind, batteries, and electrolyzers in recent decades. Source: [Way et al. \(2022\)](#).

3. Match supply push with demand pull

Market Introduction can be delayed if producers hold back from producing the new technology because they have low confidence in demand, and consumers do not purchase the new technology because there is a lack of supply to the market. While each waits for the other, the system remains locked-in to the incumbent technologies. Governments can resolve this by acting on supply and demand at the same time. Europe, China, and California are among those that have taken this approach to deploying electric vehicles, imposing regulations that force manufacturers to supply EVs at the same time as purchase incentives to encourage consumers to buy them (see [Case Study 13](#)).



2.4 Case studies for Market Introduction



CASE STUDY 5

Public procurement: French tram systems (1970–2000)



Figure 15. Grenoble light rail system. Source: [Boussard \(2010\)](#).

Public procurement was an essential mechanism for the reappearance of tram systems in France in the 1980s, which was initially motivated by concerns over urban congestion and accidents, and by the success of French high-speed railways (and the rise of a successful rail industry). Because urban trams were complex and expensive infrastructure systems, their construction happened through projects that were commissioned and co-designed by public authorities (rather than bought off the shelf as in the procurement of commodity products). While public procurement created demand for tram technology, this was complemented by knowledge-oriented measures that improved the supply of the new technology.

Building on preparatory design and policy work in the early 1970s, urban policymakers were essential actors in the commissioning of new tram systems, with newly elected Socialist mayors (in Nantes, Strasbourg, Grenoble) advancing new transport ideas for their cities, which in the late 1970s and early 1980s led to more detailed design and planning studies.¹¹⁸ These initiatives were enabled and stimulated by two wider policy developments. The first development was the introduction of the *Versement Transport* financing instrument in 1971, which raised employment tax locally to pay for large public transport schemes. First introduced in Paris to support metro-like schemes, it was subsequently extended to other cities and used to fund the construction of tram systems. The second development was Mitterrand's devolution of planning powers to cities (through the 1982 *Gaston Defferre laws*), including responsibilities and resources for public transport (through the 1982 domestic transport guidance law). On top of local transport taxes (collected through *Versement Transport*), the French government centrally funded between 15% and 40% of capital costs of early tram systems.¹¹⁹ These new funding schemes enabled local policymakers to commission new tram systems, with Nantes opening the first modern tramway in 1985, demonstrating the technical and commercial viability of new designs (for carriages, infrastructure, signalling).

¹¹⁸ Turnheim, B. & Geels, F. W. (2019). *Incumbent actors, guided search paths, and landmark projects in infra-system transitions: Rethinking strategic niche management with a case study of French tramway diffusion (1971–2016)*. Research Policy. 48. pp.1412–1428.

¹¹⁹ ACUF (2007). *Financement des transports publics urbains*. Association des Communautés Urbaines de France.

Grenoble's tramway system opened in 1987 (Figure 15), and included low-floor carriages for increased accessibility for disabled users and full pedestrianisation of a segment crossing the urban centre.

The funding schemes were complemented by 'supply push' measures to improve the new technology. In 1982, the government created a 'Technical Committee for the Standard French Tram', which brought together various actors in the light rail field and codified technical knowledge.¹²⁰ During Market Introduction in the 1980s and 1990s, government-affiliated technical services played important technical and engineering advisory roles, overseeing large tram projects and feasibility studies.

Other cities followed these measures (Figure 16), with lessons from one project feeding into the subsequent projects, leading to more stabilised knowledge and increasing confidence and enthusiasm.¹²¹ Tram systems diffused to 15 out of 19 French cities of more than 300,000 inhabitants and in some instance to cities with less than 200,000 inhabitants. Most tram systems are publicly owned (e.g. by city authorities) but privately operated (e.g. by Keolis, Connex/Veolia Transport, RATP, CTS¹²²) based on a mix of passenger fares and public support, including from the *Versement Transport*).

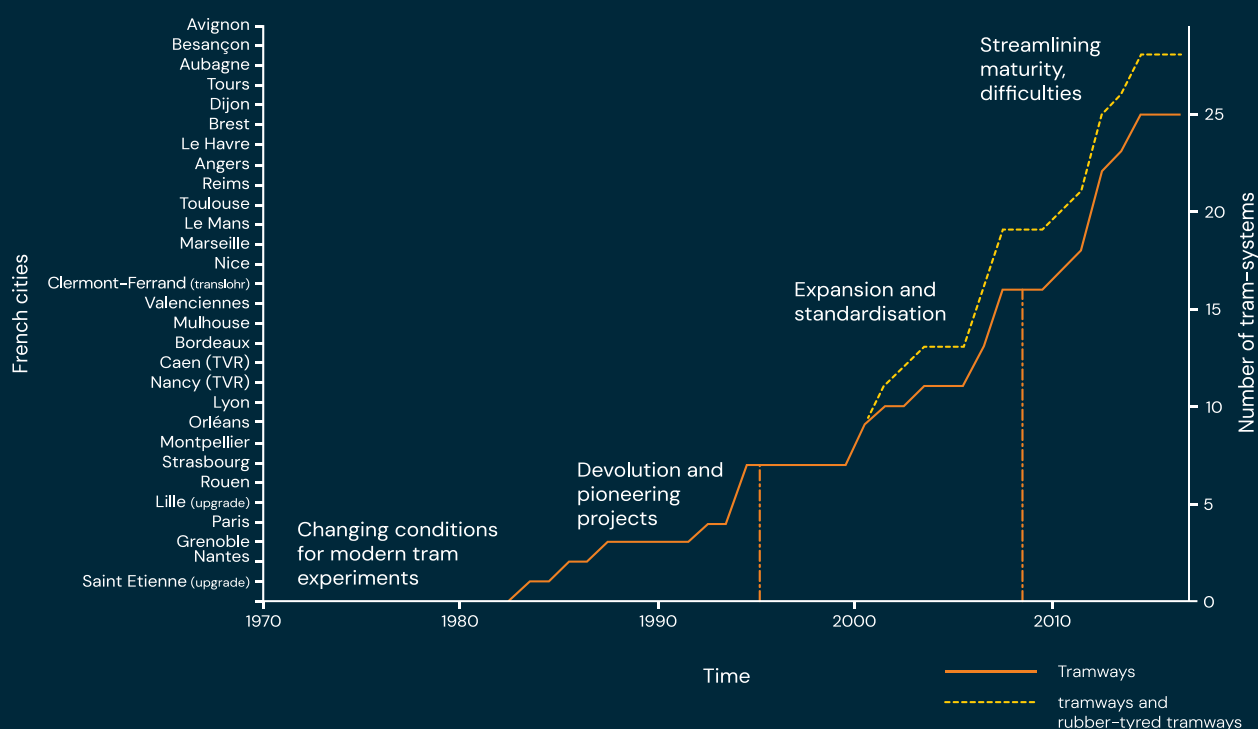


Figure 16. Modern tramway diffusion in French cities Source: [Turnheim & Geels \(2019\)](#).

120 Hamman, P. (2015). *Negotiation and social transactions in urban policies: The case of the tramway projects in France*. Urban Research & Practice. 8, pp.196–217.

Turnheim, B. & Geels, F. W. (2019)

121 Turnheim, B. & Geels, F. W. (2019)

122 RATP stands for the Parisian Autonomous Transport Administration. CTS stands for Compagnie des Transports Strasbourgeois.

From the late 1990s, increasing tram use led to declining car use in various French cities (Figure 17). Trams were also increasingly seen as instruments for wider urban transformation as they enabled the pedestrianisation of historic piazzas and became linked to non-transport considerations such as quality of life, access, sustainability, and urban renewal. This broadened the attractiveness of trams and helped to build a broader coalition, so that trams became 'irresistible' for mayors of medium and large cities.¹²³

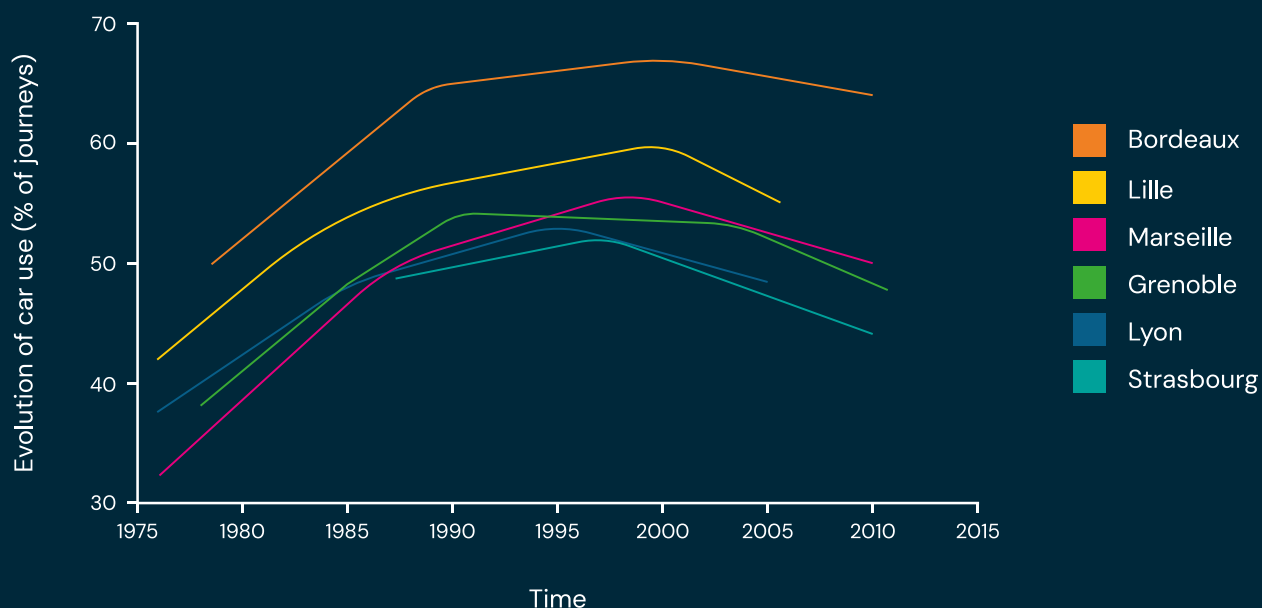
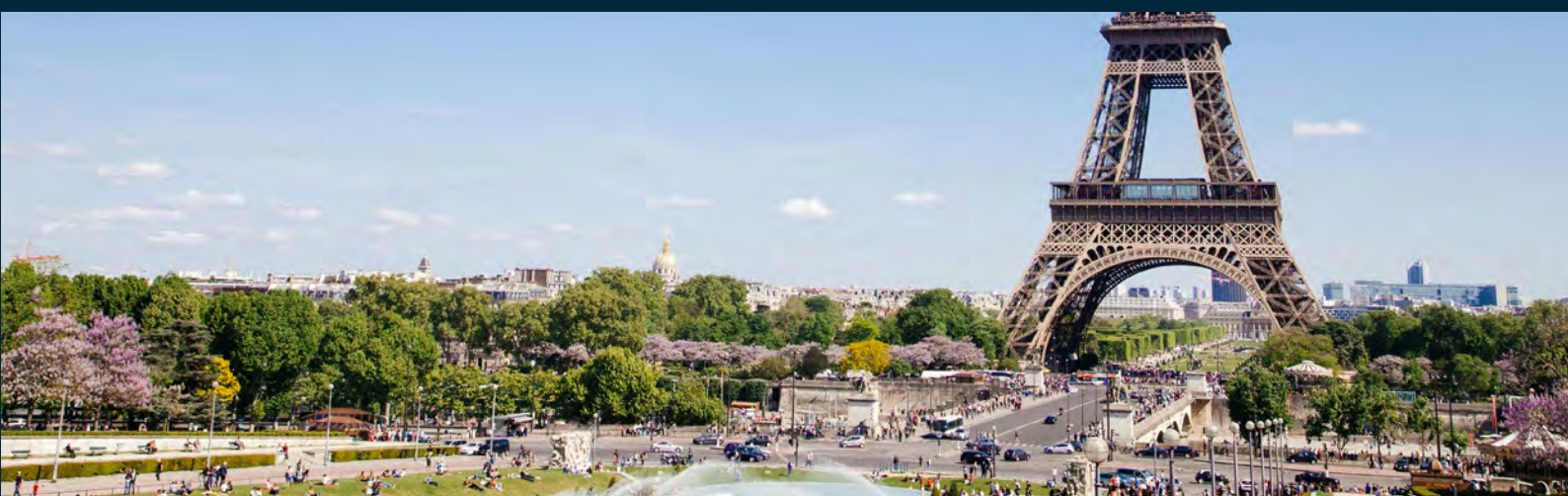


Figure 17. Evolution of car use (% of journeys) in selected French cities with tramways. Based on data from [CERTU](#)

123 Turnheim, B. & Geels, F. W. (2019).



CASE STUDY 6

Public procurement and capital subsidies: Electric buses in India

Bulk public procurement combined with capital subsidies successfully introduced electric buses into Indian cities and brought down their costs. Policymakers recognised and backed the 'winning' battery-electric and hybrid electric vehicle technologies, and not the less promising hydrogen fuel cell technology. By directing support primarily to electric vehicles, and not to more efficient diesel or petrol vehicles, the policy demonstrated the principle of focusing on zero-emission solutions.

The context: air pollution, oil imports, and insufficient public transport

Buses are India's main form of public transport, accounting for about 40% of passenger kilometres travelled by road.¹²⁴ This makes India one of the largest bus markets in the world.¹²⁵ However, it was estimated that in 2019, the country had less than a fifth of the number of buses required to meet the needs of its citizens.¹²⁶

India has important reasons for meeting this need through a shift towards EVs, rather than through more fossil fuelled vehicles. In 2015, India was ranked second globally in the number of deaths attributable to transport emissions, with 74,000 premature deaths from this cause;¹²⁷ and a 2024 study found that in 2009–2019, 3.8–16.6 million deaths (5–25% of total mortality in the country) were attributable to the particulate matter PM_{2.5}.¹²⁸ These problems have persisted, with India's cities having some of the highest air pollution levels in the world.¹²⁹ Moreover, India is a large importer of fuel. Estimates suggest that the country could save \$40bn on crude oil imports by achieving a 30% market share of EVs by 2030 along with a high level of use of public transport.¹³⁰

The challenge

The first electric bus was introduced in India in 2014, but market demand then and in subsequent years remained very low. Obstacles to further deployment included high costs (arising from high battery costs, and a lack of local manufacturing facilities), performance challenges relating to battery safety, lack of charging infrastructure, and underdeveloped supply chains.¹³¹

124 SAREP (2024). [Report on Findings and Next Steps in Scaling Up E-Bus Deployment in India](#). USAID.

125 Chowdhury, A. & Roy, S. (2024). [Procurement and Financing of Electric Buses in India, Lessons for Africa](#). Centre for Science & Environment.

126 ITDP India (n.d.). [Where does India stand in its public e-bus transition?](#)

127 ICCT Factsheet India (2019). [Health Impact of Air Pollution from Transportation Sources in Delhi](#)

128 Jaganathan, S., Staffoglia, M., Rajiva, A. et al. (2024). [Estimating the effect of annual PM_{2.5} exposure on mortality in India: A difference-in-differences approach](#). The Lancet Planetary Health. The range is based on whether the Indian National Ambient Air Quality Standards, or the WHO guidelines, are used, respectively.

129 Gresser, E. (2025). [India has 84 of the world's 100 most air-polluted cities](#). PPI

130 Soman, A., Kaur, H., Jain, H. et al. (2020). [India's Electric Vehicle Transition](#). CEEW.

131 GGGI & C-STEP (2016). [Electric Buses in India: Technology, Policy and Benefits](#).

The policies

In 2015, the Indian government launched the Faster Adoption and Manufacturing of Electric Vehicles in India (FAME India) scheme, with the aim of creating demand for EVs, piloting the new technology, and building charging infrastructure.¹³² In 2017, the scheme extended subsidies for electric buses at 60% of their purchase cost up to a maximum of \$110,000, or up to \$129,000 for those with higher levels of local content.¹³³ The subsidies were provided to state transport undertakings (STUs), public sector bus operators owned and managed by state governments, with a mandate to provide affordable public bus transport. STUs could choose to use the subsidies either to purchase buses directly from the manufacturers and operate the buses themselves, or to use a gross cost contract (GCC) model where they paid private companies to supply, operate, and maintain the services for a fixed fee per kilometre. In the latter model, the STUs take the financial risk of passenger revenues, while the operator is responsible for providing the service at a fixed cost.¹³⁴

By the end of the first phase of the scheme, in March 2019, 425 electric and hybrid buses had been deployed in 10 cities.¹³⁵ This was somewhat slower progress than had been expected. Difficulties included the high upfront costs of the buses, limited readiness of the manufacturers (with shortages of spare parts), and insufficient charging infrastructure. Electric buses at this stage were still two to three times more expensive than diesel buses,¹³⁶ and the poor financial health of the STUs made it difficult for them to purchase the buses even with the support of the subsidies. The STUs that operated the buses themselves struggled with inexperienced staff managing immature technology, but those that chose the GCC model performed much better, with their operational costs being comparable to those of diesel buses, and in some cases lower.¹³⁷

The second phase of the scheme (FAME II), implemented from 2019 to 2022, evolved in response to the lessons from the first. It had a larger budget, with money for charging infrastructure and administration as well as for the bus purchase subsidies. The GCC model was made mandatory, to reduce operational risks. The subsidies were offered to 64 cities,¹³⁸ but to be eligible, a city had to have a provision to waive the registration charges and road taxes for EVs,¹³⁹ as well as an overarching policy to promote EVs. The STUs had the responsibility to provide land for vehicle parking and repair, and to connect depots with high voltage power lines, while the private bus operators were required to install the necessary charging points.

Importantly, from 2021 the scheme included arrangements for aggregating demand for electric buses from different cities, with combined tenders and bulk procurement managed by a public agency created specifically for this purpose. The aim was to reduce costs through economies of scale and greater bargaining power – an approach that had been successful previously in the bulk public procurement of diesel buses.¹⁴⁰

132 Chowdhury, A. & Roy, S. (2024).

133 Percentage of a vehicle's components or value that is manufactured or sourced within India.

134 Chowdhury, A. & Roy, S. (2024).

135 Sutar, S. M. & Kumthekar, M. B. (2023). Review on FAME-INDIA scheme for electric vehicles. International Research Journal of Engineering and Technology. 10. pp.391–393; ITDP India (n.d.).

136 ITDP India (n.d.).

137 Chowdhury, A. & Roy, S. (2024).

138 Press Information Bureau Government of India Ministry of Heavy Industries (2019). Sanction for 5595 Buses under FAME Phase-II.

139 Singh, V. (2022). Rollout of Electric Buses in India. ITDP India.

140 Chowdhury, A. & Roy, S. (2024).

The results

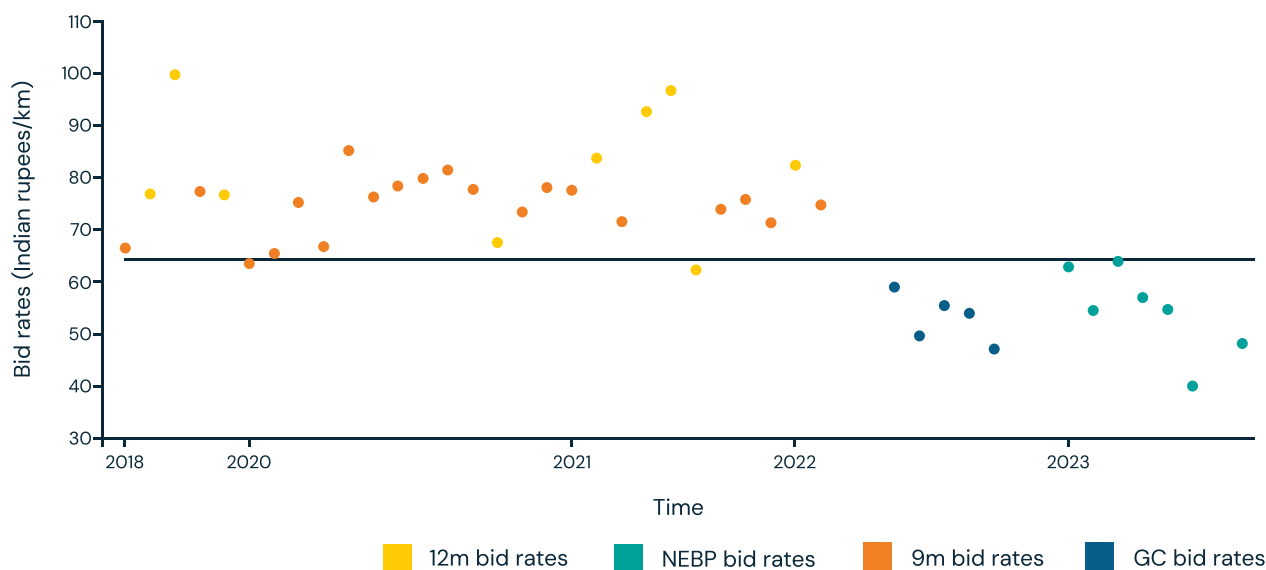


Figure 18. Cities achieve lower bid rates by putting their demand into part of a larger tender, compared with tendering alone. Notes: The graph compares individual city tenders with aggregated tenders 2018–2023 (for different bus sizes, 9 m and 12 m). The red dots labelled ‘GC bid rates’ represent buses under the Grand Challenge (GC), the demand aggregation effort. The dark blue dots labelled ‘NEBP bid rates’ reflect the National Electric Bus Programme bids, another round of aggregated procurement launched after the Grand Challenge. This shows how, pre-2022, bid rates from city-specific tenders mostly ranged from 70 to 90 rupees/km, whereas post-2022, with GC and NEBP, bid rates dropped to 45–55 rupees/km. This provides useful evidence that demand aggregation drove significant cost reductions. Source: [Dubedi \(2024\)](#).

FAME II generated a high level of interest, with 26 Indian states and union territories putting forward 86 proposals for a total of 15,000 electric buses. From among these, the government selected projects to support the deployment of over 5,000 buses.¹⁴¹

Demand aggregation and bulk procurement was found to achieve lower costs than when cities tendered for buses individually (Figure 18).¹⁴² A ‘Grand Challenge’ bulk procurement in 2021, in which demand from the five major cities of Delhi, Bangalore, Hyderabad, Kolkata, and Surat was aggregated, produced the world’s largest tender for electric buses, and the lowest prices yet realised in India. The cost of purchasing and operating these electric buses was around 23–27% lower than the equivalent cost of diesel and CNG (compressed natural gas) buses.¹⁴³

Buoyed by this success, in 2022 the government developed a more ambitious National E-Bus Programme with the aim of deploying 50,000 electric buses by 2027.¹⁴⁴ More than 10,000 electric buses were on the road in India by November 2024, with the number continuing to rise rapidly.¹⁴⁵ The World Bank, which supported the Indian government in its implementation of the FAME scheme, has since begun applying the lessons from this experience to provide similar support to other countries.¹⁴⁶

141 ITDP India (n.d.).

142 Dubedi, A. (2024). *Electrification of bus based public transport in India. Opportunities and Challenges*. WRI India.

143 CESL (2022). *‘The Grand Challenge’ for Electric Bus Deployment: Outcomes and Lessons for the future*.

144 Chowdhury, A. & Roy, S. (2024).

145 WRI India (2024). LinkedIn Post: [India’s electric bus fleet surpasses the 10,000 mark!](#)

146 The World Bank Group (2023). *Reality Check: Lessons from 25 policies advancing a low-carbon future*.



CASE STUDY 7

Auctions and feed-in tariffs: Wind power in Uruguay (2005–2016)

In Uruguay, policymakers used a reverse auction policy for renewable power, combined with a feed-in tariff to rapidly increase wind power deployment. This approach was motivated by the increasing challenges faced by hydropower due to drought, and by the cost reductions in wind power and its viability for bulk power production. The government backed a winning technology in terms of cost, performance, and resilience.

The challenge

Uruguay is a small, strongly urbanised country, and correspondingly it has a traditionally highly centralised power supply system: until the 2000s, it relied almost entirely on hydropower from four dams on the Uruguay and Rio Negro rivers. As repeated droughts struck in the early 2000s, power supply was short, and Uruguay increasingly relied on power imports, especially from neighbouring Argentina, to maintain services. As Argentina faced supply problems too, previous import contracts were reduced and then set to expire by 2007. This required Uruguay to buy electricity on the Argentinian spot market at high cost. Above all, Uruguay was forced to ramp up generation in the country's reserve oil power plants – at a time of dramatically increasing global oil prices.¹⁴⁷ The Uruguayan energy import bill soared.

In 2005, the government reformed its electricity policy to diversify the electricity supply to increase security of supply, increase national energy autonomy, and minimise energy import costs – in part by supporting wind power.¹⁴⁸ Previous market organisation and reform attempts had proven unsuccessful, not triggering any mentionable investment in any form of power generation capacity.¹⁴⁹ A central problem was that the uncertain market situation, combined with a generally high national risk profile, drove up financing costs and made long-term investment, such as in power generation assets, unattractive.¹⁵⁰ The power market reforms met and exceeded the intended goals: the Uruguayan renewable power auction policy is widely seen as one of the most successful renewable energy policies, both in general and especially outside the industrialised countries.

Policy approach

The central elements of these reforms were to allow independent power producers, and to incentivise investment through auctions. The auctions were designed as reverse auctions – the lowest bidder is awarded – for tranches of capacity, resulting in power purchase agreements with fixed prices for 20 years. The first auction for wind power was held in 2006, for 20 MW capacity. Further, larger, auctions followed in 2009 and 2011, for 150 MW each. As the awarded prices in 2011 were much lower than expected, submitted but unsuccessful bids were later awarded in an additional tendering round.¹⁵¹ In addition, feed-in tariffs for small-scale wind power, set at the strike price of the last auction (USD0.064 per kWh¹⁵²), were introduced in 2012, allowing industrial consumers to feed in 'surplus' energy, amounting to up to 50% of their yearly production; also this FIT set a fixed price for 20 years.¹⁵³ The FIT was to last for two years, or support up to 200 MW of capacity, and was suspended as the capacity cap was reached.

147 Spencer, T., Islam, M. & Pang, L. (2012). *Transformational Climate Finance: An Exploration of Low-Carbon Energy* (Working Paper). WRI.

148 IRENA (2015). *Renewable Energy in Latin America 2015: Country Policy Brief – Uruguay*.

149 Markert, S. (2024). *The Uruguay Way: Achieving Energy Sovereignty in the Developing World*. Earth.Org; BloombergNEF (2021). *Uruguay – Climatescope 2021 market profile*.

150 Spencer, T., Islam, M. & Pang, L. (2012).

151 IRENA (2015).

152 Hafner, S. & Lilliestam, J. (2019). *The Global Renewable Power Policy dataset*. doi:10.5281/zenodo.3371375

153 Ibid. Note that the prices were fixed to the US dollar, giving generating companies a guaranteed return on their investment. SOAS (2025). *How Uruguay built national backing for its renewable energy revolution*. The Institute of Development Leadership Dialogue.

Outcomes

In sum, the auctions, FIT, and market reforms triggered investment in over 20 wind farms (of more than 10 turbines each), and a host of smaller installations, leading to 1,500 MW wind power by 2017, about a third of total capacity (Figure 19).¹⁵⁴ During the expansion years 2014–2016, Uruguay saw the fastest-growing wind share of all countries worldwide. By 2020, wind power supported the country with 41% of the total energy generated (5,438 GWh), making it the main energy source and demonstrating a successful new energy mix which had evolved from hydropower dominance into a diversified one with an important share of renewables.¹⁵⁵

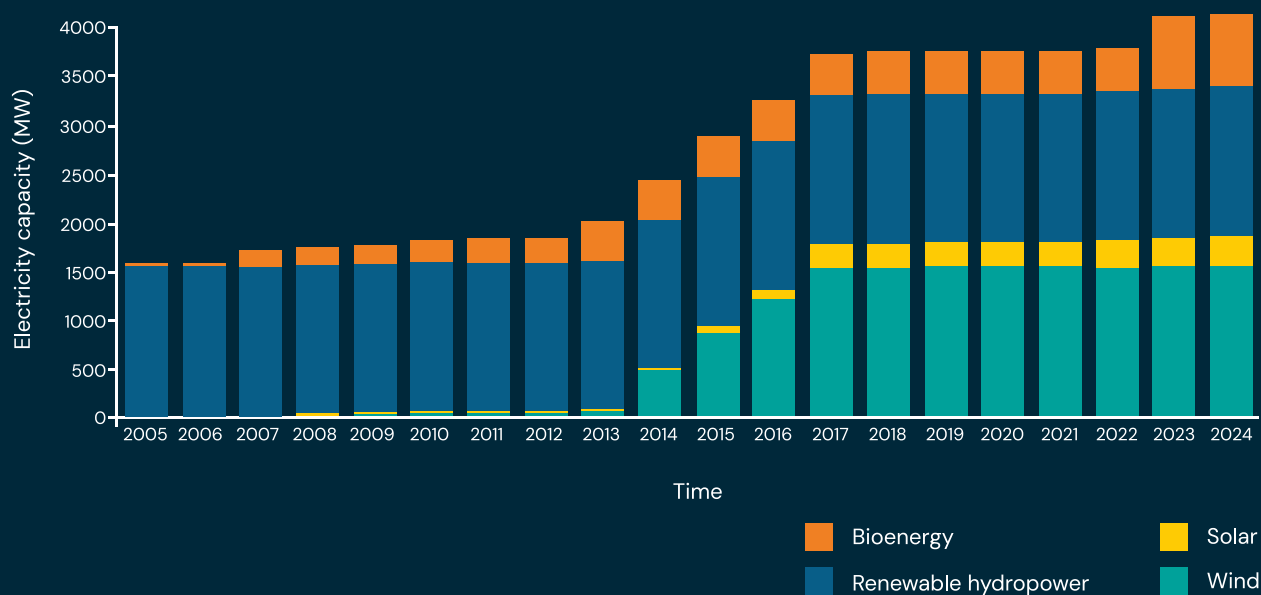


Figure 19. Renewable power capacity Uruguay, 2005–2024.
Source: IRENA (2015).

After reaching the renewable energy target in 2015, the wind power auctions and consequently deployment stopped.¹⁵⁶ The FIT for wind had already expired. Since 2017, Uruguay has seen only minor additions of biomass and solar PV capacities.

¹⁵⁴ The Wind Power (2025). *Uruguay – Wind farms*. The Wind Power.

¹⁵⁵ Correa, K., Uriona-Maldonado, M. & Rodrigues Vaz, C. (2022). *The evolution, consolidation and future challenges of wind energy in Uruguay*. Energy Policy. 161. pp.112758.

¹⁵⁶ BloombergNEF (2021).



CASE STUDY 8

Grants and subsidies for consumption: Birth of aviation (1890–1930)

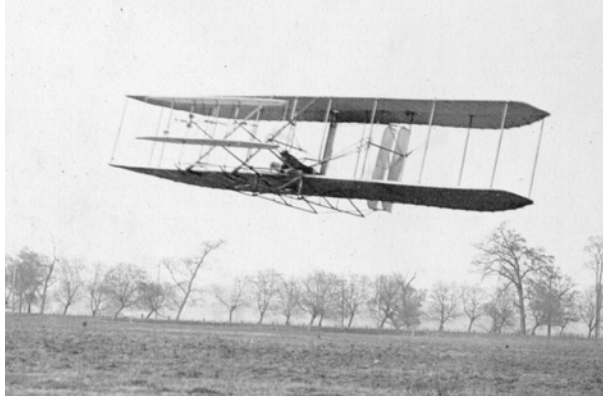


Figure 20. The Wright brothers' aircraft (1903).
Source: [Wright Airplanes \(n.d.\)](#).



Figure 21. The Douglas DC-3 aircraft.
Source: [The Aviation History Online Museum \(2014\)](#).

The birth of civil aviation in the early 20th century demonstrates that government subsidies may be essential to create viable market niches for new technologies that otherwise may struggle to overcome market introduction hurdles. After years of failed experiments, the first airplane (which was a glider with added propeller and light-weight piston engines) flew in 1903 (Figure K).

World War I boosted the production of bomber, fighter, and reconnaissance aircraft as well as technical performance, as engines with more engine power and planes with stronger wings and fuselage increased flight speed, altitude, and distance. After the war, European governments continued to support fledgling aviation industries (because of imperial policy, military strategy, and political prestige), whereas US government contracts were cancelled, leading to the decline of US aircraft manufacturers. Newly created airline companies tried to create a commercial market niche by providing line services between major European cities (e.g. London to Paris in 1919). But these efforts failed because the comfort in converted bombers was too low (as passengers had to wear heavy leather jackets and goggles).



Figure 22. Airline services in America in 1927. Source: Chant (1986).¹⁵⁹

¹⁵⁹ Chant, C. (1986). *De Geschiedenis van de Luchtvaart* ('The History of Aviation'). Atrium (translated from English, first published in 1978 as 'Aviation: An Illustrated History').

American policymakers first helped to create a subsidised mail transport niche, with the Contract Air Mail Act of 1925 providing large indirect subsidies to airline companies.¹⁵⁸ Mail communication was still important in the 1920s and 1930s, when less than 40% of the US population had telephone connections, and faster airmail was thus deemed desirable and worthy of subsidies. The subsidised airmail niche provided about 50% of airline revenue between 1931 and 1939¹⁵⁹ and helped the creation of a network of air routes and airport, fuelling, and repair infrastructures that gradually extended across the continent (Figure 22). To regulate and improve safety in the emerging aviation industry, the 1926 Air Commerce Act also introduced rules and regulations for pilot licensing, aircraft registration and inspection, and airspace control.

By the early 1930s, a passenger transport niche emerged, with businessmen and politicians being the main early customers, partly because flying enabled large distances to be covered rapidly and partly because flying identified them with the modern and the daring.¹⁶⁰ The use of aeroplanes in the airmail and passenger transport niches yielded learning processes and user demand for stronger, safer, and more fuel-efficient planes. This stimulated manufacturers to develop and implement innovations such as more powerful piston engines, more aerodynamic propellers, new navigation instruments (e.g. altimeters, airspeed indicators, rate of climb indicators, directional gyro). They also shifted from biplanes to monoplanes, from wood to duralumin, and introduced monocoque airframes (that carry load and shape the aircraft).¹⁶¹ The combined innovations resulted in the DC-3 (1936), which became the dominant design for commercial aviation (Figure 21). The DC-3, which could seat 21 passengers and fly 1,000–1,500 miles, became the workhorse of commercial aviation, which expanded rapidly by the late 1930s (Figure 23). This expansion was also enabled by airline public relations campaigns featuring celebrity passengers and female pilots (to convince people that flying was safe) and by airport expansions which were 75% government funded by New Deal arrangements between 1932 and 1938.

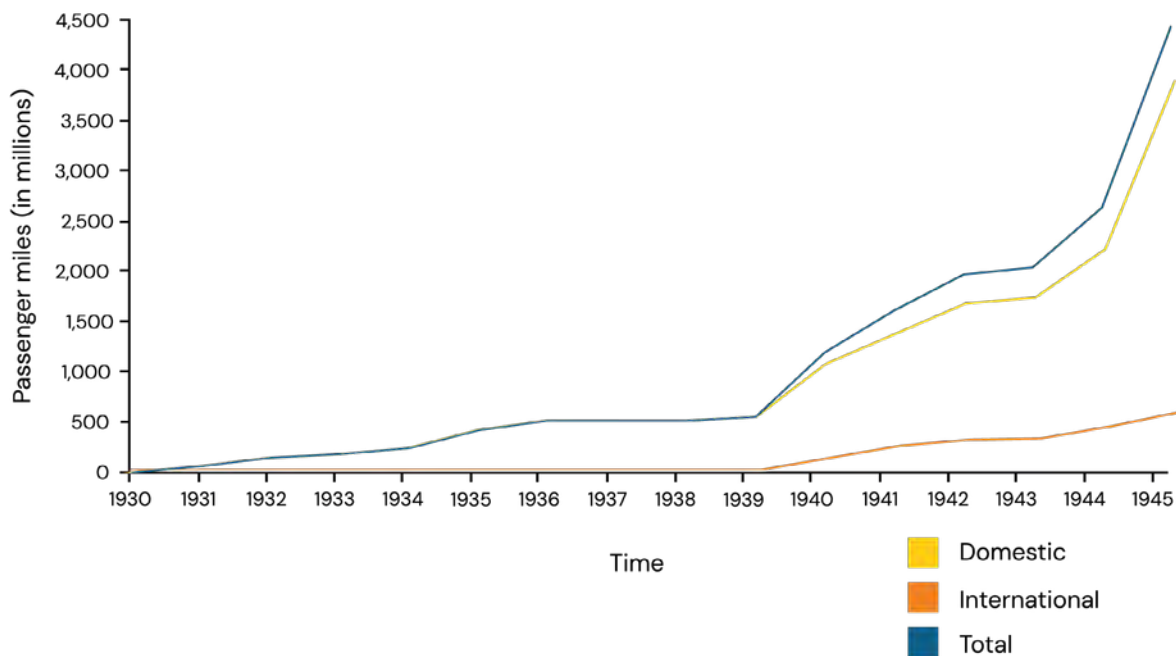


Figure 23. Development of American civil aviation in million passenger miles, 1930–1945. Constructed with data from American Air Transport Association.

158 Van der Linden, F. R. (1995). Progressives and the Post Office: Walter Folger Brown and the creation of United States air transportation. In: Trimble, W. D. (ed.), *From Airships to Airbus: The History of Civil and Commercial Aviation, Volume 2: Pioneers and Operations*, pp.245–260. Smithsonian Institution Press.

159 Heppenheimer, T. A. (1995). *Turbulent Skies: The History of Commercial Aviation*. John Wiley & Sons.

160 Rae, J. B. (1968). *Climb to Greatness: The American Aircraft Industry, 1920–1960*. MIT Press.

161 Heppenheimer, T. A. (1995).

CASE STUDY 9

Case Study 9. Grants and subsidies for production: From mixed farming to specialised wheat farming in the UK (1930–1970)



Figure 24. A line of tractors driven by trainees at the Oxford Institute of Agricultural Engineering, 6th August 1940. Source: William Vanderson/Fox Photos/Getty Images.

The UK transition from mixed agriculture to specialised wheat farming provides a good example of the role of production support measures.¹⁶² UK policymakers were keen to accelerate this transition when the Second World War, particularly German U-boats, disrupted wheat imports that provided more than 80% of wheat for human bread consumption. The traditional mixed farming system (based on horses, manure fertiliser, seasonal farm labour, and small plots of land) was deemed insufficient to address existential concerns about wartime food security. Policymakers therefore wanted to stimulate a rapid shift to modern wheat agriculture practices (based on tractors, combine harvesters, land drainage schemes, artificial fertilisers, pesticides, larger plot sizes, and reduced labour inputs), which had emerged in the 1930s but remained confined.

To rapidly increase domestic wheat production, policymakers made several drastic policy interventions.¹⁶³

1. They introduced market controls that enabled the setting of wheat prices at a level that provided stable and attractive income for farmers (thus reducing the risk of investments).
2. They provided capital grants and cheap loans to enable farmers to buy new machinery (like tractors and combines – see Figure 24) and invest in land improvement and drainage schemes (which were needed to prevent machines getting stuck in muddy fields).
3. They improved the speed and scale of knowledge flows with technological extension schemes, which included both home visits from experts (to inform farmers) and organized trips to demonstration farms (so that farmers could see for themselves).
4. They introduced War Agricultural Executive Committees that oversaw, planned, and coordinated food production at the local level.

¹⁶² Roberts, C. & Geels, F. W. (2019a). *Conditions for politically accelerated transitions: Historical institutionalism, the multi-level perspective, and two historical case studies in transport and agriculture*. *Technological Forecasting and Social Change*. 140. pp.221–240.

¹⁶³ Bowers, J. K. (1985). *British Agricultural Policy since the Second World War*. *The Agricultural History Review*. 33. pp.66–76; Martin, J. (2000). *The Development of Modern Agriculture: British Farming Since 1931*. Palgrave.

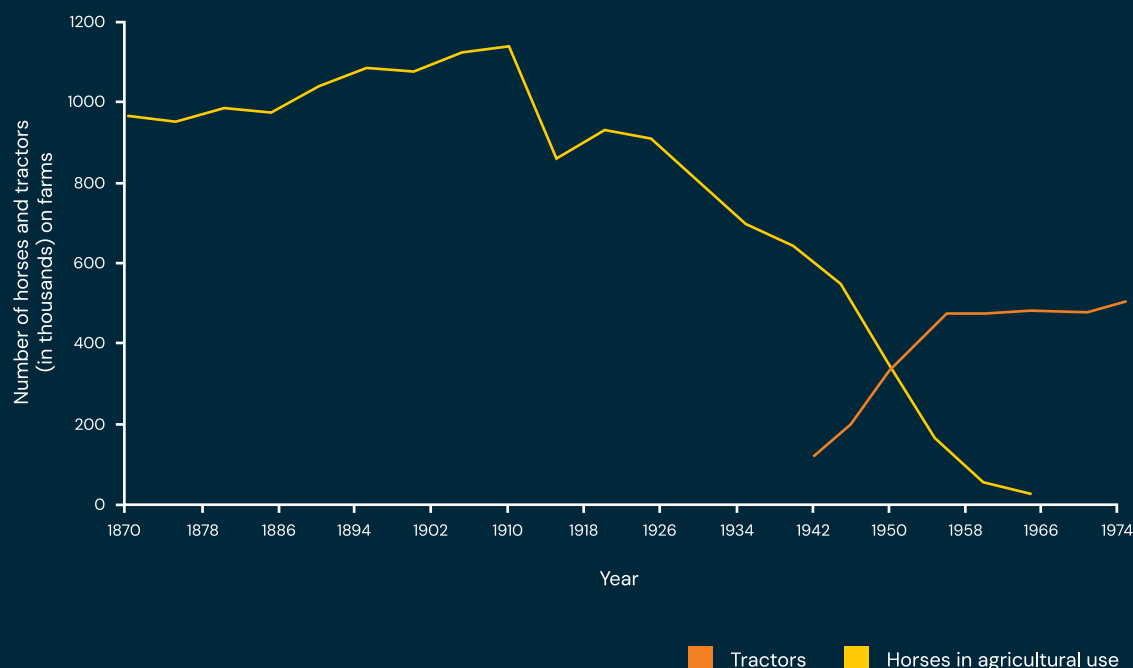


Figure 25. Number of horses and tractors (in thousands) on farms in Great Britain, 1870–1975. Constructed using data from Marks (1989).¹⁶⁴

These policies were effective in driving rapid change such as the diffusion of tractors (Figure 25), which increased the available draught power. Policies also led to increases in the areas of land under cultivation, the spread of drainage infrastructures, and increased use of machinery (such as combines) and fertilisers. Support policies continued after the war, and the resulting transition greatly boosted wheat yields per acre and total wheat yields (Figure 26). Many smaller farms went out of business, however, as the shift to more capital- and input-intensive farming coincided with scale increases. Price controls were lifted in 1956. Wheat prices rapidly decreased in the 1950s and 1960s (Figure 27) as the transition to mass-production systems gathered pace and total wheat production increased.

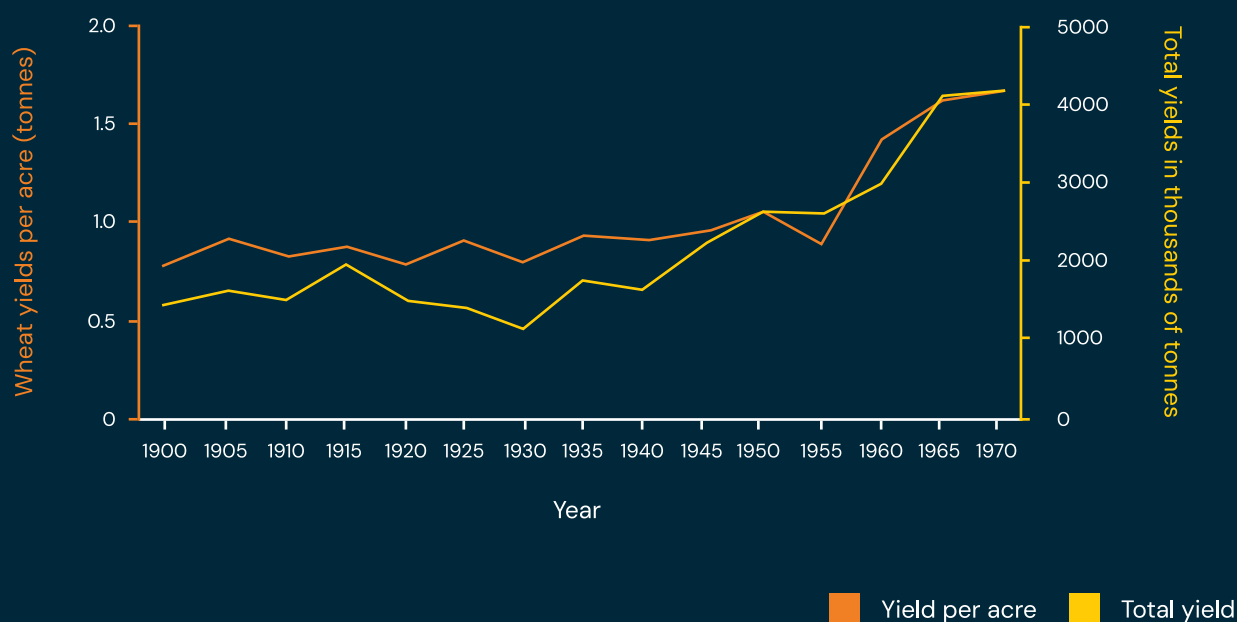


Figure 26. Wheat yields per acre in tonnes (left-hand y-axis) and total yields in thousands of tonnes (right-hand y-axis) in the UK, 1885–1970. Constructed using data from Mitchell (2011).¹⁶⁵

¹⁶⁴ Marks, H. F. (1989). *A Hundred Years of British Food & Farming: A Statistical Survey*. Taylor & Francis.

¹⁶⁵ Mitchell, B. R. (2011). *British Historical Statistics*. Cambridge University Press.

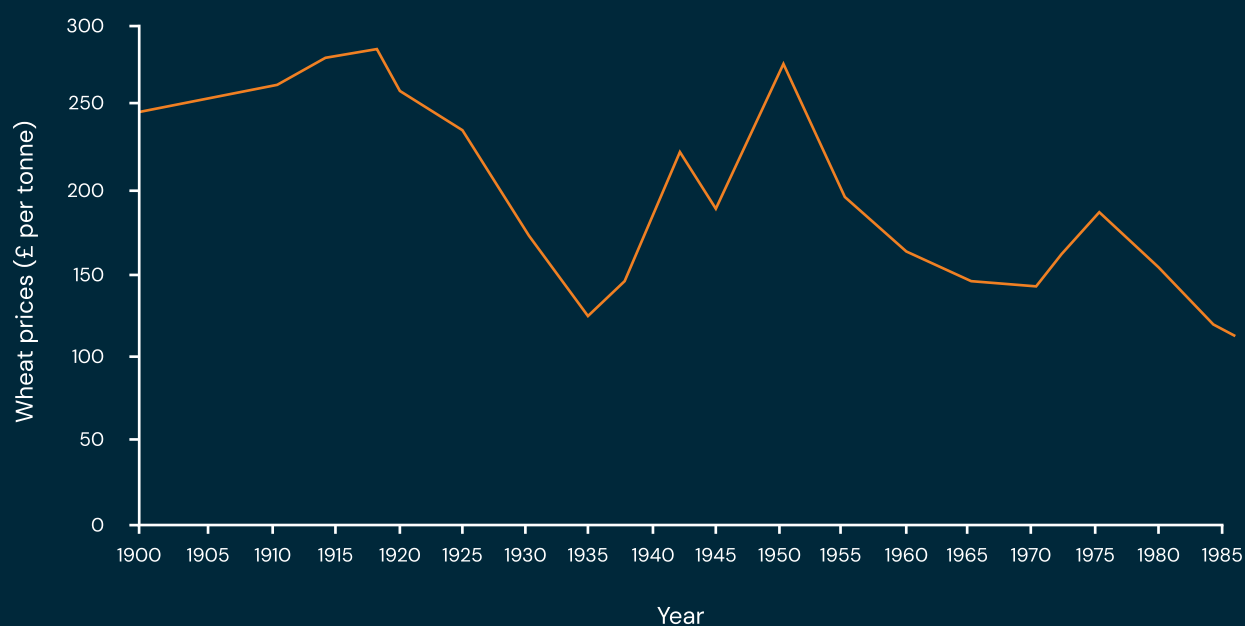


Figure 27. UK wheat prices (£ per tonne) in 1986 money values. Wheat prices fell in the 1920s and 1930s because of mass importation of cheap grain from Canada and the United States; prices increased during the war and remained high during post-war austerity years; prices rapidly decreased in the 1950s and 1960s. Constructed using data from Marks (1989).



3 DIFFUSION

3.1 Overview

Spread the new technology through markets and society, decrease costs, and adapt the wider system to the new technology

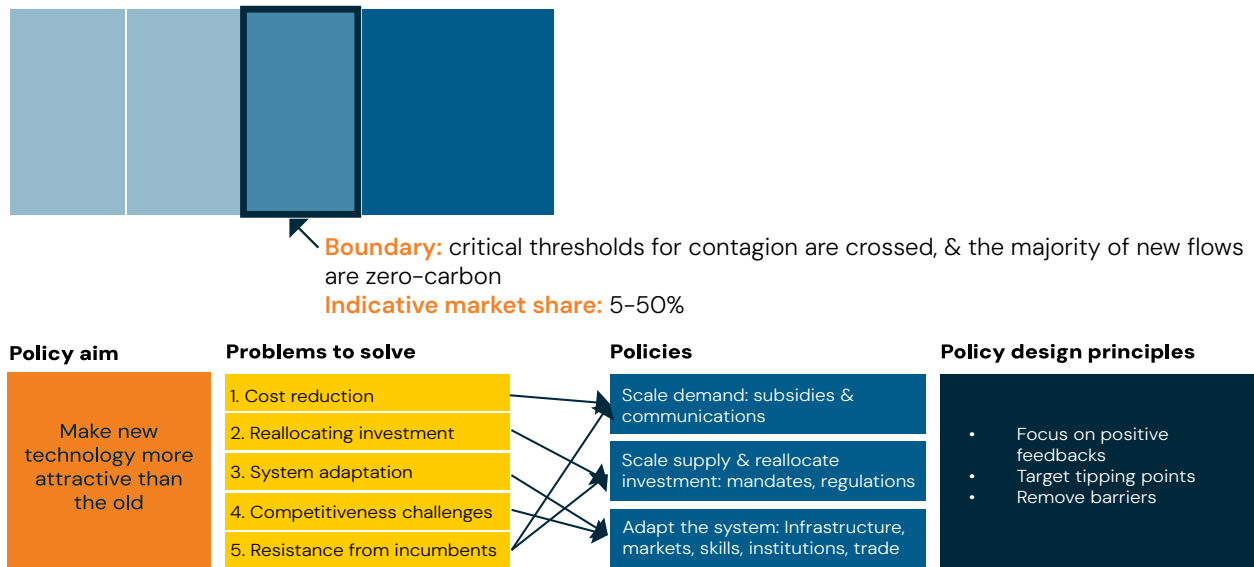


Figure 28. Diffusion – Overview of aims, problems to solve, policies, and policy principles. Source: authors' own.

Aim: The aim for policymakers at this stage is to spread the new technology through markets and society. This is achieved by deployment and resulting cost reductions, and adapting the wider system, so that the new technology becomes more affordable, attractive, and accessible than the old one.

The process: Having been established in small, protected market niches during the Market Introduction stage of the transition, the next challenge is to enable the new technology to spread to an increasing share of the market. As technologies diffuse, they often benefit from self-reinforcing positive feedback effects that lower costs and improve performance. Effects such as economies of scale, learning-by-doing, and the increasing availability of complementary technologies, already present in the Market Introduction stage, can provide even stronger positive feedback to accelerate progress in the Diffusion stage. These cost reductions and performance improvements improve the legitimacy of further transition policy measures, and help to increase the market share of new technologies and associated firms, which can enhance political influence and social acceptability. However, these changes are often strongly opposed by businesses, workers, and political representatives of regions whose positions depend on the incumbent technology, and whose profits, jobs, and livelihoods may see early signs of destabilisation by the growth of the new industries.

The crossing of thresholds where the new technology begins to outperform the old in terms of cost, attractiveness to consumers, or profitability for producers, can significantly accelerate diffusion. Reaching these critical thresholds as deployment increases, while ensuring that the sector continues to provide its core products or services, can require significant adaptation of market structures and the wider infrastructural, behavioural, and regulatory system to fit the characteristics of the new technology.

It is only once new technologies have become more affordable, attractive, and accessible than the old technologies that the policy focus shifts towards phase-out of the old. Countries have tried and struggled to phase out old technologies sooner. In Germany, the government attempted to phase out new fossil fuel heating systems at a time when the new technology, heat pumps, had only reached 25% of sales, and had to abandon the attempt as it met overwhelming opposition. In contrast, Norway's government waited until electric vehicles made up over half of car sales before announcing a future goal for all new car sales to be zero-emission, and this was broadly accepted. These experiences suggest that policies to end sales of the old technology should not be the main focus until the old technologies account for a minority of sales or new investments. Similarly, it may be best for policies to set a trajectory towards banning the use of the old technology only after it represents less than half of the products or assets in operation.

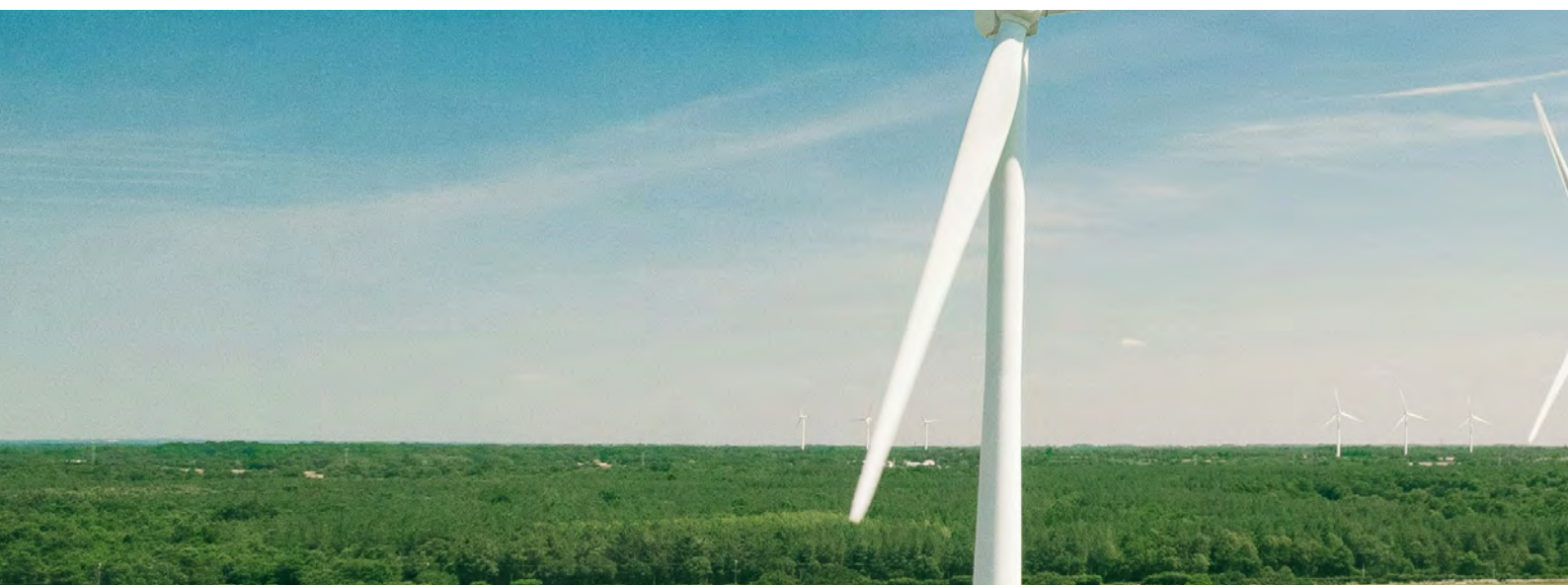
Problems to solve

1. Cost reduction

A critical barrier to rapid deployment during the Diffusion stage can be high costs. Whereas during Market Introduction these costs can be managed through niche market creation with price-tolerant consumers, or subsidies for small-scale deployment, they must be more substantially addressed for widespread diffusion to occur. Because costs decrease with deployment, the critical challenge is starting and strengthening the positive feedbacks of deployment, learning-by-doing, and economies of scale. More generally, the new technology needs to be made attractive to consumers and producers, which may involve aspects of convenience, safety, technical performance, and infrastructure availability.

2. Reallocating investment

Diffusion requires huge investment as technologies must scale up from niche to mass deployment, which demands large-scale manufacturing capacity and often new infrastructure construction. Industry may still be reluctant to commit all its investment to the new technology, even if its market share is growing, while it faces uncertain returns, risks, and systems designed for incumbents. The investment needs of the Diffusion stage are likely to exceed what governments can manage from public budgets, so for governments, mobilising and redirecting private capital is essential.



3. System adaptation

Existing infrastructure, market structures, regulations, norms, and business practices are all tailored to the incumbent technologies. Without reforms to these system elements, the diffusion of the new technology can be held back even if it approaches cost-competitiveness, or can disrupt the sector's provision of its core goods and services. Examples include rules of electricity markets that can favour either fossil fuel plants or renewables; infrastructure for road transport that can be petrol stations or charge points; and safety standards in construction that can be designed around old or new materials.

4. Competitiveness challenges

In highly trade-exposed sectors, competitiveness risks can act as a strong barrier to the transition when the new technology is still higher-cost than the old. When the new technology is increasingly cost-competitive, countries that have not led its development may have to choose whether to import low-cost products from abroad, or invest in creating domestic industries despite higher costs.

5. Resistance from incumbents

Incumbent firms initially often oppose the transition both politically and commercially, as they see the threat from the new competition. During earlier stages of the transition, the threat was less visible. They can, however, reorient from old to new technologies in response to pressures (from policymakers, the wider public, and new entrants) and the perception of opportunities (such as growing markets, declining cost and increasing profitability of new technologies).¹⁶⁶ Political opportunists may also take advantage of real and perceived challenges associated with the transition, stoking opposition to it to advance their own interests.

¹⁶⁶ Geels, F. W., Stegen, K. S., Trencher, G. & Wells, P. (2025). The evolution of resistance strategies during low-carbon transitions: Insights from a comparative analysis of American, German, and Japanese automakers in the unfolding electric vehicle transition (1990–2024).



Example: Light road transport

In the light road transport sector, electric vehicles (EVs) have moved far beyond protected niches and are now competing on price and performance with incumbents in the mass market, even without subsidies in leading countries. EVs reached 18% of new sales globally in 2023 and 38% in China.¹⁶⁷ EV sales are also growing in smaller emerging markets such as Thailand and Costa Rica, with the EV share of sales reaching 10% and 12% in 2023 in those countries, respectively.¹⁶⁸ Diffusion-stage challenges mentioned above remain.

Cost reduction: EV purchase prices remain significantly higher than those of petrol or diesel cars in most markets. This can make EVs unaffordable to consumers even when their much lower operation costs lead to lower lifetime costs of ownership than petrol cars.

Reallocating industry investment: Although car companies are increasing their investment in EV technology, model development, and manufacturing facilities, many continue to introduce new petrol and diesel models to the market. Some have revised their timelines for battery-electric vehicle (BEV) investment given uncertain profitability – cutting immediate production targets, cancelling or delaying products, adjusting longer-term BEV targets or rescheduling capital investment. In 2024, Ford and GM retimed BEV capacity development, delaying when programmes would come online and how quickly capacity would be increased, and Mercedes-Benz increased investment in internal combustion engine projects.

System adaption: For EVs to be viable and attractive for all consumers, charging infrastructure must be widely available. In many countries this is not yet the case. This requires significant investment, not only in charge points themselves, but also in electricity grid upgrades.

Competitiveness challenges: China's leadership in EV manufacturing presents a trade-off for many governments, particularly those of automotive exporting countries: import low-cost EVs from China, or build or protect domestic industry and accept higher costs and a slower transition in the sector.¹⁶⁹ Northvolt illustrates the risks of rapid scaling up of manufacturing capacity in new technologies while competing with more established players elsewhere.¹⁷⁰

Resistance and reorientation from incumbents: Many car companies spend heavily on political lobbying.¹⁷¹ In an analysis of climate policy advocacy of 15 of the world's largest automakers, every automaker advocated against at least one policy promoting EVs.¹⁷² Automotive industry associations have been identified as leading efforts to delay and weaken regulations driving the decarbonisation of light-duty vehicles, and most automakers were members of at least five of those associations globally.¹⁷³ Simultaneously, though, all incumbent automakers are making and selling an increasing variety of EV models and building new EV and battery manufacturing plants. Incumbent automakers are reorienting towards EVs, while resisting politically, as every year of delay saves significant expenditures.

In summary, policymakers seeking to accelerate the transition in the light road transport sector face challenges associated with the Diffusion stage. These may be addressed with the kinds of policies outlined below.

¹⁶⁷ IEA (2024b).

¹⁶⁸ Celemín, M. & Diego, J. (2024). *Latin America EV Sales Report, Part 3: Leaders on the Podium (Colombia, Uruguay, Costa Rica)*. CleanTechnica.

¹⁶⁹ Mazzocco, I. & Sebastian, G. (2023). *Electric Shock: Interpreting China's Electric Vehicle Export Boom*. CSIS.

¹⁷⁰ Tagliapietra, S. & Trasi, C. (2024). Northvolt's struggles: a cautionary tale for the EU Clean Industrial Deal. Bruegel; Draghi, M. (2024). The future of European competitiveness: A competitiveness strategy for Europe (Part A). European Commission.

¹⁷¹ OpenSecrets.org. (2024). *Automotive industry federal lobbying summary: 2024*. OpenSecrets.

¹⁷² InfluenceMap (2024). *Automakers and Climate Policy Advocacy: A Global Analysis*. InfluenceMap. Of the eight automotive industry associations included in the study, every automaker (except Tesla), remains a member of at least two of these groups, with most automakers a member of at least five of these associations globally.

¹⁷³ Ibid.



MENNEKES
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3.2 Policies to accelerate the Diffusion stage

1. Scale up demand: subsidies and public communications

Deployment subsidies for zero-carbon technologies are likely to remain important at this stage, ensuring the affordability of (or a convincing business case for) the new technology, and driving the feedback between adoption and investment. These may be targeted at either production or consumption. Subsidies can enable the new technology to compete against incumbents. Compared with their use during the Market Introduction stage, subsidies at this stage can be lower, and it may be possible to taper them as technology costs fall, to avoid overcompensation. In some circumstances, it may still be useful to complement deployment subsidies with loan guarantees or concessional lending, to crowd in private finance to the production of zero-carbon technologies – though these instruments should be less necessary as the Diffusion stage advances.

Taxes on the sale of fossil fuel products are most likely to be useful for funding subsidies, as in the Market Introduction stage. (Taxes designed for these purposes are not the same as carbon prices, as they may be levied on a product rather than its use, and the amount of tax paid does not have to relate to emissions.) Taxes or carbon prices can complement subsidies as part of the policy mix to give an advantage to the new technologies and destabilise the old (as illustrated in Case Study 14). However, they are less likely to be effective in driving diffusion, since their cost may be absorbed by producers, passed through to consumers, or mitigated by making fossil fuel systems more efficient, none of which advance the transition to zero-carbon technologies and systems. Increasing the efficiency of fossil fuel systems can of course help to reduce emissions; this is best understood as an action that can be taken in parallel to advancing the transition, rather than one that moves the transition forward.

Public communications programmes can be used to advertise the advantages of the zero-carbon technologies, to counter misinformation spread by incumbent industries, and to ensure awareness of policies that are available to support consumers in the adoption of the new technology.

2. Scale up production and reallocate investment: mandates and regulations

We highlighted clean technology mandates, which require a minimum share of production to be met by the new technology, as a potentially useful policy for the Market Introduction stage of the transition. At that stage, mandates can be valuable in establishing the new technology and supporting the emergence of a new industry, even if they are set at a low level. In the Diffusion stage, clean technology mandates can be extended and strengthened, requiring a rising share of sales in the sector to be met with the zero-emission technology. This can be highly effective in reallocating private sector investment from the old to the new technology on a large scale, expanding economies of scale and accelerating cost reduction. Mandates are likely to be particularly useful when cost declines of the new technologies are slower (as for example with sustainable aviation fuels), meaning that price parity between new and old technologies will take longer to achieve, or never happen at all.

Performance standards for energy use or regulations that restrict allowable emissions in products or processes can require technologies to be continually improved, by increasing the floor for performance over time (e.g. requiring cars to meet stricter fuel efficiency standards). These are typically less central to the deployment of zero-carbon technologies than the policies above, often being focused on increasing the efficiency of fossil fuel products, but if they are sufficiently stringent, they can also incentivise or force a switch to zero-carbon technologies simply by removing fossil technologies as an option for new investment.

3. Adapt the system: infrastructure, markets, skills, institutions, and trade

Infrastructure investment and incentives

As the new technology grows, it will start causing friction within the existing system: wind power behaves differently from coal and needs adapted infrastructure; EVs put new strains on electricity distribution grids, and so on. The diffusion of many zero-carbon technologies will need to be accompanied by investment in infrastructure – such as EV charging networks, expanded electricity grids, and hydrogen pipelines. Public infrastructure investment can be complemented with incentives (such as tax breaks, streamlined permitting, or concessional lending) to crowd in private sector investment.

Market reforms

Market reforms may be needed to address the issue that existing markets were built for, and favour, incumbent technologies with fundamentally different characteristics from the new ones. Restructuring can undo systemic disadvantages faced by clean technology by accounting for and rewarding its different characteristics. This can include support for deployment of complementary technologies, whose use enhances the performance of the core technologies. Examples in the power sector include capacity mechanisms rewarding flexibility, dynamic pricing reflecting renewables variability, and subsidies for energy storage.

Skills programmes

Skills programmes, funding, incentives, and partnerships for training can help develop the workforce capabilities needed to deploy, operate, and maintain zero-carbon technologies at scale. This helps to break the inertia of entrenched systems which rely on established methods. Support of this kind for communities that have lost jobs associated with fossil fuels can not only benefit the new industries but also mitigate the risks of social and political opposition to the transition.

Institutional reform

Institutions play multiple roles through the transition –enabling long-term planning, aligning national and local policies, and coordinating across sectors and ministries. New or reformed institutions may be needed to govern markets that did not exist before, or that have changed substantially. For example, the International Civil Aviation Organization was founded to ensure safety and security in air transport, but in recent years has had to grapple with the problem of decarbonisation. Institutions can also change the broader political economy. For example, many countries have created climate change councils to hold governments accountable for progress in reducing emissions. In India, climate-oriented entities have emerged within various Indian government ministries, incorporating climate goals into existing organisational frameworks and priorities.¹⁷⁴

Trade policy and rules

In trade-exposed sectors where decarbonisation increases costs, international agreements on standards, tariffs, or taxes may be used to enable zero-carbon technologies to be produced, sold, and adopted more effectively across borders. This can be important earlier or later in the transition, depending on the sector. Measures to facilitate trade in zero-carbon technologies may also expand demand for those technologies, enable countries to specialise, and improve access to or affordability of zero-carbon technologies in emerging markets.

174 The World Bank Group (2023).

3.3 Policy design principles for Diffusion

1. Focus on positive feedbacks

The transition often becomes more politically contested during the Diffusion stage, because emerging competition is more visible to incumbent businesses than in earlier phases, and more jobs associated with the old technology come under threat.¹⁷⁵ When governments prioritise policies that are feasible in the current context, and that develop, improve, and grow markets for the new technologies, these can transform the political economy over time and open up new policy options (see Figure 29).¹⁷⁶ For example, subsidies for solar and wind power have created jobs in many countries, increasing support for the continued transition to clean power.

Policies can strengthen or broaden stakeholder support for the transition if they increase returns to a target group (e.g. production subsidies supporting the existing EV industry), start creating returns for new stakeholder groups (e.g. tax breaks for the use of EVs in corporate fleets), or reduce opposition by lowering the costs of transition (e.g. purchase subsidies, road tax reductions, or other incentives for EV consumers).¹⁷⁷

Sequencing policies so as to support the growth of the new industries first, and the decline of the old industries later, is the predominant pattern globally. The policies at each stage of the transition make those needed at the next stage possible. Invention of a new technology enables it to be introduced to the market, Market Introduction paves the way for greater Diffusion, and Diffusion enables eventual Reconfiguration including phase-out.

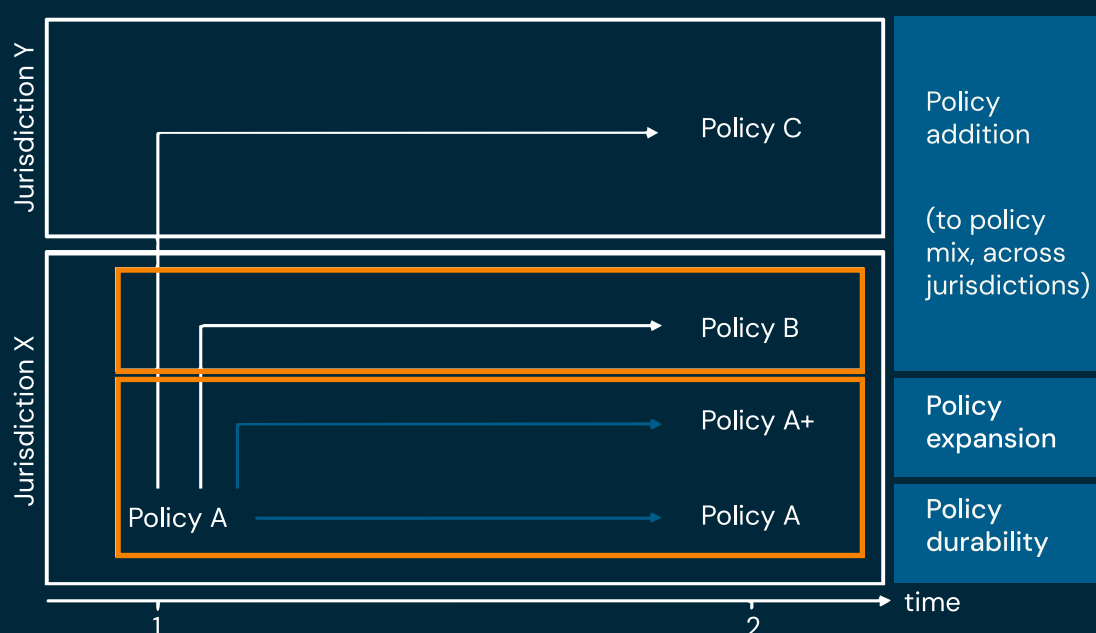


Figure 29. One policy can have feedback effects, leading to expansion of that same policy, the introduction of another complementary policy, and even the introduction of that policy in a different jurisdiction, thereby having international influence. Source: Meckling (2025) – presentation.

¹⁷⁵ Geels, F. (2014). *Regime resistance against low-carbon transitions: Introducing politics and power into the multi-level perspective*. Theory, Culture and Society. doi:10.1177/0263276414531627.

¹⁷⁶ The World Bank Group (2023).

¹⁷⁷ Meckling, J., Kelsey, N., Biber, E. et al. (2015). *Winning coalitions for climate policy*. Science. 349. pp.1170–1171.

2. Target tipping points

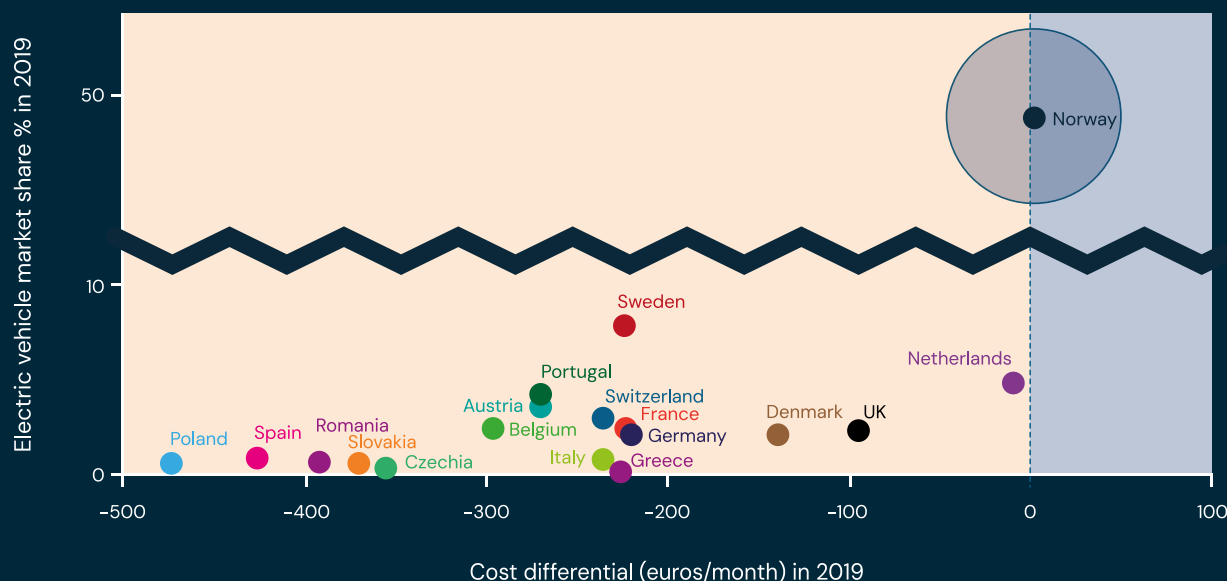


Figure 30. Cost parity between fossil fuelled and electric vehicles in Norway meant that by 2019, EV market share was far higher than in other European countries. Source: Sharpe & Lenton (2021). Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope. Climate Policy. Copyright © Taylor & Francis Ltd, reprinted by permission of Informa UK Limited, trading as Taylor & Francis Ltd <https://www.tandfonline.com>.

Affordability, accessibility and attractiveness to consumers, and profitability to producers, are all important during the diffusion stage. These are relative measures: what matters is how well zero-carbon technologies perform compared to the fossil fuel alternatives. Targeted policy interventions that change the balance of technology competitiveness, cost or profitability can help to activate ‘tipping points’ in consumer preference, investor confidence, or social support. A tipping point has two key characteristics: a small input leads to a disproportionately large change, given self-reinforcing feedbacks; and the change will not reverse, because all critical system elements (e.g. not only price, but also infrastructure and behaviour) have become the new norm.¹⁷⁸

Tipping points have played a role in the world’s fastest decarbonisation of the power sector, in the UK, and in the world’s fastest transition in road transport, in Norway. In Norway, a combination of subsidy and tax made EVs cheaper to buy compared to similar petrol models, making EVs the ‘common sense’ purchasing decision.¹⁷⁹ Policy support often needs to remain in place beyond an initial tipping point, being maintained until it is clear that the direction of travel is irreversible. In Norway, continued subsidies, taxes, and investment in EV charging infrastructure ensured this irreversibility.

3. Remove barriers

While investment and regulation play a critical role in the diffusion of zero-carbon technologies, so too must the removal of barriers. For example, barriers to the rapid scale-up of clean power and electrification of other sectors include delays and difficulties in planning, permitting and land acquisition.¹⁸⁰ Such processes may need to be streamlined or removed to enable construction of the new systems.¹⁸¹ Barriers may be regulatory (such as complex regulation, inflexible permits and adverse legal systems), administrative (for example, multiple authorities in charge of permitting and lack of data aggregation slowing down the process), and societal (local concerns, or biodiversity protection processes).

¹⁷⁸ Geels, F. & Ayoub, M. (2023). A socio-technical transition perspective on positive tipping points in climate change mitigation: Analysing seven interacting feedback loops in offshore wind and electric vehicles acceleration. *Technological Forecasting and Social Change*. 193. 122639; Mey, F., Mangaliagiu, D. & Lilliestam, J. (2024). Anticipating socio-technical tipping points. *Global Environmental Change*. 89. 102911.

¹⁷⁹ Sharpe, S. & Lenton, T. (2021). Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope. *Climate Policy*. 21. pp.421–433.

¹⁸⁰ Energy Transition Commission (2023). Streamlining planning and permitting to accelerate wind and solar deployment; McKenna, R., Lilliestam, J., Heinrichs, H. et al. (2025). System impacts of wind energy developments: key research challenges and opportunities. *Joule*. 9. 101799.

¹⁸¹ Klein, E. & Thompson, D. (2025). *Abundance*. Simon & Schuster.

Long grid connection queues arising from lack of network capacity are also leading to a backlog of onshore wind and solar projects in many countries. Solutions include assigning priority status to renewables, streamlining and clarifying legal processes, and setting and enforcing permitting targets.¹⁸² China and Spain are both on track to surpass their renewables targets, thanks in part to the removal of barriers.¹⁸³

Development stage	Technology	Indicative time (months)	Expedited time (months)	Time savings (months)
Site mapping and selection	Onshore	24	12	- 12
	Offshore	24	12	- 12
	Solar	4	2	- 2
Environment surveys	Onshore	36	18	- 18
	Offshore	42	24	- 18
	Solar	16	4	- 12
Stakeholder consultation	Onshore	9	9	None recommended
	Offshore	9	9	None recommended
	Solar	9	4	- 5
Permit application and examination	Onshore	36	12	- 24
	Offshore	48	18	- 30
	Solar	24	3	- 21
Obtaining grid connection	Onshore	36	9	- 27
	Offshore	48	12	- 36
	Solar	20	1	- 18
Legal challenges	Onshore	84	12	- 72
	Offshore	108	18	- 90
	Solar	39	4	- 36

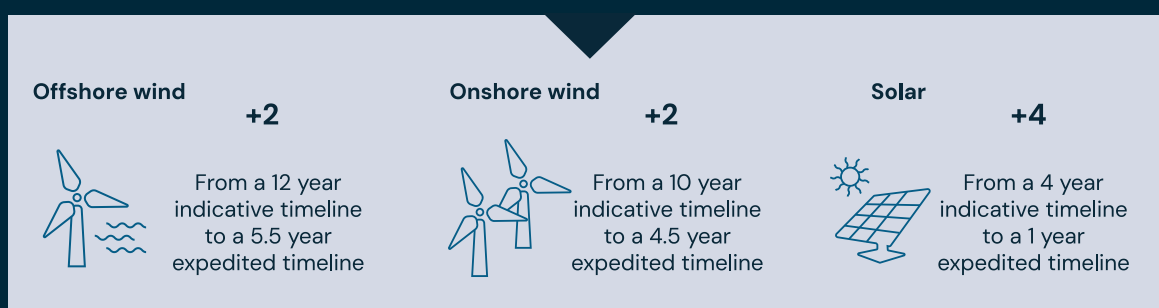


Figure 31. Project development stages can be reduced by streamlining permitting, legal challenges, and grid connections. Source: [Energy Transition Commission \(2023\)](#).

¹⁸² Energy Transition Commission (2023).

¹⁸³ Ibid.

3.4 Case studies for Diffusion



CASE STUDY 10

Mandates/portfolio standards and quotas: From oil to district heating in Denmark (1950–1980)

An historical example of strong regulatory instruments driving diffusion is the transition from oil-based heating to district heating in Denmark after the 1970s oil crises.¹⁸⁴

The 1973 oil crisis was a major shock because Denmark at the time imported 99% of its primary energy, principally oil and coal,¹⁸⁵ and relied significantly on building-based oil-fired boilers for domestic and industrial heating. The oil crisis led to immediate energy conservation measures (such as banning Sunday driving and turning off every other streetlight) and to urgent debates about alternative heating options.

Policymakers initially preferred the building of new nuclear power plants that would power heat pumps to heat Danish homes and buildings,¹⁸⁶ but this plan faced societal opposition (Figure 32) and lack of interest from electric utilities in subsequent years. The expansion of district heating systems, which had been operated for decades by municipalities or local cooperatives, mostly using oil and organic waste as fuels,¹⁸⁷ was another option, but this received limited policy interest and support. Policymakers did, however, create the Danish Energy Agency in 1975 to increase capabilities and support policy debates. The 1976 Electricity Supply Act also mandated that all new electricity production plants should also produce heat, which increased the supply of heat that could be used for future district heating projects.¹⁸⁸



Figure 32. Antinuclear protest march, from Gyllingnæs to Aarhus, 1978 and the ‘Nuclear? No Thanks’ icon from the Danish anti-nuclear movement. Source: [Johansen and Werner \(2022\)](#).

The 1979 oil crisis, combined with public resistance to nuclear power, finally settled the debate, and led Danish policymakers to introduce strong policies to drive the further diffusion of district heating and a fuel input shift from oil towards coal, natural gas, waste, and biofuels. The 1979 Heat Supply Act, in particular, advanced several regulatory measures.

¹⁸⁴ Roberts, C. & Geels, F. W. (2019b). *Conditions and intervention strategies for the deliberate acceleration of socio-technical transitions: Lessons from a comparative multi-level analysis of two historical case studies in Dutch and Danish heating*. Technology Analysis & Strategic Management. 31. pp.1081–1103.

¹⁸⁵ Hawkey, D. (2016). *European heat policies and practices*. In: Hawkey, D., Webb, J., Lovell, H. et al. (eds.) Sustainable Urban Energy Policy: Heat and the City. Routledge.

¹⁸⁶ Nyborg, S. & Røpke, I. (2015). *Heat pumps in Denmark – From ugly duckling to white swan*. Energy Research & Social Science. 9. pp.166–177.

¹⁸⁷ Eikeland, P. O. & Inderberg, T. H. J. (2016). *Energy system transformation and long-term interest constellations in Denmark: Can agency beat structure?* Energy Research & Social Science. 11. pp.164–173.

¹⁸⁸ Hawkey, D. (2016).

1. It required municipalities to produce 5-year heating plans and granted them broad legal powers to enforce the plans.
2. Using technical analyses from the Danish Energy Agency of local heat demand and available heat sources, it also established different heating zones, and indicated that some zones (in dense built-up areas) should use district heating, while other (less dense) zones should use gas, which required the creation of gas networks.
3. It envisaged that, by 2020, gas would meet about 15% of heat demand, and district heating about 60%.
4. It gave local policymakers strong powers to secure the user base for commercially viable operation, for example by requiring buildings to connect to district heating networks, or by banning the use of electric heating in new buildings.¹⁸⁹
5. It included strong consumer protections by requiring all district heating systems to be run on a non-profit basis. This requirement is still in place.¹⁹⁰

The implementation of these policies (and others) in the 1980s stimulated the diffusion of district heating (Figure 9), while new energy taxes made oil-based heating even less competitive, accelerating its decline. Kommunekredit arrangements, in which municipal governments underwrote loans, also lowered the cost of capital for district heating systems, making it easier to finance their construction.

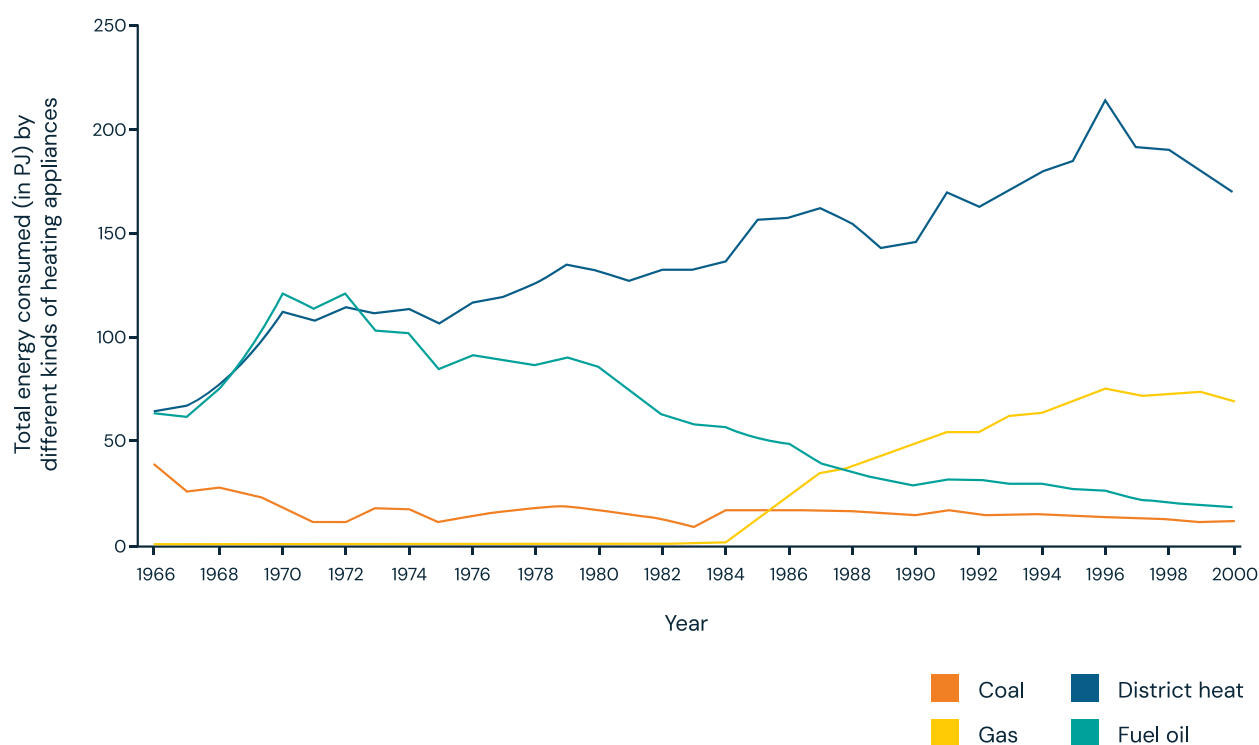


Figure 33. Total energy consumed (in PJ) by different kinds of heating appliances used by Danish households and industries, 1966–2000. Constructed using data from Statistics Denmark (2016).¹⁹¹

189 Klok, J., Larsen, A., Dahl, A. & Hansen, K. (2006). *Ecological tax reform in Denmark: History and social acceptability*. Energy Policy. 34. pp.905–916.

190 Johansen, K. & Werner, S. (2022). *Something is sustainable in the state of Denmark: A review of the Danish district heating sector*. Renewable and Sustainable Energy Reviews. 158. 112117.

191 Statistics Denmark, 2016. *Gross energy consumption in common units by type of energy, industry and time*. Statbank Denmark.

CASE STUDY 11

Public campaigns: From wells and rivers to pumped indoor water in the Netherlands (1870–1945)

The Dutch water supply transition from wells and surface waters (rivers, canals) towards piped systems that delivered clean water indoors started in the 1860s and 1870s in cities, which suffered most pollution from urine, excrement, and other wastes that spread infectious diseases. It was driven by better medical science insights, public health campaigns by medical doctors and engineers, demand from rich citizens and firms (e.g. beer breweries, paper factories, textile firms) that were willing to pay for more comfort and clean water, and private initiatives from newly created water companies.¹⁹²

In the 1880s and 1890s, socio-political concerns about working-class living conditions and increased interventionism by city authorities also led to more public initiatives to provide clean water to city dwellers. By 1900, around 40% of the Dutch population was connected to piped water, mostly in cities. Although households initially used clean water mostly for drinking and cooking purposes, it was subsequently also used for other purposes such as waste disposal (e.g. flushing toilets and disposing excrements through sewer systems) and washing (e.g. showers, baths, washing machines). Increased household connections and the diversification of usage steadily increased water use in the twentieth century (Figure 34).

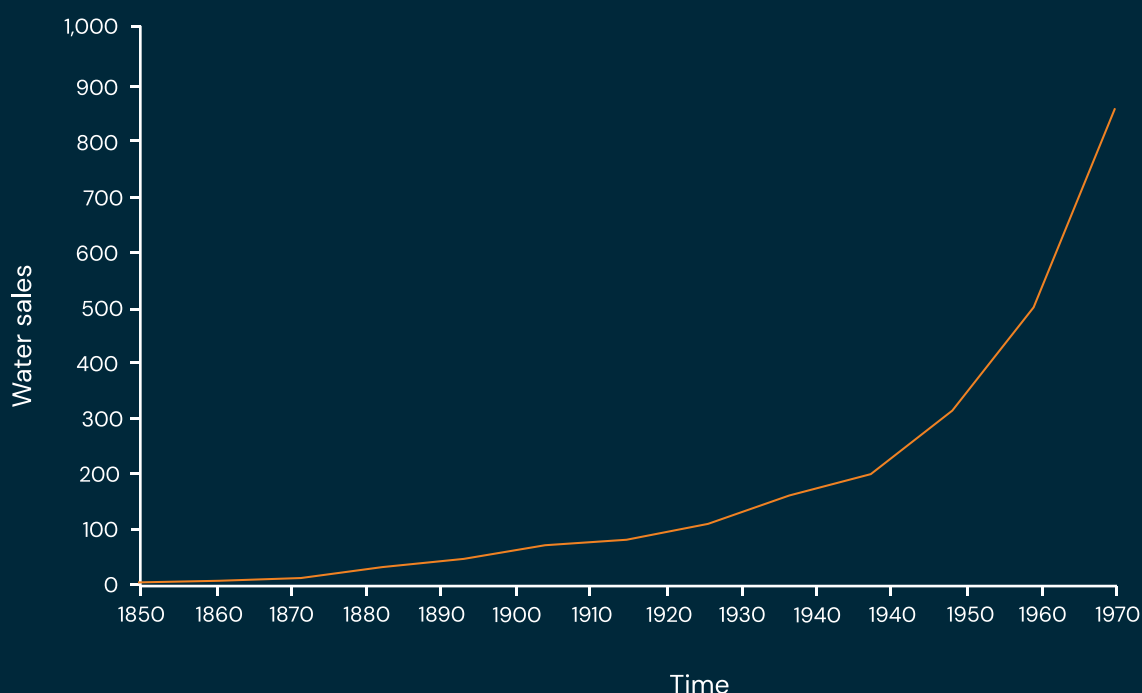


Figure 34: Water sales (in million cubic meters) by modern water companies in The Netherlands, 1850–1970. Constructed using data from Leeflang (1974).¹⁹³

¹⁹² Geels, F. W. (2005). *Co-evolution of technology and society: The transition in water supply and personal hygiene in the Netherlands (1850–1930) – a case study in multi-level perspective*, Technology in Society. 27. pp.363–397.

¹⁹³ Leeflang, K. W. H. (1974). *Ons drinkwater in de stroom van de tijd* ('Our drinking water in the flow of time'). Vereniging van Exploitanten van Waterleidingbedrijven in Nederland; 1974.

Nevertheless, the spread of piped water systems to 100% of the population was a struggle in the first half of the twentieth century. It was particularly challenging to reach working-class families, who often lacked the money to pay for piped water supply and sanitary facilities like wash basins, toilets, baths, and showers. Piped water diffusion was also hampered by traditional beliefs such as the idea that a layer of dirt formed a buffer against disease, and that multiple washing wore out clothing.¹⁹⁴ The diffusion to rural areas was also challenging, because farmers were often unconvinced that piped water was better than traditional water sources and because water companies were reluctant to pay large sums to build very long water pipelines.

To reach working-class families, policymakers supported and contributed to a wider 'civilisation offensive', which between 1890 and 1920 linked the diffusion of piped water systems, water closets, baths, showers, washbasins, and washing machines to new norms around cleanliness, health, and hygiene.¹⁹⁵ Policymakers joined and reinforced hygiene and public health campaigns by doctors, clubs, associations, and other civil society organisations, which resulted in a stream of brochures, health booklets, and magazines providing advice on hygienic practices (Figure 35). Nurses, midwives, home inspectors, social workers, and schoolteachers also contributed to the transmission and anchoring of hygienic norms to working-class people, including the relevance of clean water for health and hygiene.¹⁹⁶



Figure 35. Leaflets advocating hygienic practices in the battle against tuberculosis. Source: Wijmer (1992).¹⁹⁷



Figure 36. Advertisement from the Limburg water company in 1930. Source: Wijmer. (1992)

To reach rural areas, policymakers designed and implemented PR campaigns in the 1920s and 1930s, using films and leaflets that contrasted the hard work involved in pumping water outdoors with the ease of 'modern' piped waterworks (Figure 36). Policymakers also provided subsidies to water companies to reduce the cost of building new water infrastructures. Although modern waterworks gradually entered rural areas, traditional water sources continued to be used by some farmers until after World War II.

194 Meulders, C. (1992). The struggle for cleanliness: A socio-historical analysis of the laundry process. Master's Thesis, Catholic University of Leuven.

195 Goubert, J. P. (1989). The Conquest of Water: The Advent of Health in the Industrial Age. Princeton University Press.

196 De Leeuw, K. (1988). Hygiene en gezondheid als terrein van beschavingsoffensief: Regulering en Disciplineren in Nederland en Noord-Brabant 1880–1940 ('Hygiene and health as domains of the civilization offensive: Regulation and discipline in the Netherlands and North-Brabant 1880–1940'). Sociale Wetenschappen. XXXI. pp.145–152.

197 Wijmer, S. (1992). Water om te drinken ('Water for drinking'). Vereniging van Exploitanten van Waterleidingbedrijven in Nederland (VEWIN).

CASE STUDY 12

Infrastructure investment and conversion: From coal to natural gas in Dutch heating (1960–1980)



The historical example of the transition from coal to natural gas in Dutch heating¹⁹⁸ illustrates the importance of several policies in adapting the system. Policies to build and convert infrastructure, fund appliance retrofits, and set prices for gas that were competitive against coal combined to make the new technology more attractive than the old. The latter policy can be seen as an example of the principle of targeting tipping points. Meanwhile, compensation of affected workers helped to stabilise public support for the transition.

Figure 37. Sponsored conversion of kitchen appliances to natural gas. Source: [The Hague \(1964\)](#).

A crucial impulse for this transition was the 1959 discovery of a huge and easy-to-exploit natural gas field (in Schlochteren) by the NAM (an alliance of Exxon and Shell). This led to debates with the government on how to develop and exploit the gas field. One option was to use the natural gas in small, high-value market niches (such as cooking and lighting) to optimise profits. Another option was to aim for a broader transition that also included heating, which was a bigger application domain. After a few years of analysis, discussion, and negotiation about responsibilities and revenue sharing, the government in 1962 chose the second option because it wanted to maximise revenues.

The 1962 agreement included the following principles:

1. NAM would have a monopoly on exploiting and selling natural gas in the Netherlands.
2. NAM would pay special taxes and fees to the government.
3. The gas would be sold at a market value price, set at levels similar to or slightly cheaper than alternative fuels (such as coal, oil, or coal gas); this enabled NAM (and the state) to make significant profits because the cost of natural gas extraction and distribution was well below the sales price.¹⁹⁹
4. Natural gas was priced more cheaply at higher usage levels to incentivise gas use for heating; the main advantage for natural gas, however, was increased convenience and comfort, especially in the form of central heating, which entailed a qualitative shift from heating single rooms towards heating the whole house.

¹⁹⁸ Roberts, C. & Geels, F. W. (2019b).

¹⁹⁹ Correljé, A., van der Linde, C. & Westerwoudt, T. (2003). Natural Gas in the Netherlands: From Cooperation to Competition? Oranje-Nassau Groep.

The subsequent transition from coal to natural gas in Dutch heating also required several system adaptations, enabled by policies. First, new institutions were created for pricing and exploitation (discussed above) as well as for the construction of a national gas transmission network. The GasUnie consortium (owned half by Shell and Exxon and half by the state) was created in 1963 to finance and orchestrate this construction process. Second, the new national gas transmission network that connected all Dutch cities to the Schlochteren gas field was completed in 1968. Third, municipalities were required to create or convert local gas distribution infrastructures. Conversions were needed because many cities already had distribution networks for coal gas (made from coal gasification), which had to be repurposed because natural gas had different properties from coal gas. Fourth, appliances using coal gas had to be adjusted because natural gas had different caloric properties. To address this consumer switching hurdle, the state financed and sponsored a campaign to convert appliances to natural gas (Figure 37).²⁰⁰ Fifth, policymakers compensated groups that were negatively affected by the physical construction of gas pipelines (e.g. farmers, road and railway organisations). Traditional coal mining interests were also compensated. The Dutch coal mining company (DSM) received financial stakes in natural gas exploitation, and coal and coal gas workers were often employed in the retrofitting of consumer appliances.²⁰¹ The various agreements, adjustments, support, and compensation schemes enabled a rapid transition from coal to natural gas in heating (Figure 38).

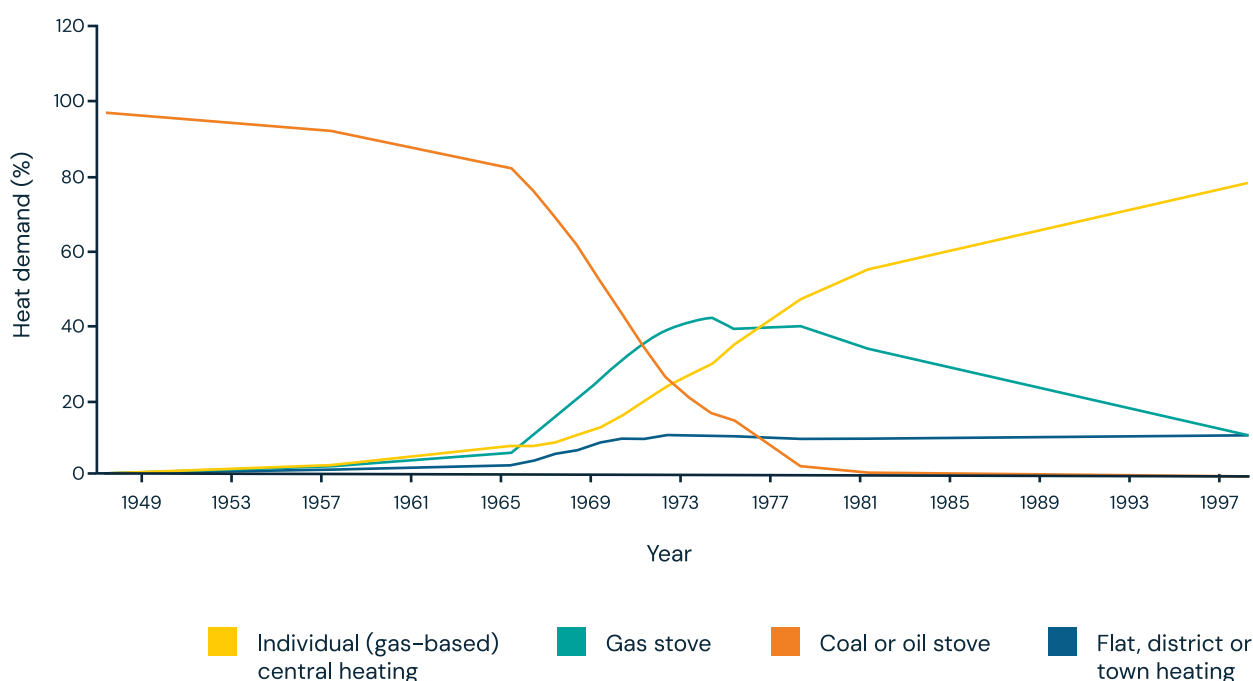


Figure 38. Average (mean) heating options in the Dutch transition from coal to natural gas, 1947–1998 (represented as percentage of heat demand). Constructed using data from Van Overbeeke (2001).²⁰²

200 Correljé, A. & Verbong, G. P. J. (2004). The transition from coal to gas: Radical change of the Dutch gas system. In: Elzen, B. & Geels, F. W. (eds.) *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy*. Edward Elgar Publishing.

201 Correljé, A., van der Linde, C. & Westerwoudt, T. (2003).

202 Van Overbeeke, P. (2001). *Kachels, Geisers en Fornuizen: Keuzeprocessen en energieverbruik in Nederlandse huishoudens 1920–1975* ('Heaters, boilers and furnaces: Choice processes and energy use in Dutch households, 1920–1975'). PhD thesis, Eindhoven University of Technology, The Netherlands.

CASE STUDY 13

Subsidies and regulations: China's road transport transition (early 2000s to present day)

In China, purchase subsidies, regulations, and infrastructure investment drove a rapid transition to EVs. These policies strengthened the positive feedback between industry investment, technology improvement, cost reduction, and consumer demand.

Context

China's policies on the road transport transition were primarily motivated by industrial opportunity, and supported by the objectives of cutting oil imports and improving air quality.

Policies

In 2006, the government identified 'new energy vehicles' (NEVs, defined as electric vehicles or highly efficient hybrid vehicles) as a priority in its national long-term plan for science and technology development.²⁰³ State funding supported research and development of a portfolio of technologies relevant to battery-electric, plug-in hybrid, and hydrogen fuel cell vehicles.

From 2010, purchase subsidies at national and provincial levels supported the growth of the EV market. These were as high as \$18,500 per vehicle in 2013²⁰⁴ and gradually reduced afterwards as the costs of EVs decreased, before being ended entirely at the end of 2022.²⁰⁵ At the same time, the government invested in charging infrastructure, and, in large cities including Beijing and Shanghai, administrative policies made it significantly easier to register and obtain a licence plate for a new EV than for a new petrol car. These policies all increased demand for EVs.

Regulatory policies began to shape the market in 2011, with the introduction of fleet average fuel efficiency standards similar to those implemented in the EU.²⁰⁶ In 2018, the government introduced the 'dual credit' regulation, a hybrid between a zero-emission vehicle mandate and an efficiency regulation. Manufacturers could meet the regulation's targets through a combination of selling EVs as a high proportion of their sales, and ensuring high energy efficiency in their petrol car sales.²⁰⁷ The regulation applied to imports as well as domestic production, and required NEVs to be 10% of car sales in 2019, 12% in 2020, 14% in 2021, 16% in 2022, and 18% in 2023.²⁰⁸

Results

This combination of demand-creating incentives, supply-side regulation, and investment in infrastructure drove rapid growth in EV sales (see Figure 39). The dual-credit regulation proved powerful in forcing manufacturers to increase the supply of the new technology and make it affordable. After it was introduced in 2018, the EV share of car sales grew from around 5% in 2019 to over 20% in 2022.²⁰⁹

203 State Council (2006). National Long-term Plan on Science and Technology Development. State Council, Beijing.

204 Beijing Government (2013). Beijing's New Energy Vehicle Supporting Policies and Subsidy. Beijing Municipal Government.

205 IEA (2023a). *Global EV Outlook 2023 – Policy developments*.

206 IEA (2021). *Fuel economy in China*.

207 Manufacturers were allowed to make up a deficit in credits for the efficiency of petrol cars by using a surplus of credits for NEV sales, but were not allowed to do the reverse. A deficit in NEV credits from NEV production in a given year could only be made up by using NEV credits banked from surpluses in previous years, or by buying NEV credits from other manufacturers.

208 IEA (2023b). *Dual Credit System*.

209 Wang, N., Li, X. & Yang, X. (2025). *The efficacy of New Energy Vehicle mandate policy on passenger vehicle market in China*. World Electric Vehicles; ICCT (2022). *How will the dual credit policy help China boost new energy vehicle growth?*

By 2020, China had developed the world's largest EV market, accounting for nearly half of global sales over the preceding decade, as well as the world's largest EV manufacturing industry.²¹⁰ In 2023, the share of EVs in China's car sales exceeded 33%, far ahead of the 18% target, despite an end to EV subsidies at the national level.²¹¹ At the same time, China became the largest car exporter in the world.

Growth in EV manufacturing and investment has been accompanied by rapid and sustained cost reduction. This suggests the presence of strong reinforcing feedback effects, including learning-by-doing and economies of scale. Within China, EVs in the lower-cost segments of the market are now not only cheaper than petrol cars in terms of total cost of ownership, but also have lower purchase prices.²¹²

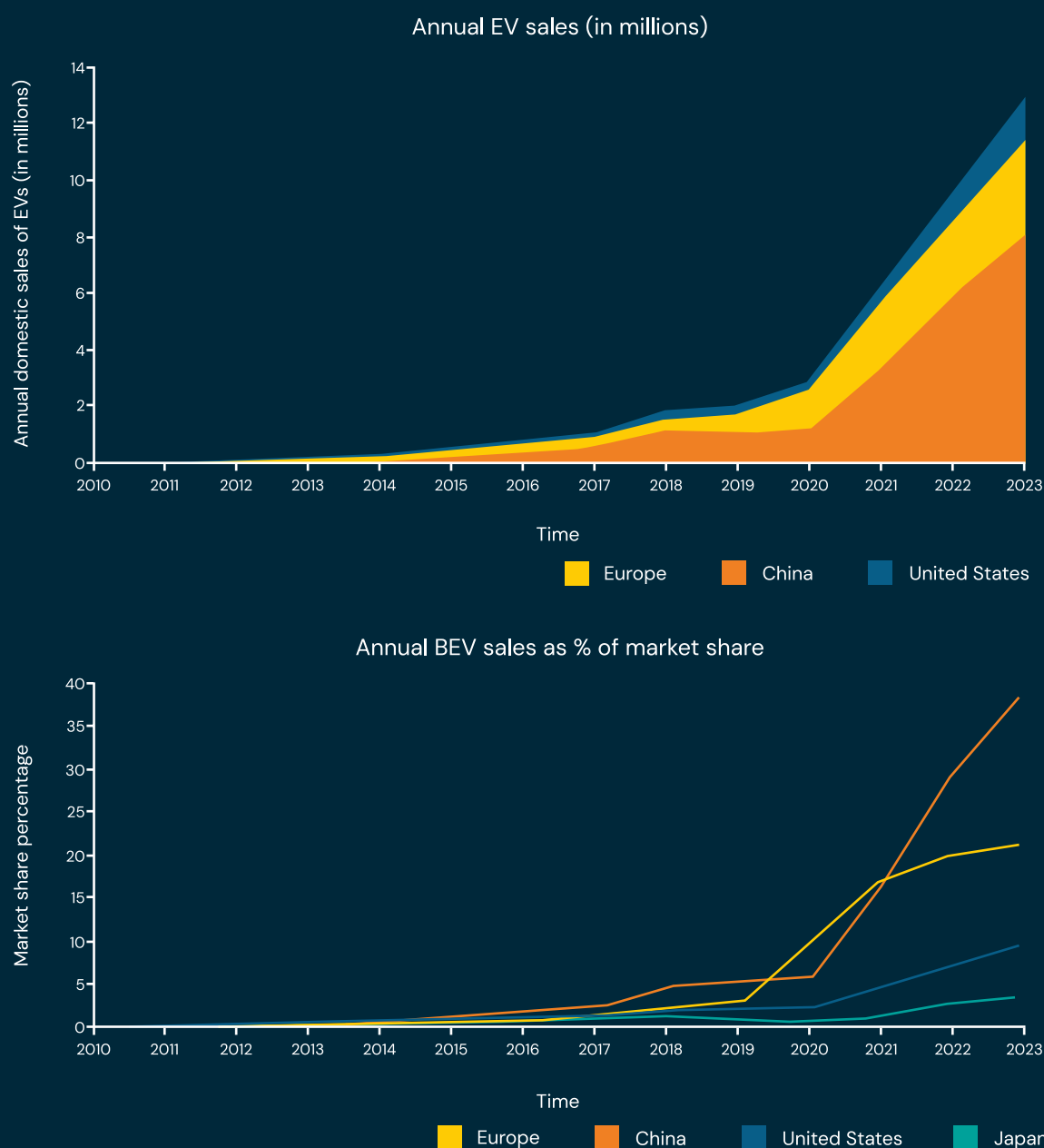


Figure 39. Annual domestic sales of EVs in millions (panel A) and as market share percentage (panel B) in China, Europe, the United States, and Japan from 2010 to 2023. Constructed using data from the IEA (2024b).

²¹⁰ Jin, L., He, H., Cui, H. et al. (2021). Driving a Green Future. *A retrospective review of China's EV development and outlook for the future*. ICCT & EV100.

²¹¹ IEA (2024b). *Global EV Outlook 2024 – Moving towards increased affordability*. Trends in electric cars.

²¹² IEA (2023a).

CASE STUDY 14

Case Study 14. A carbon floor price: Phasing out coal in the UK (2000s to present day)

The phase-out of coal power in the UK happened as the result of multiple policy measures over several decades. In the final stages, these included a carbon tax that made gas power cheaper than coal power. This acted as a tipping point: it switched the positions of coal and gas in the merit order, leading coal stations to operate for fewer hours, become unprofitable, and be rapidly closed down.

In the UK, where the world's first coal power plant was opened in 1882, the last coal power plant closed in October 2024.²¹³ In the 2010s, the UK electricity system's carbon intensity decreased by 9% per year – twice as fast as any other industrialised country, and a staggering eight times faster than the global average during the same period.²¹⁴

How was this achieved? At first glance, it seems that coal was outcompeted by a dedicated expansion of wind power triggered by an auctioning scheme, *Contracts for Difference*, from 2015. But the story is more complicated, and much longer, and the phase-out of British coal was a combination of coal being economically *and politically* outcompeted by wind *and* gas power, and ultimately, after the replacement technologies were available, by dedicated policies to make coal uncompetitive (Figure 40).

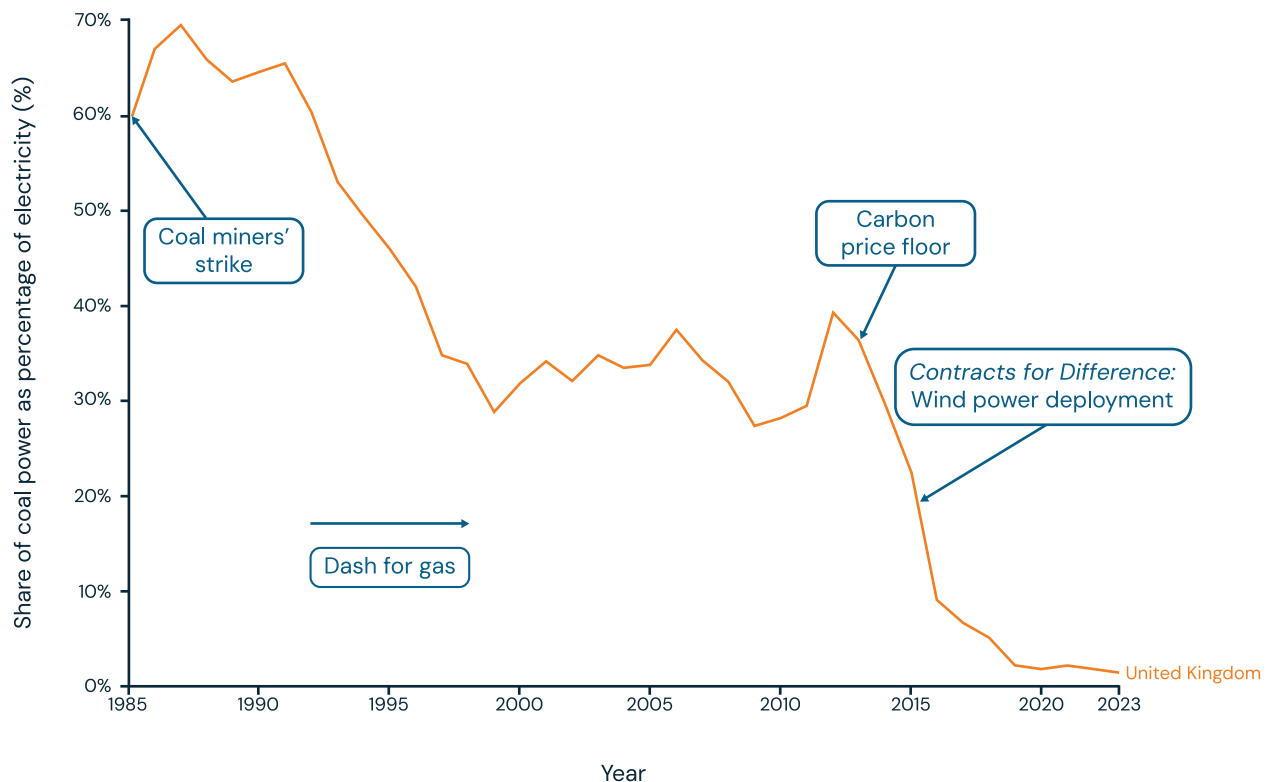


Figure 40. The share of coal power in the United Kingdom, and key events leading to its ultimate phase-out. Source: [Our World in Data \(2024\)](#).

213 BBC News (2024). [Today the UK quits coal power after 142 years.](#)

214 Drax Group plc (2020). [Half year results for the six months ended 30 June 2020.](#)

The demise of British coal started, as in other European countries, soon after World War II, with most coal mines not being economically competitive. In the UK, the mines were nationalised, and the costs of keeping mines open mounted. In 1979, the strongly neoliberal government of Margaret Thatcher won the elections. Among her main aims was to diminish the power of trade unions while also minimising state spending, and during the 1980s, this led to an all-out conflict between coal miners and the Thatcher government, including the largest strikes in the UK since the 1920s. Eventually, Thatcher won, the unions lost, the mines lost their economic state support, and the final descent of British coal mining began, with domestic coal production decreasing by some 50% per decade. The last British coal mine closed in 2015.

In the run-up to electricity market liberalisation in the 1990s, and resonating very well with the government's desire to reduce the coal sector's influence, natural gas was allowed as an electricity generation fuel. Simultaneously, the high interest rates of the 1990s made capital-intensive electricity investments unattractive, such as coal and nuclear power, but investments in technologies with high fuel and low capital costs attractive, such as gas power. The result was the 'dash for gas', a period with an outright investment frenzy during which the gas power share grew from 1% in 1990 to 38% in 1999.²¹⁵ The gas power started chipping away at coal's market share, as it could generate the same type of electricity as coal: it could replace coal in the market more or less 1:1. Over the 1990s, many coal power stations closed down – at least 10 GW in 1991–1995 alone²¹⁶ – many of them well ahead of their projected economic lifetime,²¹⁷ but as the gas construction slowed down, the coal power sector stabilised at about half the market share it had had in the 1980s.

Coming into the 2000s, the UK coal sector – both mining and power – was severely politically weakened. At this point, in 2008, the EU's Large Combustion Plant Directive required coal-burning installations to decide whether they would install smoke-cleaning equipment and comply with pollution regulations – or close. Many operators of the ageing coal power fleet decided that retrofitting made little economic sense and opted out, deciding to close by 2015 at the latest: another 11.5 GW closed.²¹⁸ This further weakened the coal sector – mining was about to end, and power generation took yet another blow – cementing its decreasing political influence.

The year 2013 saw many changes to UK energy policy, many of which sought to diminish the role of coal. In April, the carbon price floor entered into force, setting a minimum price and adding to the EU ETS price for all British participants. This did not trigger much in terms of investment, and it did not affect consumer prices significantly, so electricity demand was largely unaffected. But even the relatively modest carbon price floor of initially £9/tCO₂ (2013), later rising to £18/tCO₂ (2015), combined with decreasing gas prices to shift the relative cost of coal and gas power: previously, coal power had been cheaper than gas power, but now gas power was generally cheaper than coal power.²¹⁹ A tipping point had been crossed. This meant that during increasingly many hours, coal generators were pushed out of the market: the demand could be satisfied using cheaper generators.

In June, the parliament adopted the Energy Act with the aim of ensuring security of supply as coal power stations were retired. This introduced the Emissions Performance Standard, which allows operators to build whatever baseload power station they want, as long as it emits less than 450 gCO₂ per kilowatt-hour. This effectively bans new coal plants, unless they are equipped with CCS technology. The Act also included the introduction of a capacity market, in which generators are paid to have available capacity in case it is needed to meet demand (as may happen, for example, on a still winter's night when there is no supply from solar or wind). This auction-based system mainly provides additional revenue to gas power stations, which are flexible enough to credibly ramp up fast in times of need. Politically, the capacity market was important to give confidence that the UK would be able to 'keep the lights on' without coal power.

215 Our World in Data (2025). [Electricity production in the United Kingdom.](#)

216 Wikipedia. (n.d.). [List of power stations in England.](#)

217 Wikipedia. (n.d.). [List of power stations in England.](#)

218 National Energy System Operator (NESO). (n.d.). [Clean Power 2030.](#)

219 Hirst, D. & Keep, M. (2018). [Carbon Price Floor \(CPF\) and the price support mechanism](#), Research Briefing SNO5927. House of Commons Library.

The third part of the 2013 Energy Act was Contracts for Difference (CfD), which replaced a previous quota system, the Renewables Obligation. The CfD system is a reverse auction instrument, in which the bids requesting the lowest strike price are awarded. The strike price is a fixed price for all electricity sold, offered for 15 years to reduce the investment risk and reduce the financing cost of projects. The scheme is to some extent technology-agnostic, but has split technologies into 'pots' defined roughly along their technological maturity; this way, mature technologies and immature technologies compete among themselves, but not against each other. For each auction round, each technology gets an Administrative Strike Price, which is the maximum allowed bid for that technology. The scheme has been very successful, awarding over 40 GW of new capacity, 23 GW of which is offshore wind;²²⁰ since the first CfD auction, wind power has grown from 11% in 2015 to 28% in 2023.²²¹

The UK power system saw two major forces during the late 2010s and early 2020s: growing wind power supply, driven by the CfD auctions, and decreasing electricity demand, driven by de-industrialisation of the UK economy.²²² During increasingly many hours, the most expensive source of power was pushed out of the market, squeezed between zero marginal cost wind power and decreasing demand. With the carbon price floor, the most expensive generator was coal power, and so for each year, coal power stations got to operate for fewer and fewer hours. Without the carbon price floor, the most expensive generator would have been gas power, and gas – not coal – would have been pushed out. This proved to be the final nail in the coffin of British coal, and enabled a government pledge to close all coal power by 2025 – which ultimately turned out to be unnecessary, as the last coal plant closed in 2024.

There are three main lessons to learn from the British coal phase-out. First, no single instrument led to the phase-out: it was a long sequence and mix of different policies, each in itself insufficient to trigger the needed change, but effective together. The rapid diffusion of wind power, supported by the CfD scheme, combined with the carbon price floor as the immediate trigger. Both the CfD and the price floor were made politically feasible by a series of decisions in previous years and decades, mainly resulting in the political and economic weakening of the coal sector.

220 Wikipedia. (n.d.). [Contracts for Difference \(UK energy\) – Generating capacity awarded.](#)

221 Our World in Data (2025). [Electricity mix.](#)

222 Electric Insights/Drax (2023). [Is electricity demand about to take off after a decade of decline?](#) Electric Insights Q3 2023.



Second, a carbon tax can be useful, if the policy aims to adjust relative and not absolute prices. In the electricity sector, the absolute price is largely irrelevant because the inelastic demand will not dramatically change: a carbon tax will never increase the final consumer price strongly enough to significantly reduce demand. It can, however, be high enough to shift the cost ranking of individual technologies, and thus drive the now-unprofitable technology out of the market if other technologies exist to maintain system stability. A climate policy mix must drive structural change towards zero-carbon systems, and for that investment is a central parameter, but not every instrument must trigger investment. In this case, the gas power investment came from the market (later supported by the capacity market) and the wind power investment from the CfD. In this situation the carbon tax made the difference and helped push out the last coal plants.

Third, the UK electricity transition is nowhere near complete: coal is gone, but gas is still going strong, providing around a third of generation. The policy sequence that ended coal will not work for gas; above all, the carbon tax will not end gas, because the alternative – mainly wind power – is already cheaper, both with respect to the marginal costs relevant within the merit order system and to its total costs of generation, so making gas power even more expensive with a carbon tax will not change the relative cost order of the two. Further market reforms are needed to move to a fully fossil-free system: the challenge to transition a system while maintaining functionality is highly context-specific. Just as the capacity market supported confidence that lights will stay on as coal is phased out, other reforms are needed to phase out gas while keeping the lights on. At the time of writing in spring 2025, new, deep reforms for managing a power system based on variable renewables, and where low-cost renewables are increasingly often the price-setting technology, are under consideration by the UK Government in the Review of Electricity Market Arrangements programme.²²³

223 UK Government (2025). [Review of Electricity Market Arrangements \(REMA\)](#).



4 RECONFIGURATION

4.1 Overview

Pursue market saturation of the new technology, and phase out the old

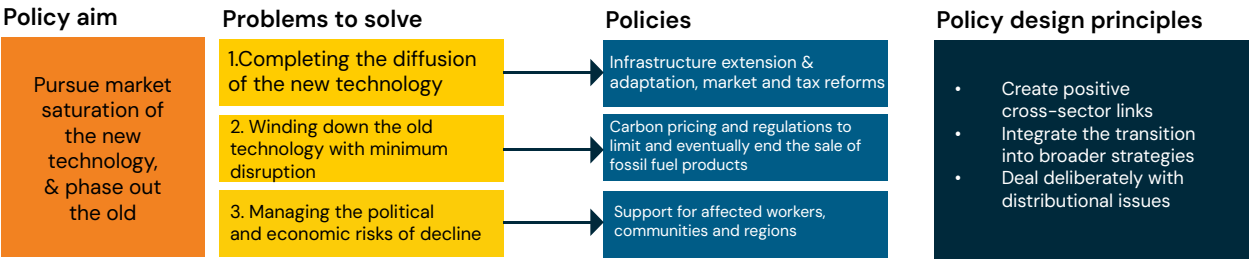
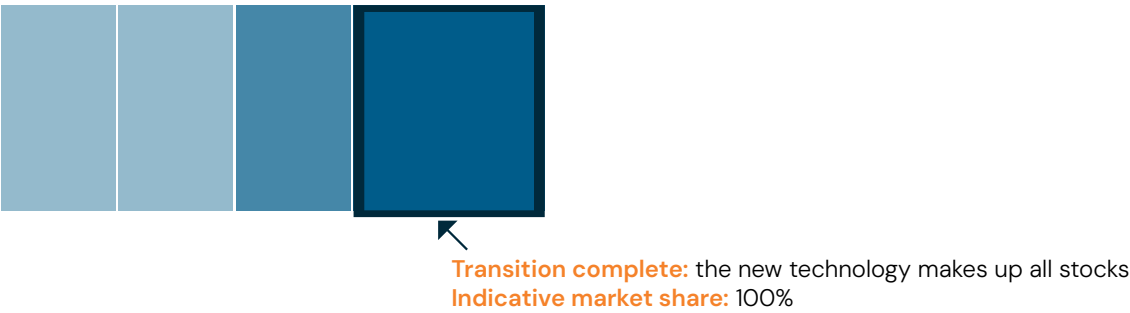


Figure 41. Reconfiguration – Overview of aims, problems to solve, policies, and policy principles. Source: authors’ own.

Aim: The aims for policymakers at this stage are to enable the new technology to reach a full share of the market, to phase out the old technology with a minimum of disruption, and to adapt all elements of the system – such as skills, markets, infrastructure, and institutions – to accommodate this change.

The process: Three different but related processes occur during the Reconfiguration stage. The first is the further diffusion of the new technology, towards its adoption by almost all producers and consumers. The new technology must first reach market saturation in terms of flows (for example, electric vehicles becoming 100% of new car sales, or clean power accounting for all investment in new power capacity), and then in terms of stocks (100% of cars on the road, or all electricity generation).

The second process is the wind-down of the old technology and its infrastructure. In many past transitions, old technologies have continued to coexist with new ones for a long time, but this is not consistent with policy objectives of the zero-carbon transition. Completing the transition may require the old technology to be proactively phased out, particularly where its assets have long lifespans (such as coal power plants, steel plants, or heating systems).

The third process involves adaptation of the wider system within which the transition takes place, to avoid problems arising either from the final stage of growth of the new technology, or from the wind-down of the old technology. This can include training in new skills, extension of infrastructure, and market reforms to accommodate the rise of the new technology, and changes in taxes, social policies, and regional development strategies to manage the decline of the old technology and its industries.

Problems to solve

1. Completing the diffusion of the new technology

The final part of the process of diffusing the new technology may be particularly challenging for a variety of reasons, including social ones (such as particular user-groups having difficulty adopting the new technology), geographical ones (such as problems with ensuring access to the new technology in remote areas), or technological ones (the need for complementary technologies). It may involve more expensive infrastructure expansion: for example, installing EV charging points in rural communities where the returns are not enough to attract private investment and the power grid is weaker. There may also be technical or market design challenges, such as ensuring security of supply in a power system without any (unabated) coal or gas plants available for backup. Complementary technologies, such as long-duration energy storage and vehicle-to-grid solutions, may need to be deployed at scale.

2. Winding down the old technology with minimum disruption

Just as reinforcing feedbacks can drive the diffusion of the new technology, they can also drive a rapid decline of the old. When incumbent industries contract, unit costs rise, eroding profitability and leading to further contraction. Decreasing investor confidence can push up the cost of capital, reducing profitability and leading to stranded assets. Too fast a decline presents a challenge: the overly rapid retirement of the assets of the old system, deliberate or not, without sufficient system reconfiguration, can undermine stability or the availability of services to citizens. If the assets and infrastructure of the old technology are retired before the end of their economic life, this can impose losses on industry, or costs on consumers or taxpayers.

3. Managing the social, political, and economic risks of decline

Although the creation of new industries can be rich in jobs and economic opportunity, the decline of old industries – particularly if unanticipated and unmanaged – can lead to unemployment, social opposition to the transition, and regional economic decline. The political challenge may emerge during the Diffusion stage as affected stakeholders begin to foresee change, but the broader impacts become most prominent in the Reconfiguration stage, as the old starts to decline. In the zero-carbon transition, these risks are greatest in regions that depend on fossil fuel industries such as coal mining, oil and gas extraction, or refining, for a large share of their economic activity. Where the extraction or use of fossil fuels contributes significantly to tax revenues, replacing these revenues is likely to present an additional challenge.



Example: Reconfiguration in the transition to clean power

Globally, renewables have already become the default source of new power capacity, accounting for nearly 93% total capacity expansion, compared with 86% in 2023.²²⁴ These technologies already outperform incumbents on cost: in 2023, 81% of newly commissioned, utility-scale renewable projects had lower costs than fossil fuel alternatives.²²⁵ The cost of solar power together with energy storage is now lower than that of power from coal or gas in China, India, the EU, and the US.²²⁶

Transforming the system to complete the diffusion of clean power technologies: As variable renewables expand their share of generation, batteries, demand-side response, and interconnectors are increasingly needed to increase system flexibility. In the most advanced markets, the role of gas plants is shifting from providing baseload power to meeting peak demand. Hydropower and nuclear power are available as additional sources of clean power generation in some countries, but not in others. Eliminating the final power-sector emissions will require further technological changes, such as deployment of long-duration energy storage, possibly peaking plants using hydrogen or gas with CCS, and the use of new technologies for frequency regulation. Some of these new technologies may need to be supported by new market structures or public sector investment, given their highly uncertain revenues.

Phasing out coal and gas power with a minimum of disruption: If coal or gas plants become unprofitable more quickly than expected in the late stages of the transition, leading to unanticipated plant closures, there could be risks to security of supply. Mechanisms such as capacity markets or strategic reserves are likely to be needed to ensure sufficient capacity remains available to meet peak demand.

In countries with large numbers of relatively new coal or gas plants, phasing out coal or gas power can involve managing the costs of early plant retirement. Closing Indonesia's coal fleet by 2040 has been estimated to cost \$37bn,²²⁷ mainly to buy out existing power purchase agreements and compensate power plant owners. Securing and structuring this financing, avoiding overcompensation, and ensuring fair distribution of costs are difficult technical and political challenges.

Adapting to the decline of coal power; managing social and political risks: Countries with large coal mining industries face the largest socio-economic risks from the transition to clean power. China already lost more than 2m coal mining jobs as efficiencies improved, and processes were increasingly automated.²²⁸ Its government's \$15bn transition fund is committed to finance lay-offs and support coal industry workers in finding re-employment.²²⁹ The European Union has created Just Transition funds, partly to mitigate the socio-economic effects of declining coal mines and coal-fired power plants in Eastern Europe.

As the power sector in many countries has already entered or is on the cusp of entering the Reconfiguration stage, policies of the kinds described below may be needed.

224 IRENA (2025). Renewable Capacity Statistics 2025.

225 IRENA (2024a). Renewable Power Generation Costs in 2023.

226 IRENA (2024b). LCOE and value-adjusted LCOE for solar PV plus battery storage, coal and natural gas in selected regions in the Stated Policies Scenario, 2022–2030; IEA (2023c). Batteries and Secure Energy Transitions (World Energy Outlook Special Report).

227 Grey, M. (2022). Introducing the Coal Asset Transition Tool. Transition Zero.

228 He, G, Lin, J., Zhang, Y. et al. (2020). Enabling a rapid and just transition away from coal in China. One Earth. 3. pp.210–225.

229 WRI (2024). These 10 Countries Are Phasing Out Coal Power the Fastest. WRI Insights: Climate Investment Funds (CIF) (n.d.). Special Fund for coal and steel industry layoffs, China. Just Transition Toolbox. See also IEA (2023) China's coal and steel capacity cuts and worker re-employment.



4.2 Policies to accelerate the Reconfiguration stage

During the Reconfiguration stage, there may be a continued need for some of the policies outlined in previous stages that support the spread of the new technologies, such as mandates or subsidies. However, the emphasis shifts to the whole supporting system of surrounding technologies, markets, infrastructure, institutions, regulations, norms, and behaviours, which must be adapted to support the new technology to entirely take over from the old.

1. Complete system adaptation: infrastructure extension and adaptation with public investment and regulation; market reforms, and tax reforms

Infrastructure

In this final stage of the transition, the infrastructure to support the new technologies must be extended to cover all users and uses. In road transport, charging infrastructure networks will need to be extended nationwide. In industry, CCS infrastructure may be required to support the decarbonisation of industrial processes where no alternative solutions can be found; hydrogen production and pipelines may also be needed. Electricity grids will need to be upgraded to manage large volumes of variable renewable supply, and increased demand arising from the electrification of transport and heating (as well as, in some countries, increased demand arising from economic development and growth). The extension of infrastructure can be achieved by direct public investment, or by incentivising or regulating private investment. Examples of such regulation include mandating the provision of electric vehicle charging in carparks, and using building codes to require heat pumps to be installed in new buildings. To ensure access to services in rural areas, EV charging infrastructure companies might be required to cover remote locations, in the same way that electricity companies already have a legal obligation to serve all customers.

During reconfiguration, cross-sectoral infrastructure becomes increasingly important to harness opportunities from the deeper integration of new technologies. For example, using vehicle-to-grid technology and industrial demand-side response can help balance electricity systems.

Additional measures may be needed to ensure that the final removal of fossil fuel infrastructure is achievable without significant inconvenience to consumers. In heating, for example, district heat networks may need to be extended to reach households that would have difficulty installing heat pumps, as gas grids are wound down.

Market reforms

Further market reforms are likely to be needed during the Reconfiguration stage to enable the clean technology to reach full market saturation. For example, to ensure security of supply in a zero-emission power system, market reforms may be needed to support the deployment of energy storage, demand-side response, and flexible grid technologies. These can include policies to allow time-of-use pricing, or targeted support policies for complementary technologies, such as subsidies or revenue cap-and-floor contracts to incentivise investment in long-duration energy storage and gas-CCS peaking plants. Capacity markets, strategic reserves (with coal or gas power plants with CCS, to be used only in situations of high system stress), and long-range interconnectors can be used to ensure security of supply.

Tax reform

Tax reform may be required to replace decreasing revenues from sources that are disappearing as a result of the transition. This can involve a delicate balance. Many countries have high taxes on petrol, but these revenues will disappear as EVs replace petrol cars, and there may need to be a shift from a fuel tax to alternatives, such as road tolls, to avoid a negative impact on governments' budgets. In countries or regions where the government derives a significant amount of tax revenues from coal mining or oil and gas extraction, alternative revenue sources will need to be found. For countries that are exporters of fossil fuels, this need will arise as a result of the actions of other (importer) countries. Governments may also need to consider the balance of taxes across sectors. For example, many countries have higher taxes on electricity than gas, and this disincentivises the transition from gas boilers to heat pumps.

2. Carbon prices and regulations to limit and eventually end the sale of fossil fuel products

Policies that focus on limiting, disincentivising, and eventually ending the use of the old technology are most feasible, and most necessary, in the Reconfiguration stage. Carbon pricing is one such policy. Its main advantage is that by changing the relative costs of technology options, it can push the most carbon-intensive technologies and assets out of the market first, provided that less carbon-intensive ones are already in place to take over. This is how carbon pricing has achieved emission reductions in the past, notably in pushing a shift from coal power to already existing gas power.²³⁰ A carbon intensity regulation can achieve a similar effect. Which of these is more politically feasible may depend on the context. A price-based approach may be preferable if there is value in letting market forces decide the order in which assets are phased out, which may be more important in sectors where emissions cannot be fully eliminated, but only minimised and offset by negative emissions (as may be the case for cement, for example). It is less important in sectors that can and must reach zero emissions, such as power and road transport.

In the zero-carbon transition, the ultimate aim at this stage is to completely phase out the old fossil fuel technologies. This can happen when the new technologies outcompete them, after technological learning and systemic changes make the zero-carbon technologies sufficiently attractive. However, in many cases, the phase-out may need active policy measures.

Regulations, if politically viable, are likely to be more effective than carbon pricing to phase out fossil fuels: banning a product or technology is stronger than merely disincentivising it. Regulations can take the form of explicit bans on the sale or use of specific fossil fuel technologies, mandates that require zero-carbon technologies to reach 100% of sales or production, or carbon intensity standards that the fossil fuel technology cannot meet. Which of these is best may depend on what is politically feasible. An example of the latter is the UK's Emissions Performance Standard that limits the carbon intensity of new power stations to 450 gCO₂/kWh, acting as a de facto ban on new coal plants. Unlike incentive-based policies such as carbon taxes, these regulatory policies impose direct constraints, forcing fossil fuels out of the system with clear timelines. The relative certainty that they create can incentivise investment not only in the new technologies, but also in their associated infrastructure. Bans on the use of fossil fuels may also be necessary to complete the transition in sectors where assets have long lifetimes.

230 Green, R. & Staffell, I. (2021). [The contribution of taxes, subsidies and regulations to British electricity decarbonization](#). Joule. 5. pp.2625–2645; Gugler, K., Haxhimusa, A. & Liebensteiner, M. (2021). [Effectiveness of climate policies: Carbon pricing vs subsidising renewables](#). Journal of Environmental Economics and Management. 106. 102405.

3. Support for affected workers, communities, and regions

Many transitions in the past have unfolded without much support being provided to the workers in the declining industries. Carriage drivers suffered from the transition from horse to car; sailors and small merchants suffered from the transition from sailing ships to steamships; cottage industry workers, artisans, and weavers suffered from the Industrial Revolution; and smallholder farmers suffered during the Green Revolution. More recently, in regions that have lost jobs in the transition away from coal, such as Appalachia in the US (which lost 33,500 coal mining jobs between 2011 and 2016²³¹) and the UK (where more than 200,000 miners lost their jobs in just over a decade in the 1980s to 1990s²³²), communities have suffered immense losses as a result of this transition and the lack of policy support.

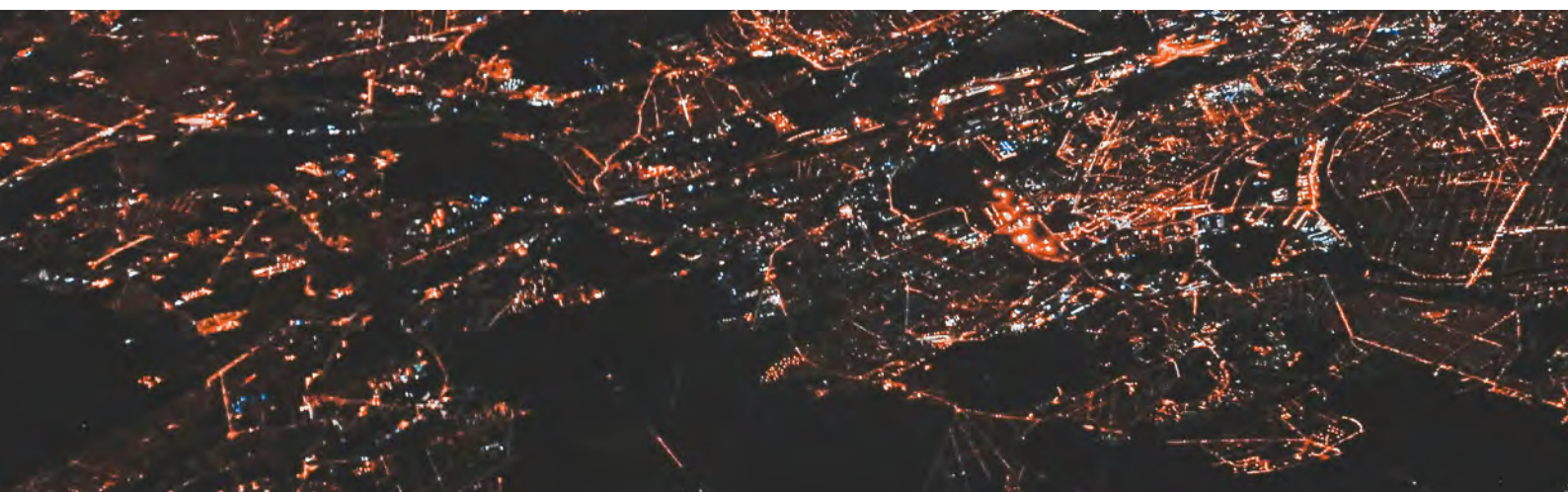
For many governments, economic development and social cohesion are goals to be pursued at the same time as decarbonisation. Supporting workers, communities, and regions that stand to lose from the decline of the old industries may be desirable as an end in itself, and to avoid strong social opposition to the transition. This may need to start during the Diffusion stage, but becomes even more critical in Reconfiguration. Regional development programmes may be needed to support new drivers of economic growth in regions most affected by the closure of fossil fuel industries, such as coal mining, oil extraction, or refining.

There are no easy answers to this problem. A synthesis of learning from past experience, including in the US, Poland, and India, indicates five main channels of public policy support: temporary income support (e.g. employer severance pay, national social safety nets); increasing workers' capacity to qualify for jobs in new sectors (e.g. through skills or entrepreneurship training, or 'skills passports'); connecting workers to potential employers (e.g. through job search assistance and mobility grants); stimulating private sector labour demand and local or regional business development (e.g. through investment incentives aligned with strategic national, local, and/or regional priorities; and matching grant programmes); and ensuring that the business environment and labour regulations are conducive to provide sector investment and job creation.²³³

231 Appalachian Regional Commission (2017). [Investing in coal-impacted Appalachia](#).

232 Rud, J., Simmons, M., Toews, G. & Aragon, F. (2022). [Job displacement costs of phasing out coal](#). Institute for Fiscal Studies.

233 See Bulmer, E. R., Pela, K., Eberhard-Ruiz, A. & Montoya, J. et al. (2021). [Global Perspective on Coal Jobs and Managing Labor Transition Out of Coal](#). The World Bank Group.



4.3 Policy design principles for Reconfiguration

1. Create positive cross-sector links

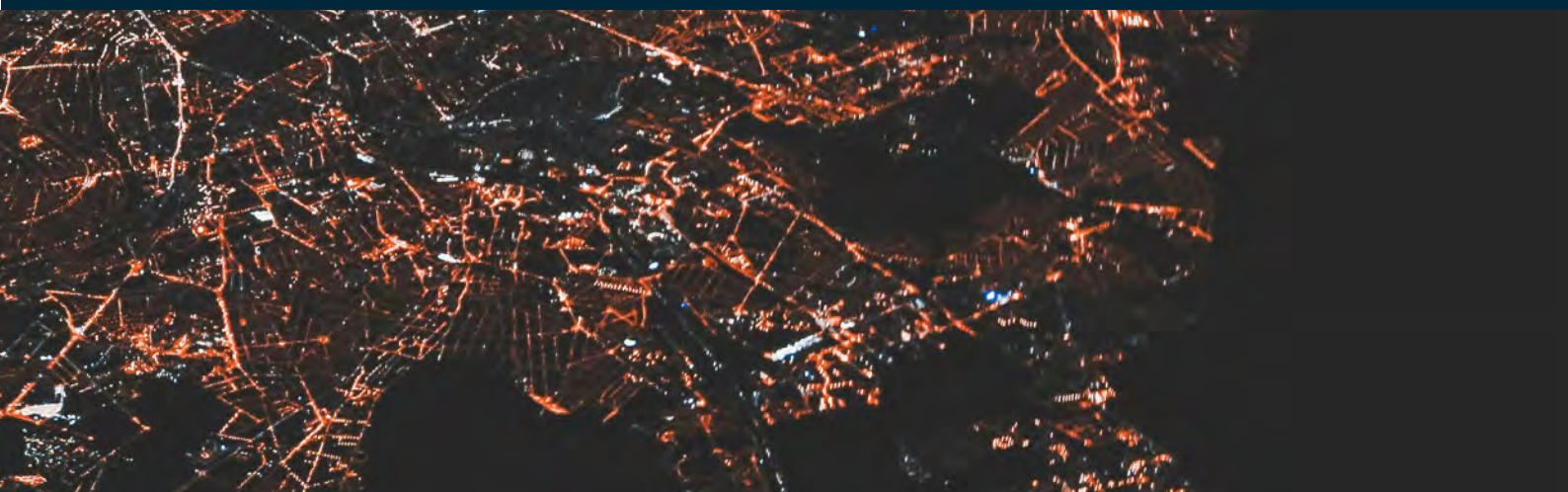
In this stage, the transition involves changes on a broader scale than in its earlier stages. This means there are more diverse ways in which the transition can be held up, but also new opportunities to help it move forward, in combination with transitions in other sectors.

To prevent the transition being held up, it may be useful to identify cross-sector interdependencies in advance, map out potential barriers, and address them pre-emptively. For example, upgrading electricity networks can prevent grid constraints being a barrier to the large-scale electrification of road transport, heating, and industry.

Positive cross-sector links can be created through shared infrastructure (such as electricity grids, hydrogen production, transport and storage infrastructure, and CCS facilities); shared technologies, such as energy storage; lifecycle emissions standards (for example for buildings or cars, which can create demand for near-zero-emission steel, cement, and plastics); and market designs (such as those that enable vehicle-to-grid charging, or business models that incentivise smart energy appliances within buildings).

2. Integrate the transition into broader strategies

Because the zero-carbon transition is multidimensional (involving technologies, skills, manufacturing, social acceptance, financial investment, competition, trade), coordination across government is important at all stages. In this stage, when the depth and breadth of change is greatest, it becomes particularly important to integrate policies for the transition into broader government strategies. These can include skills, regional development, and industrial strategies (all relevant to the growth of new industries and the decline of old ones); national infrastructure and investment strategies; housing and land use strategies; and financial planning, economic, and trade strategies. With this integration, there is a greater chance of policies for the transition, and other policies, supporting each other, and less risk of their being in conflict.



3. Deal deliberately with distributional issues

Low-carbon transitions involve transfers of economic resources and large-scale socio-economic change, with inevitable transfers of resources across sectors, technologies, producers, geographies, and social groups. This can make them deeply contested and political. Diverging interests, competing narratives, power dynamics, and institutional inertia can slow or reverse progress at any stage, unless deep coalitions in favour of the transition have been created. Effective transition policy must be politically embedded, not just economically rational. This can require institutional reform, building broad-based coalitions for change, combining technical policy with legitimacy-building measures, and carefully managing distributional issues.

The distributional impacts of the transition become most significant during the Diffusion and Reconfiguration stages, as structural changes accelerate, and as old technologies are phased out and associated industries decline. Governments of different political persuasions may approach distributional issues with different priorities. As a general principle for policy to advance the transition, we suggest these issues should be dealt with deliberately, meaning that the distributional impacts of policy options should be identified and consciously considered, before a course of action is chosen. Without this, there is a greater risk of unintended effects leading to social and political opposition to the transition.

Distributional concerns can be important in relation to various issues. The first is access. Infrastructure networks for the new technology must eventually be extended to all regions, including low-income and rural areas. The second is affordability of the new technology. If zero-carbon technologies still involve some higher costs to the consumer, then this could particularly affect lower-income households during the Reconfiguration stage, when adoption of the new technology must be spread to the whole market. In lower-income countries, the near-poor and lower middle-class households have particular price sensitivity around fuel and energy-consuming assets, and the poorest households are particularly sensitive to any increase in food prices.²³⁴ Third, there are distributional implications in the decision around who pays to maintain old technology infrastructure: as consumers move away from fossil fuel technologies such as gas heating systems, the costs of maintaining their infrastructure networks in the final years before their retirement could fall disproportionately on the last remaining users. Fourth, as new sources of tax revenue are found to replace the tax revenues from fossil fuels, this is likely to have different effects on different market or demographic segments. Distributional analysis can be used during policy appraisal to compare options, which could include shifting the tax burden to change the balance between environmental taxes and income taxes.²³⁵ The most significant issue may be employment. The transition could contribute to economic growth and job creation in some regions of a country, and job losses and industrial decline in other regions. These effects may be moderated to some extent by regional development policies. Strengthening social protection mechanisms, and providing skill enhancement and youth employment programmes, can also be important.²³⁶

²³⁴ The World Bank Group (2022). *Beyond Mitigation: Quantifying the Development Benefits of Carbon Pricing*.

²³⁵ Vona, F. (2021). *Managing the distributional effects of environmental and climate policies: The narrow path for a triple dividend*. OECD.

²³⁶ The World Bank Group (2023). *Reality Check: Lessons from 25 Policies Advancing a Low-Carbon Future*. *Climate Change and Development Series*.

4.4 Case studies for Reconfiguration



CASE STUDY 15

Case Study 15. Infrastructure investments and extensions: Horse-and-carriages to automobiles (USA) (1900–1992)



Figure 42. New holiday practices in the 1950s. Source: [The History Lounge \(2023\)](#).

The transition from horse-and-carriages to cars in the USA was supported by large-scale public investment in infrastructure.²³⁷ Policymakers integrated the transition into wider strategies, using road construction to create employment, and designing interstate highways with national security objectives in mind.

The transition started in the early twentieth century, when cars were initially used as ‘toys for the rich’ (for racing, touring, and promenading) and then gained some practical use (by doctors, wealthy farmers, travelling salesmen). Cars diffused more widely to working-class families after the Second World War, which led to wider system reconfigurations, including the rise of a new car culture and social practices.²³⁸ Commuters started travelling by car between suburban homes and down-town jobs; people went on holidays with cars (Figure 42), leading to campgrounds and motels; drive-in cinemas and drive-in restaurants appeared for entertainment purposes. Additionally, the car industry became a crucial economic sector, with linkages to the petroleum industry, steel industry, and construction sector.

237 Geels, F. W. (2005a). *The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930)*, Technology Analysis & Strategic Management. 17. pp.445–476.

238 Flink, J. J. (1990). *The Automobile Age*. MIT Press; Belasco, W. J. (1997). *Americans on the Road: From Autocamp to Motel, 1910–1945*. MIT Press.

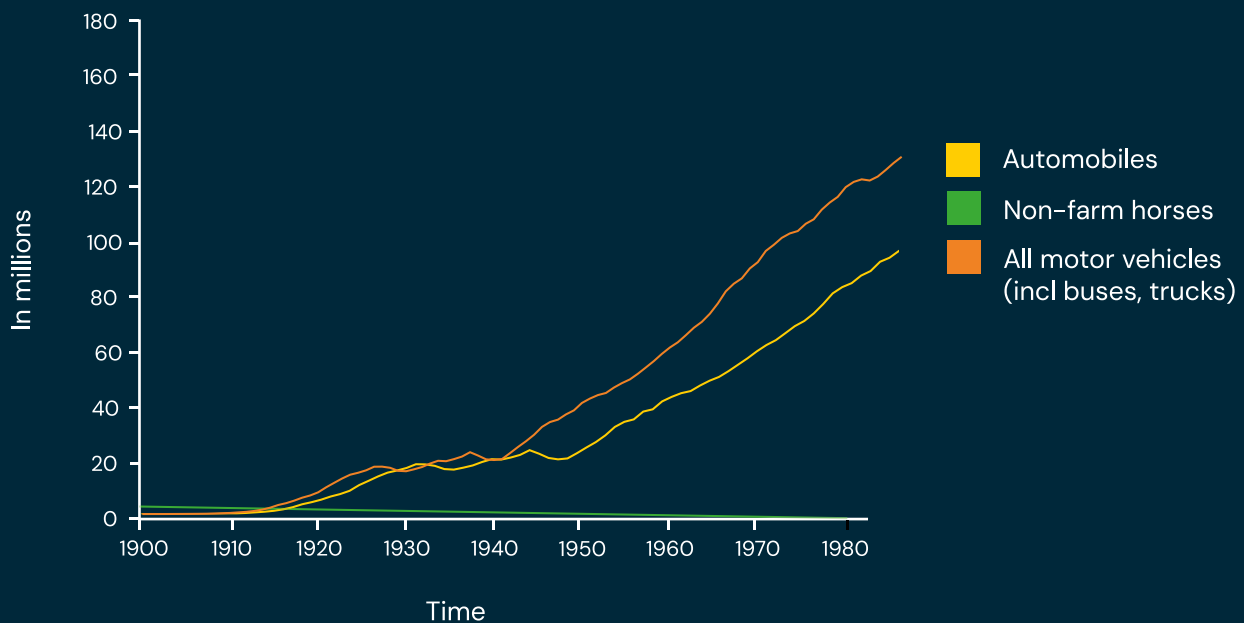


Figure 43. Transition from horse-and-carriages to motor vehicles in the US (in millions), 1900–1995. Constructed using data from [Nakićenović \(1986\)](#) and [Federal Highway Administration \(2010\)](#).

The emergence and diffusion of automobiles (Figure 43) was supported by large-scale investment in road infrastructures that were constructed at increasing scale and speed during the twentieth century with high involvement of public authorities. In the 1910s and 1920s, municipal and city authorities supported the building of new roads that enabled cars to travel outside cities. During the 1930s Depression and New Deal, federal authorities became more involved, funding road construction as an antidote to unemployment. The 1944 Federal-Aid Highway Act increased federal funding of state-level highway construction by 60%. To enable long-distance travel of people, goods, and military materiel in case of war, the 1956 Interstate and Defense Highway Act envisaged the construction of an interstate highway system, which would be 90% funded by the federal government.²³⁹ The construction of this massive infrastructure system was completed in 1992, costing \$114 billion (\$521 billion in today's prices).

239 Lewis, T. (1999). *Divided Highways: Building the Interstate Highways, Transforming American Life*. Cornell University Press.



CASE STUDY 16

Institutional changes to address unforeseen expansion problems: From propeller aircraft to jetliners, 1945–1980 (USA)

The partial transition from propeller aircraft to jetliners in US civil aviation (1945–1980) illustrates the emergence of unforeseen problems that require new policies and wider system reconfiguration. Institutional changes, particularly the creation of a new regulatory agency, were central to addressing these problems. Complementary technologies, including long-range radar, computers, and sound barriers, also played an important role.



Figure 44. The B-52 long-range heavy bomber (1952), and the Boeing 707 (1958) and Boeing 747 (1969) jetliners. Sources: Geels (2002).²⁴⁰

Jet engines were first used in fighter aircraft during the Second World War. After the war, jet engines were initially rejected for bombers, because of their high fuel consumption. This changed with the development of refuelling in the air, which led Boeing engineers in 1948 to opt for jet propulsion for the design of the B-52 bomber, which entered service in 1952. To complement the B-52, Boeing also designed the Dash 80 tanker aircraft based on a dual-use strategy.²⁴¹ Demand from airline companies for jetliners led Boeing to convert the design to the civilian Boeing 707, which entered service in 1958, raising cruising speeds to 550–600 mph (Figure 44). Civil jetliners were first introduced in the long-distance market niche, where their advantage of high speed made the greatest difference. Their diffusion to other markets and routes was gradual and incomplete, because turboprops (which used gas turbines rather than piston engines to drive a propeller) were more efficient on short and medium-distance routes.

Although airline companies initially made losses on jetliners, the new aircraft were popular with customers because they were faster and could fly ‘above the weather’. Airline companies also experienced cost savings, because jetliners needed less repair and maintenance (because of fewer moving parts), could carry more passengers, and were fuel-efficient at high speed and altitude. By 1963 a period of profitable operations began in the jet age. The 1969 introduction of the Boeing 747, which could carry 450–500 passengers and fly at 640 mph, enabled further cost reductions and flying for the masses in the 1970s (Figure 45).

²⁴⁰ Geels, F., (2002). Understanding the dynamics of Technological Transitions: a Co-evolutionary and Socio-technical analysis. Twente University Press.

²⁴¹ Heppenheimer, T. A. (1995).

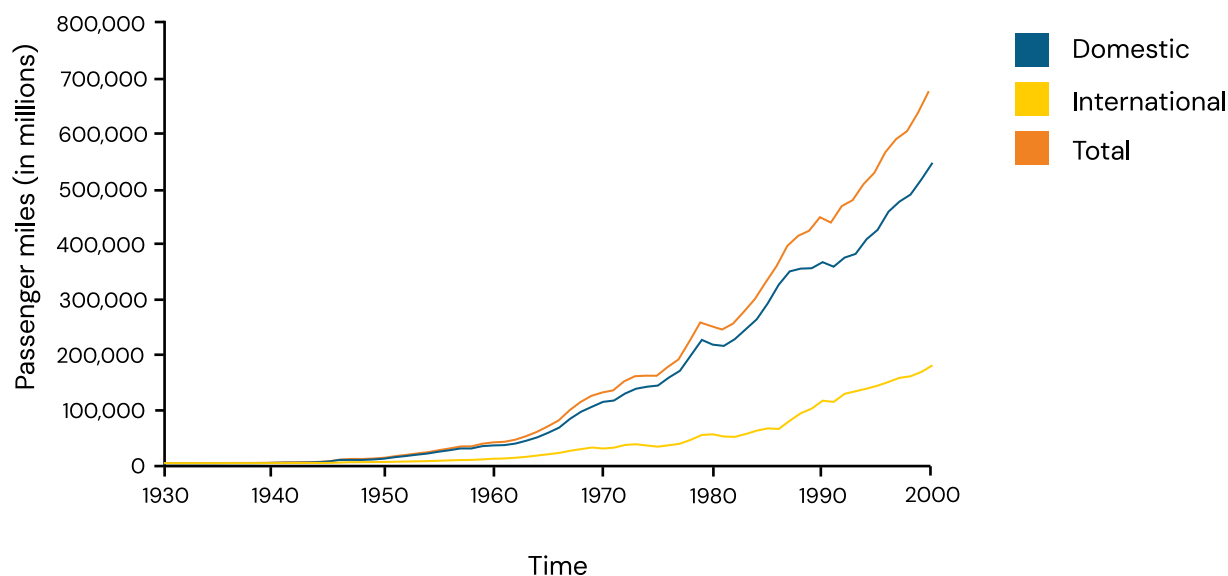


Figure 45. Development of American civil aviation in million passenger miles, 1930–2000. Constructed using data from the American Air Transport Association.

The expansion of air travel created unforeseen problems with regard to safety and noise. The mid-air collision of two aircraft in 1956, killing 128 people, led Congress to pass the Federal Aviation Act in 1958, creating a new regulatory agency, the Federal Aviation Agency. The FAA was charged with updating air traffic control systems (which until then only monitored aircraft around airports) so that they could maintain safe separation of aircraft through all phases of flight. This required the introduction of long-range radar, which could track and space aircraft continuously. The FAA also defined segments of airspace, called sectors, which had to be monitored separately.²⁴²

The diffusion of jetliners caused further problems because it increased differences in aircraft speeds (which by 1959 ranged from 400 to 950 km/h). This complicated the task of air traffic controllers, who were still calculating aircraft positions by hand. The increasing volume of bookkeeping functions and data-processing requirements led to the introduction of computers in air traffic control systems to improve safety.²⁴³

The diffusion of jetliners also increased the noise burden for local residents near airports, leading to increasing protests and political debates, followed by noise regulations for airports and aircraft.²⁴⁴ In response, airports introduced sound barriers while aircraft manufacturers introduced high-bypass turbofans, which were less noisy and more fuel-efficient. Nevertheless, noise problems continued to create social acceptance problems for the expansion of aviation and airports.

²⁴² La Porte, T. R. (1989). The United States air traffic system: Increasing reliability in the midst of rapid growth. In: Mayntz, R. & Hughes, T. P. (eds.), *The Development of Large Technical Systems*. Routledge.

²⁴³ Ibid.

²⁴⁴ Heppenheimer, T. A. (1995).

CASE STUDY 17

A Coal Commission: Phasing out coal in Germany (2000 to present day)

Germany's government created a Coal Commission with broad participation – including politicians, industry, unions, scientists, local leaders, and civil society – to negotiate a plan to phase out coal power. Distributional issues were a central consideration in this process. By working deliberatively across stakeholder groups, and combining a clear closure schedule with €40 billion in structural support, the government secured significant social support and reduced resistance from affected communities and sectors.

Context and challenge

The German government had successfully pursued renewable energy growth since 2000 to reduce energy costs to consumers, reduce the negative impacts of fossil fuel production, and avoid the risks of nuclear power. By 2023, renewables supplied over 50% of German electricity. As renewables grew, nuclear power was phased out, and as European and national climate targets tightened, the German government sought a plan to phase out coal power. In 2018, about 20,000 people worked in the lignite coal sector (Figure 46), with another 40,000 jobs indirectly depending on it. Coal mining and related activities provided up to 70% of the local value creation in the coal regions, so the aim of phasing out coal power faced significant social and economic challenges.²⁴⁵ Previous attempts to regulate the phase-out of coal had failed because of resistance by utilities and mining companies that saw their business models threatened; industry actors worried about increasing energy prices;²⁴⁶ and some trade unions that feared negative socio-economic consequences of job and tax revenue losses.²⁴⁷ The issue was further complicated by political conflict lines being within the major political parties, rather than between them.²⁴⁸

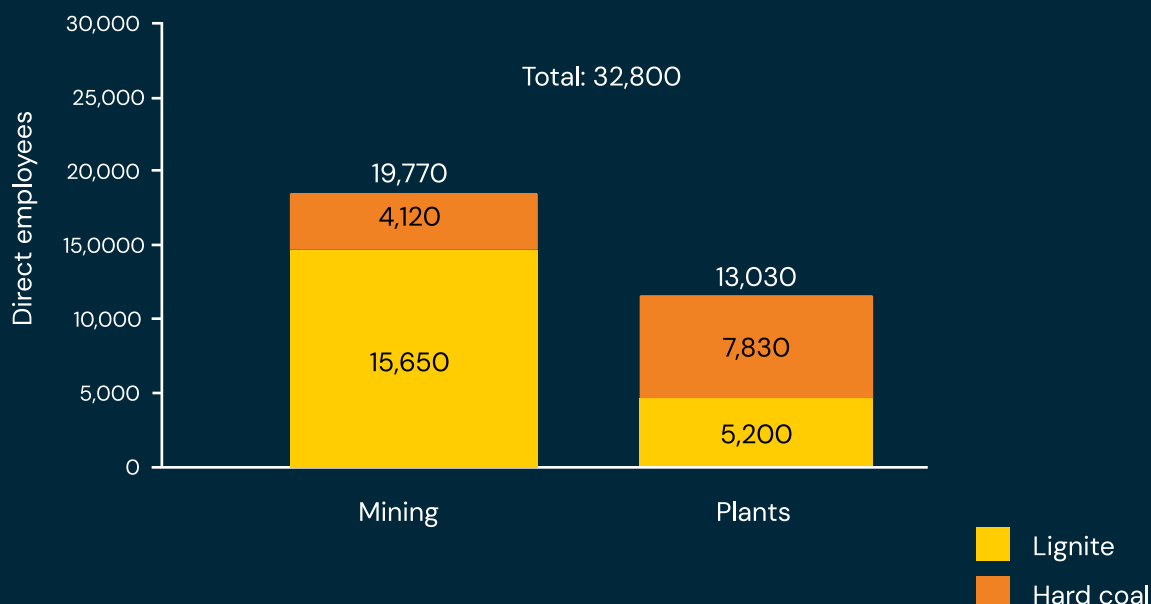


Figure 46 Employees in the lignite and hard coal sector at the end of 2018. Source: [Agora Energiewende und Aurora Energy Research \(2019\)](#).

²⁴⁵ Federal Ministry for Economic Affairs and Energy (2019). [Commission on Growth, Structural Change and Employment: Final Report](#).

²⁴⁶ Hauenstein, C., Braunger, I., Krumm, A. et al. (2023). [Overcoming political stalemates: The German stakeholder commission on phasing out coal](#). Energy Research & Social Science. 103. 103203.

²⁴⁷ Oei, P.-Y., Hermann, H., Herpich, P. et al. (2020). [Coal phase-out in Germany – implications and policies for affected regions](#). Energy. 196. 117004.

²⁴⁸ Hauenstein, C., Braunger, I., Krumm, A. et al. (2023).

Deliberative approach: the Coal Commission and its recommendations

In 2018, the government formed a 'Commission on Growth, Structural Change and Employment' to explore how to phase out coal power in a socially just way.²⁴⁹ This was the institutional solution to the highly contested and uncertain future of coal, the lack of sufficient power for one interest group or coalition to enforce their interests, and political parties with more to lose than gain from taking the responsibility for a decision.²⁵⁰ The Commission included national and regional politicians, representatives from affected sectors including local mayors, social organisations, conventional and renewable industry, trade unions, and scientists (Figure 47). To ensure a 'societal consensus', it consulted many stakeholders, from industry CEOs to individual local citizens, on ways to reach climate targets while maintaining local employment and supporting economic modernisation. This followed the German tradition of negotiated agreements for large-scale societal decisions.

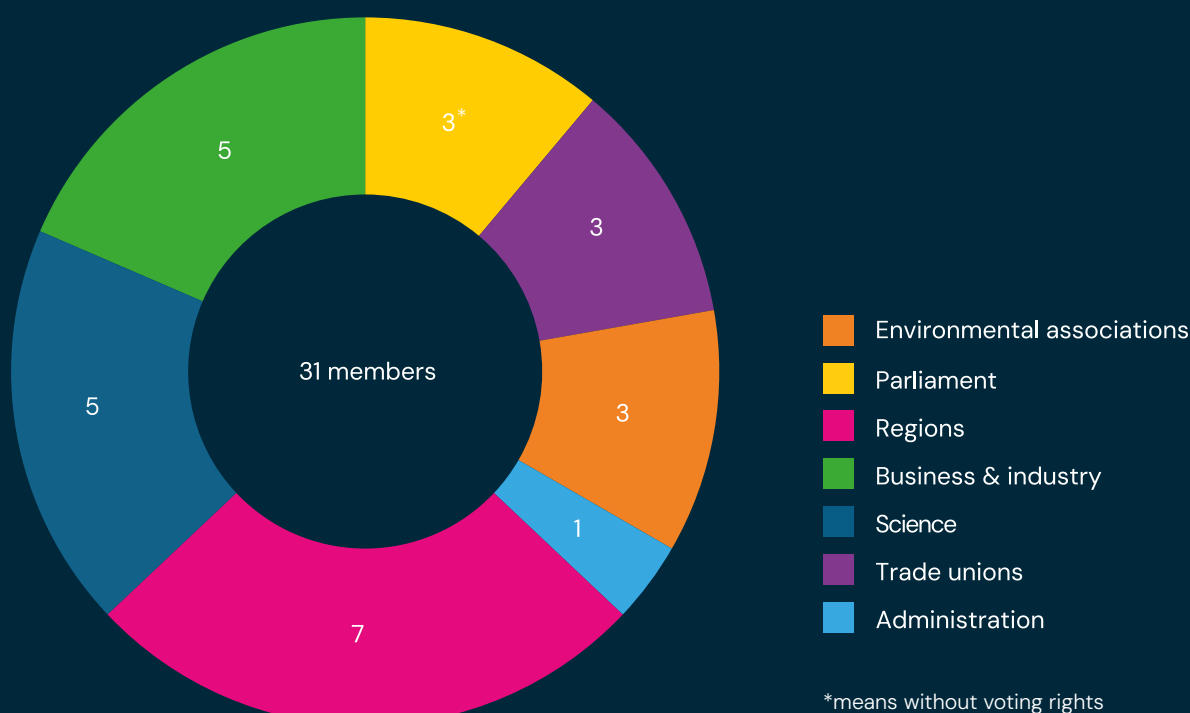


Figure 47. Composition of the Commission on Growth, Structural Change and Employment. Source: *Agora Energiewende und Aurora Energy Research (2019)*.

The challenge facing the Coal Commission was to find compromises between the conflicting goals of the numerous interest groups involved.²⁵¹ In January 2019, the Coal Commission published its final report.²⁵² It recommended a phase-out schedule for both hard coal and lignite power, with the last power station closing in 2038 to match the long-term national climate targets. It also proposed a €40 billion structural aid programme (2 billion per year for 20 years) mainly to help coal mining regions to transform their economies and buffer social hardship. In reality, key issues including the specific phase-out pathway and end date, and the size of the structural change fund, were talked about in plenary only on the last day of negotiations, and individuals met separately to negotiate compromises on these points into the night.²⁵³ The structural aid budget was doubled from €1 billion per year within one of the Coal Commission's working groups, without being discussed in plenary.²⁵⁴

249 Bundesministerium für Wirtschaft und Energie (n.d.). *Strom 2030*.

250 Hauenstein, C., Braunger, I., Krumm, A. et al. (2023).

251 Ibid.

252 Federal Ministry for Economic Affairs and Energy (BMWi) (2019). *Commission on Growth, Structural Change and Employment – Final Report*.

253 Hauenstein, C., Braunger, I., Krumm, A. et al. (2023).

254 Hermwille, L. & Kiyar, D. (2022). *Late and expensive – the political economy of coal phase-out in Germany*. In Jakob, M. & Steckel, J. C. (eds.), *The Political Economy of Coal: Obstacles to Clean Energy Transitions*. Routledge.

The overall recommendations were well received by most of society. Industry was satisfied with the clear timetable and commitment to affordable energy prices and security of supply, the coal companies were satisfied by the compensation payments and certainty about timings, and communities in the coal regions were satisfied by the large-scale investment programme. Most critique came from climate scientists and environmental NGOs, stating that the plan was insufficient to meet the target of limiting global temperature increase to 1.5°C. Members of the Commission felt they had pushed the issue as far as consensus would allow.²⁴⁸ There was little critique about the cost about the structural change fund, though some criticism of the €4.35 billion compensation payments to coal companies.²⁵⁶

Several commission members voted to explore the effects of a carbon floor price to help push out coal power, and politicians have since sought to scrap the phase-out mandate in favour of focusing on the carbon price of the ETS. This has been consistently rejected on the grounds that the price-only phase-out instrument would be too slow and would upset the achieved consensus.

Policy approach

In 2020, the federal government adopted a legislative package largely following the recommendations of the Coal Commission including a phase-out plan and a structural change support scheme for the affected regions.

The phase-out plan had a fixed schedule for closing lignite power plants and the associated nearby lignite mines. For the hard coal and small lignite power stations, seven rounds of reverse auctions were held, with compensation awarded to those operators that asked the least in return for closing their plant. From 2027 on, no further reverse auctions will be held, and the phase-out path will be met through regulatory measures without compensation payments.

The pathway set by the government to phase out coal power was slower than that recommended by the Coal Commission, though elements of it have since been brought forward (including accelerating the lignite phase-out in the Rhineland from 2038 to 2030).²⁵⁷

The structural change fund was central to making coal phase-out politically feasible. It holds €40 billion and supports measures to help avoid regional economic collapse in the three already economically weak lignite regions (one in the west near Aachen; two in Eastern Germany, near Leipzig and Cottbus).²⁵⁸

Despite its high costs, the structural change fund was hardly contested – indicating the consensus on the need for it that emerged from the Coal Commission. The government's decisions largely followed the Coal Commission's recommendations to invest in economic opportunities and transport infrastructure²⁵⁹ to attract new industry and high-skilled workers into affected regions. About 40% of the committed federal money, as of 2024, is used by the Federal Ministry for Education and Research to fund various new research institutes such as the Center for Advanced Systems Understanding (CASUS), and the German Aerospace Center branch for Electrified Aero Engines.²⁶⁰ The fund created at least 5,000 new jobs through the creation or moving of public authorities into these areas, and there are substantial funds to maintain the cultural coal heritage, including for museums and for maintaining coal-related buildings.

255 Ibid.

256 Zauner, D. (2025). War der Kohleausstieg für nichts? Klimareporter.

257 Bundesministerium für Wirtschaft und Energie (2022). Federal Cabinet decides on early coal phase-out in the Rhenish mining area.

258 Bundesministerium für Wirtschaft und Energie. (n.d.) Structural Strengthening Act for Coal Regions.

259 €6.5 billion will go to infrastructure measures, and of this some 90% is used for electrification and capacity upgrades of railways between and to the big affected cities, especially Leipzig–Cottbus–Berlin and Cologne–Aachen.

260 Die Bundesregierung (2024). Bericht der Bundesregierung zum Umsetzungsstand des Investitionsgesetzes Kohleregionen 2024.

Results

Up to 2025, the time of writing, the coal power phase-out has proceeded as planned. The end date of 2038 has not been pushed back further. In 2024, the coal plant closure target for 2027 had already been achieved, with market pressures having driven many plant closures, so that no further forced closures were needed.²⁶¹

It is too early to say whether the structural change will succeed and the €40 billion will be effective. The coal regions are in dire need of investment, and dedicated work to attract new economic activity and high-skilled citizens is needed. However, it is questionable whether the fund's strong focus on high-tech and tourism will pay off. Many high-skilled workers may use the now-improving railways to commute to the new institutes and high-tech clusters from already well-off cities, rather than move to rural coal towns. There is some criticism that, despite its legitimacy deriving from its inclusion of regional stakeholders' interests, the fund is not locally anchored, and that it has raised unrealistic hopes among coal miners about future employment prospects.²⁶² However, the fund is not (yet) a source of political conflict.

Other countries have since adopted similar approaches to govern politically challenging structural change, including Czechia, which created a coal commission to recommend a phase-out plan, and Poland, which developed a support package for coal miners. Often these countries are not able to mobilise resources on the same scale as Germany. Czechia's structural change fund is intended to support coal workers, restore landscapes, and enable economic change – but has only €1.7 billion,²⁶³ entirely from the EU. Canada's commission enabled deliberations which involved individual workers and citizens directly, unlike others which brought together representatives of stakeholder groups.²⁶⁴ As in the case of Germany, Czechia and Chile's coal commissions have been criticised for deciding on coal phase-out dates that critics view as not fully consistent with the Paris Agreement.²⁵⁴

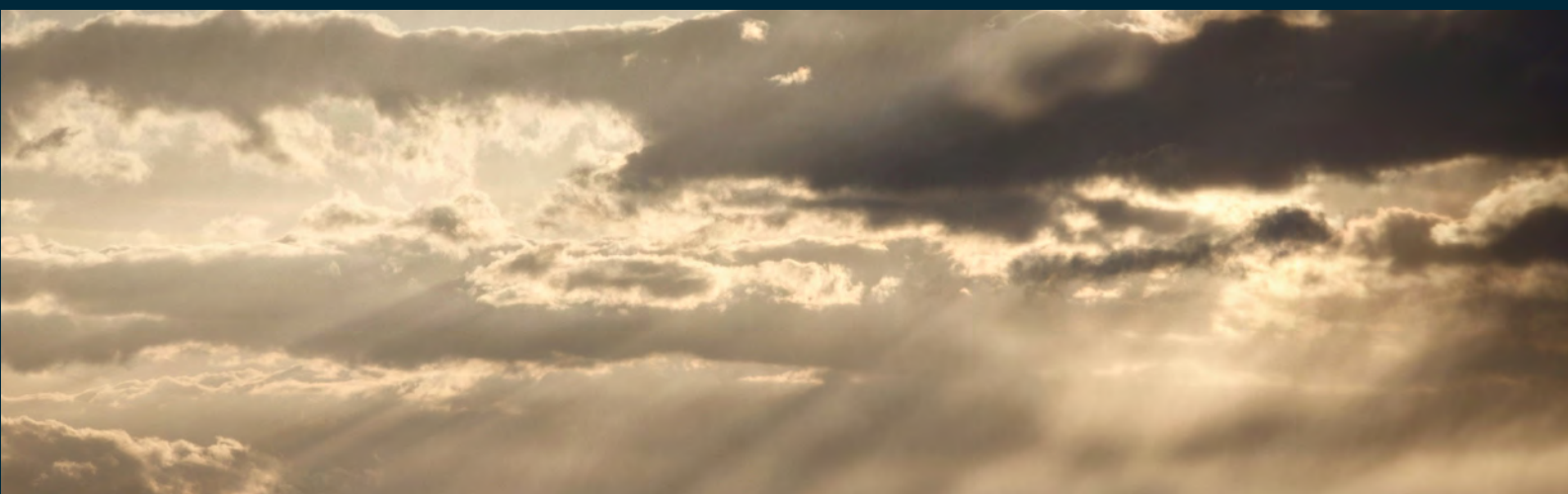
261 Collins, J. (2024). Germany's coal exit on track, no forced closures needed. Clean Energy Wire.

262 WRI (2021). Germany's 'Coal Commission': Guiding an Inclusive Coal Phase-Out.

263 State Environmental Fund of the Czech Republic (n.d.). Operational Programme Just Transition.

264 Brauers, H. & Fenner, D. (2022). Comparing coal commissions: What to learn for future fossil phase-outs? Coal Transitions.

265 Ibid.



CASE STUDY 18

Case Study 18. Regulation, subsidies, and public communications: Heat reconfiguration in Zurich, Switzerland (2023 to present)

The City of Zurich faced the challenge of replacing gas heating, which was still used in most buildings despite growing adoption of heat pumps. It developed a coordinated strategy.²⁶⁶ After a ban on new fossil fuel-based heating, it combined expansion of district heating with a district-by-district gas network shutdown. This avoided gas delivery infrastructure being operated for a small customer base, and the associated high costs. Transferring institutional responsibility for district heating to the municipal electricity supplier allowed for better integrated sector coupling and lower costs of capital.

The problem

Across the country of Switzerland, air–water heat pumps have emerged as the fastest-diffusing technology for building decarbonisation. These rely on heat exchange units outside buildings, where compressors and fans do the work of pumping heat from the ambient air to water that is circulated through the building’s thermal radiators. In denser city neighbourhoods, heat pumps face the technical challenge of insufficient space. In these neighbourhoods, district heating systems have been the preferred option, using surplus heat primarily from waste-based power generation. The availability of such heat is limited, however, to the areas close to waste incineration plants.

	Installation cost	Annual operating cost	Total annual cost (20-year amortisation at 3% interest)
Natural gas	19,000	4,000	5,300
District heating	19,000	2,300	3,600
Air–water heat pump	27,000	1,300	3,100

Figure 48. Approximate costs (in CHF) of alternative heating systems for a typical new-build single-family house in Switzerland.

Converting from one system to another in an existing building entails additional installation costs, which vary widely by building (see Figure 48 for an example). Contributing to the comparative advantage for both heat pumps and district heating relative to natural gas has been a national carbon tax on heating fuels. With the cost advantage, in 2023 nearly all new buildings, and the majority of heating system replacements in old buildings, went for a non-fossil option. At the same time, given the long life of buildings and heating systems, the majority of buildings in 2023 were still being heated with fossil fuels.

It was in 2023 that the City of Zurich set 2040 as the target year for reaching net zero emissions. Building heating is the largest source of emissions, accounting for 50% of direct emissions within the city. District heating networks already covered areas containing 30% of the city’s buildings, and heat pumps had been installed in an additional 10%, such that 58% of the buildings were still being heated by fossil fuels, mainly natural gas. The challenge was to convert the remaining fossil-based systems by 2040, in order to achieve the net zero target.

²⁶⁶ This case study is based on the website pages of the City of Zurich, EWZ, and Energie 360°; and personal communication with the City of Zurich sustainability office and the former mayor of Saint Gingolph; energieheld.ch (for the relative cost data).

Policy approach

The city's approach encompassed five elements:

1. An immediate ban on the installation of new fossil heating systems;
2. Expansion of the district heating networks, financed through municipal bonds, to cover all densely built neighbourhoods, comprising 60% of all buildings, making use of heat pumps with a lake-based heat source;
3. Subsidies covering a share of the cost of installing of renewable-based heating systems, including connection to district heating networks, as well as compensation for the early replacement of existing heating systems that had been installed prior to 2023 but were still not completely amortised;
4. Development of a plan for the cessation of natural gas delivery, on a neighbourhood-by-neighbourhood basis coupled to the expansion of the district heating networks; and
5. An information platform for residents and building owners.

The ban on installation of new fossil heating systems extended to the surrounding administrative region ('canton') of the country, and was approved by 63% of voters in a public referendum. It was tied to one part of the subsidies, supporting the costs of improved thermal efficiency of buildings as well as investments in non-fossil-based heating systems. The additional subsidies for connection to the district heating network, and the compensation for the early retirement of existing fossil heating systems, were adopted only by the city.

A main element of the approach was the expansion of the district heating networks to well beyond those regions close to a waste incinerator. Here, a core element was to rely on Lake Zurich as a thermal energy source for heat pumps. The advantage of this is that during the winter months, lake water at a particular depth remains at a temperature of about 10 °C, substantially warmer than the ambient air. This allows the heat pumps to operate at higher efficiency. One example of the successful use of lake-source heating is from the much smaller community of Saint Gingolph. Saint Gingolph straddles the Swiss–French border on the shores of Lake Geneva, and like Zurich had the opportunity to make use of lake water as the thermal energy source for a municipal heat pump. The project there was completed over the period 2019–2022 and now provides carbon-free heat to close to 100% of the buildings in the town core.



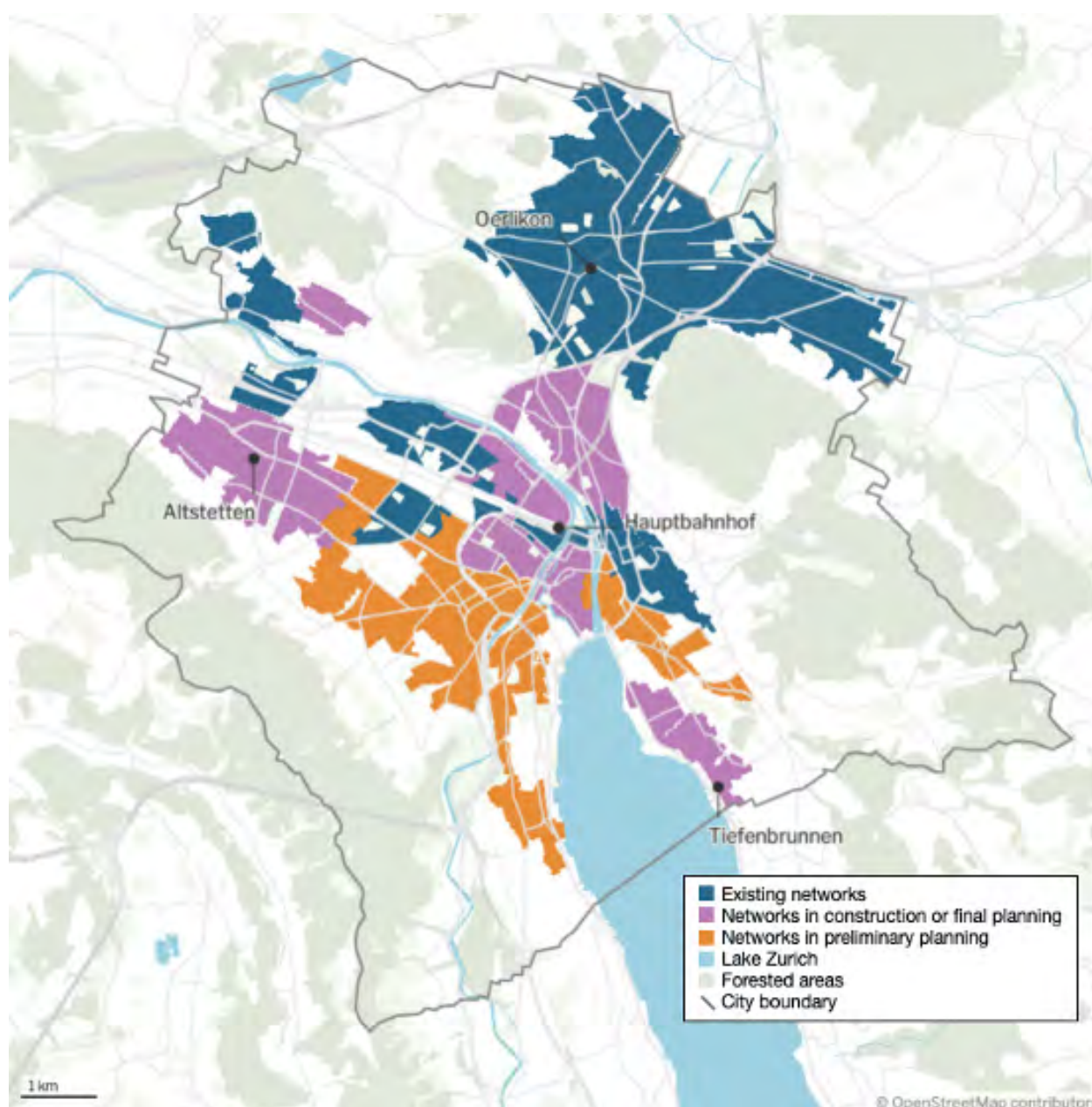


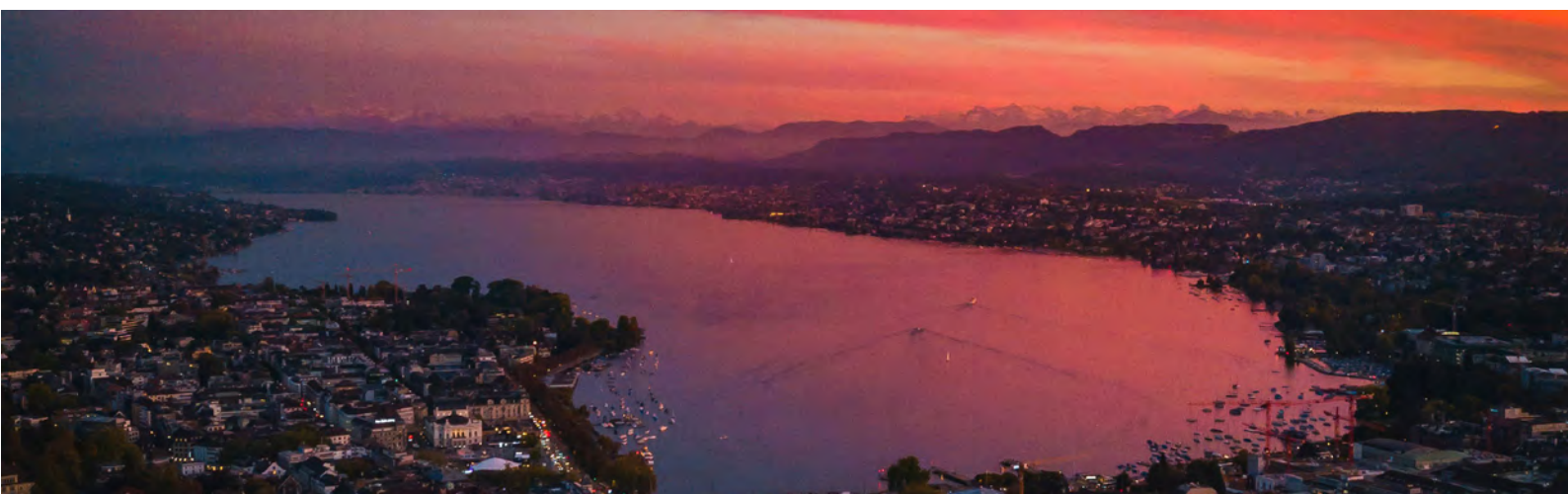
Figure 49. A map of Zurich, with locations for the district heating networks that exist, or are under construction or in planning. Source: Open StreetMap (n.d.).

Figure 49 shows a map of Zurich, and the locations for the district heating networks already existing, in construction or final planning, and in preliminary planning. Tied to this, the city made an important administrative change. Historically, the provision of electricity had been handled by a municipal department, Electricity Works Zurich (EWZ), while natural gas delivery and district heat delivery had been provided by a separate entity, Energie 360°, which was majority-owned by the city but nevertheless a private corporation. The new district heating networks are to be developed by EWZ, and the existing networks will be transferred from Energie 360° to EWZ. This will put all energy delivery within a single municipal department, which could prove relevant given the electricity demands of the new district heating networks. More importantly, the consolidation within EWZ, a municipal department, will allow the financing for the district heating expansion to benefit from the City of Zurich's AAA credit rating. In 2025, the city government approved a plan to issue up to CHF 2.26 billion in municipal bonds to finance the construction work by EWZ.

The final and critical piece of the reconfiguration process that the city decided on was to move forward with ending natural gas delivery throughout the city. The decommissioning of natural gas pipelines had started in 2011 in those parts of the city already covered by district heating systems. After the adoption, in 2022, of the net zero target, the city accelerated this to complete the decommissioning process in these city neighbourhoods by 2024. In 2024, the city also announced the continuing plan to cease natural gas delivery on a neighbourhood-by-neighbourhood basis. By coupling this to the expansion of the district heating networks, the intent is to avoid a situation where gas delivery infrastructure is being operated for a small customer base, which would result in high delivery costs for those remaining natural gas customers throughout the city. Those areas that are not slated for district heating coverage will also face a 2040 date for the stoppage of natural gas delivery. The information platform provides precise geographical information about all of this and is complemented by the availability of a city service providing consultation on heating system renovation.

Outcomes

The project is currently in its early phases, and it is too soon to evaluate the final outcome. So far, however, everything is proceeding according to plan. Importantly, public acceptance has been and remains high. It was clear at the time of the adoption of the 2040 net zero target that heating system reconfiguration would be an important element, and a public referendum was held to formally adopt the 2040 target: 75% voted in favour. Similarly, the 2022 law banning installation of new fossil heating systems was approved by referendum, with close to 80% of city residents voting in favour, compared with 63% in the canton as a whole. Associated with this, 84% of voters approved an initial CHF 500 million financial commitment by the city. The political parties that had most visibly supported these plans – the Social Democratic and Green parties – won an increased number of seats on the City Council in elections held in 2022. There has been no visible public opposition to the heating reconfiguration since then, including at the time that the detailed plan for cessation of natural gas deliveries was released in 2024.



CONCLUSION

The transition to zero-carbon technologies and systems is happening fast in some countries and sectors – and still needs to accelerate in many others. While political debate often focuses on setting goals, the challenge for governments is to decide on pathways, and design and implement policies to move forward along them. This requires high-quality strategic decisions, good policy design to overcome problems faced in the moment, and the foresight to prepare for emerging challenges. This report has set out an analytical framework to clarify these challenges and guide policymaking towards working constructively with the dynamics of technology transitions. We have emphasised two foundational principles:

- 1. First build, then break:** Governments must make sure that new technologies are widely available, affordable, and attractive before seeking to phase-out the old. Without doing so, efforts to phase out old technologies will be politically and economically costly, and risk using vast resources for little positive effect. Policymakers must focus first on invention, early deployment, infrastructure construction, and cost reduction of the new technologies.
- 2. Match policy to the stage of transition:** Just as the problems faced differ at each stage of the transition, so do the policies that are likely to work. This framework enables policymakers to identify where a sector stands, and quickly shortlist policies that might be needed. It can also be used to anticipate upcoming challenges, and identify policies likely to be needed in the near and long-term future, as the transition of any given sector progresses.

These principles can be understood in relation to feedbacks. The approach set out in this report helps policy to start and strengthen positive feedbacks that carry the transition forward with its own momentum.

In the early stages of the transition, powerful feedbacks can be harnessed to build the new system. Deployment of the new technologies drives improvement, cost reduction, and increasing demand, making it increasingly compelling for the private sector to invest and build more. A high level of effort and resource is needed at the start, to invent and introduce the new technologies to markets, and to build the systems they need. But this effort is rewarded as the new technologies cross critical thresholds in their competition against the old, and their diffusion gains a momentum of its own.

In the later stages of the transition, the availability of the new solutions enables policymakers to shift attention towards dismantling the old systems, navigating incumbent resistance, supporting affected people, and finally phasing out the old technologies. This process too gains its own momentum: once the old technologies have entered into decline, reinforcing feedbacks such as economies of scale and network effects act in reverse, hastening progress towards obsolescence.

The context of the zero-carbon transition is unprecedented: never before has modern civilisation faced the threat of climate change and the need to respond with rapid, structural economic change on a global scale. But policymakers should not make the mistake of seeing the transition itself as an entirely new phenomenon. Technology transitions have happened throughout history, and the case studies we present in this report are only a small selection. Many more examples can be found from which to draw inspiration.

The transitions towards solar and wind in the power sector, and towards electric vehicles in the road transport sector, show that the patterns of historical technology transitions can be repeated in the zero-carbon transition. In both sectors, leading countries have adopted policies that map closely to the framework described in this report – and have exceeded expectations, thanks to the positive feedbacks that amplified the effect of their efforts. The opportunity now is to take the learning from these sectors, from international experience and from history, and to use this knowledge to accelerate progress elsewhere.



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