Dynamics of the Energy Transition: Innovation, Transition Economics, Path Dependency, and Decision Making

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Abstract

This paper surveys recent progress, evidence and theory around innovation in energy—which has historically been marked by low rates of innovation—and the economic dimensions of a wider transition under way towards low carbon systems. Energy provision is central to economic development, yet it is at the heart of the growing crisis of climate change. Innovation is also intrinsic to economic progress. Energy-related innovation has accelerated due to a wide range of policies targeted at decarbonization, involving many beyond research and development (R&D). Middle-income countries increasingly dominate global emission prospects, and there is no compelling evidence that low-carbon energy systems ultimately need be more expensive than fossil fuel–based systems. However, the transition faces numerous obstacles, particularly in many developing countries, with the cost of capital as a critical factor, alongside political and institutional obstacles.

The transition brings opportunities and risks. Long capital lifetimes and path-dependence of energy systems and institutions amplify risks of asset-stranding, as growing climate impacts accelerate global decarbonization. Opportunities are likely to arise from earlier action, most obviously for energy importers, but more widely if and as countries gain a share of the new supply chains involved. Middle-income countries need active policies to gain a share of the global benefits associated with the accelerated transition.

Keywords: Energy transition; energy innovation; climate change; energy costs; development pathways

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Executive Summary

- Our economies are rooted in physical, technological, and social systems, which evolve. Many "classical" economic perspectives focus upon the optimal use of resources within existing systems (often based on equilibrium concepts) and the cost of marginal changes in resource inputs and prices. These perspectives are less well suited to the large-scale changes and potential instabilities and system transitions associated with climate change and the need for deep decarbonization.

- Energy systems have strong path dependence. Positive, self-reinforcing dynamics include the fact that technology costs tend to reduce with the scale of deployment. But energy systems overall have significant inertia, and involve complex physical, institutional, and financial networks, so that rapid large-scale changes can be costly and disruptive. While most developed countries, after many years of struggle, are now on paths of substantial decarbonization, most middle-income countries, starting from lower per capita emissions, face crucial choices about the direction of their energy sectors this decade, with enduring consequences.

- The energy and major energy-using sectors have traditionally had low research and development (R&D) intensity compared to many other economic sectors, reflected in almost a century of relatively incremental improvements in energy technologies and systems (power stations, combustion engines, blast furnaces, and so on). However, rapid technological change is under way in electricity generation and usage technologies (including storage), extending now into transport and industrial systems (see accompanying paper on energy technologies and systems (Melekh, Grubb, and Dixon 2024).

- Many of these innovations have substantially been driven by a broad set of decarbonization policies and have created new possibilities, with new value chains. Innovation is most rapid in technologies with relatively small unit scale and replicability (like solar and wind generation, and electric vehicles). These are increasingly cost-competitive with fossil fuels, but this also depends strongly on the cost of capital, the policy environment (including structures of subsidies and taxes), and adequacy of supporting infrastructure (such as electricity networks) as the contribution increases, as well as the wider business environment.

- There is no compelling evidence that low-carbon energy systems ultimately need be more expensive than fossil fuel–based systems. Empirical and theoretical evidence indicates that in the long term, energy systems have a large capacity to adapt and evolve (including through higher resource efficiency offsetting unit costs). However, the transition is not easy, and faces many obstacles, including incumbent interests. Overall, the long-term economic impacts of deep decarbonization depend upon numerous assumptions, including the future costs of fossil fuel versus low-carbon energy systems, the productive use of revenues from fossil fuel or carbon taxation, and the relative position of production and import versus export positions of fossil fuels and renewables (as well as the severity of climate change impacts in themselves).

- Many factors (including institutional and labor force capabilities) create challenging conditions for middle-income countries to enhance innovation capacity, and higher cost of capital raises the cost of low-carbon technologies compared to advanced economies. However, there are some ways in which they could be better positioned, particularly for "short-cycle" technologies with more rapid learning potential and lower cost barriers.

- Dimensions of transitional and adjustment costs (and potential benefits), *aside* from reduced climate damages and "co-benefits," include the following:
    - Resource/investment displacement effects (sometimes called crowding out) could reduce GDP to the extent that decarbonization takes human or investment resources away from other more productive uses. This is typically represented through general equilibrium models (which

    often assume a baseline of optimal resource allocation), with a global carbon price. In such models, a global carbon price exceeding \$100/tCO_2 is typically assumed to drive deep decarbonization by 2030, reducing GDP growth rates by about 0.1 percent/year to 0.2 percent/year during the transition.
  - Conversely, however, economies typically underinvest in productive investments, which could include enhanced energy efficiency, cheap low-carbon energy, and related innovation. Econometric and post-Keynesian economic models, which do not embody the assumption of an optimum baseline, increasingly suggest potential positive economic impacts of the energy transition, at least for countries that import fossil fuel—but this does depend, among other things, upon the terms of finance.
  - In addition, the *pace* of the transition, and the choice of instruments, will determine adjustment costs. Large and abrupt increases in energy prices (including carbon pricing) are likely to have more adverse impacts than more targeted investment instruments. Several "agent-based" models also indicate the potential for macroeconomic instability transmitted through the financial system, in the event of an abrupt transition, which would most likely be forced as a result of delayed action, followed by climate "tipping point" instability.

- The deep path dependencies in energy, including capital stock and infrastructure, enhance the benefit of early action, and amplify the economic costs of deferral. However economic and financial systems tend to have short time horizons and at present, the valuation of fossil fuel energy assets and capital is clearly inconsistent with delivering the agreed goals for tackling climate change—and indeed, inconsistent with the observed pace of transition already under way —while clean energy resources and industries appear widely undervalued.

- Both theory and evidence point unambiguously to the need for a range of policy instruments to accelerate the energy transition. The damage from fossil fuels is not adequately priced in most economies, which is an economic distortion; however, the price changes involved in removing fossil fuel subsidies, and introducing carbon pricing, while having fiscal benefits, can involve difficult distributional impacts—and sudden large-scale price changes are disproportionately disruptive. Markets and prices are important, but need to be developed in tandem with other instruments. Policies to enhance energy efficiency, and to help build up new low-carbon industries and supply chains, are an essential complement to the evolution of appropriate energy markets and pricing structures.

- The example of the United Kingdom's relatively rapid and widespread transition underlines the role of complementary policies. Diverse policies to enhance energy efficiency have contributed to declining energy (and electricity) demand, reducing overall energy costs; sizeable upfront investment in renewables has led to sharply declining technology costs; while carbon pricing has driven coal out of the UK system. Comparative ex ante modelling studies of the UK transition confirmed that economic models could produce either negative or positive GDP impacts of mitigation policies, depending upon the model and assumptions made. There is no comprehensive ex post macroeconomic analysis of the UK transition, but several lines of evidence indicate that, in the recent energy crisis, the contributions of energy efficiency and renewable energy have been strongly positive, and could have saved at least £1000 per household more, if some earlier program had been maintained.

- Low-carbon technologies are currently expanding most rapidly in developed economies and China. Combinations of domestic policies and international measures, including risk-underwriting (to reduce the cost-of-capital), have potential to rapidly accelerate the global transition, with net economic benefits.

1. Introduction: purpose and context

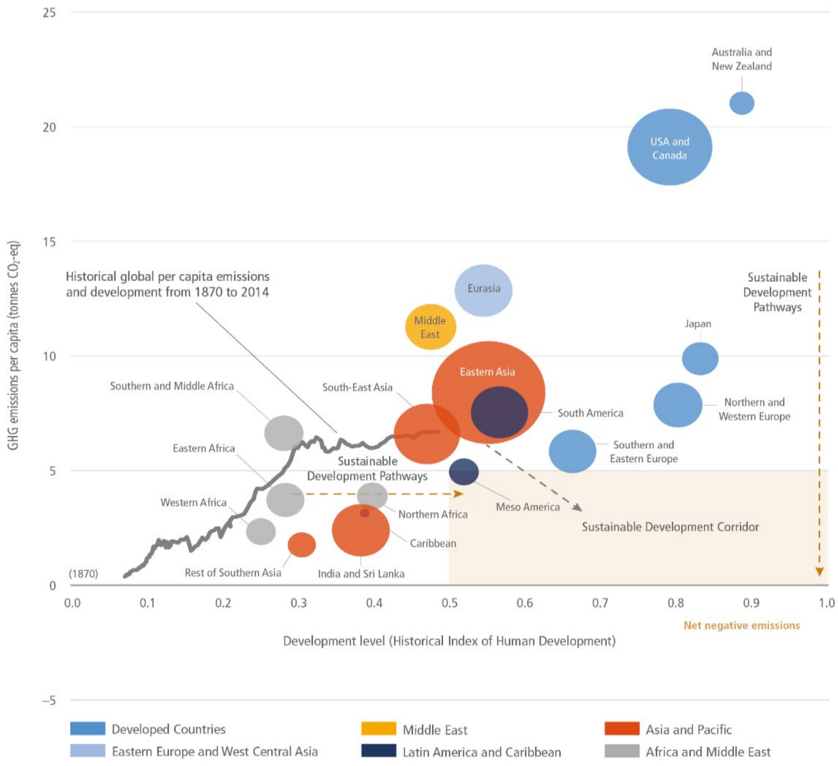
> ".. A wide cast of characters shares responsibility... [including] economists like me, and people like you. Somewhat frighteningly, each one of us did what was sensible given the incentives we faced. Despite mounting evidence that things were going wrong, all of us clung to the hope that things would work out fine, for our interests lay in that outcome. Collectively however, our actions took the world's economy to the brink of disaster, and they could do so again."
>
> *– Rajan Raghuram, Governor of the Central Bank of India and former Chief Economist of the International Monetary Fund, on the financial crisis* (Raghuram 2010, 4)

> "When in a hole, stop digging."
>
> *—Traditional saying*

This review paper takes stock of research on the dynamic and innovation characteristics of the energy transition and draws out the importance for fostering innovation and growth in middle-income countries. In combination with an accompanying paper on energy technologies and systems (Melekh, Grubb, and Dixon 2024), it offers theoretical and empirical foundations for decision making within the global energy transition, drawing on economic understanding of innovation, inertia, and path dependencies, including the risks of carbon lock-in and the opportunities and challenges of energy transition.

The Intergovernmental Panel on Climate Change (IPCC) Mitigation Report (IPCC 2022c) offers a useful framing for the international context, as illustrated in Figure 1.

Figure 1. Per capita emissions (2020) plotted against Human Development Index, for the IPCC twenty-region classification



Source: IPCC 2022c, chapter 1, figure 1.5.

Figure 1 shows how per capita emissions of greenhouse gas emissions relate to the stage of development, as represented by the relative Human Development Index (including a historical HDI comparison index), for the twenty-region classification used in the IPCC Sixth Assessment. The main developed country regions lie to the right; they display a very wide range of per capita emissions, most well above 5 tonnes CO_2e per capita (tCO_2e/cap), though a few European countries have recently reduced CO_2 emissions below this level. The least developed economies lie to the left, with per capita emissions mostly below tCO_2e/cap. The middle-income regions also display a very wide range of per capita emissions at similar levels of development.

All countries need to find ways to develop toward the lower right of the diagram—reducing the large inequality between regions, but with low emissions, heading toward net zero if the atmosphere is to be stabilized. As illustrated by the size of circles, middle-income countries together now account for more than half (and a rapidly growing proportion) of global emissions.

Some progress has been made. More than twenty developed countries have sustained greenhouse gas (GHG) emissions for at least a decade, some for much longer (Lamb et al. 2021); and almost all have goals to reach net zero by mid-century, with Nationally Declared Contributions for substantial reductions by 2030.

The challenge is thus to chart paths forward that increase welfare without further degrading the global environment. The goals of the Paris Agreement cannot be achieved without accelerated emission reductions in the highest income countries, and a rapid change of course across many middle-income countries. This review outlines modern understanding of the economics of this process, which starts with acknowledgment and understanding of the scope for innovation in its broadest sense.

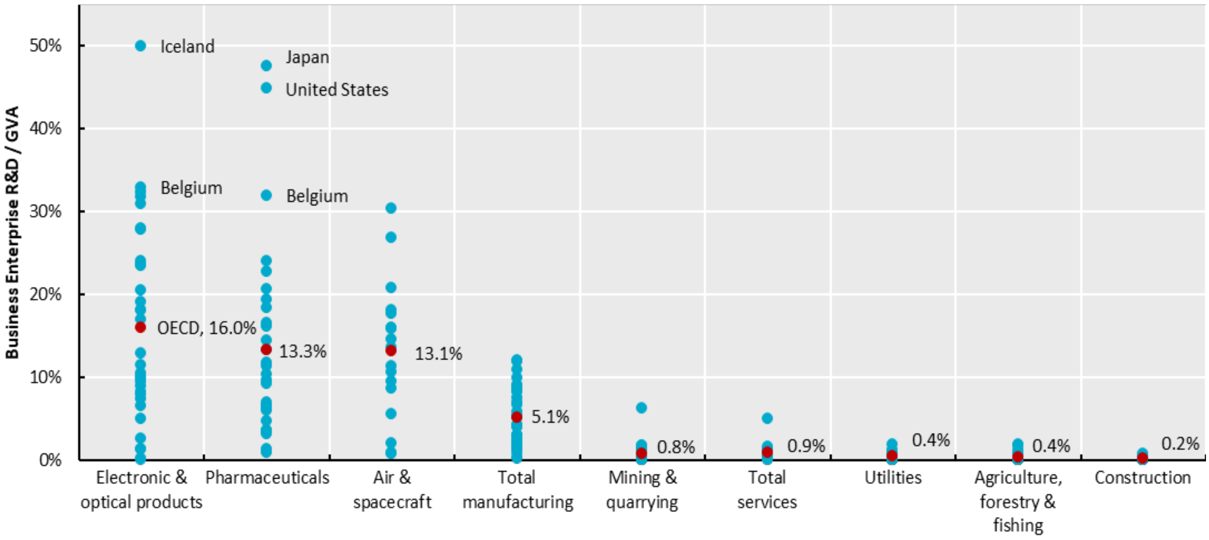
2. Innovation and technology transition

This section outlines innovation processes and transition dynamics within the energy sector, and highlights how their consideration in policy and investment decisions is important to accelerate the energy transition in middle-income countries.

2.1. Structural underinvestment and incumbency in energy innovation R&D

Energy has traditionally been one of the least innovative economic sectors in terms of private R&D expenditure. R&D has tended to be dominated by member countries of the Organisation for Economic Co-operation and Development (OECD), and companies across the OECD typically spend less than 1 percent on energy-related R&D, as indicated in Figure 2. On average, firms in the utilities sector spend 0.4 percent of gross value added (GVA) on R&D in the OECD, compared with 13 percent to 16 percent in highly innovative sectors such as electronics and pharmaceuticals (and more than 30 percent in some leading countries) (OECD 2021).

Figure 2. R&D intensity by industry for OECD countries in 2018



Source: OECD 2021.

Note: This figure shows average, unweighted means of research and development (R&D) intensity expressed as business enterprise expenditure on R&D as a share of gross value added (GVA) (2018 or nearest year), based on 17 countries with data available for air and spacecraft, and on 31–34 countries for all other industries. Industries are defined in accordance with the International Standard Industrial Classification (ISIC) codes, where "Utilities" refers to electricity, gas, and water supply; sewerage, waste management, and remediation activities. OECD averages are shown in red.

Certain systemic characteristics of the energy sector help explain this structural underinvestment in innovation. A large literature covers the "technology valley of death" in the energy sector, referring to an observed break in the innovation chain that limits the ability of new innovations to successfully complete the journey from invention through development, demonstration, commercialization, deployment, and ultimately diffusion (see, for example, Ellwood, Williams, and Egan 2022; Nemet, Zipperer, and Kraus 2018; Weyant 2011). The reasons for this disparity result from varying degrees of connectivity between innovators and consumer markets, and intrinsic differences between the strength of innovation "push" and "pull" forces. The inherently weak innovation forces within the energy sector can be attributed to a series of key characteristics, including:

- *Lack of product differentiation.* Innovations in energy technologies cannot provide materially different or new products to consumers, as they ultimately deliver voltage to drive electrons or a limited range of hydrocarbon molecules. This means that new innovations generally compete on cost margins against incumbent technologies. Energy innovators thus have little potential for radical profits from offering different consumer products, unlike highly innovative industries such as information technology (IT) or pharmaceuticals.
- *Lengthy development cycles.* Development cycles in energy supply technologies have tended to be lengthy, owing to the typically large, complex, and expensive nature of technology and associated infrastructure; for example, carbon capture and storage (CCS) has been in the development and initial deployment phase for over a quarter of a century. This contrasts with innovations in IT, for example, which can be relatively cheap and rapid.
- *Barriers to entry.* A small number of incumbents tend to dominate the energy industries, which benefit from decades of experience, learning, preexisting infrastructure, and lobbying power; new entrants must compete with incumbents while offering essentially the same product for final consumers.

Since innovation is generally positive for economic development, this suggests an opportunity. A large body of evidence now shows that policies and market signals can overcome these structural challenges in the energy sector to enhance innovation, and to a significant degree have stimulated the renewables cost revolution of the last decade (see Grubb et al. 2021 for a systematic review of 228 research papers on induced innovation).

While much of the earlier literature focused on “the cost of abatement,” as represented by “abatement cost curves,” Acemoglu et al. (2012, 2016) emphasized—and introduced to the mainstream economics literature—that this approach risks misrepresentation: the reality involves competition between incumbent high-carbon systems (which benefit from a century of development and refinement. along with protective institutions and financing capacity), and low-carbon systems. Abatement therefore need not necessarily represent a cost. The IPCC Mitigation Report (IPCC 2022b, Summary for Policymakers, SPM) presents data indicating the extent to which key low-carbon technologies are now competitive with fossil fuels (see also our accompanying paper on energy technologies and systems, Melekh, Grubb, and Dixon 2024).

Important factors (such as institutional structure and capacity, labor force capabilities, and higher cost of capital) create challenging conditions for middle-income countries to develop innovation capacity and break through into international markets (Cimoli, Dosi, and Stiglitz 2009; Doner and Schneider 2016; Paus 2014). Yet there are some ways in which emerging economies could be better positioned, particularly for “short-cycle” technologies with more rapid learning potential and lower cost barriers (see the discussion that follows, and Lee 2013).

2.2. Innovation: beyond R&D and “technology neutral” market-pull

Given that innovation is acknowledged to contribute to economic development—as does cheaper energy—a deeper understanding of which policies and market conditions foster energy innovation, and by what mechanisms, is important in order to understand how middle-income countries can stimulate innovation and cultivate domestic low-carbon energy systems.

The influence of individual policies and their combination on technological innovation has been the subject of much debate across economics and innovation literature. Economics discourse has long focused on “technology push” interventions such as public R&D funding, combined with patents, as mechanisms to overcome technology spillover market failures and enhance innovation. Sociotechnical transitions and innovation theory literatures have paid greater attention to “demand pull” forces, in particular policy packages, that in combination stimulate innovation by shaping markets to create favorable conditions for their success (Gallagher et al. 2012; Geels et al. 2017).

For deployment, the economics discourse has often favored “technology neutral” policies that avoid “picking winners,” such that the market self-selects the most cost-effective approaches to reduce greenhouse gas emissions through competitive market forces (Powell 2011; Gawel, Korte, and Lehman 2018). However, true technology neutrality is difficult to implement in practice, and tends to implicitly favor certain technologies that maintain the status quo (Greenberg 2016; see also section 3.3 on carbon lock-in).

Policies such as energy and carbon pricing tend to encourage the uptake of least-cost opportunities for short-term emissions reduction, and incentivize the deployment and incremental development of relatively mature clean technologies, but may not induce more radical changes in which the dominant energy industries have no established comparative advantage (see box 1).

While introducing greater competition into energy systems (notably, electricity and gas markets) is certainly no panacea, Songwe, Stern, and Bhattacharya (2022) find that in the OECD, 81 percent of "green transformation investments" are financed by the private sector, whereas in developing countries, the figure is only 14 percent. This correlates with the fact that many electricity systems in the developing world are state-owned enterprises, with more limited scope for competition and innovation from new entrants.

Box 1. The impact of energy and carbon pricing on innovation—mixed messages

A systematic review on induced innovation (Grubb et al. 2021) identifies how energy and carbon pricing has influenced innovation (mainly indicated using patents) in key sectors.

Transport. The impact of gasoline prices on innovation in alternatively fuelled vehicles appears strong and path dependent; firms that have previously engaged in clean innovation have been much more likely to respond to price stimuli (see, for example, Aghion et al. 2016; Barbieri 2015, 2016; Fredriksson and Sauquet 2017). Studies generally find the impact of oil price on biofuel patenting to be positive, though the effect varies significantly in magnitude between studies (see Guillouzouic-Le Corff 2018; Jang and Du 2013; Kessler and Sperling 2016; Kruse and Wetzel 2016). Knittel (2011) finds gasoline prices to be the main driver of a 60 percent improvement in US car and truck fuel efficiency between 1990 and 2006. Countries with larger oil endowments have generated comparatively less patent activity on efficient or alternative vehicle technologies (Kim 2014).

Electricity generation. Studies on the innovation impact of the European Union Emissions Trading System (EU ETS) (and other forms of carbon pricing) mostly find that it did accelerate research and development (R&D) activity in regulated firms, but mainly relating to incremental improvements in energy efficiency, with limited or no effect on radical innovation and renewable energy uptake (Hoffmann 2007, 20; Rogge and Hoffmann 2010; Gulbrandsen and Stenqvist 2013; Borghesi et al. 2015). Kim, Heo, and Kim (2017) find carbon taxes to have an insignificant impact on patent applications for wind and solar photovoltaics (PV). Examining the impact of oil prices on renewable energy patenting for the Organisation for Economic Co-operation and Development (OECD), Cheon and Urpelainen (2012) find the marginal effect increases with existing share of renewables in electricity generation, suggesting an important role for knowledge stock and path dependency.

Industry. Energy prices are generally found to have a positive influence on industrial innovation (Ley, Stucki, and Woerter 2016; Lin et al. 2018; Ye, Dai, and Zeng 2018), with much stronger influence on firms that are energy-intensive, have strong existing management and technological capacity, and engage with wider knowledge networks (Triguero, Moreno-Mondéjar, and Davia 2014; Garrone, Grilli, and Mrkajic 2017). Studies on carbon taxes find similar results to those for electricity generation, with resulting innovation found to stimulate incremental innovation rather than radical innovation.

Buildings and appliances. The evidence of energy and carbon pricing on innovation is much more limited, and appears mixed and inconclusive. Noailly (2012) finds that "portable" household technologies (such as those that can be replaced by occupants) do respond strongly to end-user energy prices, though such prices have no effect on technologies that are less easily modified (heat distribution, building materials), which the authors suggest may be due to principal-agent issues. Costantini, Crespi, and Palma (2017) finds energy efficiency technology patents to be strongly linked to taxation, whereas Girod, Stucki, and Woerter (2017) finds negligible effects.

Institutional context. The underlying institutional context has been found to influence the innovation response to price changes. A lack of clear quality standards (Taylor 2008), unclear regulatory regimes with weak compliance (Kivimaa, Kangas, and Lazarevic 2017), and weak innovator networks (Sköld, Fornstedt, and Lindahl 2018) dampen the innovation response to pricing. Conversely, Christiansen (2001) finds the presence of an intermediary organization to facilitate innovation to amplify the innovation response to a carbon tax.

Source: Grubb et al. 2021.

While energy and carbon pricing clearly play an important role in driving energy efficiency improvements and low-carbon technology adoption, evidence points to *targeted* policies and policy packages as largely responsible for the renewables cost revolution, particularly incentives and regulations designed to foster early-stage deployment and market growth (Peñasco, Anadón, and Verdolini 2021) (see sections 2.2 and 4.2).

For example, the cost revolution in solar photovoltaics resulted from countries introducing a package of policies and deployment programs that actively "picked" solar PV, including R&D and procurement in the United States, residential deployment subsidies to cultivate a niche market in Japan, feed-in-tariffs (FiTs) in Germany, and scale-up subsidies in China, which in combination brought down costs by a factor of 10,000 in six decades (Nemet 2019). Rapid technological progress in other key technologies including on-shore and off-shore wind, concentrating solar power, and lithium-ion batteries for electric vehicles (EVs), were also driven by innovation policy packages (to a large extent demand-pull policies) involving deliberate technology choices that facilitated deployment and cost reduction, rather than generic R&D investments and carbon pricing (IPCC 2022c).

FiTs have been a strong driver of innovation, particularly in solar PV, and especially when combined with a wider environmental policy framework (including energy and carbon pricing). Renewable Portfolio Standards and investment supports play a less significant role for "new to market" technologies, though these broader instruments do drive innovation in more mature emergent technologies that are better suited to capturing this support at least cost. In general, literature supports the conclusions of Johnstone, Haščič, and Popp (2010) that targeted subsidies such as feed-in tariffs are more effective in generating innovation in novel technologies, whereas market-wide or general policies such as quota obligations with tradable certificates better encourage innovation in mature technologies that have already benefitted from learning-by-doing cost reductions.

Innovation is likely to be most strongly sustained over time when there is alignment between the "technology push" and "demand pull" policies, which is facilitated by policy coordination and consistent policy direction.

2.3. Interrelationship of innovation and deployment

The vast cost reductions achieved in key low-carbon energy technologies in recent decades have continued to surprise economists (Meng et al. 2021), and have sparked much interest in a better understanding of "experience curves," the relationship between cumulative deployment and technology cost reduction.[1]

The evidence clearly shows that expanding deployment is positively correlated with cost reductions, across a wide range of low-carbon technologies. Although few studies attempt to explicitly test the direction of causality, those that do find a strong role for deployment-induced learning and economies of scale. For instance, Isoard and Soria (2001) perform a Granger causality test, finding that cumulative installed capacity resulted in capital cost changes in solar PV and onshore wind.

Some studies that produce multi-factor learning curves (see box 2) find an important shift in the relative contribution of factors to cost reductions over time. Kavlak et al. (2018) find that between 1980 and 2000, public R&D and spillovers accounted for nearly 50 percent of cost reductions in PV, but after 2000 this pattern reversed, with public R&D and spillovers accounting for just one-quarter of the contribution to cost reduction, compared to that of scale economies and learning-by-doing. Kruse and Wetzel (2016) find similar results.

Table 1 presents indicative learning rate ranges observed in key technologies. The table shows that expansion is almost always accompanied by cost reduction, but the "learning rate" varies significantly between technologies.

Box 2. Forms of induced innovation and representation in models

Gillingham, Newell, and Pizer (2008) distinguish three types of induced innovation process and modelling approaches:

- In the "direct price-induced" approach, the changes in relative prices can trigger innovation and reduce the demand for expensive inputs (Hicks 1932; Popp 2002).
- In the R&D-induced approach, investments in research and development (R&D) shape the direction of technological change (Aghion and Howitt 1998; Acemoglu 2002; Nordhaus 2002; Popp 2004), and
- In the learning-induced approach, the unit cost of a technology decreases based on the accumulation of capital linked with that technology, and so with experience as it matures (see Wright 1936; Arrow 1962; Grübler 1998).

They also distinguish between models that include the accumulation of R&D investments in a stock of knowledge (Buonanno, Carraro, and Galeotti 2003; Smulders and de Nooij 2003), reduction of carbon intensity (Nordhaus 2002), or abatement costs of technology (Goulder and Mathai 2000). The general implication of spillover effects in these studies is a higher rate of innovation diffusion and positive outcomes for decarbonization.

Simpler and more technology-specific treatments of innovation use learning curves, with either one or more factors:

- *Single-factor learning curve (relating costs only to scale of deployment).* Most of the relevant literature examines the correlation between cumulative deployment and cost reduction to generate "single factor" learning curves, without probing much into causation or directionality, the distinction between deployment and diffusion, or the various factors that may be responsible for the cost reduction (economies of scale, R&D expenditure, changes in input resource costs, various processes of learning, spillovers, and so on). This simplicity also implies limitations (Söderholm and Sundqvist 2007; Nordhaus 2014).
- *Multi-factor learning curve,* distinguishing between R&D, and experience via diffusion and scale (see, for example, Miketa and Schrattenholzer 2004; Yu et al. 2017; Zhou and Gu 2019). Klaassen et al. (2005) and Söderholm and Klaassen (2007) use two-factor learning curves to explain how a decrease in cost in technology is dominated by R&D investment at the start, and from learning by doing during technology diffusion. Probabilistic forecasts allow more robust estimation of future costs within uncertain ranges (Anadón, Baker, and Bosetti 2017; Way et al. 2022).

A recent review (Pasqualino et al. 2024) categorizes six different modelling approaches to including induced innovation in models relevant to evaluating the low-carbon transition. These approaches vary in particular in the extent to which they extrapolate directly from past data, or start with theoretical underpinnings that are then populated with data.

Table 1. Indicative learning rate ranges by technology

Technology	Indicative learning rate ranges observed in literature[a]	Notes
Solar PV	20% (±6%)	Variation in geography observed; however, little evidence that learning rates have declined over time.
Onshore wind	5%–15%	Most studies focus on Europe.
Offshore wind	5%	Based on just one study with limited data and poor statistical fit.
Nuclear	n/a	Some studies indicate negative learning rates since the 1960s; others indicate negligible or slightly positive rates. Overall, learning is limited and highly context-specific.
Biofuels	Wide range from negative (cost increases) to + 40%	Extremely divergent results between studies and periods. Studies taking a long-term average for Brazilian ethanol have gravitated toward 16%–20%, though this may be largely due to exogenous technology spillovers.
Household and consumer goods	18% (±7%)	Average, cross-technology learning rate for 15 (mainly building and appliance-related) technologies, found by Weiss et al. (2010). Higher rates (20%–30%) found for consumer electronics and components, heat pumps, and compact fluorescent light (CFL) technologies.
Hybrid vehicles	<10%	Often well below 10%, probably in part because initial deployment represented a very small, loss-leading fraction of sales by major global car companies.
BEVs	9%–16%	Studies of both full battery electric vehicles, and their components—particularly lithium-ion batteries—find consistently higher learning rates than hybrid vehicles.
Energy storage	15%-25%	Learning rates for stationary battery technologies (including lead-acid) have tended to find similar, though perhaps slightly lower learning rates than their mobile counterparts.

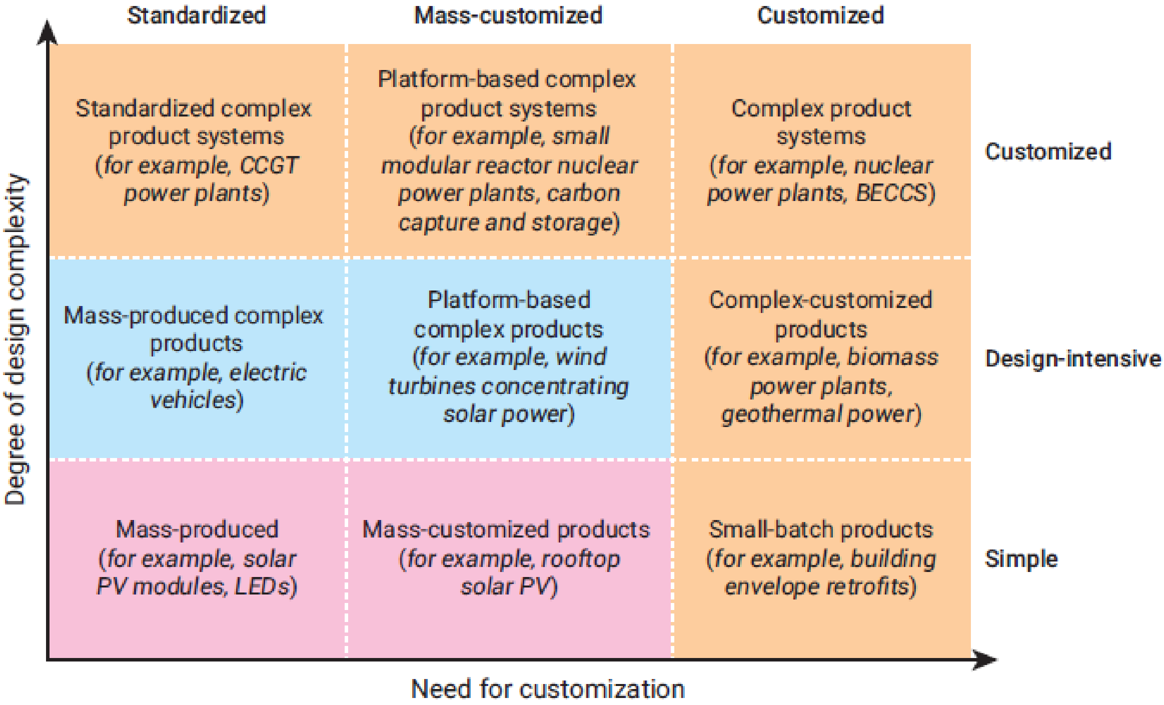
Source: Summarized from Grubb et al. 2021.

Note: References are too numerous to list here; see section 6 of Grubb et al. (2021), which covers 87 papers on learning curves. The learning rate is the cost reduction associated with a doubling of installed capacity or generation.

a. As reviewed in Grubb et al. (2021).

Two other observations can be drawn from the patterns of energy technology innovation over recent decades. First is the improved understanding of the determinants of learning rates between different types of technologies. As analyzed in Malhotra and Schmidt (2020) and summarized in Figure 3, larger, more complex technologies (such as those with many large-scale design components that interact in multiple ways) tend to learn more slowly and have a greater propensity for cost overruns. So do technologies that require a greater level of customization to local environments (for example, due to regulatory content or user preferences), as compared to with "plug and play" technologies. In contrast, small "granular" technologies can innovate and diffuse much more rapidly; Wilson et al. (2020) emphasize their role in rapid decarbonization.

Figure 3. Technology characteristics that influence the potential for cost reductions



Standardized	Mass-customized	Customized	
Standardized complex product systems (*for example, CCGT power plants*)	Platform-based complex product systems (*for example, small modular reactor nuclear power plants, carbon capture and storage*)	Complex product systems (*for example, nuclear power plants, BECCS*)	Customized
Mass-produced complex products (*for example, electric vehicles*)	Platform-based complex products (*for example, wind turbines concentrating solar power*)	Complex-customized products (*for example, biomass power plants, geothermal power*)	Design-intensive
Mass-produced (*for example, solar PV modules, LEDs*)	Mass-customized products (*for example, rooftop solar PV*)	Small-batch products (*for example, building envelope retrofits*)	Simple

Source: Malhotra and Schmidt 2020.
Note: Technologies are classified as type 1 (tan), type 2 (blue), and type 3 (pink). Middle-income countries are best suited to become suppliers of type 1 and type 2 technologies in global supply chains. Type 1 technologies, such as solar photovoltaic (PV) modules and efficient light emitting diode (LED) lighting, are simple to assemble and distribute at scale (although individual components may exhibit complexity) and have rapid learning rates and scale economies. Type 2 technologies, such as wind turbines and electric vehicles, involve relatively more complex designs and evolve toward scalability more slowly, although they include standardized components, and have the potential for scale economies and increasing replication, and learning cycles of a few years. Type 3 technologies, such as nuclear power, require extensive customization and involve a high degree of complexity. They are susceptible to cost overruns and have limited scope for rapid learning by doing. BECCS = bioenergy with carbon capture and storage; CCGT = combined-cycle gas turbine; PV = photovoltaics.

This broad typology implies different risks and opportunities associated with different technology investments and ability to compete with the global market for middle-income countries. For example, the few countries that invested early in developing a wind industry may dominate the global market for the most complex, high-value components, but the technology diffused relatively rapidly, and many countries participate in the value chain to produce less complex, lower-value components.

Second, the energy breakthroughs of recent decades yielding major cost reductions, leading on to emergent transformations, suggest a broader range of policy-relevant insights from case studies, including those summarized in box 3.

Box 3. Three case studies of recent low-carbon technology transformations

A study by the international consortium the Economics of Energy Innovation and Systems Transition (EEIST) provides three case studies of the radical technology change in wind energy, solar photovoltaics (PV), and efficient lighting (EEIST 2021).[a] Conducted with partner research institutions in Brazil, China, and India, these case studies focus on the key decisions and strategies, and their interaction, that helped to drive the dramatic cost reductions achieved.

- **Wind energy in Europe, Brazil, and the United Kingdom.** Early wind energy markets were created and developed in California and Europe, through scale up in Brazil, and induced innovation in offshore wind in the United Kingdom. Key policies and strategic decisions highlighted include early market-creating legislation in California, research and development (R&D) efforts in Europe, including in Germany and Denmark in particular; the Brazilian PROINFA incentive program; subsequent policy support and Brazilian National Development Bank (BNDES) financing; and the Renewable Obligation followed by contracts-for-difference (CfD) in the United Kingdom. The major technological and industrial developments associated with larger onshore wind turbines, combined with offshore engineering expertise from the oil industry and supportive policies, then enabled the emergence of economically viable offshore wind energy.[b]

- **Solar photovoltaics in Germany and China.** Following intensive and subsequently scaled back solar R&D efforts across numerous governments in the aftermath of the oil shocks in the 1970s, Germany's Renewable Energy Act, technology-specific feed-in-tariffs (FiTs), and ultimately the *Energiewende* drove much of solar PV's development and capacity installations during the 2000s, though initially with lower than anticipated cost reductions. China's investment in solar PV largely triggered the rapid cost reductions, at first through the development of its PV manufacturing industry for foreign export (incentivized by Germany's surging demand), and later, through domestic deployment programs. Drawing on early exploratory efforts in solar PV, the German and Chinese developments interwove to create a radical transformation in solar technology and deployment that stand to benefit all countries. Germany created a market and confidence that stimulated manufacturing in China, which drove down costs and built investor confidence, paving the way for large scale domestic roll-out in China, and increasingly around the world.[c]

- **Energy-efficient lighting in India.** Drawing upon primary technology developments first in compact fluorescent lamps (CFLs) and subsequently light emitting diodes (LEDs), India became one of the world leaders in rapidly deploying and reducing the cost of high-efficiency lighting. Starting from 2008/09, the Bachat Lamp Yojana (Energy Saving Lighting Scheme) was a voluntary scheme seeking to replace inefficient incandescent bulbs in households with CFLs, through an emission credit system involving international investors. This laid the groundwork for the UJALA (Unnat Jyoti by Affordable LEDs for All) program, involving bulk public procurement through a public sector joint venture. Domestic component requirements introduced in 2015 contributed to the rapid development of the domestic LED manufacturing industry. Policy decisions emerged as a result of extensive consultation with government departments, investors, lighting companies, and consumers, driven by strategic objectives of maintaining energy affordability and supply in light of rapidly expanding electrification. Bolstered by the scale and confidence derived from bulk procurement, the cost of energy efficient lighting (LEDs) fell by 85 percent within four years, and generated rapid uptake that ultimately led to the use of LEDs in 90 percent of electrified households in India.[d]

Separate appendixes on each case study are available at https://eeist.co.uk/eeist-reports/the-new-economics-of-innovation-and-transition-evaluating-opportunities-and-risks/, with an overall synthesis of the program and country studies (EEIST 2024) at https://eeist.co.uk/eeist-reports/.

Sources: EEIST (2021): case studies.

a. Additional national technology case studies included in a subsequent report (EEIST 2023) include small hydropower in Uganda (case 3), EVs in China (case 5), and PV in Brazil (case 6). All are available from eeist.co.uk/eeist-reports.
b. Wind case study: Synthesis by Paul Drummond (UCL, United Kingdom), João Carlos Ferraz (Federal University of Rio de Janeiro, Brazil), and Luma Ramos (Boston University, United States).

c. PV case study: Synthesis by Alex Clark (Oxford University, United Kingdom) and Zhu Songli (Energy Research Institute, Beijing).
d. LED case study: Kamna Waghray (The Energy and Resources Institute, Delhi).

The consortium involved in these case studies drew five main observations of common characteristics across all the case studies:

1. *Cumulative progress.* Decisions taken built directly on developments that had previously happened; progress was *cumulative,* and *path dependent*.
2. *Market-based innovation*. Market-based innovation was instrumental in much of the progress seen in recent decades, in particular relating to the deployment phase.
3. *Sustained and targeted support for deployment.* Targeted public policy sustained over time was a crucial component in each transition during the technology demonstration and deployment phases, in most cases for one to two decades beyond an initial R&D period, with "market-correcting" instruments such as carbon pricing playing a limited (or no) role.
4. *Deep uncertainties*. Early stages were characterized by deep uncertainties of future costs, benefits, and impacts, at least until critical thresholds were passed.
5. *Strong international dimensions.* Often internationalization sustained the growth of the technologies and helped them pass critical thresholds.

2.4. From innovation to transition: S-curve dynamics, barriers and incumbency

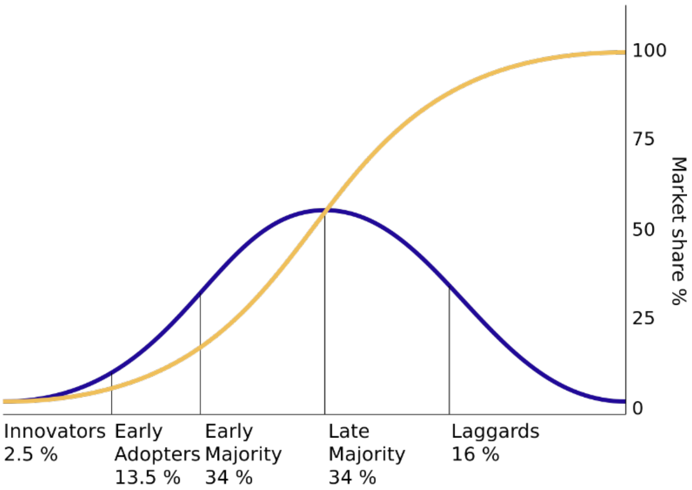
Following the technology cost breakthroughs of the past decade, the IPCC Mitigation Report (IPCC 2022c) assessed that on an average "engineering cost" basis, varied technologies already offer large potential to reduce emissions at a "negative costs," on a levelized-cost-of-energy (LCOE) basis—that is, with net lifetime savings compared to fossil fuels. The biggest such potentials identified are from wind and PV in electricity generation, energy efficiency and avoidable demands in building, and many options across transport (IPCC 2002b, figure SPM.7, in which all the blue bars indicate potential to cut emissions at "costs lower than the reference case").[2]

In a traditional "equilibrium" economics setting, a technology that is cost-effective in this way would be expected to promptly dominate. There are various reasons why this does not happen:

- *Multiple non-cost obstacles to adoption.* These can impede the pace of uptake (if not entirely block) uptake at scale, including structural barriers and incumbent interests that resist the new technology, discussed later in this paper.
- *Hidden costs.* Examples include information, search costs, and transaction costs, which are often cited in the context of energy efficiency options (though many "hidden costs" are transitional). These could also include technology-specific adjustment costs, such as search costs.
- *Averaging/aggregation.* The IPCC numbers are best estimates typically of global average conditions. Aside from resource variations, many models and extrapolations assume a constant cost of capital/discount rate. In practice, most developing countries face a much higher cost of capital, which drives the realized cost of capital-intensive investments (like renewables, which are mostly capital-intensive and cost very little to run). The extent to which such technologies are in practice cost-effective thus depends on the scale and terms of access to capital, domestically and internationally, as well as resource and other more country-specific conditions. Our accompanying paper on energy technologies and systems (Melekh, Grubb, and Dixon 2024) shows that the high cost of capital in many developing countries could increase the cost of renewables by 50 percent or more (though for PV in subtropical developing countries at least, this may be offset by the stronger and more regular solar resource).

These point to a much wider set of issues affecting the potential for rapid transition and associated costs, which have been more widely studied in the innovation systems and transitions literatures, which treat time, inertia, and path dependencies as core concepts and processes integral to analysis. In this literature, logistic or "S-curve" dynamics have long been recognized as describing the typical diffusion of new technologies (and other innovations) throughout a social system. Figure 4 presents an illustrative S-curve, driven by a bell-curve distribution of adoption patterns across time, from innovators and early adopters to laggards (Rogers 2003).

Figure 4. Diffusion of innovations model

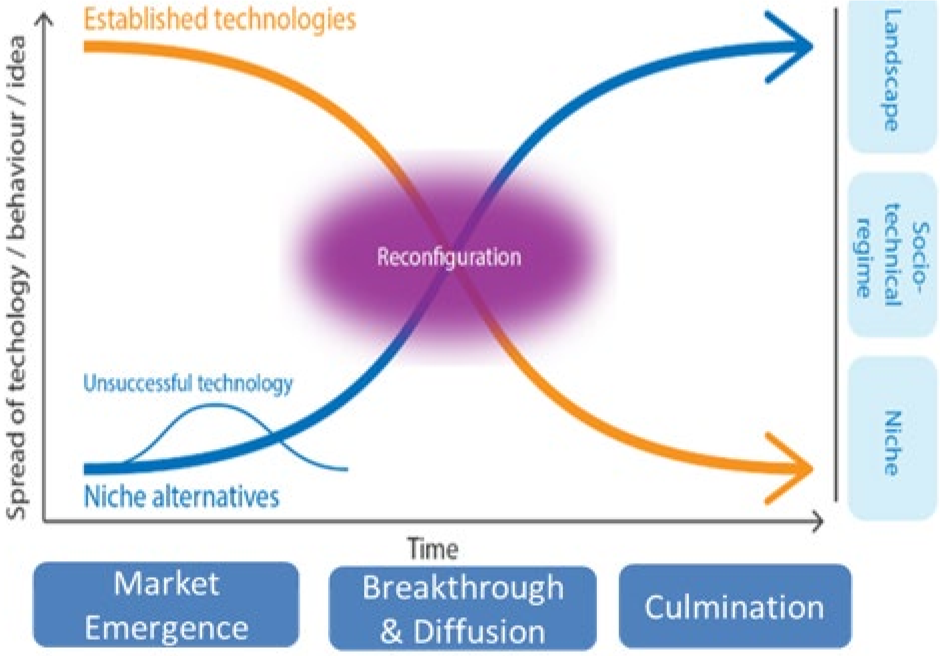


Source: Based on Rogers 2003.

Time lags in technology adoption due to inertia within entrenched cultural, institutional, and infrastructural "socio-technical regimes" (Geels 2014) provide an alternative explanation for economists' "hidden cost" diagnosis (see Falk and Kosfeld 2006) of competitive but underutilized technologies. For example, long asset life cycles and limited policy reach lead to long delays in adoption of new technologies in the buildings sector, and the fact that electricity from solar PV energy may now costs less than from fossil fuel in large swathes of the world will not cause supply systems to switch overnight.

The inherent dynamics of diffusion, combined with varied sources of adjustment costs and wider institutional inertia in the existing "socio-technical regime" that governs the relevant systems, inhibits abrupt take-up (Geels 2014; Newell and Paterson 1998). Note in particular that rapid early growth of new technologies may have limited impact on incumbents, but if they do directly compete, that impact can rapidly escalate as diffusion accelerates, and regimes adjust to accommodate the new and better technologies. This, together with the impact on incumbent technologies, is schematically illustrated in Figure 5. Some high-level policy implications are discussed in section 4.

Figure 5. Stylized stages of S-curve growth and technology displacement



Source: IPCC Sixth Assessment Report–Mitigation (IPCC 2022c: chapter 1/Technical Summary).

A broader literature explores the pace of historical transitions, finding wide variations (Grübler 1996; Grübler, Wilson, and Nemet 2016). The major global transitions of entire systems (for example, from coal to oil, or the rise of the motor car) have taken many decades. However, local and national transitions can occur more rapidly, or for more consumer-driven technologies, particularly when these can utilize existing infrastructure. For example, initially cars rapidly substituted horses in US towns, but growth slowed when entire road and refueling infrastructures were required (Nakicenovic (1986). This example suggests that renewables may be able to rapidly displace thermal power stations in the context of existing electricity systems, until they reach limits (for example, from variability) which require larger system and infrastructure adjustments (Gils, Gardian, and Schmugge 2021; Lam and Mercure 2021).

Finally, a factor often neglected in the technical and economics literature concerns political resistance. This includes the lobbying and power dynamics of incumbent interests impeding new entrants and thwarting the ambition of reforms and climate policy, combined with wider institutional inertia in the existing socio-technical regime (Newell and Paterson 1998; Jones and Levy 2009; Geels 2014; Breetz, Mildenberger, and Stokes 2018). Incumbent industries are often more concentrated than those benefiting from climate policy and lobby more effectively to prevent losses than those who would gain (Meng and Rode 2019). Drawing upon wider networks (Brulle 2014), campaigns by oil and coal companies against climate action in the United State and Australia are perhaps the most well-known and largely successful of these (Pearse 2017; Brulle, Aronczyk, and Carmichael 2020; Mildenberger 2020; Stokes 2020) although similar dynamics have been demonstrated, for example, in Brazil and South Africa (Hochstetler 2020), Canada (Harrison 2018), Norway, and Germany (Fitzgerald, Braunger, and Brauers 2019). In other contexts, resistance by incumbent companies is more subtle, but nevertheless has weakened policy design on emissions trading systems (Rosembloom and Markard 2020), and limited the development of alternative fuelled automobiles (Levy and Egan 2003; Wells and Nieuwenhuis 2012).[3]

Resistance, however, does not only come from incumbent industries; it often comes from consumers, particularly if the instrument adopted is a general price instrument like removing fossil fuel subsidies, or carbon taxation. Kahn and Lall (2022) note that in middle-income countries, “The emerging middle class are buying and operating energy intensive durables ranging from vehicles to air conditioners to computers. Owners of these durables represent an interest group with a stake in opposing carbon pricing….", and exhibit associated characteristics highly relevant to plausible policy (section 4).

3. Transition costs, scenarios, inconsistencies, and risks

3.1. Short- and long-term impacts of energy prices on energy demand, costs, and structural change

There is a huge literature on energy elasticities. Energy demand has historically almost always risen with income (at least up to a relatively advanced stage of economic development). Thus, energy has a positive demand elasticity. The income elasticity of energy demand is typically less than 1, so energy intensity (energy per unit GDP) generally declines—at least past the stage of basic industrialization (Csereklyei, Rubio-Varas, and Stern 2016; Saunders et al. 2021), but overall demand still increases with development.

Demand-price elasticities across geographies, time scales, and economic scale display an extraordinary range of results. Labandeir, Labeaga, and López-Otero (2017) conduct a meta-analysis of nearly 1000 estimates of energy price elasticities for different products, sectors, and countries, finding average price elasticities of (total) energy demand to be -0.22 in the short term and -0.60 to -0.66 in the long term, with relatively wide ranges. These conclusions highlight that in general energy demand is relatively price inelastic, and estimates vary widely by scope and analytical time scale.

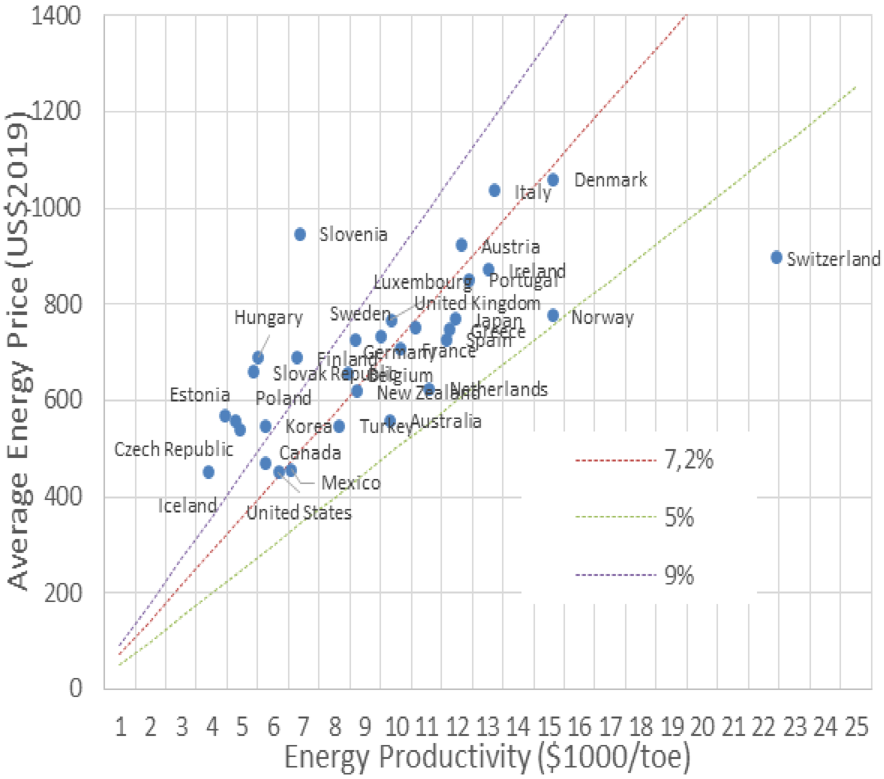
The combination of relatively high income elasticities and modest price elasticities, as usually measured, suggest strongly that global energy demand (and particularly that of middle-income countries) is likely to continue growing, notwithstanding efforts to enhance energy efficiency.

There are, however, caveats to this prediction. First, debate continues, derived from literature on the "Environmental Kuznets Curve" (EKC) as to whether CO_2 emissions at least (if not energy demand itself) tend to peak above a certain income level. The literature is now extensive, with a recent systematic review covering over 1600 articles and finding that "The majority of the studies have confirmed an inverted U-shaped EKC for both panel and time-series studies…the average turning point of the Kuznets curve is at 9,260 USD" (Naveed et al. 2022). This finding, however, masks wide variations across countries, studies, time periods, and methodologies, including the extent to which, for example, they take account of trade effects. Strengthening energy and environmental policies have played an important role in getting emissions on a declining course.

Also relevant—and still contentious—is evidence on the extent to which economies do adjust to price shocks given time. One recent study (Bashmakov et al. 2024) offers both evidence and some underlying theory to support the proposition of national "energy cost constancy" that countries with structurally higher energy prices do not end up paying more for their energy as a percentage of GDP —that higher energy prices are, ultimately, fully compensated by higher energy efficiency (figure 6 and box 4).

Figure 6. National energy cost shared (despite widely varying energy end-user prices) across OECD countries

*Energy prices versus energy productivity (average values for 1970–2019)**



Source: Bashmakov et al. 2024.

Note: OECD = Organisation for Economic Co-operation and Development. Toe = tonnes of oil equivalent

An extended and updated analysis suggests that most developed countries, over the decades since the first oil shocks, have spent about 7 percent of GDP on energy (end-use prices). This reflects the fact that countries with energy prices that are twice as high have emerged as roughly twice as productive in their use of energy, while the highest energy costs have occurred in those eastern European countries, which historically had very low energy prices, leaving them with profoundly energy-inefficient infrastructure and a serious adjustment challenge as they moved toward market prices. The authors suggest a more subtle interpretation than the apparent headline implication of price elasticities of "minus 1" (see box 4).

Box 4. The impact of energy prices on energy demand and costs

The seminal contribution by Bashmakov (2007) and subsequent literature (such as Bashmakov 2017) have argued that long-term energy cost-to-income ratios fall within a limited range, a hypothesis termed "energy cost constancy" [or constant "energy cost share" of income (ECS)]. Bashmakov et al. (2024) more extensively explore the applicability and drivers, referring to a sustainable range of energy costs, rather than a specific value. Instead of estimating energy demand price elasticities with limited scope (of time, country, or sector), they take a long-term and cross-country perspective—focusing on energy intensity (productivity) rather than energy demand; and on adjustments to large-scale energy price shocks, rather than estimation of elasticities in response to marginal price changes. They aim to explore the enduring impact of large-scale energy price variations on overall energy bills (on time scales of decades or longer), as a proportion of wealth, particularly at the national level.

Using a newly constructed dataset of national ECS covering 32 member-countries of the Organisation for

Economic Co-operation and Development (OECD), complemented by longer-term (72-year) data for the United States, Bashmakov et al. (2024) find that energy cost-to-income ratios across geographies lies within the range 4.2±0.8 percent relative to gross output, and 7.2±1.5 percent relative to GDP. If this finding from panel data across OECD countries is used to infer long-term time dynamics, ECS constancy would be logically equivalent to a very-long-term price-to-energy-intensity elasticity of -1. This implies that although price changes incur short-term costs, over the long term, there may be negligible ongoing costs associated with energy price rises as energy systems adapt, within a certain range. However, Bashmakov et al. (2024) argue that elasticities are not constant, as often assumed in economic applications of elasticities, but vary in a systematic way. When ECS is below the sustainable range, elasticity is low—close to zero—as many consumers neglect energy use entirely. When ECS exceeds the upper threshold, elasticity and responsiveness rises rapidly, through innovation, structural changes, and capital investments that accumulate over years to decades.

The authors conclude that energy systems are ultimately highly adaptive, and a key aspect of these adaptive processes is that when prices are high, energy systems act to restore overall energy costs to within the sustainable ECS range, while low prices induce inattention and growing wastage. They suggest that this asymmetric adaptive capacity is a result of dynamic phenomena of induced innovation embodied in capital. They offer theoretical explanations that draw on the Three Domains framework of behavioral, optimizing, and strategic investment economics (Grubb, Hourcade, and Neuhoff 2014; Grubb et al. 2023), as well as energy science studies that point logically to the same conclusion for multistage energy systems. Ultimately, they suggest that politically tenable levels of energy/carbon pricing need to be accompanied by timely complementary measures to improve energy/carbon intensity, so that prices and systemic efficiency (including distributional concerns) evolve together.

Source: Bashmakov et al. 2024.

Other studies evaluate the impact of energy price changes on other outcomes such as employment or productivity at the firm, sector, or economy level. André et al. (2023) explore the short- and medium-to-long term impacts of energy price changes on firms' productivity and associated dynamics in 21 countries between 1995 and 2020. They find that a 5 percent rise in energy prices reduces productivity by 0.4 percent one year later; however, taking a longer view, a shock corresponding with 10 percent energy price increase is associated with a 0.9 percent productivity *growth* four years later. They find productivity gains to be more pronounced in less energy-intensive sectors.

Dechezleprêtre, Nachtigall, and Stadler (2020) investigate the impact of energy prices on manufacturing employment at both the sector and firm level in OECD countries between 2000 and 2014. At the sector level, they find a small, negative relationship between prices and employment (price elasticity of employment = -0.07), with energy-intensive sectors being most affected. At the firm level, they find the opposite results—a small positive relationship, which they explain through an increased level of firm exit that allows surviving firms to expand, increasing firm-level employment.

D'Arcangelo, Pavan, and Calligaris (2022) explore the causal impact of the European Union Emissions Trading System (EU ETS) on Italian manufacturing firms' total output produced and input usage, utilizing total factor productivity (TFP), in particular, to determine whether EU ETS is merely increasing firms' costs or driving increased efficiency in production. The authors find a small negative impact of the EU ETS on TFP, though the effect is heterogenous across industries. The authors conclude that the affected firms have not faced sufficient incentives to stimulate structural production changes, and have instead responded with marginal adjustments, predominantly through fuel switching.

The broadest implication is that time and adjustment processes matter (as well as, of course, whether energy price increases are exogenous, directly affecting trade balances, or arise from domestic taxation). In the short term, price increases can be problematic, but the evidence suggests a large capacity to adjust over time, potentially with benefits.

3.2. Transition costs: modelling evidence

The modelling literatures have yielded contrasting results concerning transitional costs, in particular arising from carbon tax shocks, and these results are mostly dependent on the type of models employed. Major differences for policy can be found depending on whether the models rely on the assumption of general equilibrium and optimization (general equilibrium models), or whether they assume the economy to operate in out-of-equilibrium conditions (post-Keynesian econometrics and agent-based models).

The majority of the "integrated assessment models" (IAMs) used in the IPCC global assessment are, in one form or another, based on multi-period equilibrium or related representations with limited dynamics. Based on modelling studies accepted in the IPCC modelling database by 2021, the mean suggests that steep global emission reductions, consistent with the Paris goals over the decade to 2030, could reduce global GDP growth rates by about 0.1 percent/year to 0.2 percent/year (leading to GDP being about 1 percent to 2 percent lower than the reference projection by 2030), associated with a global carbon price mostly in the range \$80/tCO$_2$–\$200/tCO$_2$ (IPCC 2022b).[4]

Obviously, national impacts would depend upon many factors, and evaluation depends also on the type of model used, which this section briefly considers.

General equilibrium models

The use of the supply-led Environmental Stochastic General Equilibrium (E-DSGE) model suggests that the application of sudden carbon tax shocks at different levels in a supply chain can leading to cycles and overall long-term stability in the results. The implication for policy is that an optimal carbon tax can be found by learning where in the system the tax generates more instability and where it would ultimately generate negative impacts on the economy. When testing a carbon tax change from 5 percent to 10 percent, Chan and Zhao (2023) find that increasing the downstream carbon tax rate is the most effective way to reduce carbon emissions because downstream industries account for the largest share of output. Price increases reduce consumption, household welfare, wage rates, and output of the productive sector. Based on these assumptions, a carbon tax would always constrain the efficient operation of the economy.

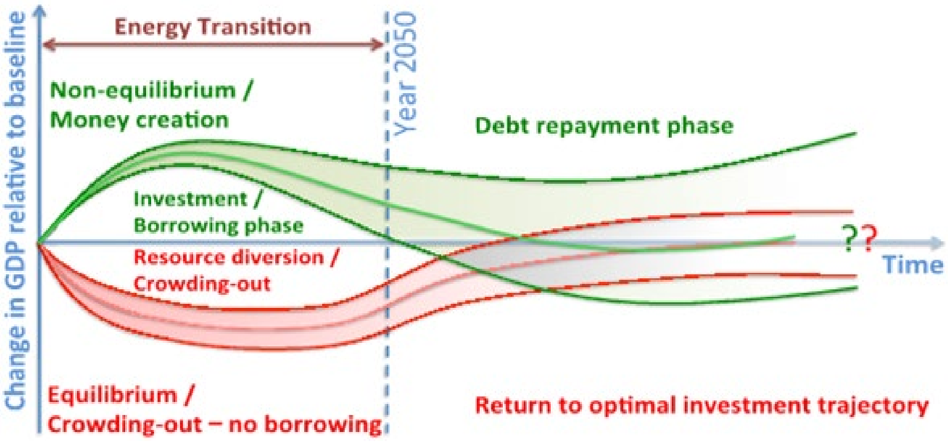
NiGEM (National Institute Global Econometric Model) is a global supply-led general equilibrium model that integrates econometric relationships linked to input output data with general equilibrium assumption to estimate long-term effects of policies for several countries (Hurst, Liadze, and Lisenkova 2014). It includes a fully functioning financial sector composed of credit creation and interest rates. Brand et al. (2023), Holland et al. (2021), and Liadze et al. (2023) use the global NiGEM model to compare carbon tax shocks for several countries, including EU countries, the United States, China, India, Japan, and Russian Federation. For example, Liadze et al. (2023) test a sudden increase in carbon tax that leads to increases in carbon prices between \$130 and \$800 per tonne of CO$_2$ by 2028. In the first two years of simulation, they find a disruptive effects of carbon taxes for all countries analyzed. These include negative effects on energy consumption (reductions of <5 percent for gas, 20 percent for oil, and more than 70 percent for coal, with an increase in renewables of almost 20 percent by 2028 in comparison to the base run); negative effects for investments across countries (from -6 percent to -3 percent, on average); lower GDP growth rate (from -3 percent to -0.5 percent, on average); a general increase in inflation (from 0.5 percent to 3 percent); a decline in the income tax rate due to the income from the carbon tax (up to –4 percent); a reduction in asset prices (up to 3 percent); and an increase in real interest rates (from 0.6 percent to 0.8 percent).

Out-of-equilibrium models

Post-Keynesian macroeconometrics

Unlike general equilibrium models, Post-Keynesian demand-side macroeconomic models with financial sectors and supply-side effects (see E3ME-FTT in Mercure et al. 2019; Mercure et al. 2018) allow the exploration of an economy that operates in persistent nonequilibrium. These models are suitable to explore persistent path dependency in the economy due to short- to medium-term economic disruptions that may lead to excess savings in some periods and overinvestment in others, in particular for settings with multiple policies. Mercure et al. (2018) show that while the carbon tax appears to stimulate most of the decarbonization, this is only a reflection of the dominance of power sector emissions. The absence of other policies would imply that the technology compositions in other sectors would not change substantially. Most importantly, the combined application of other policies such as feed-in-tariffs or public procurement within the renewable energy sector could stimulate the development of renewable energy technologies within the power sector, support innovation and lower costs, with the benefit of a renewed GDP growth stimulus. These results represent the opposite to the standard supply-led equilibrium models as a response to investment stimulus (the green-shaded part in Figure 7), as intended by "green-stimulus" packages (Balint et al. 2017; Mercure et al. 2019).

Figure 7. Two worlds—energy transition outcomes under alternative model assumptions (Keynesian versus general equilibrium)



Source: Mercure et al. 2019, as reproduced in IPCC 2022c, chapter 15, box 15.6.

Agent-based modelling

Due to wider assumptions on the heterogeneous structures of the models, the emergent field of agent-based modelling (ABM) suggests that a carbon tax shock can have multifaceted effects on the transition, depending on the strength of the shock, including generating financial instability and economic crisis (Lamperti et al. 2020; Lamperti and Roventini 2022). Berthold et al. (2023) apply ABM to EU countries to explore the sensitivity of carbon taxes set by policy makers while avoiding economic crises. This logic is also followed by the study for the International Monetary Fund (IMF) by Lamichhane (2023), which applies an ABM to study the transition effects of carbon taxation on the private sector in the United States. These ABM models are often referred to as "theoretical" models due to their difficulties in ingesting data from the micro-level foundations that they rely on, but claim that the behavior reproducibility tests based on more realistic assumptions in comparison to DSGEs provide strong evidence to validate model results.

Implications of model selection and state of the art

While models can be informed with data analysis and literature review, decisions relating to the underlying structure of the models may be more important. Models dominated by equilibrium assumptions will tend to conclude that carbon pricing is systematically the most efficient instrument to reduce emissions, but will have a negative short-term (at least) impact on the economy. Non-equilibrium econometric models can yield a wide range of results, but the long-term effects can be diametrically opposite, because green stimulus may also generate an expansion of the economy that offsets the negative effects of any carbon tax—the debate then shifting to what would be the most appropriate instruments or mix of instruments. Non-equilibrium agent-based models proposed might go even beyond that, exploring how stronger carbon taxes could influence not only the final results but also the instability of the economy toward a certain condition. The EEIST programme culminated with a Synthesis Report (EEIST 2024) that brought together insights from policy experience along with varied results from different models, and introduced a classification of model types appropriate to dynamic transitions analysis.

State of the art

The macroeconomic dimensions of transition costs, and their setting in the wider climate policy debate, have belatedly received more widespread attention, particularly following a brief by Pisani-Ferry (2021) that highlighted multiple dimensions of the transition dynamics, including finance/debt and risk of macroeconomic shocks. This important work ultimately led to a major report convened by *France Stratégie* (Pisani-Ferry and Mahfouz 2023) to the French Prime Minister, published in English in late 2023, which represents a major contribution to analysis of the macroeconomics.

The report recognized that tackling climate will involve "a transformation on a scale comparable to an industrial revolution. Yet unlike past industrial revolutions, this transformation will be global, it will be faster, and it will be primarily driven by public policies…" Concerning the economics of this transition in Europe, it concludes that:

- "There is no permanent trade-off between growth and climate. In the long term, redirecting technological progress could even lead to rates of green growth that are higher than past—or potential future—rates of fossil fuel-centered growth.
- …[but the EU] emissions-reduction targets by 2030...needs to achieve in 10 years what has barely been achieved in 30. This sudden acceleration implies that all sectors will have to contribute.
- .. In the coming years, emissions reductions will rely mainly on substituting capital for fossil fuels. [EU] decarbonization will require significant additional investment in the next decade (more than 2 percentage points of GDP in 2030, or €70 billion)... despite recent progress, we are not yet on the path to climate neutrality.
- Financing these investments will likely entail an economic and social cost between now and 2030, since they do not increase the growth potential. Of course, the extra investment will have a positive effect on growth by stimulating demand. But the transition away from fossil fuels will likely result in a temporary slowdown in productivity, estimated at one quarter of a percentage point per year…
- The transition will affect well-being in ways that are inadequately measured by conventional indicators such as GDP... The tools used to assess the economic implications of climate action in all these dimensions require further improvement.
- To be accepted politically and socially, the economic cost of the climate transition must be distributed fairly… Households and businesses will require substantial support from the public purse."

Some of the issues arising, including those concerning risks and opportunities, debt and finance, are discussed in the rest of this paper.

3.3. Time horizons, path dependence, and carbon lock-in

The co-evolution of infrastructure, technologies, institutions, industries, and social norms is strongly path dependent, whereby the decisions and events leading to a particular state of an economy shape the range of opportunities for further change. Possible future scenarios therefore diverge from one another as small differences in a given trajectory accumulate (Lyapunov 1992). In the context of climate change, path dependency of interwoven infrastructural and technological change can drive carbon lock-in (Unruh 2000), as well as corresponding renewables lock-out (Lehmann et al. 2012).

Path dependency is the natural consequence of several important dynamic characteristics. Inertia arises from the lifetime of capital stock such as power stations, roads, buildings and other urban forms, which are built to last for decades or longer. The resulting difficulty and cost (including stranded asset implications) associated with switching capital stock contributes to path dependency as adjustment costs increase with each new investment dependent on fossil fuel.

Processes of innovation also contribute to path dependency in energy systems by creating increasingly favorable conditions for further innovation. Looking at the US auto industry, Aghion et al. (2016) find that innovation activity in clean technologies is stimulated by firms' past exposure to innovation, both in terms of spillovers and their own past innovation activity (see also Barbieri 2015, 2016; Fredriksson and Sauquet 2017).

A wide range of additional, interrelated factors contribute to path dependency and resulting carbon lock-in; for a more detailed exploration see the systematic review by Seto et al. (2016), drawing out 12 contributions to carbon lock-in (which they refer to as a "special case" of path dependency).

The consequence of strong path dependency (and associated dynamic characteristics) is a techno-institutional system that necessitates significant upfront effort to overcome the aggregate impact of past events (inertia), but which is likely to become increasingly lower cost through the cumulative effects of innovation. When modelled against traditional economic counterparts, this leads to strikingly different policy implications, such as optimal upfront investment that may be substantially higher, as demonstrated by some developments in stylized model (see box 5).

Box 5. Modelling approaches to stranded capital and path dependence in integrated assessment models

The general abatement cost curve approach utilized in most stylized economic "cost-benefit" integrated assessment models (IAMs) (such as DICE and related models) assumes that the costs of cutting emissions at any given point in time is independent of the emissions levels in previous time periods. In principle, this implies that significant reductions could occur during any point in time regardless of historical action or system inertia; it is primarily net-present-value discounting that produces a smoother trajectory, not inertia.

The empirical and theoretical basis of induced innovation and path dependence have been well mapped. Most detailed "process-based" IAMs now have some representation of capital stock (see IPCC 2022c for review), and most impose assumed constraints on the pace of growth of new technologies. Others constrain the pace of growth and a few that relate costs to the pace of expansion (Bauer et al. 2016) assume quadratically increasing costs of renewable deployment with the rate of accelerating renewable growth.

Among these models, the IMACLIM-R hybrid general equilibrium model focuses on the long-distance race between technical change and inertia (Waisman et al. 2012). It finds two major implications for policy: high short-term carbon prices may involve high transitory losses (especially in developing countries); and the purely price-based response in some sectors may be insufficient to limit long-term losses, notably because of the very specific dynamics of the transportation sector, where energy prices are swamped by other determinants (such as real estate markets, political bargaining behind infrastructure policies, and just-in-time processes in the industry). They find that the bulk of the transition problem must be addressed through other policies (fiscal policies, differentiated tariffs, subsidies for energy efficiency in the residential sector, etc.) targeted to avoid the impact of high carbon prices on household energy bills, especially in developing countries.

The sensitivity of abatement costs to technological change parameters (see, for example, Golosov et al. 2014, as well as various IAM comparison studies) suggests that support to low-carbon technologies are appropriate measures to foster early investments and endogenous improvements of low-carbon technologies (Kverndokk and Rosendahl 2007) and reduce the need for high carbon prices (Bosetti et al. 2009).

While some more stylized models have introduced inertia (see, for example, Pottier et al. 2015; Vogt-Schilb, Meunier and Hallegatte 2018) and induced innovation (most notably, Acemoglu et al. 2012), few (if any) explicitly combine these to wider path dependence that may arise from wider institutional, social, and political factors beyond capital stock inertia and innovation. One highly stylized approach (Grubb et al. 2024) represents system-level adjustment costs through a characteristic adjustment time for the global energy system, finding that the implied combination of inertia, induced innovation and path dependence further amplifies the benefits of stronger (and by implication, diverse) early actions to change the course of energy sector developments globally.

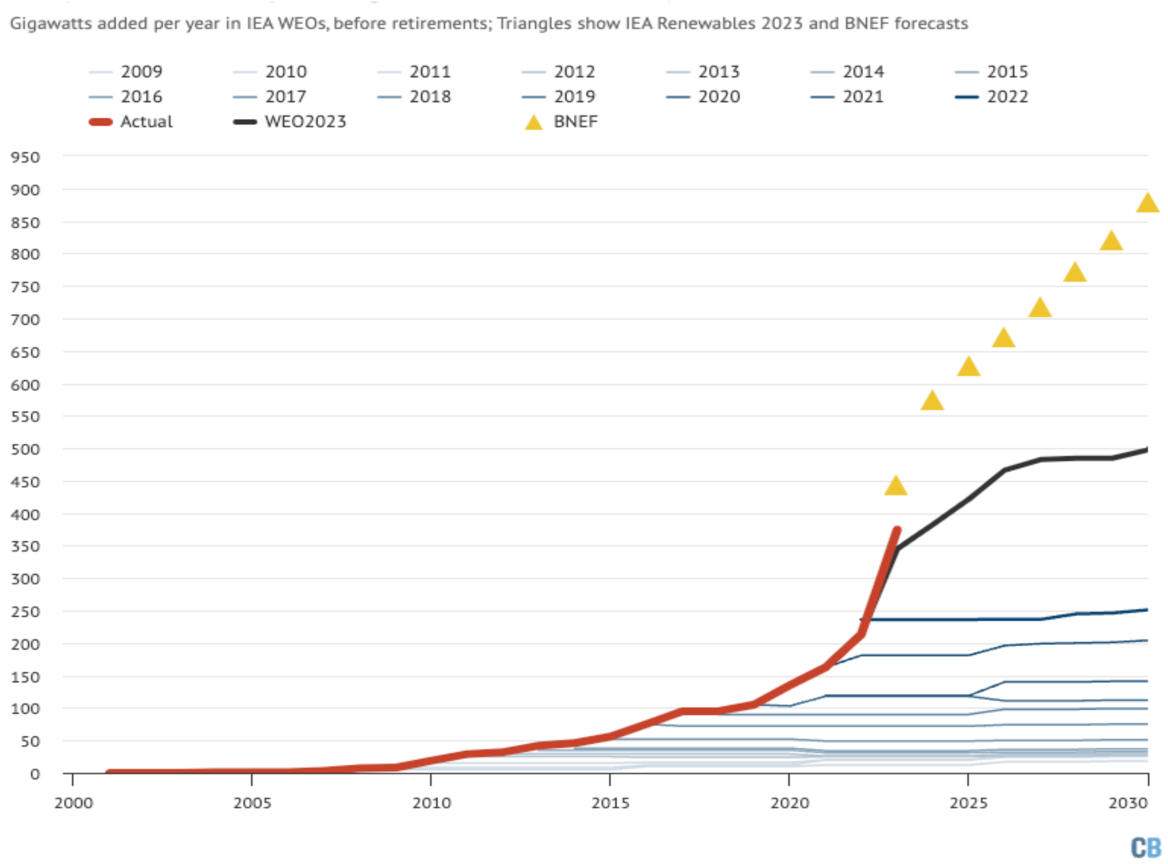
While most developed countries, after many years of struggle, are now on paths of substantial decarbonization, most middle-income countries, starting from lower per capita emissions, face crucial choices about the direction of their energy sectors this decade, which will have enduring consequences. These deep path dependencies, including capital stock and infrastructure, enhance the benefit of early action, and amplify the economic costs of deferral (for example, see ElSayed, Aghahosseini, and Breyer (2023), who demonstrate this in the context of the energy transition in the Arab Republic of Egypt).

3.4. Global scenarios and asset inconsistency risks

These more dynamic perspectives on the global energy transition, combined with the specific assessment of energy technologies in our accompanying paper on energy technologies and systems (Melekh, Grubb, and Dixon 2024) have many implications.

There are now innumerable scenarios for development of the global energy system. One limiting factor—for example, concerning many of the scenarios assessed in the IPCC mitigation report—is a tendency to use forward-looking, “global optimization” models, with limited ability to project the dynamics of diffusion and induced cost reductions observed. The “reference case” in many of these models can rapidly become outdated, while the “optimal policy scenarios” often imply discontinuous global policy change to meet climate goals. History suggests that neither have been particularly good representations of the actual dynamics of change. However, “linear” projection of even recent trends may lead people to extrapolate the continued growth of fossil fuels in ways that complete overlook the implications of exponential growth in low–carbon technologies. For example, Figure 8 shows successive revisions of projections by the International Energy Agency (IEA) of solar capacity installations, demonstrating the impact of inadequate understanding of these technology dynamics from forecasting analyses.

Figure 8. Solar capacity added around the world each year, 2002–23



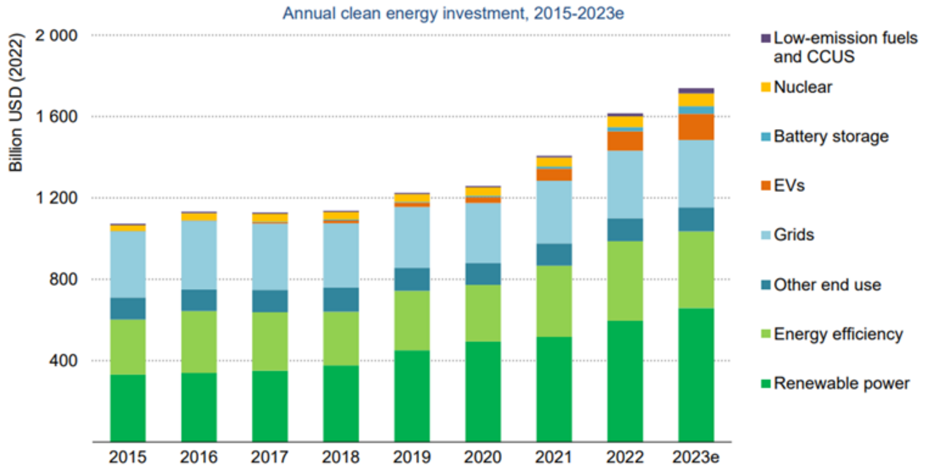
Sources: Carbon Brief analysis of International Energy Agency (IEA) World Energy Outlook (WEO) reports (2009–22) and Bloomberg New Energy Finance (BNEF) forecasts, updated with latest figures via personal communication. *Note:* Data are in terms of gross gigawatts. The red line shows historical trends of annual PV installation, along with projections from successive IEA World Energy Outlook published between 2009 and 2022. The orange triangles show BNEF data, the first showing the capacity actually installed in 2023, together with BNEF projections for the rest of the decade.

The IEA has continually underestimated the pace of growth and revised its estimates. Its Renewable Energy Market Update of June 2023 (IEA 2023c) estimated about 300 GW–320 GW PV installation for 2023; Bloomberg and other sources indicate the actual installations during 2023 totalled more than 400GW of new PV capacity (Figure 8). The total projected capacity by 2030 from the Bloomberg New Energy Finance (BNEF) estimates would have a very large impact on the operation of fossil fuel plans.[5]

Exponential growth is not confined to PV; since 2021, investment in electric vehicles (EVs) has more than doubled: global heat pump sales have also seen double-digit annual growth.

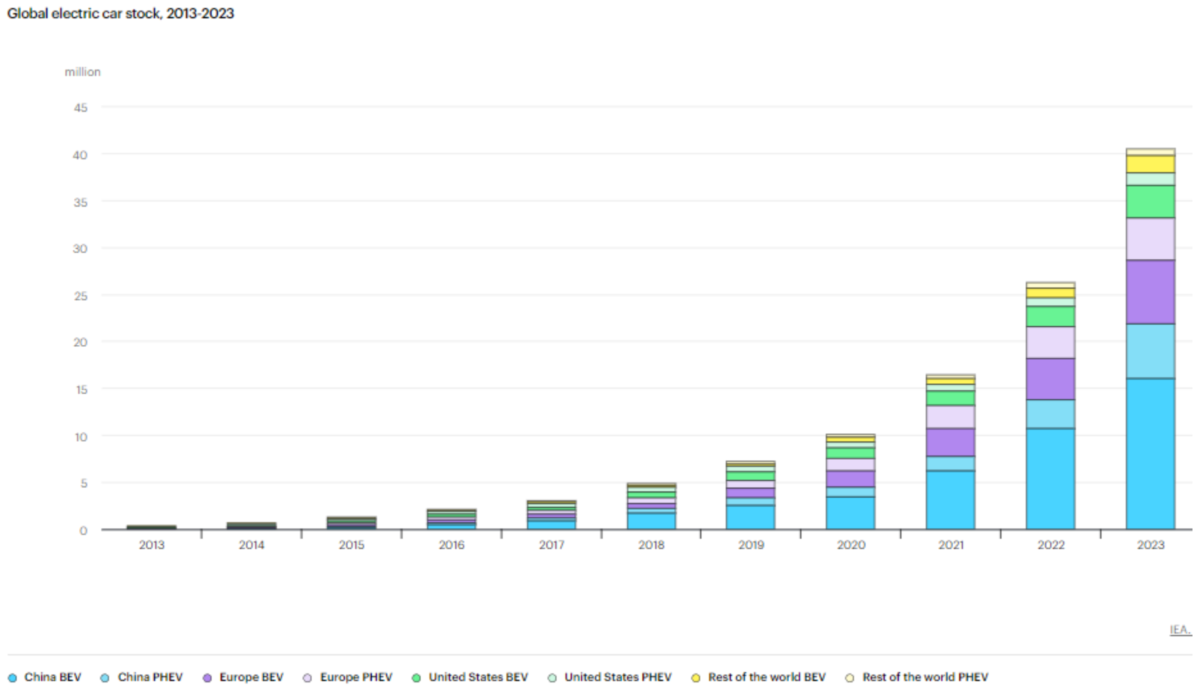
IEA energy investment data (IEA 2023a) show that 1.7 US dollars are now spent on clean energy for every US dollar spent on fossil fuels. This ratio has risen dramatically from 1.1:1 just five years ago. In 2023, low emissions power is anticipated to account for nearly 90 percent of total investment in electricity generation. Figures 9 and 10 present some key data on low-carbon power generation and EV investment, and corresponding changes in the EV global fleet.

Figure 9. Annual clean energy investment, 2015–2023e



Source: IEA 2023a.
Note: CCUS = carbon capture, utilization, and storage; EVs = electric vehicles; 2023e = estimated values for 2023.

Figure 10. Global trends in electric passenger light-duty vehicle markets, 2013–2023



Source: Global EV Outlook (IEA 2024).
Note: EV includes battery electric vehicles and plug-in hybrid passenger vehicles.

This rapidly scaling investment across low-carbon technologies aligns with expectations under S-curve technology diffusion (see section 2.4), suggesting that fossil fuel investments are likely to lose market share to renewables at a faster rate than predicted by traditional model technology forecasts.

Nonetheless, so far, the momentum behind clean energy investment is far from evenly distributed across countries (or sectors), with more than 90 percent of the increase in clean energy investment since 2021 driven by advanced economies and China. This reflects multiple obstacles for less developed countries, such as higher near-term returns on fossil fuel investments and increasing borrowing costs and debt burdens (IEA 2023b), discussed further in section 4.3.

Implications for stranded assets

One of the most sophisticated academic scenarios analyses of these dynamic issues combines a macroeconomic model with a suite of dynamic sector-technology models, to explore more realistically the implications of current trends and alterative pathways (Mercure, Salas, et al. 2021). The central finding is that, based on current dynamics, electricity systems dominated by renewables (especially PV) now seem almost inevitable, given the pace of change, the scale of cost reductions, and the widespread global resources. Contrary to investment risk valuations based on traditional forecasts that extrapolate historical trends more linearly and exhibit strong status quo bias, this dynamically sensitive approach implies that many new fossil fuel assets are highly likely to become stranded even without further climate policies (see box 6).

Box 6. Implications of observed dynamics and recent trends for projected energy and emissions

Using the E3ME-FTT-GENIE integrated framework (E3ME—energy-economy-environment macro econometric; FTT—future technology transformation; GENIE—grid enabled integrated Earth), Mercure, Salas, et al. (2021) construct four scenarios of future energy production, use, trade, and income, projecting associated changes in output, investment and employment and drawing out possible geopolitical incentives for each.

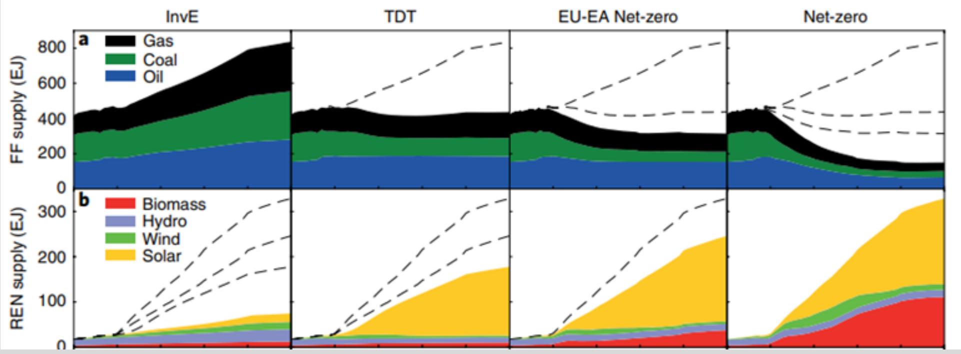
Their central "technology diffusion trajectory" (TDT) draws on observed trends in technology, energy markets, and macroeconomics to simulate a current pathway of technological and economic evolution, independent of new climate policies. This "dynamics extrapolated" scenario, with no new policies, holds global warming to 2.6°C, and:

- Coal use falls steeply to 2030 before flatlining, as market share is displaced by solar photovoltaics (PV).
- Other fossil fuels and nuclear peak by 2030.
- Oil experiences a gradual decline to 2060, influenced by rapid uptake of electric vehicles (EVs).

The balance of fossil fuel and renewable technology investments in this TDT scenario, in which demand projections incorporate key dynamic considerations (such as endogenous oil & gas price, induced innovation, and S-curve dynamics), contrast sharply with that of their "investment expectations" (InvE) scenario, drawn from the IEA World Energy Outlook (WEO)2019 "current policy scenario" (IEA 2019, 810), a world-view that arguably helped inform some of today's ongoing investments. In that scenario, coal and natural gas continue to dominate power generation, and continued gasoline and diesel use in transport increase oil demand—with projected near-term growth in solar, wind, EVs, and heat pumps much slower than already observed (by a wide margin). It ultimately leads to warming of 3.5°C, but the authors observe it is unlikely to materialize in practice, even under a no- further-policies scenario.

Two further scenarios are elaborated: "Net-zero CO_2 globally in 2050" ("Net-zero," consistent with 1.5°C warming); and "Net-zero in Europe and East Asia" ("EU-EA Net-zero," consistent with 2°C warming). If (increasingly legislative) international climate targets are to be met, investment must clearly swing much further toward renewables and away from fossil fuels than outlined in either of the no further policy scenarios, representing a significant deviation from the IEA WEO current policy scenario (Figure B6.1). As a result of learning-by-doing and diffusion feedback, solar PV becomes the cheapest form of energy generation by 2025–30 in all scenarios except InvE.

Figure B6.1. Fossil fuel (FF) and renewable (REN) energy supply under each scenario



Source: Adapted from Mercure, Salas, et al. 2021.

Note: The dotted lines reflect the totals of the other scenarios indicated, respectively, to the left (fossil fuels) and right (renewables). Note that overall global energy production required to meet demand (not shown) is substantially lower in the high renewables scenarios because of the intrinsically higher conversion efficiencies of renewables compared to the losses involved in fossil fuel combustion. EU-EA Net-zero = Net-zero in Europe and East Asia; InvE = investment expectations scenario; Net-zero = Net-zero CO_2 by 2050; TDT = technology diffusion trajectory scenario.

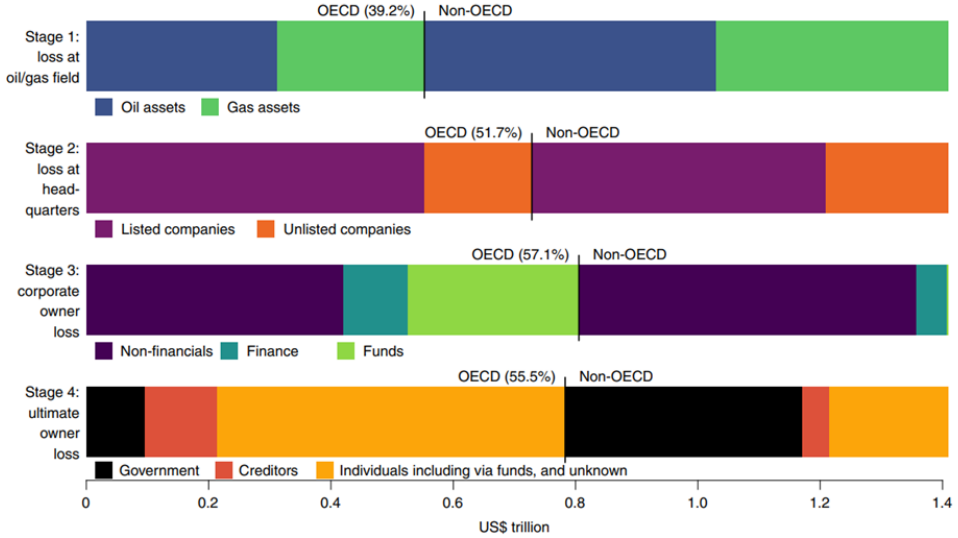
The conclusion that dynamic extrapolation of existing trends already implies a world heading for about 2.6°C is also comparable to the IEA's recent study (IEA 2023a), which concludes that we may already be on trajectory for as low as 2.4°C—with peaking of global demand of all fossil fuels this decade, due to the exponential expansion of low-carbon sources—a radical change from its earlier projections.

Such analysis has important implications for asset stranding, and therefore the real value of new fossil fuel investment. Continued installation of coal plants, and current valuation of fossil fuel assets and investment, would seem to reflect that this WEO 2019/Investor Expectations scenario is a world than many fossil fuel investors (and/or their governments) still believe in. However, such valuations—not only neglecting the Paris Agreement commitments, but based on traditional models that neglect transition dynamics—are likely to be inconsistent with the way global energy systems develop, and therefore underestimate stranded assets and overvalue new fossil fuel investment.

This is clear even from comparing the "investor expectations" with the "technology diffusion trajectory" scenarios, which assumes no new policies (see box 6). The disjoint is substantially bigger still for the scenario in which delivering the Net Zero commitments of the EU and East Asia are sufficient to bring the world to about 2°C; the authors find that the EU-EA Net-zero scenario would represent stranded fossil fuel assets between $7 trillion and $11 trillion against the InvE scenario, a finding largely corroborated by earlier geopolitical scenario analysis (see, for example, Bazilian et al. 2020).

Building on this analysis, Semieniuk et al. (2022) explore the distribution of ownership of transition risk associated with stranded fossil fuel assets, tracing potential losses from extraction sites through to corporate headquarters and their immediate shareholders, and on to the ultimate owners (governments and individual shareholders) for oil & gas extraction companies worldwide. Figure 11 shows how the estimated $1.4 trillion in discounted profit loss across the ownership chain from losses at direct extraction through to ultimate owners, broken down between OECD and non-OECD country groups, and major institutional categories.

Figure 4. Ownership chain of stranded assets by OECD/non-OECD countries and major institutional categories



Source: Semieniuk et al. 2022.
Note: Each bar represents $1.4 trillion in losses. OECD = Organisation for Economic Co-operation and Development.

The finding are entirely consistent with the IPCC Mitigation Report (IPCC 2022c), which warns of the increased risks of stranded assets, especially in developing countries, particularly for coal builds, which may appear low cost but face increasing business risks that are not well captured, and finds that the global value of stranded assets associated with warming of up to 2°C may be within the range of $1 trillion to $4 trillion, with the most immediate risk facing coal assets at risk of stranding before 2030.[6]

In short, the global energy transition is well under way in electricity, and is rapidly emerging in transport. This, as well as climate change itself, has profound implications for the choices facing middle-income countries, as discussed in the next section.

4. Response options

4.1. Overview

Middle-income countries span a huge diversity of situations. For those that are net exporters of fossil fuels, this can be a major source of revenue and foreign exchange (not withstanding cases of “resource curse”)—enhanced hugely by the energy crisis. Some others with fossil fuel resources hope to gain such benefits to help fund continued development. Others in turn suffer from the burden of energy import costs. Most have substantial renewable energy resources, some with potential to become renewable energy exporters. Almost all face the risk of accelerating climate change impacts.

All need also to consider their options in the light of two seismic shifts from the patterns of last century’s energy systems: the technical revolutions of renewables and electrification; and the growing urgency to mitigate climate change to meet the goals of the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement.

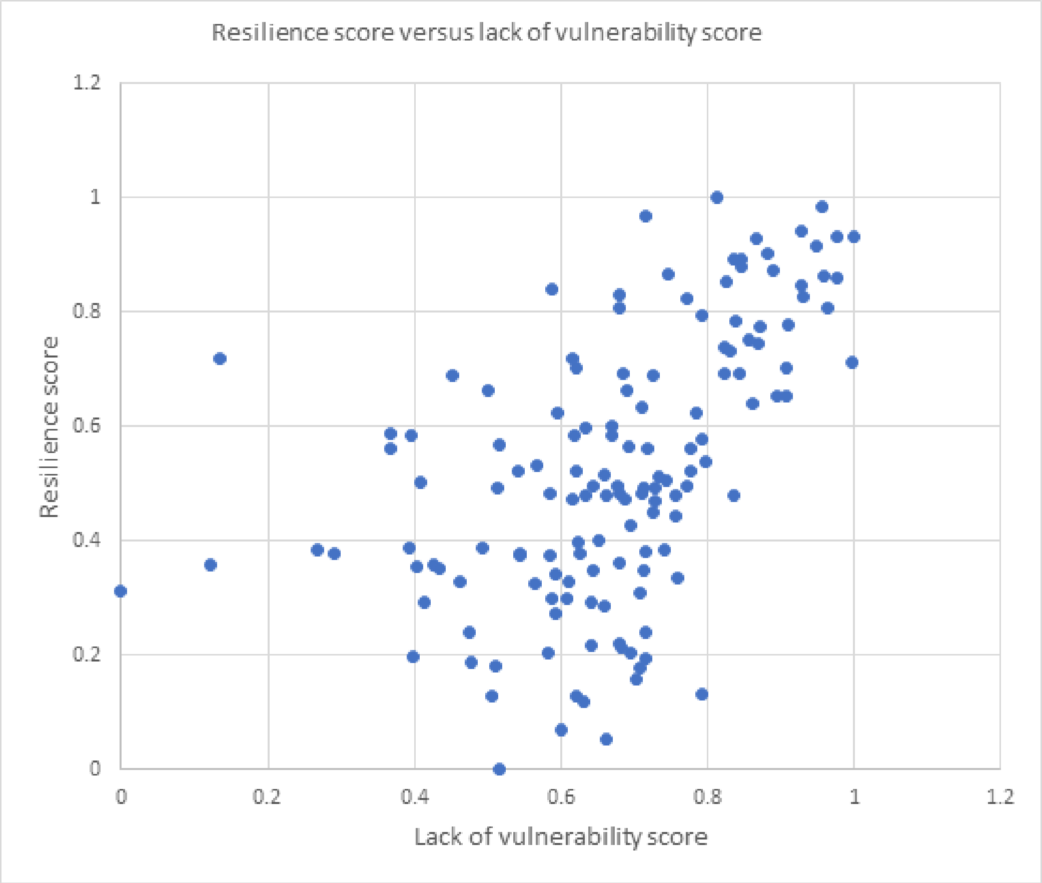
UNCTAD’s report, The State of Commodity Dependence, (UNCTAD 2023b) defines a country to be commodity-dependent if more than 60 percent of merchandise export value comes from commodities, noting that this brings an intrinsic vulnerability to commodity-related shocks and volatility. Even before the energy crisis, oil exports accounted for 30 percent of global commodity trade in value, with gas and coal at 5.3 percent and 2.2 percent respectively. Energy exports are particularly concentrated and important for a number of countries in Africa, the Middle East, and Central Asia, as well as Russia. Decarbonization obviously involves substantial challenges for such exporter regions, as also illustrated in the previous section.

Fossil fuel exports will be affected whatever a country does itself; the impacts will also depend on the wider resilience of the country, and its domestic response. Building upon the earlier study of the World Bank, *Diversification and Cooperation in a Decarbonizing World* (Peszko et al. 2020), figure 12 presents an updated indication of potential preparedness of countries in relation to indexes of both exposure and vulnerability.

Given this, responses must involve a sober assessment of national options in a rapidly evolving global technology and policy landscape, with respect to domestic resources and current and potential business growth areas, while endeavoring to enhance energy efficiency to the extent possible. Countries can either contribute to, or seek to resist, acceleration of the global energy transition. For growth to be sustained and sustainable, though, all these countries need to find ways to align economic and development aspirations with low-carbon growth.

Faced with an “externality” problem like climate change, the traditional economic prescription is to “internalize the externality” with a carbon price (along with “fixing” some market failures); and because it is a global problem, with a globally harmonized carbon price, reflecting the cost of global damages. This prescription is in fact inadequate in economic theory and inconsistent with social and political science, as observed in box 7.

Figure 5. Indications of resilience and lack of vulnerability to impacts of the low-carbon transition in 143 countries



Source: Angelova, Sciarra, and Ameli 2024, adapted and updated from Peszko et al. 2020.

Box 7. A broadened economic approach to policy packages

A carbon price—and preferably, a globally harmonized carbon price—has for many years been promoted in economics as the optimal response to climate change, but the issues in fact are far more complex. Theoretical limitations include that a carbon price on its own tends to be regressive, both domestically, and potentially even more so internationally, given the frequent higher dependence of developing countries on more carbon-intensive activities. Consequently, it has been observed for almost 30 years that a single global carbon price would only be welfare-maximizing in theory if there were sizeable international compensatory transfers (Chichilnisky and Heal 1994), which clearly are not forthcoming at the implied scale.

Moreover, the assumption that carbon pricing is the *most* efficient instrument, even in simple terms of maximizing aggregate GDP irrespective of distributional issues, hinges on very strong assumptions about the optimality of economies and decision making, and the ability of other policies to “fix market failures.” A recent paper in the *Oxford Review of Economic Studies* (Grubb et al. 2023), drawing upon an earlier book by Grubb, Hourcade, and Neuhoff (2014), articulates these caveats and complexities in terms of three distinct “domains” of socioeconomic decision making.

Behavioral economics has documented for decades systematic biases in human decision making, including persistent inattention to “incidental” costs, habituation, and aversion to change. In energy, these biases help to explain for example the persistent structural bias in favor of large-scale supply technologies and systems, instead of enhanced energy efficiency.

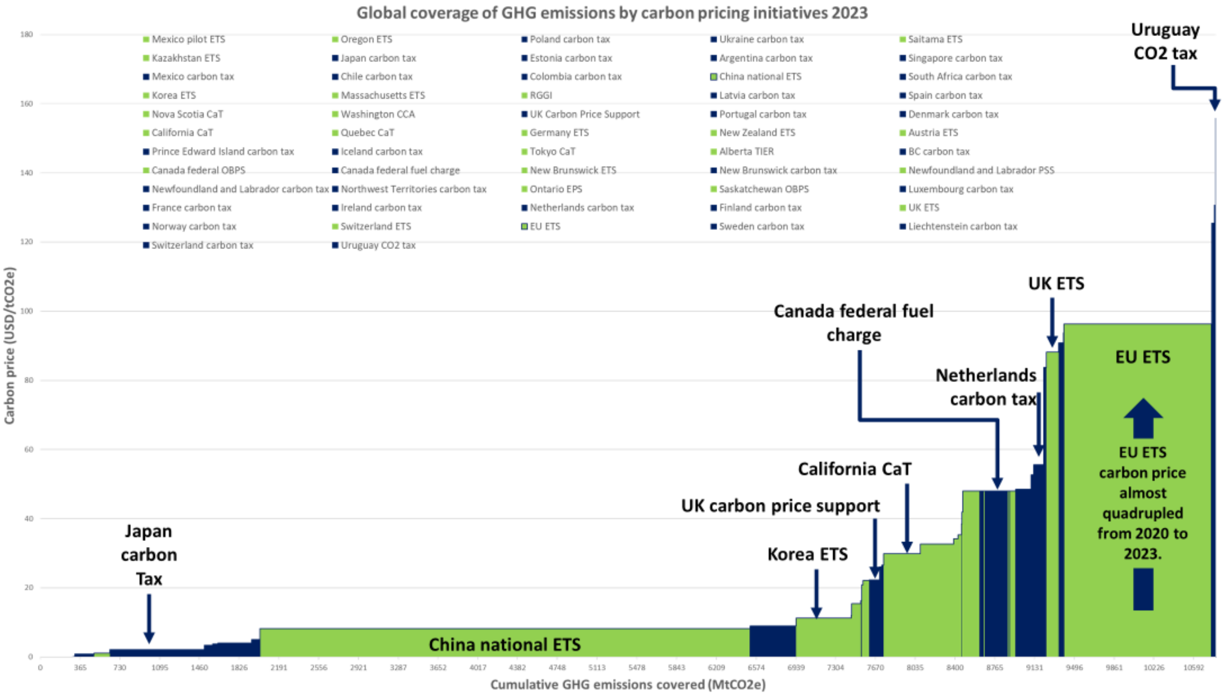
Specific market failures associated with innovation have long been recognized in economics (justifying, for example, public expenditure on research and development and patent protection), as well as the case for public provision of public goods like infrastructure. The phenomenon of path dependence has also been a subject of economic research for many years. The evidence from innovation studies, and from evolutionary economics theories (which also encompass evidence on processes of adoption and global diffusion), further highlight the extent to which carbon pricing and research and development (R&D) on their own cannot be expected to deliver an appropriate degree of innovation or pace of diffusion in response to a problem like climate change.

The *Oxford Review* paper explains how the approach is grounded in long-standing recognition of the appropriate boundaries of neoclassical economic theories, and argues that transforming energy systems and tackling climate change *necessitates* such a broader set of economic perspectives. This is because of the unprecedented scope of the problem in terms of the range of both social characteristics (from individual energy consumers to vast, complex, and international techno-economic supply chains) and temporal characteristics (from short-term consumer decisions to infrastructures and impacts spanning many decades).

None of this negates the relevance of energy and carbon prices as an important part of policy responses: if prices in an economy do not align with the strategic public objectives, including pricing of externalities, then everything else is likely to be harder.

These limitations and the political obstacles to the “classical” economic prescription of global carbon pricing are reflected in the limited progress to date. After three decades of economic advocacy, the use of carbon pricing remains very constrained, in both scope and price levels, as illustrated in Figure 13. With the advent of the Chinese emissions trading system in 2021, the global coverage has risen to about 31 percent of fossil fuel CO_2 emissions (about one-quarter of global GHG emissions). The European carbon price (EU ETS) price has also risen sharply in recent years following reforms (amplified by high gas prices in the energy crisis). Nevertheless, the carbon price in most systems, and the global average, remains far below recent estimates of the “social cost of carbon” at over well over \$100t/CO_2 (Rennert et al. 2022) or levels plausibly required for carbon pricing to be a major driver of global decarbonization (High Level Commission on Carbon Prices 2017; IPCC 2022c, chapter 3).

Figure 6. Greenhouse gas emissions covered by an explicit carbon pricing mechanism versus price level



Sources: Data from World Bank Carbon Pricing Dashboard and Coverage Data 2023 https://carbonpricingdashboard.worldbank.org/map_data, as presented in Grubb et al. 2023.
Note: The horizontal axis indicate emissions coverage of different carbon pricing systems. The vertical axis shows the price of those systems in 2022/23 (US dollars/tCO_2e). BC = British Columbia; CCA = (UK) Climate Change Agreement; CaT = cap and trade; ETS = emissions trading system; EU = European Union; GHG = greenhouse gas; OBPS = Output-Based Pricing System; PSS = Performance Standards System; RGGI = Regional Greenhouse Gas Initiative (United States); TIER = Technology Innovation and Emissions Reduction.

Consequently, several factors suggest a far more complex policy landscape in practice, of which we highlight three:

- The implications of broadened economic understanding of economic dynamics, including the role of innovation in growth and the economics of "Schumpeterian creative destruction" (Akcigit and Howitt 2014; Akcigit and Van Reenen 2023), as well as behavior and evolutionary economics (see box 7) with implications for complex interactions between market prices, the disposition of direct subsidies for both R&D, and deployment and diffusion (see also section 3);
- The specific situation of middle-income countries, which compared to developed countries may have fewer financial resources and less fully developed infrastructure, higher cost of capital, and deeper distributional concerns;
- The short-term distributional and macroeconomic impacts of carbon-price–led solutions, which while making an important contribution, may be even harder to implement in many developing countries.

The IPCC Mitigation Report notes, *"A systemic perspective on technological change can provide insights to policymakers supporting their selection of effective innovation policy instruments"* and highlights the potential for synergies in climate change and wider sustainable development responses. Specifically, the *"combination of scaled-up innovation investments with demand-pull interventions can achieve faster technology unit cost reductions and more rapid scale-up than either approach in isolation"* (all citations from IPCC 2022c, Technical Summary, drawing on the Innovation chapter 16).

Against this broad background, the discussion that follows suggests some key principles and options for policy, first at the national level, following by some observations for the international landscape.

4.2. Approaches to policy making and policy packages

There is growing concern that the inadequate pace and scale of policy responses to climate change reflects in part inappropriate decision-making processes (Farmer et al. 2015; Mercure et al. 2016; Mercure, Salas, et al. 2021). Traditional economic advice stresses the role of cost-benefit analysis of policy options, typically interpreted to mean a quantified comparison of options in terms of discounted net present value (which at national level may be at quite high discount rates).

Traditional appraisal methods focused on cost-benefit analysis and partial/general economic equilibrium analysis draw on conventional welfare economics, and are most appropriate concerning interventions that do not substantially alter the economic landscape; in which stakeholder interests are relatively homogenous or distributional impacts can be broadly neglected in favor of an aggregate efficiency goal; and in which costs and benefits of outcomes are known with reasonable confidence or quantifiable uncertainty, so as to ground calculations in "rational expectations." Stern, Stiglitz, and Taylor (2021) give the most trenchant critique of this approach.

In reality, the transition from high- to low-carbon energy systems involves pervasive and transformative change including nonmarginal elements (Fouquet 2016; IPCC 2018), highly heterogeneous interests (Geels, Berkhout, and van Vuuren 2016), and deep uncertainty regarding costs, benefits, and path dependence in the outcomes of policies (see, for example, Hughes, Strachan, and Gross 2013). Decisions that have proven pivotal for the energy transition so far have largely been driven by strategic choices and political factors—often despite, not because of, the predominant economic analysis and advice. As such, governments may need to consider decision-making tools that are broader and more suited to these conditions, as indicated briefly in box 8.

Box 8. Decision-evaluation approaches

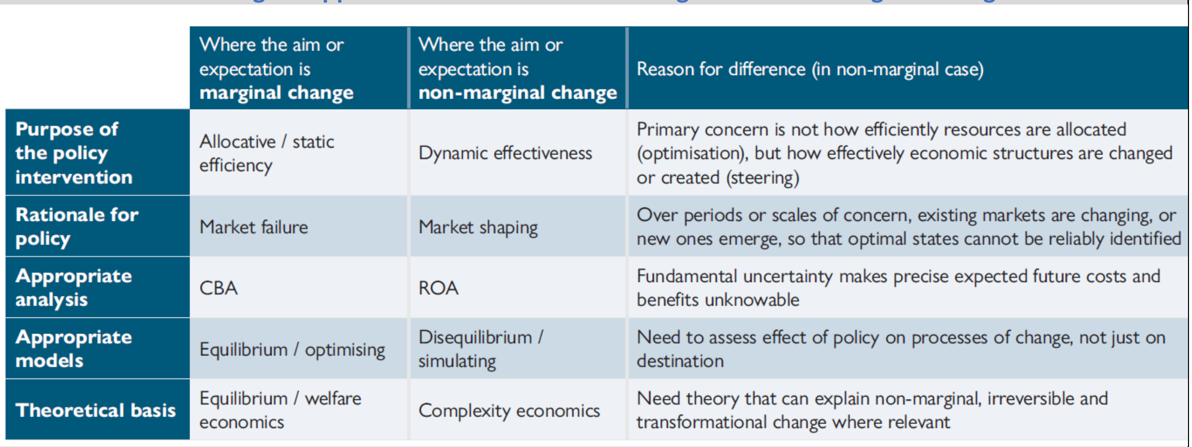
Given the deep complexities of climate change and energy transition, researchers have explored methodologies and approaches to support decision making under conditions of nonmarginal change, very heterogenous actors and interests, and deep uncertainty. Examples include the Robust Decision Making (RDM) approach (Marchau et al. 2019), as summarized alongside other approaches in the AR6 Working Group II report (IPCC 2022a, chapter 17, Cross-Chapter Box DEEP).

Mercure et al. (2021) draw on these approaches to develop a "Risk-Opportunity Analysis" (ROA) approach. Unlike other frameworks, however, ROA is intrinsically rooted in cost-benefit analysis (CBA), offering a generalization of its methodology while avoiding its most important flaws when applied to problems of transformational change. Key methodological divergences from the CBA approach include the following:

- The mapping of costs and benefits is expanded to include risks and opportunities, meaning that a much wider range of potential policy effects are captured, even when they cannot be robustly quantified.
- Dynamic processes of economic change are introduced into the analysis rather than just considering expected outcomes at one snapshot in time. This involves an interrogation of feedback processes and how they may be reduced or enhanced to improve policy outcomes, as well as the identification of "sensitive intervention points" where small actions can trigger large impacts.
- Different outcomes are assessed in their own right, instead of converting all outcomes into a single monetary metric. This improves the transparency and intentionality of weighing up various interests and avoids issues associated with masked value judgements, improving accountability of decision making.

Fuller methodological detail and theoretical underpinnings can be found in Mercure, Salas, et al. (2021) and summarized in research by the Economics of Energy Innovation and Systems Transition (EEIST) consortium (EEIST 2021), alongside examples of applications looking forward relating to electric vehicles and low-carbon steel. Table B8.1 summarizes key differences between the purpose and rationale for policy action when marginal or nonmarginal change is the objective or expectation, along with the appropriate assessment framework, their theoretical underpinnings, and analytical models.

Table B8.1. Methodological approaches in the context of marginal and nonmarginal change



	Where the aim or expectation is **marginal change**	Where the aim or expectation is **non-marginal change**	Reason for difference (in non-marginal case)
Purpose of the policy intervention	Allocative / static efficiency	Dynamic effectiveness	Primary concern is not how efficiently resources are allocated (optimisation), but how effectively economic structures are changed or created (steering)
Rationale for policy	Market failure	Market shaping	Over periods or scales of concern, existing markets are changing, or new ones emerge, so that optimal states cannot be reliably identified
Appropriate analysis	CBA	ROA	Fundamental uncertainty makes precise expected future costs and benefits unknowable
Appropriate models	Equilibrium / optimising	Disequilibrium / simulating	Need to assess effect of policy on processes of change, not just on destination
Theoretical basis	Equilibrium / welfare economics	Complexity economics	Need theory that can explain non-marginal, irreversible and transformational change where relevant

Sources: EEIST 2021, based on Mercure, Salas, et al. 2021.
Note: CBA = cost-benefit analysis; ROA = risk-opportunity analysis.

For middle-income countries, a key to national strategy is to recognize that new technologies involve new supply chains, with numerous components of varied complexity. For a few fundamental, highly advanced technologies, it may be hard for most middle-income countries to challenge the dominance of the major global centers of innovation in the United States, Europe, and (increasingly) China. But supply chains will involve a far wider range of component activities and capabilities, not all of them high-tech. Moreover, there are emerging technology areas that may involve limited “high-tech” capabilities, such as some of the wide range of storage technology options for the diversity of emerging storage needs, as outlined in our accompanying paper on energy technologies and systems (Melekh, Grubb, and Dixon 2024).

An UNCTAD report *Opening Green Windows* (UNCTAD 2023a) examines 17 “green frontier technologies,” noting their rapid growth and projecting that their market value could rise from $1.5 trillion in 2020 to $9.5 trillion in 2030. They suggest that “for developing countries and specific renewable energy products, the rapidly changing technological scene offers green windows of opportunity.” This will involve “switching to products that are more complex, have greater value-added, and lower carbon footprints…”, in part implying “green industrial policy.” To an extent, this contrasts with traditional economic advice, which supports “horizontal” policies to promote innovation but has been wary of more targeted, sector-specific policies. It does, however, reflect a wider concern about the persistent tendency of developing countries to lag behind the technology frontier, and consequently, also to struggle to reap the full benefits of innovation—the “innovation paradox” noted by the World Bank, because in principle these countries have more to gain (Cirera and Maloney 2017).

Faced with the more nuanced understanding of the economic issues, a report by the research consortium Economics of Energy Innovation and Systems Transition (EEIST) suggests five principles for policy design in the energy transition (EEIST 2022):[7]

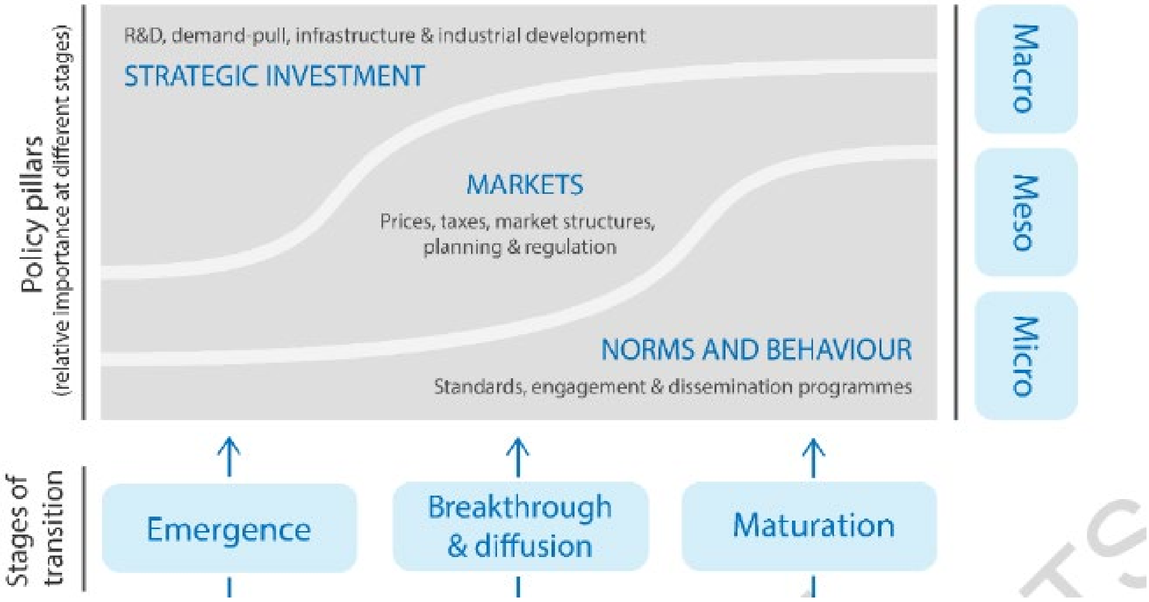
- *Technology choices need to be made.* In a context of innovation and structural change, policies will almost always advantage some technologies more than others. It is better to choose deliberately rather than accidentally, supporting innovation in low-carbon directions. Some policies intended to be neutral can have a bias toward incumbents, and toward incremental change.
- *Invest and regulate to bring down costs.* Well-designed investment and regulation policies can bring down the cost of clean technologies by creating a "demand pull" for innovation that complements the "supply push" of research, development, and demonstration, strengthening learning-by-doing feedback loops in technology development, deployment, and diffusion.
- *Actively manage risks to crowd in investment. Low-*carbon transitions involve many sources of uncertainty. Efforts to reduce the risks of private investment in clean technologies, including public finance acting as a lead investor, can reduce technology risk and financing costs and greatly increase rates of investment and deployment.
- *Target tipping points.* Well-targeted interventions can activate tipping points in technology competitiveness, consumer preference, investor confidence, or social support for transitions, where a small input leads to a large change. This can inform the targeting and level of subsidies and taxes, as well as the stringency of regulations.
- *Combine policies for better outcomes.* A combination of policies will be needed to drive each low-carbon transition. Because the effect of each policy depends on its interactions with others, assessing policies individually can be misleading. Assessing policies as a package can identify those that are mutually reinforcing, generating outcomes "greater than the sum of the parts."

Concerning the last of these principles in particular, in much of economics the idea of "policy packages" is viewed with caution, as risking duplication and overlap, except concerning policies that are targeted at fixing specifically identified market failures. This view contrasts sharply with approaches for *mission-oriented* innovation and *market shaping* policies (Mazzucato 2015, 2016).

One way of understanding and organizing the potential complementarity of different policies stems from the economics framing of different domains of decision making. The book *Planetary Economics* (Grubb, Hourcade, and Neuhoff 2014) articulates an intrinsic complementary of policies targeted at actors with different horizons, decision-making processes, and positions in relation to the evolution of the technology frontier. This view leads to a "three pillars" approach to policy making for innovation and transition, illustrated in Figure 14:

- *Emergence.* At the "emergence" stage, some element of strategic investment is needed to establish a market and drive adoption by actors ahead of the current best-practice frontier within a given context, perhaps initially for niche applications. These investments stimulate various forms of learning and initial economies of scale to help bring down technology costs and stimulate timely investment in associated infrastructures of various kinds, enabling further subsequent diffusion.
- *Breakthrough and diffusion.* Once innovations have moved beyond emergence and into breakthrough and diffusion stages, markets play a critical role in influencing uptake, including through pricing instruments that tilt economic incentives in favor of the new technology, accelerating the rate of deployment and diffusion and associated cost reductions.
- *Maturation.* However, varied barriers to uptake—behavioral and structural—can inhibit widespread adoption. These barriers may be more influenced by norms and behavioral processes than overt economic incentives. To remove barriers, policies of standards and engagement may be essential for the technology and associated markets to mature.

Figure 7. The evolution of complementary policies in the course of transition



Source: As presented in IPCC 2022c, chapter 1 and Technical Summary.

Recent development of this work (Grubb et al. 2023) argues that this approach cannot meaningfully be reduced to a simple set of "market failures," and articulates more fully the ways in which policies in one pillar may support development of other pillars. Competitive markets can facilitate new entry and innovation, and energy/carbon pricing has a clear role to encourage the adoption and development of "low-hanging fruit"—but transition policy toward net-zero needs to actively enhance adoption (especially for end-use efficiency) and accelerate it, encouraging "new fruit to grow on other branches," while recognizing that we must "eventually pick all of the apples on the tree" (Patt and Lilliestam 2018).

As also suggested by the history of energy subsidy reform and carbon pricing systems in different parts of the world, markets and appropriate pricing will themselves, inevitably, evolve. Policies to enhance energy efficiency and to lower carbon intensity, and expand clean technologies and associated industries, will themselves all also enhance the political space and impact of such market evolution, as well as helping to avoid the costs and risks of carbon lock-in and stranded assets.

4.3. International dimensions and finance

Given that climate change is a global problem that needs to be addressed in a world of extensive trade and multinational companies, in the context of widely varied levels of economic development, international cooperation is essential to achieve effective responses. As noted, the traditional economic prescription of a global carbon price is in reality inappropriate and infeasible, and does not take adequate account of the opportunities afforded by the developments in technology or broader economic sciences of behavior and innovation.

From the standpoint purely of economics, Acemoglu, Aghion, and Hémous (2014) provide a useful archetype of international cooperation taking account of directed technical change, noting the double-edged nature of international trade in a North-South model. This finds that innovation led by "the North" could generate global solutions if low-carbon innovations are "imitated" globally, but that trade could undermine this if "the South" specialized in incumbent and carbon-intensive technologies, which are traded and undercut cleaner technologies.

This highly stylized approach neglects financial dimensions and many nuances. The IPCC chapter on international cooperation (IPCC 2022c, chapter 14) gives a broad overview of literature in the context of the international negotiating processes. As yet, however, there is no remotely comprehensive theory of international cooperation that takes into account induced innovation and path dependence in energy systems in an unequal world. This concluding section merely offers three broad observations relating to trade, finance, and the nature of international cooperation in this more complex context.

Trade

Trade has been vital to international economic development. Induced innovation and the wider "third domain" economic processes involved in economic transformation imply some potential areas of tension, as noted by the Acemoglu, Aghion, and Hémous (2014) study. There is an essential role for public funding to support emerging low-carbon industries, but there is also a clear benefit from globalized markets to enhance scale economies, supply chain specialization, and accelerated diffusion. This could imply a case to review the World Trade Organization (WTO) Agreement on Subsidies and Countervailing Measures with respect to low-carbon support, and perhaps wider aspects of "global public goods" (Jain et al. 2024).

In contrast, it may be harder to justify local content requirements, which—notwithstanding their political appeal in both developed and developing countries—drive up the costs of low-carbon technologies and inhibit the globalization of production chains that have played such an important role in the renewables revolution (see, for example, Bazilian, Cuming, and Kenyon 2020).

In a world of international trade, moreover, more attention could be given to consumption-based policies. These could take the form of standards on "embodied carbon" in products (Gerres et al. 2021), for example in building materials; or consumption-based carbon pricing. In a pure form, either involves tracing emissions through the supply chain.

Carbon border adjustments, which have been extensively debated (see, for example, Böhringer et al. 2022; Durán 2023; Mehling et al. 2019), offer a form of consumption-based pricing. If applied in a nondiscriminatory way, this approach reflects a principle that consumers in countries with carbon prices should pay for the embodied emissions wherever these occurred, as a way also to "level the playing field," prevent carbon leakage, and reward lower-carbon production elsewhere. Inevitably, such consumer-based pricing would still have differential impacts, reflecting the carbon-intensity of production (which indeed is part of the rationale, given the associated environmental damages). Das et al. (2019) provide a detailed analysis of the legal issues; a broader review of options, including novel policy approaches to the problem, is reviewed by Grubb et al. (2022).

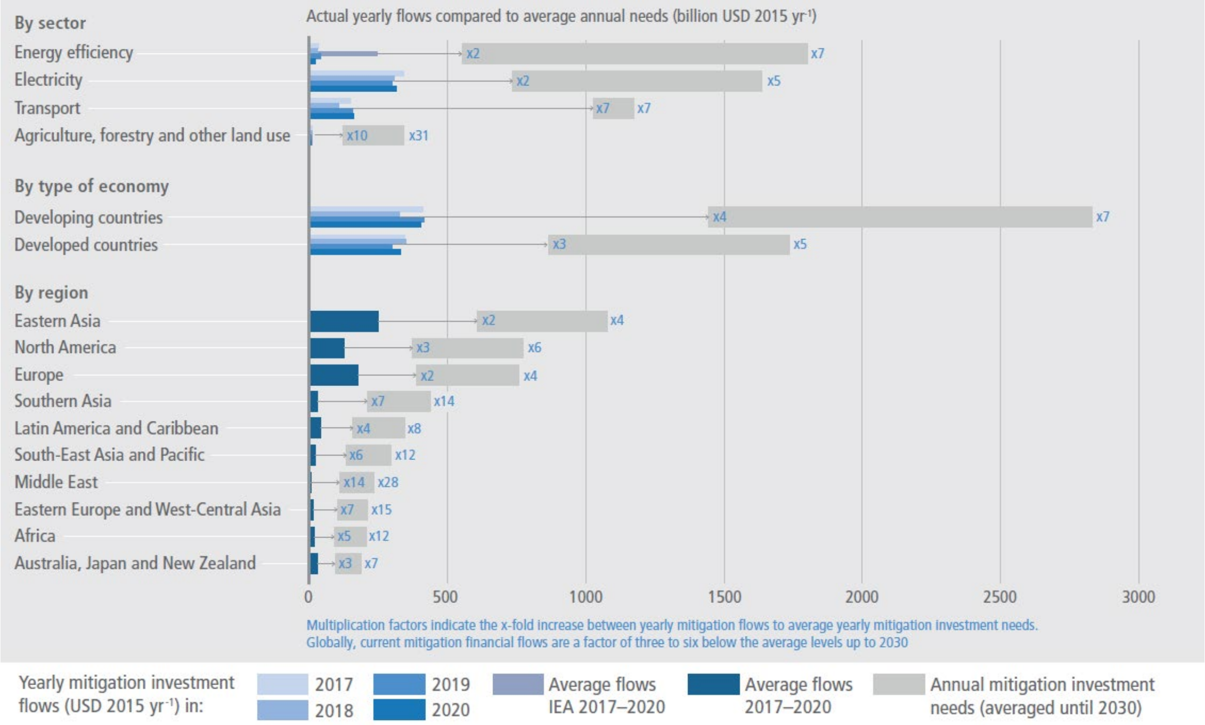
Finance

Meeting the Paris goals will require far greater financial flows, both for adaptation and emissions mitigation. One long-standing source of debate and friction concerns the "$100 billion" goal for North-South finance, which notwithstanding definitional debates, clearly had not been met by the target date of 2020.

The Paris Agreement also established as one of its three primary aims to "Make finance flows consistent with a pathway toward low greenhouse gas emissions and climate-resilient development …", which is an even larger agenda. Figure 15 illustrates the IPCC's estimates of mitigation investment needs, with a range of $2.5 trillion to $5 trillion per year in capital investment/($1.5 trillion to $3 trillion in non-OECD countries—3 to 6 times the current rate) needed over this decade. The Independent

High-Level Expert Group on Climate Finance pinpoints the needs of developing countries outside of China at $2 trillion to $2.8 trillion annually, of which at least $1 trillion a year would need to be from international investment.

Figure 8. Low-carbon investment by region, recent and projected average annual needs to 2030



Source: IPCC 2022c, Technical Summary and chapter 15.
Note: IEA = International Energy Agency.

Private investment is essential to this goal, but as noted, in many lower-middle-income countries this is inhibited by the risks potential investors perceive (as well as other potential barriers). As noted in our accompanying paper on energy technologies and systems (Melekh, Grubb, and Dixon 2024), the well-known trade-off between perceived risks and rewards then results in a much higher cost of capital for investment in low-carbon assets, which have costs concentrated in capital, with very low operating costs. This can as much as double the cost of renewable energy investments.

Consequently, analysts increasingly emphasis the huge leverage that could be obtained if public money is used to underwrite the risks of low-carbon investment, an opportunity noted in the IPCC finance chapter (IPCC 2022c, chapter 15). Hourcade, Dasgupta, and Ghersi (2021) estimate that a given amount of such underwriting could leverage 8 to 16 times as much private investment in low-carbon assets.

There are important debates about the kind of risks involved. A recent influential paper by Prof Avinash Persaud (2023) argues that the risks are dominated by exchange-rate risks, given that most renewables generate for local supplies in local currency, unlike oil, which can be largely sold in dollars for international markets. International investors may also use exchange rates as a proxy for wider macroeconomic risks.

There are, however, many other sources of perceived risk—and strong evidence of path dependence in financial systems themselves. Big investors have extensive established network relations with fossil fuel markets, and tend to be more wary of new technologies and new types of on-the-ground or smaller-scale investments. ‘Imperfections’ in finance that seem hard to explain rationally have been well traced for many years in the finance literatures, including behavioral finance at many levels.[8]

It is widely acknowledged that there is adequate private capital in the world to fund the global transition, and the factors outlined suggests that there should not be any insuperable obstacles to securing finance to greatly broaden and accelerate the global energy transition. Public underwriting of low carbon investment may in part help to compensate for the intrinsic bias toward the status quo of fossil fuel investment in both private and state-owned enterprises.

The differing circumstances between developed and many developing countries in part help to explain an apparent disjuncture in the IPCC’s Mitigation Assessment (2022c) between the top-down global modelling of costs, and ‘bottom-up’ sectoral/technology analysis. The latter finds that “many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030,” and “Large contributions with costs less than USD20/tCO_2 come from solar and wind energy, energy efficiency improvements, reduced conversion of natural ecosystems, and CH_4 emissions reductions (coal mining, oil and gas, waste).” The accompanying figure (IPCC 2022b, figure SPM.7) suggests more than 10GtCO_2e in emission reductions, with net cost savings compared to the reference fossil-fuel-led trajectory.

To the extent that this difference reflects the higher cost of capital in developing countries, it amounts to a “climate investment trap” (Ameli et al. 2021). This suggests that a combination of domestic and international policies to reduce the risks and costs of clean technology deployment globally would have potential not only to address concerns about international equity, but could accelerate the transition globally far more efficiently than relying primarily on global carbon pricing.

In addition to the recent focus on currency risk, contributions to the wider debate on risk underwriting for low-carbon investment include International Solar Alliance (ISA) proposals for a Common Risk Mitigation Mechanism (CEEW et al. 2017), and a Global Credit Guarantee Facility (Gautam, Purkayastha, and Widge 2023).

It would, however, require political will to overcome the resistance of incumbent industries, to tackle both real and perceived risks, and to establish the requisite financial and political structures, domestically and internationally, to realize the opportunities.

5. Conclusion

It is well established that reducing structural inefficiencies and innovation are important components of economic growth. So is access to cheap primary energy. The revolution in renewable energy and battery technologies (and consequently, electric transport) offers the potential for low-carbon to be the bedrock of the cheapest energy and transport in history—if the capital is available at low interest rates, and accelerated investment in low-carbon energy goes along with appropriate backup and/or adequate grids in the course of wider electrification, including accelerated access.

This paper has explained why this technology revolution has involved strong government action acting in concert with private investment, in part associated with building up markets to facility learning-by-doing, scale economics, and supply chain development. It has also traced various obstacles to accelerating and globalizing the transition, which indeed have varied implications for different middle-income countries, depending on their capabilities and resource endowments.

Strong path dependencies and incumbent interests in energy systems complicate the transition, and continued carbon-intensive investment creates risks of "carbon lock-in" that would either make it impossible to achieve the goals of the Paris Agreement or result in large-scale stranding/write-down of carbon-intensive assets. However, in combination with the much higher cost of capital in many lower-middle-income countries, these factors currently risk making this the "path of least resistance."

All these obstacles can be overcome. This would require middle-income countries to identify areas of opportunity in the transition and to adopt policy packages that help them diversify away from continued dependence on fossil fuels, by engaging earlier and more strongly in the supply chains and opportunities afforded by the global transition. It would also require international cooperation to support a rapid increase in international investment.

The risk of failing to do so is not only higher rates and degrees of climate change, breaching the Paris Goals and risking larger-scale climatic instabilities. It would also amplify the uncertainties and risks facing investors, and the valuation of both capital assets and energy resources, likely enhancing energy volatility. The rewards of stronger action are not only environmental, but offer the prospect of more stable and sustainable economic development, in the most literal senses of the words.

Notes

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[1] This paper uses the term "experience curves" because the relationship embodies issues of scale economies, and supply chain development, for example, in additional to learning. However, in common with the literature, this discussion retains the term "learning rates" to describe the associated numerical parameter. The systematic review (Grubb et al. 2021) distinguishes between the terms "deployment"—the earlier and more policy-driven phase when technology costs are still significantly higher than incumbents (so purely market-driven feedback to increased deployment is weak)—and "diffusion," which takes place once a technology is largely cost-competitive, expanding through self-sustaining market forces.

[2] Across the sectors, the estimated potential to cut emissions at "costs lower than the reference case" totals about 10GtCO_2/yr by 2030, about 10 percent of global GHG emissions. Such estimates remain controversial, in part because of course they depend on the definition of the "reference case" and how this represents the dynamics of uptake of technologies that have become competitive, at least in some regions.

[3] As also cited in the IPCC Mitigation Report (IPCC 2022c).

[4] Scenarios C1–C3 can be broadly interpreted as global scenarios consistent with the Paris range of 1.5°C to < 2°C warming. These involve global GHG emissions reducing by about 30 percent to 50 percent below 2019 levels by 2030 (IPCC 2022b, SPMFigure 4). Most of these models are indexed by a global carbon price, assumed equal to global marginal cost: the corresponding carbon prices are given in IPCC (2022c), chapter 3, figures 3.22a and 3.23a; figure 3.34 (panel B) indicates corresponding GDP impacts.

[5] A minor difference between the data sources is that BNEF data measure the output capacity of the panels (Direct Current), whereas IEA reported (at least until 2023) the capacity of the invertors for Alternating Current generation (which is sometimes less). Cumulative PV installed capacity by the end of 2023 was well over 600GW. The total global installed electricity generation capacity was about 12,000 GW. The BNEF projections suggest that by 2030, the installed PV total would rise to about 7000GW (author calculations from the BNEF data). Note that this would have a significantly lower average capacity factor than fossil fuels (or wind), but it would still imply a major impact on the operation of the fossil fuel power stock.

[6] IPCC (2022b) Summary for Policymakers, and IPCC (2022c), chapter 6. The IPCC Report also finds that "Without early retirements, or reductions in utilization, the current fossil infrastructure will emit more GHGs than is compatible with limiting warming to 1.5°C {2.7}. Including the pipeline of planned investments would push these future emissions into the uncertainty range of 2°C carbon budgets {2.7}. Continuing to build new coal-fired power plants and other fossil infrastructure will increase future transition costs and may jeopardize efforts to limit warming to 2°C (>67 percent) or 1.5°C with no or limited overshoot. One study has estimated that $11.8 trillion in current assets will need to be stranded by 2050 for a 2°C world; further delaying action for another 10

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years would result in an additional USD7.7 trillion in stranded assets by 2050. {15.5.2} Experience from past stranding indicates that compensation for the devaluation costs of private-sector stakeholders by the public sector is common. Limiting new investments in fossil technologies hence also reduces public finance risks in the long term. {15.6.3}" (IPCC 2022c; Technical Summary, Box TS.8 Stranded Assets).

[7] The report also include five other principles, for policy appraisal. See also Peñasco, Anadón, and Verdolini (2021).

[8] Wikipedia gives a useful overview of behavioral finance, from roots over a century ago to recent contributions of behavioral economics, and specific contributions on finance including from Nobel Laureate Robert Schiller, among others. In addition to the well-known risk-aversion, the (long) list of characteristics includes the role of familiarity, present/recency bias, herd behavior, and status quo bias.

References

Acemoglu, Daron. 2002. "Directed Technical Change." *Review of Economic Studies* 69 (4): 781–809.

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. 2012. "The Environment and Directed Technical Change." *American Economic Review* 102 (1): 131–66.

Acemoglu, Daron, Philippe Aghion, and David Hémous. 2014. "The Environment and Directed Technical Change in a North–South Model." *Oxford Review of Economic Policy* 30 (3): 513–30.

Acemoglu, Daron, Ufuk Akcigit, Douglas Hanley, and William Kerr. 2016. "Transition to Clean Technology." *Journal of Political Economy* 124 (1).

Aghion, Philippe, Antoine Dechezleprêtre, David Hémous, Ralf Martin, and John Van Reenen. 2016. "Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry." *Journal of Political Economy* 124 (1): 1–51.

Aghion, Philippe, and Peter Howitt. 1998. *Endogenous Growth Theory*. Cambridge, MA: The MIT Press.

Akcigit, Ufuk, and Peter Howitt. 2014 "What Do We Learn from Schumpeterian Growth Theory?" *Handbook of Economic Growth*, vol. 2, 515–63. Elsevier.

Akcigit, Ufuk, and John Van Reenen, eds. 2023. *The Economics of Creative Destruction: New Research on Themes from Aghion and Howitt*. Cambridge, MA: Harvard University Press.

Ameli, Nadia, Oliver Dessens, Matthew Winning, Jennifer Cronin, Hugues Chenet, Paul Drummond, Alvaro Calzadilla, Gabrial Anandarajah, and Michael Grubb. 2021. "Higher Cost of Finance Exacerbates a Climate Investment Trap in Developing Economies." *Nature Communications* 12 (1): 4046.

Anadón, Laura Diaz, Erin Baker, and Valentina Bosetti. 2017. "Integrating Uncertainty into Public Energy Research and Development Decisions." *Nature Energy* 2 (5): 17071.

André, Chirstophe, Helia Costa, Lilas Demmou, and Fuido Franco. 2023. "Rising Energy Prices and Productivity: Short-Run Pain, Long-Term Gain?" OECD Economics Department Working Paper No. 1755, OECD Publishing, Paris.

Angelova, Denitsa, Carla Sciarra, and Nadia Ameli. 2024. "Measuring and Projecting Transition Risk and the Preparedness of Countries for a Low-Carbon Transition." UCL working paper, University College London.

Arrow, Kenneth J. 1962. "The Economic Implications of Learning by Doing." *Review of Economic Studies* 29 (3): 155–73.

Balint, Tomas, Francesco Lamperti, Antoine Mandel, Mauro Napoletano, Andrea Roventini, and Alessandro Sapio. 2017. "Complexity and the Economics of Climate Change: A Survey and a Look Forward." *Ecological Economics* 138: 252–265.

Barbieri, Nicolo. 2015. "Investigating the Impacts of Technological Position and European Environmental Regulation on Green Automotive Patent Activity." *Ecological Economics* 117 (September): 140–52.

Barbieri, Nicolo. 2016. "Fuel Prices and the Invention Crowding Out Effect: Releasing the Automotive Industry from Its Dependence on Fossil Fuel." *Technological Forecasting and Social Change* 111 (C): 222–34.

Bashmakov, Igor. 2007. "Three Laws of Energy Transitions." *Energy Policy* 35 (7): 3583–94.

Bashmakov, Igor. 2017. "The First Law of Energy Transitions and Carbon Pricing." *International Journal of Energy, Environment and Economics* 25 (1): 1–38.

Bashmakov, Igor, Michael Grubb, Paul Drummond, Robert Lowe, Anna Myshak, and Ben Hinder. 2024. "'Minus 1' and Energy Costs Constants: Empirical Evidence, Theory and Policy Implications." *Structural Change and Economic Dynamics* [Preprint], (4401851). https://doi.org/10.2139/ssrn.4401851.

Bauer, Nico, Ioanna Mouratiadou, Gunnar Luderer, Lavinia Baumstark, R. J. Brecha, Ottmar Edenhofer, and Elmar Kriegler. 2016. "Global Fossil Energy Markets and Climate Change Mitigation–An Analysis with REMIND." *Climatic Change* 136 (1): 69–82.

Bazilian, Morgan, Michael Bradshaw, Jahannes Gabriel, Andreas Goldthau, and Kirsten Westphal. 2020. "Four Scenarios of The Energy Transition: Drivers, Consequences, and Implications for Geopolitics." *Climate Change* 11 (2): e625.

Bazilian, Morgan, Victoria Cuming, and Thomas Kenyon. 2020. "Local-Content Rules for Renewables Projects Don't Always Work." *Energy Strategy Reviews* 32 (November): 100569.

Berthold, Brendan, Ambrogio Cesa-Bianchi, Federico Di Pace, and Alex Haberis. 2023. "The Heterogeneous Effects of Carbon Pricing: Macro and Micro Evidence." Discussion Paper 2319, Centre for Macroeconomics (CFM).

Böhringer, Christoph, Carolyn Fischer, Knut Einar Rosendahl, and Thomas Fox Rutherford. 2022. "Potential Impacts and Challenges of Border Carbon Adjustments." *Nature Climate Change* 12 (1): 22–29.

Borghesi, Simone, Francesco Crespi, Alessio D'Amato, Massimiliano Mazzanti, and Francesco Silvestri. 2015. "Carbon Abatement, Sector Heterogeneity and Policy Responses: Evidence on Induced Eco Innovations in the EU." *Environmental Science & Policy* 54 (December): 377–88.

Bosetti, Valentina, Carlo Carraro, Emanuele Massetti, Alessandra Sgobbi, and Massimo Tavoni. 2009. "Optimal Energy Investment and R&D Strategies to Stabilize Atmospheric Greenhouse Gas Concentrations." *Resource and Energy Economics* 31 (2): 123–37.

Brand, Claus, Gunter Coenen, John Hutchinson, and Arthur Saint Guilhem. 2023. "The Macroeconomic Implications of the Transition to a Low-Carbon Economy." *ECB Economic Bulletin,* Issue 5/2023.

Breetz, Hanna, Matto Mildenberger, and Leah Stokes. 2018. "The Political Logics of Clean Energy Transitions." *Business and Politics* 20 (4): 492–522. https://doi.org/10.1017/bap.2018.14.

Brulle, Robert J. 2014. "Institutionalizing Delay: Foundation Funding and the Creation of U.S. Climate Change Counter-Movement Organizations." *Climatic Change* 122 (4): 681–94.

Brulle, Robert J., Melissa Aronczyk, and Jason Carmichael. 2020. "Corporate Promotion and Climate Change: An Analysis of Key Variables Affecting Advertising Spending by Major Oil Corporations, 1986–2015." *Climatic Change* 159 (1): 87–101.

Buonanno, Paolo, Carlo Carraro, and Marzio Galeotti. 2003. "Endogenous Induced Technical Change and the Costs of Kyoto." *Resource and Energy Economics* 25 (1): 11–34.

Carbon Tracker. 2023. "One in Three UK Car Sales May Be Fully Electric by End '23 as S-Curve Transforms Market." *Carbon Tracker Initiative*, January 5, 2023.

Carbon Trust. 2005. *The UK Climate Change Programme: Potential Evolution for Business and The Public Sector*. Carbon Trust.

CEEW, CII, TCX, and TWI (Council on Energy, Environment, and Water, Confederation of Indian Industry, The Currency Exchange Fund, and Terrawatt Initiative). 2017. C*ommon Risk Mitigation Mechanism–Feasibility Study.* Delhi, India: CEEW.

Chan, Ying Tung, and Hong Zhao. 2023. "Optimal Carbon Tax Rates in A Dynamic Stochastic General Equilibrium Model with a Supply Chain." *Economic Modelling* 119 (February): 106109.

Cheon, Andrew, and Johannes Urpelainen. 2012. "Oil Prices and Energy Technology Innovation: An Empirical Analysis." *Global Environmental Change* 22 (2): 407–17.

Chichilnisky, Graciela, and Geoffrey Heal. 1994. "Who Should Abate Carbon Emissions? An International Viewpoint." *Economics Letters* 44 (4): 443–49.

Christiansen, Atle Christer. 2001. "Climate Policy and Dynamic Efficiency Gains a Case Study on Norwegian CO_2-Taxes and Technological Innovation in the Petroleum Sector." *Climate Policy* 1 (4): 499–515.

Cimoli, Mario, Giovanni Dosi, and Joseph Stiglitz, eds. 2009. *Industrial Policy and Development: The Political Economy of Capabilities Accumulation.* Oxford University Press.

Cirera, Xavier, and William F. Maloney. 2017. *The Innovation Paradox: Developing-Country Capabilities and the Unrealized Promise of Technological Catch-Up*. Washington, DC: World Bank.

Costantini, Valeria, Francesco Crespi, and Alessandro Palma. 2017. "Characterizing the Policy Mix and Its Impact on Eco-Innovation: A Patent Analysis of Energy-Efficient Technologies." *Research Policy* 46 (4): 799–819.

Csereklyei, Zsuzsanna, M.d. Rubio-Varas, and David I. Stern. 2016. "Energy and Economic Growth: The Stylized Facts." *The Energy Journal* 37 (2): 223–55.

D'Arcangelo, Filippo M., Giulia Pavan, and Sara Calligaris. 2022. "The Impact of the European Carbon Market on Firm Productivity: Evidence from Italian Manufacturing Firms." FEEM Working Paper 24, Fondazione Eni Enrico Mattei (FEEM), Milan.

Das, Kasturi, Harro van Asselt, Susanne Droege, and Michael Mehling. 2019. "Making the International Trade System Work for the Paris Agreement: Assessing the Options." *Environmental Law Reporter* 49 (6): 10553–80.

Dechezleprêtre, Antoine, Daniel Nachtigall, and Balazs Stadler. 2020. "The Effect of Energy Prices and Environmental Policy Stringency on Manufacturing Employment in OECD Countries: Sector- and Firm-Level Evidence." OECD Economics Department Working Papers No. 1625, OECD Publishing, Paris.

Doner, Richard F., and Ben Ross Schneider. 2016. "The Middle-Income Trap: More Politics than Economics." *World Politics* 68 (4): 608–44.

Durán, Gracia Marin. 2023. "Securing Compatibility of Carbon Border Adjustments with the Multilateral Climate and Trade Regimes." *International & Comparative Law Quarterly* 72 (1): 73–103.

EEIST (Economics of Energy Innovation and System Transition). 2021. *The New Economics of Innovation and Transition: Evaluating Opportunities and Risks*. EEIST, University of Exeter.

EEIST (Economics of Energy Innovation and System Transition). 2022. *Ten Principles for Policy Making in the Energy Transition: Lessons from Experience*. Economics of Energy Innovation and System Transition (EEIST), University of Exeter.

EEIST (Economics of Energy Innovation and System Transition): Grubb, Michael, Simon Sharpe, Varun Agarwal, Laura Diaz Anadon, Peter Barbook-Johnson, Saswata Chaudhury, Doyne Farmer, Zhangang Han, Aled Jones, Vidhu Kapur, Ulka Kelkar, Francesco Lamperti, Timothy M. Lenton, Yaroslav Melekh, Jean-Francois Mercure, Femke Nijsse, Roberto Pasqualino, Cristina Peñasco, Marcelo Pereira, Andrea Roventini, Yuyan Weng, Carlos Eduardo Frickmann Young, Hongyu Zhang, Xiliang Zhang and Songli Zhu. 2024. T*he Economics of Energy Innovation and Systems Transition: Synthesis Report*. EEIST, University of Exeter.

Ellwood, Paul, Ceri Williams, and John Egan. 2022. "Crossing the Valley of Death: Five Underlying Innovation Processes." *Technovation* 109 (January): 102162.

ElSayed, Mai, Arman Aghahosseini, and Christian Breyer. 2023. "High Cost of Slow Energy Transitions for Emerging Countries: On the Case of Egypt's Pathway Options." *Renewable Energy* 210 (July): 107–26.

Falk, Armin, and Michael Kosfeld. 2006. "The Hidden Costs of Control." *American Economic Review* 96 (5): 1611–30.

Farmer, J. Doyne, Cameron Hepburn, Penny Mealy, and Alexander Teytelboym. 2015. "A Third Wave in the Economics of Climate Change." *Environmental and Resource Economics* 62 (2): 329–57.

Fitzgerald, Louise Michelle, Isabell Braunger, and Hanna Brauers. 2019. "Destabilisation of Sustainable Energy Transformations: Analysing Natural Gas Lock-in in the Case of Germany." STEPS Working Paper 106, ESCR STEPS Centre (Social, Technological and Environmental Pathways to Sustainability), University of Sussex.

Fouquet, Roger. 2016. "Historical Energy Transitions: Speed, Prices and System Transformation." *Energy Research and Social Science* 22 (December): 7–12.

Fredriksson, Per G., and Alexandre Sauquet. 2017. "Does Legal System Matter for Directed Technical Change? Evidence from the Auto Industry." *Applied Economics Letters* 24 (15): 1080–83.

Gallagher, Kelly Sims, Arnulf Grübler, Laura Kuhl, Gregory Nemet, and Charlie Wilson. 2012. "The Energy Technology Innovation System." *Annual Review of Environment and Resources* 37 (November): 137–62.

Garrone, Paola, Luca Grilli, and Boris Mrkajic. 2017. "The Energy-Efficient Transformation of EU Business Enterprises: Adapting Policies to Contextual Factors." *Energy Policy* 109 (October): 49–58.

Gautam, Kushgra, Dhruba Purkayastha, and Vikram Widge. 2023. "Cost of Capital for Renewable Energy Investments in Developing Economies." Discussion Paper, Climate Policy Initiative.

Gawel, Erik, Klaas Korte, and Paul Lehman. 2018. *Technology Neutrality: A Critical Assessment. Technology Neutrality in the Context of Transport*. Berlin: Agora Verkehrswende.

Geels, Frank W. 2014. "Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective." *Theory, Culture & Society* 31 (5): 21–40.

Geels, Frank W., Frans Berkhout, and Detlef P. van Vuuren. 2016. "Bridging Analytical Approaches for Low-Carbon Transitions." *Nature Climate Change* 6: 576–83.

Geels, Frank W., Benjamin K. Sovacool, Tim Schwanen, and Steve Sorrell. 2017. "Sociotechnical Transitions for Deep Decarbonization." *Science* 357 (6357): 1242–44.

Gerres, Timo, Manuel Haussner, Karsten Neuhoff, and Alice Pirlot. 2021. "To Ban or Not to Ban Carbon-Intensive Materials: A Legal and Administrative Assessment of Product Carbon Requirements." *Review of European, Comparative & International Environmental Law* 30 (2): 249–62.

Gillingham, Kenneth, Richard Newell, and William A. Pizer. 2008. "Modeling Endogenous Technological Change for Climate Policy Analysis." *Energy Economics* 30 (6): 2734–53.

Gils, Hans Christian, Hedda Gardian, and J. Schmugge. 2021. "Interaction of Hydrogen Infrastructures with other Sector Coupling Options Towards a Zero-Emission Energy System in Germany." *Renewable Energy* 180 (December): 140–156.

Girod, Bastien, Tobias Stucki, and Martin Woerter. 2017. "How Do Policies for Efficient Energy Use in the Household Sector Induce Energy-Efficiency Innovation? An Evaluation of European Countries." *Energy Policy* 103: 223–37.

Golosov, Mikhali, John Hassler, Per Krusell, and Aleh Tsyvinski. 2014. "Optimal Taxes on Fossil Fuel in General Equilibrium." *Econometrica* 82 (1): 41–88.

Goulder, Lawrence H., and Koshy Mathai. 2000. "Optimal CO_2 Abatement in the Presence of Induced Technological Change." *Journal of Environmental Economics and Management* 39 (1): 1–38.

Greenberg, Brad A. 2016. "Rethinking Technology Neutrality." *Minnesota Law Review* 207.

Grubb, Michael, Paul Drummond, Alexandra Poncia, Will McDowall, David Popp, Sascha Samadi, Cristina Penasco, Kenneth T. Gillingham, Sjak Smulders, Matthieu Glachant, Gavin Hassall, Emi Mizuno, Edward S. Rubin, Antoine Dechezleprêtre, and Giulia Pavan. 2021. "Induced Innovation in Energy Technologies and Systems: A Review of Evidence and Potential Implications for CO_2 Mitigation." *Environmental Research Letters* 16 (4): 043007.

Grubb, Michael, Jean Hourcade, and Karsten Neuhoff. 2014. *Planetary Economics: Energy, Climate Change and the Three Domains of Sustainable Development*. Routledge.

Grubb, Michael , Nino David Jordan, Edgar Hertwich, Karsten Neuhoff, Kasturi Das, Kaushik Ranjan Bandyopadhyay, Harro van Asselt, Misato Sato, Ranran Wang, William A. Pizer, and Hyungna Oh. 2022. "Carbon Leakage, Consumption, and Trade." *Annual Review of Environment and Resources* 47 (1): 753–795. https://doi.org/10.1146/annurev-environ-120820-053625.

Grubb, Michael, Alexandra Poncia, Paul Drummond, Karsten Neuhoff, and Jean-Charles Hourcade. 2023. "Policy Complementarity and the Paradox of Carbon Pricing" *Oxford Review of Economic Policy* 39 (4, Winter): 711–730

Grubb, Michael, Rutger-Jan Lange, Nicolas Cerkez, Ida Sognaes, Claudia Wieners, and Pablo Salas. 2024. “Dynamic Determinants of Optimal Global Climate Policy.” Revised submission accepted for *Structural Change and Economic Dynamics*. Working paper available at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4645782.

Grübler, Arnulf. 1996. "Time for a Change: On the Patterns of Diffusion of Innovation." *Daedalus* Summer, Vol. 125, No. 3, The Liberation of the Environment, 19–42

Grübler, Arnulf. 1998. *Technology and Global Change*. Cambridge, United Kingdom: Cambridge University Press.

Grübler, Arnulf, Charlie Wilson, and Gregory Nemet. 2016. "Apples, Oranges, and Consistent Comparisons of the Temporal Dynamics of Energy Transitions." *Energy Research and Social Science* 22 (December): 18–25.

Guillouzouic-Le Corff, Arthur. 2018. "Did Oil Prices Trigger an Innovation Burst in Biofuels?" *Energy Economics* 75 (September): 547–59.

Gulbrandsen, Lars H., and Christian Stenqvist. 2013. "The Limited Effect of EU Emissions Trading on Corporate Climate Strategies: Comparison of a Swedish and a Norwegian Pulp and Paper Company." *Energy Policy* 56 (May): 516–25.

Harmsen, Mathijs, Elmar Kriegler, Detlef P van Vuuren, Kaj-Ivar van der Wijst, Gunnar Luderer, Ryna Cui, Olivier Dessens, Laurent Drouet, Johannes Emmerling, Jennifer Faye Morris, Florian Fosse, Dimitris Fragkiadakis, Kostas Fragkiadakis, Panagiotis Fragkos, Oliver Fricko, Shinichiro Fujimori, David Gernaat, Céline Guivarch, Gokul Iyer, Panagiotis Karkatsoulis, Ilkka Keppo, Kimon Keramidas, Alexandre Köberle, Peter Kolp, Volker Krey, Christoph Krüger, Florian Leblanc, Shivika Mittal, Sergey Paltsev, Pedro Rochedo, Bas J. van Ruijven, Ronald D Sands, Fuminori Sano, Jessica Strefler, Eveline Vasquez Arroyo, Kenichi Wada, and Behnam Zakeri. 2021. "Integrated Assessment Model Diagnostics: Key Indicators and Model Evolution." *Environmental Research Letters* 16 (5): 054046.

Harrison, Kathryn. 2018. "The Challenge of Transition in Liberal Market Economies: The United States and Canada." In *National Pathways to Low Carbon Emission Economies*. Routledge.

Hicks, John R. 1932. *The Theory of Wages*. London: Palgrave Macmillan.

High-Level Commission on Carbon Prices. 2017. *Report of the High-Level Commission on Carbon Prices*. Washington, DC: World Bank.

Hochstetler, Kathryn. 2020. *Political Economies of Energy Transition*. Cambridge, United Kingdom: Cambridge University Press.

Hoffmann, Volker H. 2007. "EU ETS and Investment Decisions: The Case of the German Electricity Industry." *European Management Journal* 25 (6): 464–74.

Holland, Dawn, Ian Hurst, Amit Kara, and Iana Liadze. 2021. "An Investigation of Carbon Taxes and Terms of Trade in a Large Macroeconometric Model." *National Institute Economic Review* 258 (Autumn): 47–65.

Hourcade, Jean Charles, Dipak Dasgupta, and Frederic Ghersi. 2021. "Accelerating the Speed and Scale of Climate Finance in the Post-Pandemic Context." *Climate Policy* 21 (10): 1–15.

Hughes, Nick, Neil Strachan, and Robert Gross. 2013. "The Structure of Uncertainty in Future Low Carbon Pathways." *Energy Policy* 52 (January): 45–54.

Hurst, Ian, Iana Liadze, and Katerina Lisenkova. 2014. "Overview of the NiGEM-S Model: Scottish Version of the National Institute Global Econometric Model." London: University of Strathclyde.

IEA (International Energy Agency). 2019. *World Energy Outlook 2019*. Paris: IEA.

IEA (International Energy Agency). 2023a. *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach–Analysis.* Paris: International Energy Agency.

IEA (International Energy Agency). 2023b. "Overview and Key Findings." *World Energy Investment 2023*. Paris: IEA.

IEA (International Energy Agency). 2023c. Renewable Energy Market Update–June 2023. Paris: IEA.

IEA (International Energy Agency). 2024. *Global EV Outlook 2024*. Paris: IEA.

IPCC Intergovernmental Panel on Climate Change). 2018. *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related*

Global Greenhouse Gas Emission Pathways in the Context of Strengthening the Global Response to the Threat of Climate Change. Geneva: IPCC.

IPCC (Intergovernmental Panel on Climate Change). 2022a. *AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability.* Working Group II Contribution to the IPCC Sixth Assessment Report. IPCC.

IPCC (Intergovernmental Panel on Climate Change). 2022b. *Climate Change 2022: Mitigation of Climate Change*. Summary for Policymakers. IPCC.

IPCC (Intergovernmental Panel on Climate Change). 2022c. *Climate Change 2022: Mitigation of Climate Change.* Working Group III Contribution to the IPCC Sixth Assessment Report. IPCC.

Isoard, Stephane, and Antonio Soria. 2001. "Technical Change Dynamics: Evidence from the Emerging Renewable Energy Technologies." *Energy Economics* 23 (6): 619–36.

Jain, Gautam, Chris Bataille, Noah Kaufman, and Sagatom Saha. 2024. “Resuscitating WTO for the Energy Transition: Why, How, and Who.” Background paper prepared for the *World Development Report 2024: The Middle-Income Trap*, World Bank, Washington, DC.

Jang, Heesun, and Xiaodong Du. 2013. "Price- and Policy-Induced Innovations: The Case of U.S. Biofuel." *Journal of Agricultural and Resource Economics* 38 (3): 299–311.

Johnstone, Nick, Ivan Haščič, and David Popp. 2010. "Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts." *Environmental and Resource Economics* 45 (1): 133–55.

Jones, Charles A., and David L Levy. 2009. "Business Strategies and Climate Change." Chapter 11 in *Changing Climates in North American Politics: Institutions, Policymaking, and Multilevel Governance,* 218–40. Cambridge, MA: The MIT Press.

Kahn, Matthew E., and Somik Lall. 2022. "Will the Developing World’s Growing Middle Class Support Low Carbon Policies?" NBER Working Paper 30238, National Bureau of Economic Research, Cambridge, MA.

Kavlak, Goksin, James McNerney, and Jessika E. Trancik. 2018. "Evaluating the Causes of Cost Reduction in Photovoltaic Modules." *Energy Policy* 123 (December): 700–10.

Kessler, Jeff, and Daniel Sperling. 2016. "Tracking U.S. Biofuel Innovation through Patents." *Energy Policy* 98 (November): 97–107.

Kim, Jung Eun. 2014. "Energy Security and Climate Change: How Oil Endowment Influences Alternative Vehicle Innovation." *Energy Policy* 66 (March): 400–10.

Kim, Kyunam, Eunnyeong Heo, and Yeonbae Kim. 2017. "Dynamic Policy Impacts on a Technological-Change System of Renewable Energy: An Empirical Analysis." *Environmental and Resource Economics* 66: 205–36.

Kivimaa, Paula, Hanna Lisa Kangas, and David Lazarevic. 2017. "Client-Oriented Evaluation of 'Creative Destruction' in Policy Mixes: Finnish Policies on Building Energy Efficiency Transition." *Energy Research & Social Science* 33 (November): 115–27.

Klaassen, Ger, Asami Miketa, Katarina Larsen, and Thomas Sundqvist. 2005. "The Impact of R&D on Innovation or Wind Energy in Denmark, Germany and the United Kingdom." *Ecological Economics* 54 (2): 227–40.

Knittel, Christopher R. 2011. "Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector." *American Economic Review* 101 (7): 3368–99.

Kruse, Jurgen and Heike Wetzel. 2016. "Innovation in Clean Coal Technologies: Empirical Evidence from Firm-Level Patent Data." EWI Working Paper No. 16/01. Institute of Energy Economics at the University of Cologne (EWI).

Kverndokk, Snorre, and Knut Einar Rosendahl. 2007. "Climate Policies and Learning by Doing: Impacts and Timing of Technology Subsidies." *Resource and Energy Economics* 29 (1): 58–82.

Labandeira, Xavier, Jose M. Labeaga, and Xiral López-Otero. 2017. "A Meta-Analysis on the Price Elasticity of Energy Demand." *Energy Policy* 102 (March): 549–68.

Lam, Aileen, and Jean Francois Mercure. 2021. "Which Policy Mixes are Best for Decarbonising Passenger Cars? Simulating Interactions among Taxes, Subsidies and Regulations for the United Kingdom, the United States, Japan, China, and India." *Energy Research & Social Science* 75 (May): 101951.

Lamb, William F., Michael Grubb, Francesca Diluiso, and Jan C. Minx. 2021. "Countries with Sustained Greenhouse Gas Emissions Reductions: An Analysis of Trends and Progress by Sector." *Climate Policy* 22 (1): 1–17.

Lamichhane, Sujan. 2023. "Default Risk and Transition Dynamics with Carbon Shocks." IMF Working Paper 2023/174, International Monetary Fund, Washington, DC.

Lamperti, Francesco, Giovanni Dosi, Mauro Napoletano, Andrea Roventini, and Alessandro Sapio. 2020. "Climate Change and Green Transitions in an Agent-Based Integrated Assessment Model." *Technological Forecasting and Social Change* 153 (April): 119806.

Lamperti, Francesco, and Andrea Roventini. 2022. "Beyond Climate Economics Orthodoxy: Impacts and Policies in the Agent-Based Integrated-Assessment DSK Model*." *European Journal of Economics and Economic Policies* 19 (3): 357–80.

Lee, Keun. 2013. *Schumpeterian Analysis of Economic Catch-up: Knowledge, Path-Creation, and the Middle-Income Trap*. Cambridge University Press.

Lehmann, Paul, Felix Creutzig, Melf-Hinrich Ehlers, Nele Friedrichsen, Clemens Heuson, Lion Hirth, and Robert Pietzcker. 2012. "Carbon Lock-Out: Advancing Renewable Energy Policy in Europe." *Energies* 5 (2): 323–54.

Levy, David L., and Daniel Egan. 2003. "A Neo-Gramscian Approach to Corporate Political Strategy: Conflict and Accommodation in the Climate Change Negotiations*." *Journal of Management Studies* 40 (4): 803–29.

Ley, Marius, Tobias Stucki, and Martin Woerter. 2016. "The Impact of Energy Prices on Green Innovation." *Energy Journal* 37 (1): 41–75.

Liadze, Iana, Patricia Samchez Juanino, Stephen Millard, and Barry Naisbitt. 2023. *Short-Term Impact from a Rapid Increase in Carbon Taxes.* London: National Institute of Economic and Social Research (NIESR).

Lin, Shen, Banban Wang, Wei Wu, and Shaozhou Qi. 2018. "The Potential Influence of the Carbon Market on Clean Technology Innovation in China." *Climate Policy* 18 (Sup 1): 71–89.

Lyapunov, Alexandr Mikhailovich. 1992. "The General Problem of the Stability of Motion." *International Journal of Control* 55 (3): 531–34.

Malhotra, Abhishek, and Tobias Schmidt. 2020. "Accelerating Low-Carbon Innovation." *Joule* 4 (11): 2259–67.

Marchau, Vincent A. W. J., Warren E. Walker, Pieter J. T. M Bloemen, and Steven W. Popper. 2019. *Decision Making under Deep Uncertainty: From Theory to Practice*. Springer International Publishing.

Mazzucato, Mariana. 2015. *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*. Anthem Press.

Mazzucato, Mariana. 2016. "From Market Fixing to Market-Creating: A New Framework for Innovation Policy." *Industry and Innovation* 23 (2): 140–56.

Mehling, Michael A., Harro Van Asselt, Kasturi Das, Susanne Droege, and Cleo Verkuijl. 2019. "Designing Border Carbon Adjustments for Enhanced Climate Action." *American Journal of International Law* 113 (3): 433–81.

Melekh, Yaroslav, Michael Grubb, and James Dixon. 2024. “Energy Technologies for Low-Carbon Development in Middle-Income Countries: Assessment and Implications.” Background paper prepared for the *World Development Report 2024: The Middle-Income Trap*, World Bank, Washington, DC.

Meng, Jing, Rupert Way, Elena Verdolini, and Laura Diaz Anadon. 2021. "Comparing Expert Elicitation and Model-Based Probabilistic Technology Cost Forecasts for The Energy Transition." *Proceedings of the National Academy of Sciences* 118 (27): 1917165118.

Meng, Kyle C., and Ashwin Rode. 2019. "The Social Cost of Lobbying over Climate Policy." *Nature Climate Change* 9 (6): 472–76.

Mercure, Jean-Francois, Florian Knobloch, Hector Pollitt, Leonidas Paroussos, S. Serban Scrieciu, and Richard Lewney. 2019. "Modelling Innovation and the Macroeconomics of Low-Carbon Transitions: Theory, Perspectives and Practical Use." *Climate Policy* 19 (8): 1019–37.

Mercure, Jean-Francois, Hector Pollitt, Andrea M. Bassi, Jorge. E Vinuales, and Neil R. Edwards. 2016. "Modelling Complex Systems of Heterogenous Agents to Better Design Sustainability Transitions Policy." *Global Environmental Change* 37 (March): 102–15.

Mercure, Jean-Francois, Hector Pollitt, Neil R. Edwards, Philip B. Holden, Unnada Chewpreecha, Pablo Salas, Aileen Lam, Florian Knobloch, Jorge E. Vinuales. 2018. "Environmental Impact Assessment for Climate Change Policy with the Simulation-Based Integrated Assessment Model E3ME-FTT-GENIE." *Energy Strategy Reviews* 20 (April): 195–208.

Mercure, Jean-Francois, Pablo Salas, Pim Vercoulen, Gregor Semieniuk, Aileen Lam, Hector Pollitt, Philip B. Holden, N. Vakilifard, Unnada Chewpreecha, Neil R. Edwards, and Jorge E. Vinuales. 2021. “Reframing Incentives for Climate Policy Action.” *Nature Energy* 6 (12): 1133–43.

Miketa, Asami, and Leo Schrattenholzer. 2004. "Experiments with a Methodology to Model the Role of R&D Expenditures in Energy Technology Learning Processes; First Results." *Energy Policy* 32 (15): 1679–92.

Mildenberger, Matto. 2020. *Carbon Captured: How Business and Labor Control Climate Politics.* Cambridge, MA: The MIT Press.

Nakicenovic, Nebojsa. 1986. "The Automobile Road to Technological Change: Diffusion of the Automobile as a Process of Technological Substitution." *Technological Forecasting and Social Change* 29 (4): 309–40.

Naveed, Amjad, Nisar Ahmad, Reza FathollahZadeh Aghdam, and Angeliki Menegaki. 2022. "What Have We Learned from Environmental Kuznets Curve Hypothesis? A Citation-Based Systematic Literature Review and Content Analysis." *Energy Strategy Reviews* 44: 100946.

Nemet, Gregory F. 2019. *How Solar Energy Became Cheap a Model for Low-Carbon Innovation*. Routledge.

Nemet, Gregory F., Vera Zipperer, and Martina Kraus. 2018. "The Valley of Death, The Technology Pork Barrel, and Public Support for Large Demonstration Projects." *Energy Policy* 119 (August): 154-67.

Newell, Peter, and Matthew Paterson. 1998. "A Climate for Business: Global Warming, the State and Capital." *Review of International Political Economy* 5 (4): 679–703.

Noailly, Joelle. 2012. "Improving the Energy Efficiency of Buildings: The Impact of Environmental Policy on Technological Innovation." *Energy Economics* 34 (3): 795–806.

Nordhaus, William D. 2002. "Modeling Induced Innovation in Climate-Change Policy." In *Technological Change and the Environment*. Routledge.

Nordhaus, William D. 2014. "The Perils of the Learning Model for Modeling Endogenous Technological Change." *Energy Journal* 35 (1): 1–13.

OECD (Organisation for Economic Co-operation and Development). 2021. *R&D Intensity by Industry: Business Enterprise Expenditure on R&D as a Share of Gross Valued Added, 2018 (or Nearest Year)*. Paris: OECD.

Pasqualino, Roberto, Cristina Peñasco, Peter Barbrook-Johnson, Fernanda Senra De Moura, Sergey Kolesnikov, Sarah Hafner, Femke J. M. M. Nijsse, Francesco Lamperti, Ben Hinder, Yaroslav Melekh, Simon Sharpe, Aled W. Jones, Laura Díaz Anadón, Timothy M. Lenton, and Michael Grubb. 2024. “Modelling Induced Innovation for the Low-Carbon Energy Transition: A Menu of Options.” *Environmental Research Letters* (in press), available at https://doi.org/10.1088/1748-9326/ad4c79.

Patt, Anthony, and Johan Lilliestam. 2018. "The Case against Carbon Prices." *Joule* 2 (12): 2494–98.

Paus, Eva. 2014. "Latin America and the Middle-Income Trap." Financing for Development Series, No. 250, United Nations Economic Commission for Latin America and the Caribbean (ECLAC).

Pearse, Rebecca. 2017. *Pricing Carbon in Australia: Contestation, the State and Market Failure.* London: Routledge.

Peñasco, Cristina, Laura Diaz Anadón, and Elena Verdolini. 2021. "Systematic Review of the Outcomes and Trade-Offs of Ten Types of Decarbonization Policy Instruments." *Nature Climate Change* 11 (3): 257–65.

Persaud, Avinash. 2023. "Unblocking the Green Transformation in Developing Countries with a Partial Foreign Exchange Guarantee." Climate Policy Initiative.

Peszko, Grzegorz, Dominique van der Mensbrugghe, Alexander Golub, John Ward, Dimitri Zenghelis, Cor Marijs, Anne Schopp, John A.Rogers, and Amelia Midgley. 2020. *Diversification and Cooperation in a Decarbonizing World.* Washington, DC: World Bank.

Pisani-Ferry, Jean. 2021. "Climate Policy is Macroeconomic Policy, and the Implications Will Be Significant." Peterson Institute for International Economics, Washington, DC.

Pisani-Ferry, Jean and Selma Mahfouz. 2023. *The Economic Implications of Climate Action*. Report to the French Prime Minister. France Stratégie.

Popp, David. 2002. "Induced Innovation and Energy Prices." *American Economic Review* 92 (1): 160–80.

Popp, David. 2004. "ENTICE: Endogenous Technological Change in the DICE Model of Global Warming." *Journal of Environmental Economics and Management* 48 (1): 742–68.

Pottier, Antonin, Etienne Espagne, Baptiste Perrissin Fabert, and Patrice Dumas. 2015. "The Comparative Impact of Integrated Assessment Models' Structures on Optimal Mitigation Policies." *Environmental Modeling and Assessment* 20: 453–73.

Powell, Jim. 2011. "Why Politicians Lose So Much Money Trying to Pick Winners." *Forbes,* October 24, 2023.

Raghuram*,* Rajan G. 2010. *Fault Lines: How Hidden Fractures Still Threaten the World Economy.* Princeton, NJ: Princeton University Press.

Rennert, Kevin, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard Newell, William Pizer, Cora Kingdon, Jordan Wingenroth, Roger Cooke, Bryan Parthum, David Smith, Kevin Cromar, Delavane Diaz, Frances C. Moore, Ulrich K. Müller, Richard J. Plevin, Adrian E. Raftery, Hana Ševčíková, Hannah Sheets, James H. Stock, Tammy Tan, Mark Watson, Tony E. Wong, and David Anthoff. 2022. "Comprehensive Evidence Implies a Higher Social Cost of CO_2." *Nature* 610 (7933): 687–92.

Rogers, Everett M. 2003. *Diffusion of Innovations*. New York: Simon and Schuster.

Rogge, Karoline S., and Volker H. Hoffmann. 2010 "The Impact of the EU ETS on the Sectoral Innovation System for Power Generation Technologies–Findings for Germany." *Energy Policy* 38 (12): 7639–52.

Rosembloom, Daniel, and Jochen Markard. 2020. "A COVID-19 Recovery for Climate." *Science* 368 (6490): 2019–20.

Saunders, Harry D., Joyasgree Roy, Ines M. L Azevedi, Debakuba Chakravaty, Shyamasree Dasgupta, Stephane de la Ruedu Can, Angela Druckman, Roger Fouquet, Michael Grubb, Boqiang Lin, Robert Lowe, Reinhard Madlener, Daire M. McCoy, Luis Mundaca, Tadj Oreszczyn, Steven Sorrell, David Stern, Kanako Tanaka, and Taoyuan Wei*.* 2021. "Energy Efficiency: What Has It Delivered in the Last 40 Years?" (revised submission). *Annual Review of Energy and Environment* 46: 135–65.

Semieniuk, Gregor, Philip B. Holden, Jean-Francois Mercure, Pablo Salas, Hector Pollitt, Katharine Jobson, Pim Vercoulen, Unnada Chewpreecha, Neil R. Edwards, and Jorge E. Viñuales. 2022. "Stranded Fossil-Fuel Assets Translate to Major Losses for Investors in Advanced Economies." *Nature Climate Change* 12 (6): 532–38.

Seto, Karen C., Steven J. Davis, Ronald B. Mitchell, Eleanor C. Stokes, Gregory Unruh, and Diana Ürge-Vorsatz. 2016. "Carbon Lock-In: Types, Causes, and Policy Implications." *Annual Review of Environment and Resources* 41 (1): 425–52.

Sköld, David, Helena Fornstedt, and Marcus Lindahl. 2018. "Dilution of Innovation Utility, Reinforcing the Reluctance Towards the New: An Upstream Supplier Perspective on a Fragmented Electricity Industry." *Energy Policy* 116 (May): 220–31.

Smulders, Sjak, and Michiel de Nooij. 2003. "The Impact of the Energy Conservation on Technology and Economic Growth." *Resource and Energy Economics* 25 (1): 59–79.

Söderholm, Patrik, and Ger Klaassen. 2007. "Wind Power in Europe: A Simultaneous Innovation–Diffusion Model." *Environmental and Resource Economics* 36 (2): 163–90.

Söderholm, Patrik, and Thomas Sundqvist. 2007. "Empirical Challenges in the Use of Learning Curves for Assessing the Economic Prospects of Renewable Energy Technologies." *Renewable Energy* 32 (15): 2559–78.

Songwe, Vera, Nicholas Stern, and Amar Bhattacharya. 2022. *Finance for Climate Action: Scaling Up Investment for Climate and Development*. Report of the Independent High-Level Expert Group on Climate Finance.

Stern, Nicholas, Joseph E. Stiglitz, and Charlotte Taylor. 2021. "The Economics of Immense Risk, Urgent Action and Radical Change: Towards New Approaches to the Economics of Climate Change." NBER Working Paper 28472. National Bureau of Economic Research, Cambridge, MA.

Stokes, Leah Cardamore. 2020. *Short Circuiting Policy: Interest Groups and the Battle over Clean Energy and Climate Policy in the American States*. Oxford, United Kingdom: Oxford University Press.

Taylor, Margaret. 2008. "Beyond Technology-Push and Demand-Pull: Lessons from California's Solar Policy." *Energy Economics* 30 (6): 2829–54.

Triguero, Aangela, Lourdes Moreno-Mondéjar, and Maria A. Davia. 2014. "The Influence of Energy Prices on Adoption of Clean Technologies and Recycling: Evidence from European SMEs." *Energy Economics* 46 (November): 246–57.

UNCTAD (United Nations Conference on Trade and Development). 2023a. *Opening Green Windows: Technological Opportunities for a Low-Carbon World.* Geneva: UNCTAD.

UNCTAD (United Nation Conference of Trade and Development). 2023b. *The State of Commodity Dependence 2023.* UNCTAD.

Vogt-Schilb, Adrien, Guy Meunier, and Stephane Hallegatte. 2018. "When Starting with the Most Expensive Option Makes Sense: Optimal Timing, Cost and Sectoral Allocation of Abatement Investment." *Journal of Environmental Economics and Management* 88: 210–33.

Waisman, Henri, Celine Guivarch, Fabio Grazi, and Jean Hourcade. 2012. "The Imaclim-R Model: Infrastructures, Technical Inertia and the Costs of Low Carbon Futures Under Imperfect Foresight." *Climatic Change* 114 (1): 101–20.

Way, Rupert, Matthew C. Ives, Penny Mealy, and J. Doyne Farmer. 2022. "Empirically Grounded Technology Forecasts and the Energy Transition." *Joule* 6 (9): 2057–82.

Weiss, Martin, Martin Junginger, Martin K. Patel, and Kornelis Blok. 2010. "A Review of Experience Curve Analyses for Energy Demand Technologies." *Technological Forecasting and Social Change* 77 (3): 411–28.

Wells, Peter, and Paul Nieuwenhuis. 2012. "Transition Failure: Understanding Continuity in the Automotive Industry." *Technological Forecasting and Social Change* 79 (9): 1681–92.

Weyant, John P. 2011. "Accelerating the Development and Diffusion of New Energy Technologies: Beyond the 'Valley of Death'." *Energy Economics* 33 (4): 674–82.

Wilson, Charlie, Arnulf Grubler, Nuno Bento, Stephen Healey, Simon De Stercke, and Caroline Zimm. 2020. "Granular Technologies to Accelerate Decarbonization." *Science* 368 (6486): 36–39.

Wright, Theodore Paul. 1936. "Factors Affecting the Costs of Airplanes." *Journal of Aeronautical Sciences* 3 (4): 122–128.

Ye, Qin, Shaoqing Dai, and Gang Zeng. 2018. "Research on the Effects of Command-and-Control and Market-Oriented Policy Tools on China's Energy Conservation and Emissions Reduction Innovation." *Chinese Journal of Population Resources and Environment* 16 (1): 1–11.

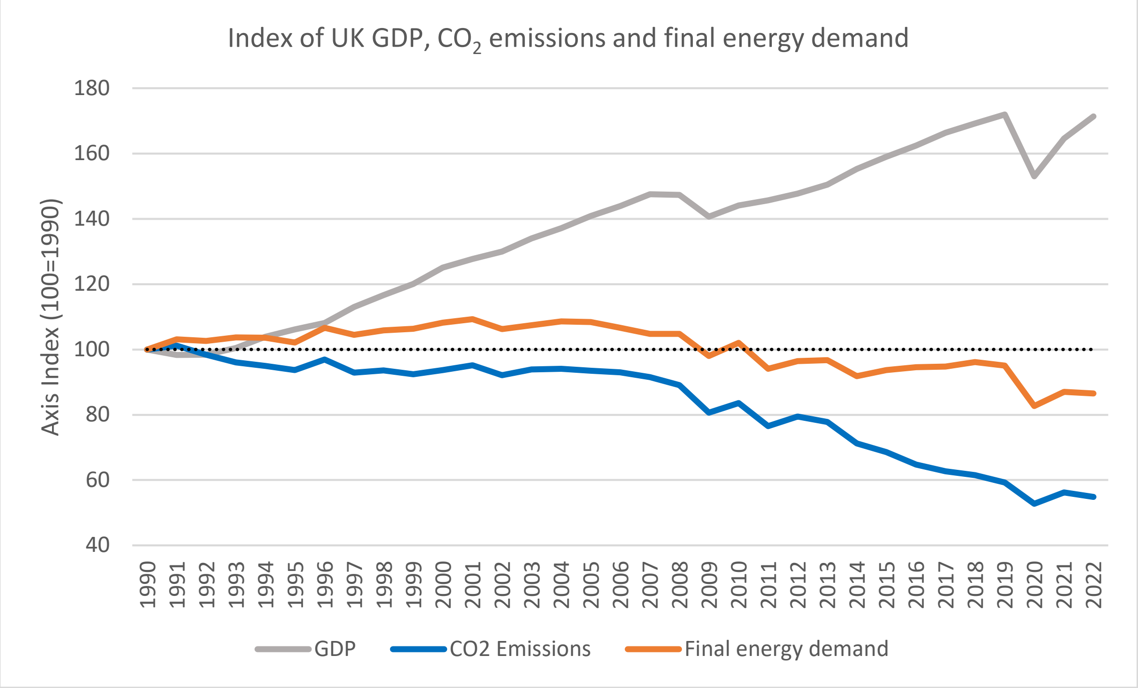
Yu, Yang, Hong Li, Yuyuan Che, and Qiongjie Zheng. 2017. "The Price Evolution of Wind Turbines in China: A Study Based on the Modified Multi-Factor Learning Curve." *Renewable Energy* 103 (April): 522–36.

Zhou, Yi, and Alun Gu. 2019. "Learning Curve Analysis of Wind Power and Photovoltaics Technology in the US: Cost Reduction and the Importance of Research, Development and Demonstration." *Sustainability* 11 (8): 2310.

Appendix A. Case study–The UK experience with the energy transition

The UK energy transition has gained international attention as one of the most dramatic seen to date. A country sometimes known in the 1980s as "an island of coal in a sea of oil and gas" has largely eliminated coal from its energy system. Territorial CO_2 emissions fell by about 45 percent between 1990 and 2022 (UK-DESNZ 2023b), with an average rate of decarbonization faster than anywhere else in the G20 (PwC 2021). At the same time, energy consumption fell by 13 percent while GDP grew by 71 percent (close to pre-pandemic levels) (Figure A.1).

Figure A.1. Comparison of UK GDP, total territorial CO_2 emissions, and final energy demand, 1990–2022



Sources: UK-BEIS 2023; UK-DESNZ 2023a; UK-ONS 2023.

Seen as a European laggard in renewable energy until early this century, the United Kingdom also became one of the world's leading countries particularly for offshore wind energy, and the contribution of renewables to its electricity generation has soared from less than 5 percent to more than 40 percent during the past 20 years (UK-DESNZ 2023c).

While middle-income countries obviously face many differences and varied conditions, the United Kingdom's experience may offer some broad insights into drivers of decarbonization and low-carbon technological development, and associated economic dimensions. This case study tracks the policies that have been instrumental in bringing about the decarbonization seen to date, particularly in the electricity sector. It sheds light on how the transition has largely been driven by strategic goals and related decisions, mostly with upfront costs that have been more than recovered through enhanced efficiency and technological progress.

Context: a multi-stage transition

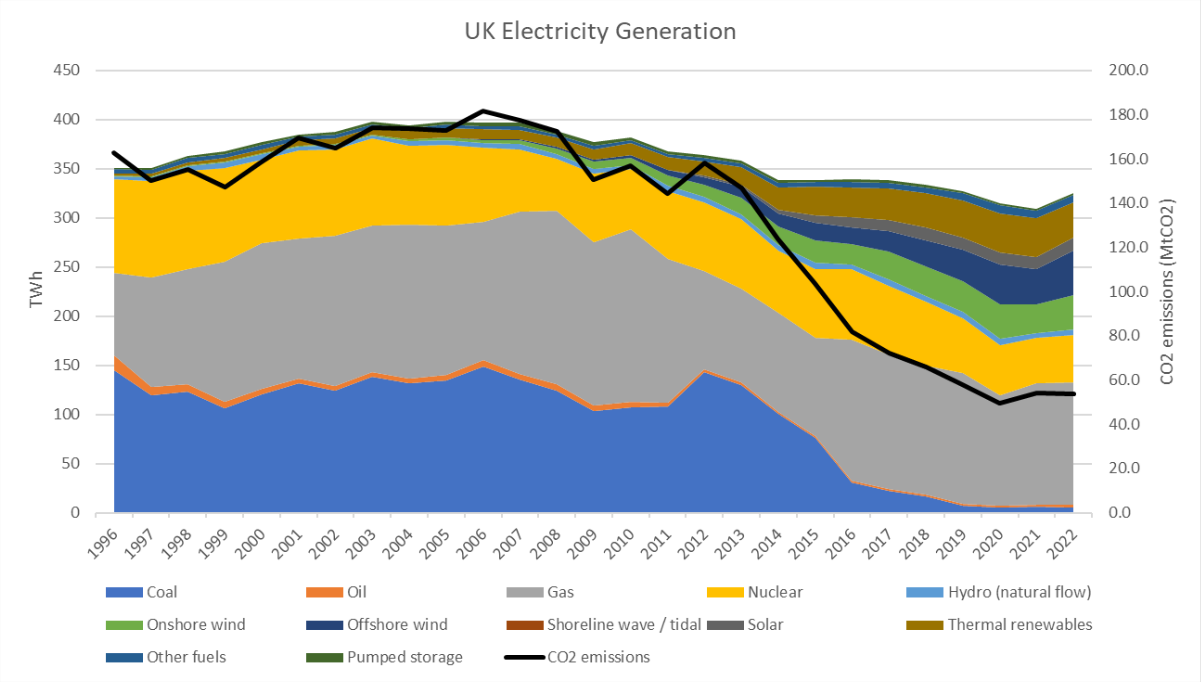
About two-thirds of CO_2 reductions in the United Kingdom over this period have been delivered by a decarbonizing power sector (UK-BEIS and ONS 2022). This has occurred in two distinct phases.

The first major step was taken against the backdrop of a major political confrontation over miners' strikes, which in 1984 led to blackouts. In the years that followed, the government reduced the dominance of contracts through which the then-Centralised Electricity Generating Board procured UK coal, opening up the system to imports, and in 1990, the government privatized and liberalized the electricity market, opening it up to much wider competition. As a result, UK energy generation diversified its sources rapidly throughout the 1990s, moving initially to imported coal, and gas generation, drawing on North Sea gas reserves. A rapid "dash for gas" ensued. Gas was economically more attractive to private industry, but had been largely excluded from the system before privatization (Winskel 2002). This, together with significant de-industrialization in favor of service industries, largely drove the pace of "decoupling" of CO_2 emissions from GDP up to about 2000.

Trends and policies since 2000

By the late 1990s a broad political consensus had already emerged about the importance of tackling climate change. From the early 2000s, initially to meet the United Kingdom's commitments under the Kyoto Protocol and related European Union (EU) goals for 2010 and 2020, a suite of policies acting across sectors and actors have worked together to produce the second major phase of emission reductions, particularly in the electricity sector, shown in Figure A.2.[1]

Figure A.2. Electricity generation profile and CO_2 emissions, 1996–2022



Sources: UK Government DUKES electricity fuel use, generation and supply (https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes) and Provisional UK greenhouse gas emissions national statistics 2022 (https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2022). $MtCO_2$ = megatonnes of carbon dioxide; TWh = terawatt hour.

Most of this case study focuses on the policies adopted and energy/emission impacts. It is hard to disentangle the macroeconomic impacts from everything else that affected the UK economy during the period—most obviously, the large increase in fossil fuel prices, the shift of UK from net exporter to importer, and above all in the late 2000s, the fallout of the global financial crisis.

Some studies were conducted at the time to project the likely impacts of the commitments and proposed policies, against an assumed "business-as-usual" scenario. A major study by the UK government's Carbon Trust (2005), as part of the first UK Climate Change Programme Review, focused on implications for the business sector and competitiveness implications of the combination of carbon pricing, energy efficiency, and renewable energy policies. The macro-insights, however, reflected significant modelling divergences, given that the study utilized both a general equilibrium model and a macroeconometric model. They agreed quite well on likely overall emission impacts, and on the fact that different elements of the policy packages examined, including the EU ETS, would make different and often complementary contributions.

Concerning macroeconomics, however, the results were diametrically opposite—with a similar number (close to 0.3 percent GDP), but opposite in sign. The general equilibrium model embodied the assumption that the carbon price and the targets would take resources away from more profitable activities assumed as broadly optimal in the baseline, while the econometric model, reflecting some observed historical relationships, predicted that the greater energy efficiency and enhanced investment associated with decarbonization would boost UK GDP (Carbon Trust 2005, 55).

In the event, overall emission reductions exceeded anything predicted in that study. In the mid-2000s, various policies were introduced or began to take effect that rapidly altered the profile of electricity generation in the United Kingdom in three ways: (1) a dramatic decline in coal-based generation; (2) a rapid increase in renewable generation; and (3) a substantial decline in total electricity demand.

Carbon pricing—the EU ETS and beyond

In 2005, the EU Emissions Trading System (EU ETS) introduced a carbon price to all electricity generation and industrial emitters across the EU. After a volatile start, it was generally plagued by low prices until reforms in the late 2010s. As a result it had limited direct impact on the electricity generation mix and subsequent emissions in the United Kingdom and across Europe (Bel and Joseph 2015), though its mere existence served to deter new coal plants—the last such proposal was abandoned in 2008.

In response to the low and uncertain ETS carbon price, to enhance investor certainty in 2013 the United Kingdom unilaterally introduced a Carbon Price Floor that applied to electricity generators alongside the EU ETS. The rapid displacement of coal with gas seen in the mid-2010s was largely driven by carbon pricing (EU ETS) with an accompanying UK Carbon Price Support—initially a floor, but subsequent amended to being a carbon tax added to UK generation.[2] While carbon pricing and earlier market liberalization have been highly effective at intensifying the switch from coal to gas generation, they have had minimal direct impact on the two remaining drivers behind the CO_2 reduction delivered—growth in renewables and decline in overall demand.

Renewables investment

Targeted policies that strategically invested in the deployment of renewables, with initial investments that would not have been justified based on cost-benefits using technology costs at the time, were largely responsible for the rapid increase in renewable generation illustrated in Figure A.2. In 2002, the Renewable Obligation (RO) was introduced, initially to achieve the United Kingdom's target of 10 percent renewable electricity by 2010 as part of an EU-wide target of 21 percent.[3] This required electricity suppliers to source a specified proportion of their supply from renewables, with the target increased annually from 3 percent of supply in 2002 to 13.4 percent in 2013.[4]

In 2008, the EU introduced three parallel targets for 2020: a 20 percent reduction in greenhouse gas (GHG) emissions (from 1990 levels); a 20 percent of final energy consumption to be satisfied by renewables; and a 20 percent reduction in final energy consumption (compared to baseline projections). To achieve these targets, a range of existing EU policy measures were tightened, and new policies were adopted. In the same year, the United Kingdom set a legally binding emissions reduction target of 80 percent by 2050 (from 1990 levels) under the newly adopted Climate Change Act.

The UK Renewables Obligation was initially technology-neutral, thereby favoring the more mature renewables (such as onshore wind). However, in 2009, "banding," with multipliers for less mature technologies, was introduced to encourage diversity—in particular, offshore wind. Alongside wider initiatives, and particularly the industrial Offshore Wind Accelerator convened by the Carbon Trust, this induced collaboration, along with various forms of learning and economies of scale, that allowed the technology and industry to establish at scale, and for costs to begin to decline (Jennings et al. 2020).

In 2013, the RO began to be replaced by contracts-for-difference (CfDs), in which new renewable capacity is sought through rounds in which eligible renewable generators compete to receive a fixed "strike price" for 15 years of generation capacity. In 2014, the process became fully auction-based, with awarded capacity that year roughly equally divided between onshore and offshore wind.[5]

The first two CfD rounds for offshore wind were expensive—the first, directly allocated by government at a price of about £160/MWh and with a total contract value of about £16 billion,[6] with the second (the first auction) at about £110/MWh (compared to wholesale electricity price about £50/MWh). Yet, following an effective moratorium on new onshore wind and solar PV from 2015, in subsequent rounds in 2017 and 2019, offshore wind represented 95 percent of new capacity (Mercure, Sharpe, et al. 2021). This allowed further learning, innovation, and economies of scale, with the new competitive element driving the resulting cost reductions through to the electricity market. Overall, offshore wind costs fell by a factor of almost *four* over the next eight years (Mercure, Sharpe, et al. 2021)—making offshore wind effectively subsidy-free at average prevailing wholesale prices over the decade to mid-2021, and substantially "subsidy-negative" at the much higher prices experienced under the 2022 energy crisis (Jennings et al. 2020; UK-Ofgem 2022). In 2022, offshore wind accounted for 15 percent of generation, up from less than 1 percent in 2010. It now forms the backbone of the United Kingdom's decarbonization and energy security strategies, with a five-fold increase in capacity targeted by 2030 (UK-DESNZ and BEIS 2022), and at least 100GW by 2050 (CCC 2020).

An evaluation of rounds 1 and 2 of the CfD scheme find that together they are projected to reduce costs to consumers by about £3 billion up to 2050 (compared with the counterfactual RO scheme). This figure rises to £9 billion when the subsequent and projected future CfD projects are included. Thus, the scheme has delivered significant value for money for consumers (UK-BEIS 2022). However, in 2023, the combination of higher interest rates, inflation, and supply chain constraints increased prices; the impact on offshore wind will be revealed from a large auction planned for summer 2024.

Energy efficiency

Turning to energy efficiency, while electricity and wider energy consumption has been influenced by energy price changes and macroeconomic conditions, particularly those shaped by the 2008/09 financial crisis (Andreoni 2020), energy efficiency policies have clearly increased the efficiency of electricity consumption in the United Kingdom over the past two decades, and have also been a driving force behind increasing the energy efficiency of the use of other fuels in other sectors, particularly transport.

Over the last two decades the United Kingdom has continued a shift from energy-intensive manufacturing to a more knowledge- and service-based economy, driven largely by growth in the latter (UK-BIS 2012). The manufacturing sector, which in 1990 accounted for more than one-quarter of UK energy consumption and one-third of electricity, has increased energy productivity by more than 40 percent since 1990 (UK-ONS 2019). This was driven primarily by a structural shift within the sector toward higher-value, less energy-intensive products, alongside greater utilization and improved efficiency of existing production capacity (CCC 2018).

Energy efficiency improvements have been driven in large part by policy. The Climate Change Levy (a small tax on industrial energy consumption) was introduced in 2000. Together with associated sectoral Climate Change Agreements, it led to a substantial overachievement of energy efficiency and carbon reduction targets—resulting in part from the "awareness effect" induced by firms seeking to comply with the Agreements (Ekins and Etheridge 2006). Other influential policies on energy efficiency include the "CRC energy efficiency" scheme, requiring businesses and the service and public sectors to buy emissions allowances, the Energy Saving Opportunities Scheme (ESOS), obliging all large organizations to undergo energy efficiency audits every four years, and to a lesser degree, the EU ETS (Martin, Muûls, and Wagner 2016).

The domestic and commercial sectors accounted for about 40 percent of total energy consumption in 1990, and about two-thirds of electricity consumption. Labels on energy-using appliances (since the 1990s) and increasingly stringent and broad minimum energy performance regulations (since the mid-2000s), introduced following EU requirements, have driven energy efficiency improvements in appliances. By 2018, these instruments together are estimated to have reduced electricity consumption in the EU equivalent to 15 percent of electricity consumption across the Union in 2018 (IEA 2021).

Overall, UK consumer expenditure on electricity (and energy more broadly) declined over time as a proportion of GDP (falling from 2.2 percent in 1990 to 1.82 percent in 2020, remaining largely constant as a share of total energy expenditure),[7] despite carbon prices and the initial investment costs renewables policies being passed through to electricity prices, either implicitly or explicitly (although this trend may have since reversed, due to the energy crisis and its implications).

Nonetheless, there have also been policy reversals and setbacks. Concerns about the complexity of some of the programs related to energy efficiency, combined with an underlying assumption in much of government that market forces should be the main approach to enhance efficiency, led in 2012 to several of energy efficiency programs being abandoned, in favor of (for homes) a "household-led" approach based on loans tied to buildings. This approach, however, failed spectacularly and led to the collapse of the UK insulation industry.[8] Then in 2015, the new government cancelled at the last moment a standard for new construction, "zero carbon homes." A political backlash against the pace of expansion of *onshore* wind and solar also led to a de facto ban (only very recently reversed, following the 2022 energy crisis).

Estimating the impact that further advanced climate policy could have had on consumer bills in the context of the recent energy crisis, the Energy & Climate Intelligence Unit estimates that households on average could have saved well over £1000 during 2022, had these key policies not been abandoned or delayed (ECIU 2023).

Notes

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[1] These efforts were related to policies directly applied by the EU (as with energy efficiency product standards), or introduced in order to meet EU obligations (notably, the Renewable Energy Directive). Following the United Kingdom's exit from the EU in December 2021, most of these policies remain in place (Watson and Drummond 2022).

[2] The Carbon Price Support was increased from £5/tCO_2 in 2013 to £18/tCO_2 from 2015 onward, while the EU ETS price remained at about €5/tCO_2 until late 2017. This combined increase encouraged rapid fuel-switching to gas from coal (and accelerated closure of the least-efficient coal plants, in particular) (Leroutier 2022), with coal decreasing from 40 percent of generation in 2012 to less than 2 percent in 2020 (UK-BEIS 2021). In 2021, the EU ETS was replaced in the United Kingdom by the UK ETS, with prices largely tracking those of the EU ETS.

[3] This target focused on electricity only, whereas the 20 percent target set for 2020 incorporated all final energy.

[4] The Renewables Obligation was implemented by requiring the supply companies to buy and surrender the appropriate number of tradable Renewable Obligation Certificates (ROCs), issued to and purchased from renewable generators. Demand for ROCs generated income in addition to the price received from the electricity wholesale market, thereby subsidizing new renewables. The Renewable Obligation remained open to new entrants until March 31, 2017, operating in parallel to early contracts-for-difference.

[5] If wholesale electricity prices are below the strike price, generators receive the difference, paid for by a levy on consumer retail prices. If wholesale prices are above the strike price, generators pay back the difference, reducing the levy (or potentially reducing prices, if the levy falls to zero). Capacity for different technologies is made available in "pots," grouped according to technology maturity. As an established technology, onshore wind was Pot 1, with offshore wind in Pot 2 as a less established technology (subsequently moved to offshore wind-only (Pot 3). Capacity for technologies in different pots are not in direct competition when put out to auction.

[6] These amounts are as stated in government review, cited and discussed in the EEIST report (EEIST 2021).

[7] These figures have been calculated using DUKES data on energy expenditure by final user (table 1.1.6) (UK-BEIS 2021) and GDP, at current prices.

[8] Since the early 2000s, home energy efficiency improvements had been promoted through obligations on energy suppliers. In 2012, this approach was abandoned in favor of a much-trumpeted "Green Deal," which shifted the emphasis to loans to homeowners tied to the buildings. The failure of this was largely predicted by energy efficiency policy experts at the time (Rosenow and Eyre 2013), but ignored, given the economic logic and political appeal of putting energy efficiency in the hands of homeowners themselves. The result—dubbed the "biggest failure in the history of UK energy policy,"—can be ascribed to many detailed explanations of barriers, behaviors, and failures in design (Rosenow and Eyre 2016). A more concise explanation is that it was a category error—applying classical second-domain economic logic to solve a first-domain behavioral and structural problem (Grubb et al. 2023).

References

Andreoni, Valeria. 2020. "The Energy Metabolism of Countries: Energy Efficiency and Use in the Period that Followed the Global Financial Crisis." *Energy Policy* 139 (April): 111304.

Bel, Germa, and Stephan Joseph. 2015. "Emission Abatement: Untangling the Impacts of the EU ETS and the Economic Crisis." *Energy Economics* 49 (May): 531–39.

Carbon Trust. 2005. *The UK Climate Change Programme: Potential Evolution for Business and The Public Sector*. Carbon Trust.

CCC (Climate Change Committee). 2018. "Reducing UK Emissions–2018 Progress Report to Parliament." CCC.

CCC (Climate Change Committee). 2020. "Sixth Carbon Budget: The UK's Path to Net Zero." CCC.

ECIU (Energy & Climate Intelligence Unit). 2023. *Cost of NOT Zero in 2022*. London: ECIU.

EEIST (Economics of Energy Innovation and System Transition). 2021. *The New Economics of Innovation and Transition: Evaluating Opportunities and Risks*. EEIST, University of Exeter.

Ekins, Paul, and Ben Etheridge. 2006. "The Environmental and Economic Impacts of the UK Climate Change Agreements." *Energy Policy* 34 (15): 2071–86.

Grubb, Michael, Alexandra Poncia, Paul Drummond, Karsten Neuhoff, and Jean-Charles Hourcade. 2023. "Policy Complementarity and the Paradox of Carbon Pricing." *Oxford Review of Economic Policy* 39 (4): 711–730.

IEA (International Energy Agency). 2021. *Achievements of Energy Efficiency Appliance and Equipment Standards and Labelling Programmes*. Paris: International Energy Agency (IEA).

Jennings, Tom, Helen Andrews Tipper, Jonathan Daglish, Michael Grubb, and Paul Drummond. 2020. *Policy, Innovation and Cost Reduction in UK Offshore Wind*. UCL's Bartlett School of Energy, Environment and Resources: Carbon Trust. Report. Carbon Trust: UCL's Bartlett School of Energy, Environment and Resources.

Leroutier, Marion. 2022. "Carbon Pricing and Power Sector Decarbonization: Evidence from the UK." *Journal of Environmental Economics and Management* 111 (January): 102580.

Martin, Ralf, Mirabelle Muûls, and Ulrich J. Wagner. 2016. "The Impact of the European Union Emissions Trading Scheme on Regulated Firms: What Is the Evidence after Ten Years?" *Review of Environmental Economics and Policy* 10 (1): 129–48.

Mercure, Jean-Francois, Simon Sharpe, Jorge E. Vinuales, Matthew Ives, Michael Grubb, Aileen Lam, Paul Drummond, Hector Pollitt, Florian Knobloc, and Femke J. M. M. Nijsse. 2021. "Risk-Opportunity Analysis for Transformative Policy Design and Appraisal." *Global Environmental Change* 70 (September): 102359.

PwC. 2021. "Net Zero Economy Index 2021: Code Red to Code Green." PwC, London.

Rosenow, Jan, and Nick Eyre. 2013. "The Green Deal and the Energy Company Obligation." *Proceedings of the Institution of Civil Engineers-Energy* 166 (3): 127–36.

Rosenow, Jan, and Nick Eyre. 2016. "A Post Mortem of the Green Deal: Austerity, Energy Efficiency, and Failure in British Energy Policy." Energy Research & Social Science 21 (November): 141–44.

United Kingdom, BEIS (Department for Business, Energy and Industrial Strategy). 2021. "Digest of UK Energy Statistics (DUKES) 2021." GOV.UK.

United Kingdom, BEIS (Department for Business, Energy and Industrial Strategy). 2022. "Evaluation of the Contracts for Difference Scheme.*" GOV.UK*. Department for Business, Energy and Industrial Strategy.

United Kingdom, BEIS (Department for Business, Energy and Industrial Strategy). 2023. "Provisional UK Greenhouse Gas Emissions National Statistics 2022."

United Kingdom, BEIS and ONS (Department for Business, Energy and Industrial Strategy and Office for National Statistics). 2022. "Final UK Greenhouse Gas Emissions National Statistics 1990–2020." London.

United Kingdom, BIS (Department for Business, Innovation and Skills). 2012. "Industrial Strategy: UK Sector Analysis." BIS.

United Kingdom, DESNZ (Department for Energy Security and Net Zero). 2023a. *Digest of UK Energy Statistics (DUKES): Energy*. DESNZ.

United Kingdom, DESNZ (Department for Energy Security and Net Zero). 2023b. *Provisional UK Greenhouse Gas Emissions National Statistics 2022*. GOV.UK.

United Kingdom, DESNZ (Department for Energy Security and Net Zero). 2023c. "UK Energy in Brief 2023." DESNZ.

United Kingdom, DESNZ and BEIS (Department for Energy Security and Net Zero and Department for Business, Energy and Industrial Strategy). 2022. "British Energy Security Strategy." DESNZ and BEIS.

United Kingdom, Ofgem (Office of Gas and Electricity Markets). 2022. "Wholesale Market Indicators." Ofgem.

United Kingdom, ONS (Office for National Statistics). 2019. *The Decoupling of Economic Growth from Carbon Emissions: UK Evidence.* London: ONS.

United Kingdom, ONS (Office for National Statistics). 2023. "Gross Domestic Product: Chained Volume Measures: Seasonally Adjusted £M.*"* ONS, London. Unruh, Gregory C. 2000. "Understanding Carbon Lock-In." *Energy Policy* 28 (12): 817–30.

Watson, Jim, and Paul Drummond. 2022. "Energy." In *Doing Things Differently? Policy after Brexit,*" 39–41. London: UK in a Changing Europe.

Winskel, Mark. 2002. "When Systems Are Overthrown: The 'Dash for Gas' in the British Electricity Supply Industry." *Social Studies of Science* 32 (4): 563–98.