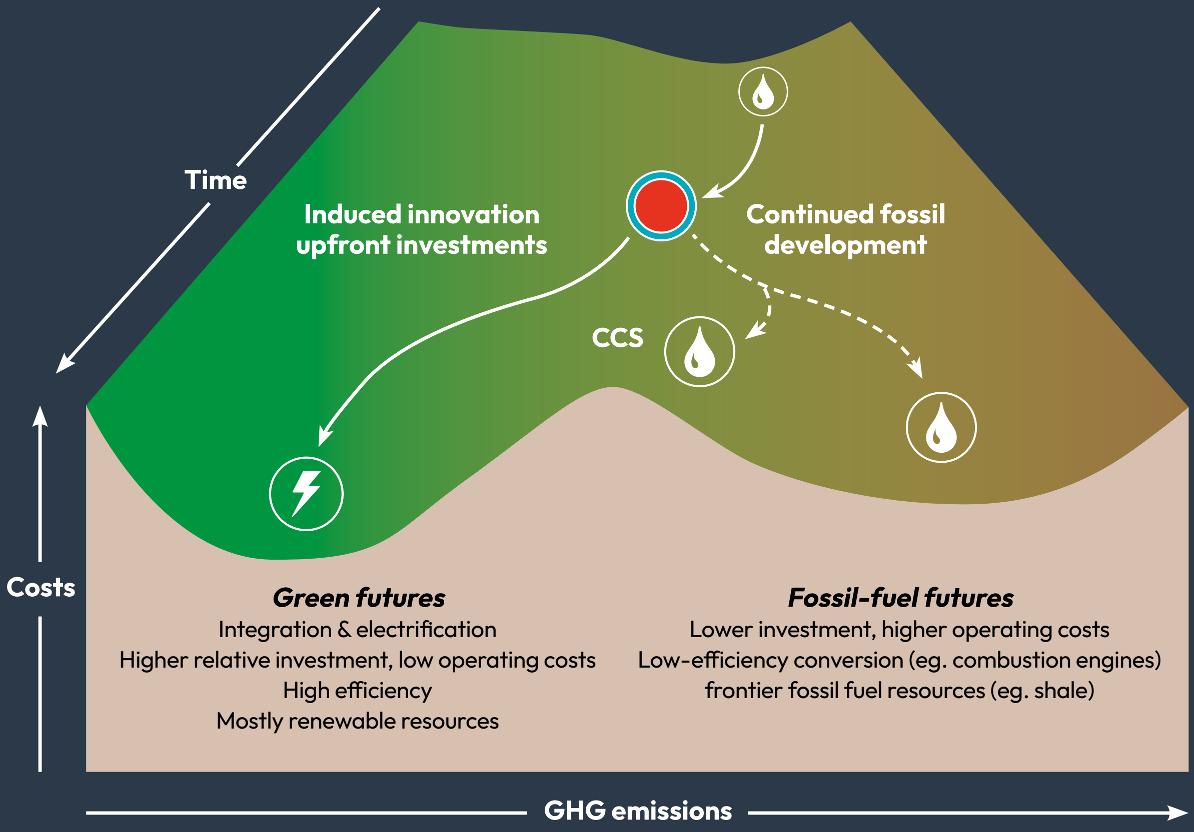
EEIST



ECONOMICS OF ENERGY INNOVATION AND SYSTEM TRANSITION: SYNTHESIS REPORT

AUTHORS: **MICHAEL GRUBB, 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

Contents

Authors and Affiliations

Prof Michael Grubb (Deputy Director) and Dr Yaroslav Melekh (Research Fellow) – University College London, Institute of Sustainable Resources.

Simon Sharpe (Senior Fellow) – World Resources Institute.

Dr Roberto Pasqualino (Centre Fellow) and Prof Laura Diaz Anadon (Research Director) – University of Cambridge, Centre for the Environment, Energy and Natural Resource Governance.

Dr Pete Barbrook-Johnson (Lecturer and Senior Research Associate) and Prof Doyne Farmer (Director) – University of Oxford, Institute for New Economic Thinking.

Dr Cristina Peñasco (Associate Professor) – University of Cambridge, Department of Politics and International Studies; now Senior Research Economist – Centre for Climate Change – Banque de France.

Prof Aled Jones (Research Director) – Anglia Ruskin University, Global Sustainability Institute.

Prof Andrea Roventini (Full Professor) and Prof Francesco Lamperti (Associate Professor) – Scuola Superiore Sant'Anna, Institute of Economics.

Saswata Chaudhury (Research Fellow) – The Energy and Resources Institute, New Delhi.

Dr Femke Nijsse (Lecturer), Prof Timothy M. Lenton (Professor) and Dr Jean-Francois Mercure (Associate Professor and Assistant Director) – University of Exeter, Global Systems Institute.

Songli Zhu (Associate Professor)– Energy Research Institute, China.

Prof Zhangang Han– Beijing Normal University of Systems Science.

Ulka Kelkar (Director) and Varun Agarwal– World Resources Institute, India.

Prof Xiliang Zhang (Director), Hongyu Zhang (Postdoctoral Researcher) and Yuyan Weng (Assistant Professor) - Institute of Energy, Environment and Economy, Tsinghua University

Prof Marcelo C. Pereira (Associate Professor) – Universidade Estadual de Campinas (UNICAMP), Brazil.

Prof Carlos Eduardo Frickmann Young (Professor) - Federal University of Rio de Janeiro, Institute of Economics.

Vidhu Kapur (Fellow) – India Climate Collaboratives.

About

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change.

By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

Led by the University of Exeter, EEIST brings together an international team of world-leading research institutions across Brazil, China, India, the UK and the EU.

The consortium of institutions are UK: University of Exeter, University of Oxford, University of Cambridge, University College London, Anglia Ruskin University, Cambridge Econometrics, Climate Strategies, India: The Energy and Resources Institute, World Resources Institute, China: Beijing Normal University, Tsinghua University, Energy Research Institute, Brazil: Federal University of Rio de Janeiro, University of Brasilia, Universidade Estadual de Campinas (UNICAMP) EU: Scuola Superiore di Studi Universitari e di Perfezionamento Sant'Anna.

Sponsors

EEIST is jointly funded through UK Aid by the UK Government Department for Energy Security & Net Zero, and the Children's Investment Fund Foundation (CIFF). The contents of this report represent the views of the authors, and should not be taken to represent the views of the UK government, CIFF or the organisations to which the authors are affiliated, or any of the sponsoring organisations.

Acknowledgements

The authors wish to thank the UK Department for Energy Security & Net Zero, the Children's Investment Fund Foundation (CIFF), the Quadrature Climate Foundation and Founders' Pledge for their support as sponsors of the EEIST project. We also wish to thank all those who contributed their time and expertise to developing and refining the analysis, concepts and ideas presented in this report, and in bringing it to publication. This includes, but is not limited to: Jacqui Richards and individuals from the Communities of Practice in EEIST partner countries, the EEIST Senior Oversight Group, and the UK government. Edited by Custom Editorial: www.customeditorial.co.uk

Executive summary

A reframing of the challenge

The economics of climate change has traditionally been framed in terms of the costs of cutting emissions, relative to a fossil-fuel dominated system, assumed to be cheaper. The reality is different. Decarbonisation involves a competition between two paths of investment: high and low-carbon ways of generating, and using, energy. The challenge is best understood not as an additional cost to existing systems, but as a choice in which lower carbon investment pathways involve profound, systemic transitions across many sectors. As such, it involves risks and opportunities of macroeconomic significance.

As the nature of this challenge has become clearer, so have the limitations of traditional economic tools. The Economics of Energy Innovation and System Transition (EEIST) project has worked to develop and apply analytical concepts and methods that can be useful to policymakers in this context of innovation and structural change. This Synthesis reports some of the key findings.

Lessons from past successes

Reviewing the most outstanding successes achieved so far in low carbon technology transitions in China, India, Brazil and Europe, we found that the policies most central to these successes were generally implemented despite, not because of, the predominant economic analysis and advice.

The critical policies were those that targeted investment towards emergent technologies – whether through subsidies, cheap finance, or bulk public procurement. These policies were successful because they strengthened the self-amplifying feedbacks of technology development and diffusion.

Cost-benefit analysis tended not to support the use of these most successful policies, because the new technologies were expensive at first, and there were cheaper ways to cut a tonne of emissions. This analysis was misleading, because the cheapest way to marginally reduce emissions at a moment in time was not the same as the cheapest way to launch a systemic transformation over time.

Decision-making frameworks

Innovation, by definition, involves uncertainty. We propose risk-opportunity analysis as a generalization of cost-benefit analysis, suitable for contexts of uncertainty, structural change, and diversity of interests.

Risk-opportunity analysis involves assessing the likely effects of policies on processes of change in the economy, instead of assessing expected outcomes at fixed points in time. It includes risks and opportunities that are uncertain, as well as costs and benefits that can be quantified. It presents outcomes in multiple dimensions, instead of converting them into one metric, allowing their relative value to be considered explicitly instead of assumed implicitly. Especially in the context of the purposive low carbon transition, risk-opportunity analysis is likely to be more appropriate to assess and compare policy options.

Principles for policymaking

Principles can inform decisions in the absence of extensive case-specific evidence. The principles that can successfully guide policy on innovation and structural change in the low carbon transition are different from those that apply when the aim is limited to the efficient allocation of existing economic resources without these dynamic considerations.

We propose principles for the transition, including that technology choices need to be made; that governments can invest and regulate to bring down technology costs, and should actively manage risks to crowd-in investment. Policy should target tipping points in the transition, to achieve disproportionate results. Multiple policies can be combined, including internationally, to achieve better outcomes. ‘Optimal’ policies in this context are impossible, so policy should instead aim to be adaptive. Analysis should consider uncertainties, dynamics, and distributional issues explicitly, and analysts should be aware of their biases.

Effective policy packages for the transition

There is no single policy that is best able to drive decarbonization. The combination of policies that is most effective is sector- and context-specific, and evolves over the course of the transition.

Typically, targeted investment policies such as subsidies or procurement are most cost effective early in the transition, when the priority is to improve new zero-emission technologies and bring them to market. In the middle of the transition, regulations, mandates, carbon pricing, and market reforms can reallocate investment from fossil fuels to clean technologies, spreading the latter quickly through markets and society. Later in the transition, deeper redesigning of markets, measures to increase social acceptance, and the establishment of new linkages between sectors all become more important.

Shifting analytical needs

The first generation of climate-economy models was designed to inform governments’ decisions on whether and how much to act to reduce emissions. As the global low carbon transition has become a reality, governments are now focused on understanding how to implement effective sector-focused and economically beneficial policy.

Though many mainstream models now illustrate the potential to move from a ‘high-carbon’ economy to a low-carbon one, by replacing fossil fuels with clean technologies, most say little about the transition process, and do not indicate which policies will be most effective. There is an increasing need for empirically validated modelling that can realistically represent an evolving economy, technological change, and a diverse range of policy options, and that can better explain and predict the effect of the low-carbon transition on jobs, economic growth, finance and trade.

Testing the new tools

The case studies contained in four EEIST project modelling reports show how a diverse range of analytical tools can be used to inform an equally diverse range of policy questions. We use probabilistic technology cost forecasts based on learning curves to show how the low carbon transition could save trillions of dollars globally, depending strongly on technology choices and the pace of the transition.

We use simulation models to compare policy options individually and in combination, in the power and road transport sectors, showing that some combinations achieve more than the sum of their parts, and others less. We model the interaction between technology choice and market design in the power sector, and the interactions between power and industry sectors that arise from alternative approaches to hydrogen infrastructure.

We use systems mapping to expose the different dynamics of alternative designs of carbon pricing policy, and economic complexity analysis to indicate where a country may have the opportunity to build new competitive advantages. We use disequilibrium macroeconomic models to simulate the effect of the transition on employment and GDP, and an agent-based model to simulate the effect of the transition on labour markets.

No model, conventional or otherwise, can offer comprehensive or precise evaluation. But useful insights can be generated by each of these techniques, and by comparing the outputs of different kinds of models – as illustrated in three national case studies.

A strong point of leverage

There is an urgent need for the analytical tools we present here to be further developed and diversified, made more widely available, and applied to policy.

Fundamentally, the energy transition requires an intellectual transition in economics, from a focus on the static costs of emissions abatement, to the dynamic economics of accelerating investment in zero-carbon systems and managing the disruptive change that follows.

Efforts to advance economic analysis and modelling might seem abstract, far removed from action ‘on the ground’, but in fact this may be a high point of leverage over global emissions. Effective policies make the difference between political will, financial capital, and industrial enterprise being deployed successfully or dissipated wastefully. Just as a change in policy can influence many investments, a change in economic understanding can influence many policies.

1. Introduction

All countries need to chart paths which increase welfare while reducing negative impacts on the environment. Though priorities differ between countries at different stages of development, a key dimension of this is transformation of energy systems away from the fossil-fuel-intensive models of the past century, as underlined in the IPCC Mitigation report.[1] Approaches to this challenge are strongly influenced by perceptions of the economics of emissions reduction, and the type of economic analysis brought to bear. Traditional approaches have often implied a focus on assumed costs of cutting emissions, sometimes with simplistic, and unrealistic, approaches to 'optimal' policy.

The need to transform whole systems, and practical experience combined with more sophisticated economic approaches, has exposed the limitations of these traditional economic tools. Just as the president of the European Central Bank complained that, in the face of the global financial crisis of 2008, "we felt abandoned by conventional tools", which were incapable of explaining what was happening to the economy,[2] so governments now feel the lack of available tools to analyse the practical options and impacts of the largest ever purposive structural change in the global economy. The EEIST project was established to help support, apply and promote more practically useful and realistic approaches, in all these dimensions:

- A 'bottom-up' approach to policy-engaged research, drawing directly on experience of successful policies (section 2) and working with research groups in different countries engaging with policy challenges through in-country Communities of Practice (Box 6).
- Distilling findings into principles to help guide decision makers contemplating a range of policy measures (section 3) and how these relate to the dynamics of transition (section 4).
- Identifying how the shifting needs of policymakers relate to modelling tools (section 5), and approaches to appraisal in terms of the risks and opportunities of low-carbon transition (section 6)
- Use of economic theories and modelling tools which can represent the dynamic nature of technological and economic systems, and potential transformations, applied to national scenarios (section 7) and more granular policy insights (section 8)

This Synthesis brings together some key insights from the project, including joint country studies (section 7), and three major cross-cutting stakeholder reports published by the project's partnership of researchers in China, India, Brazil and the UK:

- The New Economics of innovation and Transition: Evaluating opportunities and risks (launched at COP26, Glasgow, November 2021)
- Ten Principles for Policy Making in the Energy Transition: Lessons from experience (launched at Clean Energy Ministerial, Pittsburgh, September 2022)
- New Economic Models of Energy Innovation and Transition: Addressing New Questions and Providing Better Answers (launched at Energy Transitions Summit, Berlin, February 2023)

These main publications have been supplemented by policy briefs on specific aspects and a growing number of academic papers.

---

[1] The IPCC Sixth Assessment, Working Group III report Climate Change 2022: Mitigation of Climate Change, available at https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/; Hereafter (IPCC, 2022)

[2] ECB (2010)

PART A: Foundations and principles for policy

2. The most outstanding successes so far

What has driven progress to date in the low-carbon transition? The EEIST project's first major report, The New Economics of Innovation and Transition: Evaluating opportunities and risks (EEIST, 2021), combined theory with analysis of the policies that have delivered the most outstanding successes so far in the project partner countries.

The most important single development has been the revolution in renewable energy, and particularly **solar PV**.[3] From high costs and small volumes in 2005, policies for strategic deployment expanding from Germany and internationally on to China, resulted in global PV deployment by 2020 being ten times higher than had been projected only 15 years earlier: Chinese deployment soared from 300 MW in 2008 to over 250,000 MW in 2020, an 800-fold expansion in just 12 years. From being criticised as hopelessly uneconomic, by 2020 the International Energy Agency had concluded that solar PV – by far the largest global renewable energy resource – could increasingly offer 'the cheapest electricity in history', and global modelling projections for the rest of the century had to be completely recast within the space of a single IPCC assessment cycle (Box 1).

Box 1: The solar PV revolution and the upending of model assumptions

The solar revolution illustrates many of the core themes in EEIST, including the specific policy elements identified in section 3. It required **technology-specific supports** (1) for solar PV, spanning research and application to niche markets, much of it originating from US (including its space programme) and Australian R&D programmes. There followed **targeted investment and regulation** (2) particularly in Japan, helping to foster early development of commercial industries and supply chains. The large-scale developments awaited the commitments of the German Energiewende, which brought in **feed-in tariffs** for grid-connected PV to greatly reduce the risks facing investors (3) and thus crowd-in finance at multiple scales in the German economy.

The global tipping point (4) was reached when investors in China realised the potential for **scaling up production** to bring down the costs – initially to meet the demand emerging particularly in Europe, but later also spilling back into the Chinese domestic market and policy environment. As summarised in the EEIST case study with China,[4] and detailed in the book How Solar Became Cheap,[5] this was supported by a **variety of policy instruments** (5); these included a growing role for **government deployment policies** which also supported international trade and investment (including private capital to scale-up startup companies).[6]

Nothing so vividly illustrates the central importance of including induced innovation in models and mindsets. The German solar feed-in tariffs were almost universally decried by economists as a hopelessly expensive way of cutting emissions. Up until about 2010, almost all the models used to evaluate the cost of deep decarbonisation ignored the possibility for a solar revolution – as late as 2014, The Economist called solar power "by far the most expensive way of reducing emissions", adding that governments "should target emissions reductions from any other source".[7] The scope to reduce costs by mass production in the then-emerging economy of China for the policy-driven European market was largely overlooked. Most models covered in the IPCC's Fifth Assessment in 2014 continued to project a small role for solar even in the context of deep decarbonisation by mid-century.

By the IPCC's Sixth Assessment – Mitigation Report published in 2022, in contrast, the models were struggling with the opposite question: how to represent as an 'emissions mitigation policy' renewable energy options that were in many regions cheaper than fossil fuels. Earlier modelling studies had to be ditched. The assumptions have now changed, but the more general lessons, of **the need to represent technology and innovation dynamics** – as now being exemplified by the ongoing revolution in batteries and some other technologies – have yet to be adequately embodied in most models (footnotes notes 2, 4).

---

[3] Nijsse et al. (2023)

[4] EEIST (2021), Appendix 2: Solar PV in Germany and China

[5] Nemet (2019)

[6] Grubb et al. (2021); Way et al. (2022)

[7] The Economist (2014)

In India, bulk public procurement was used to promote the adoption of highly efficient **LED lighting**, together with a financing scheme in which the government subsidised the purchase price and recovered the cost through instalments on electricity bills. This catalysed explosive growth in LED sales, from 3m in 2012 to 670m in 2018, with an 85% fall in prices between 2015 and 2019 – creating the demand-side equivalent of the PV revolution, and the 'cheapest lighting in history'. As well as cutting emissions, the scheme led to the development of a new manufacturing sector in India with a market value of more than $1bn, and brought electric lighting to many homes for the first time, completing the drive to bring lighting to 99% of households in 2020.[8]

In Brazil, concessional finance from the national development bank was used to overcome high costs of capital for the development of **onshore wind power**, which was further incentivised by deployment subsidies. Onshore wind capacity rose from negligible levels in 2010 to providing nearly 10% of Brazil's electricity generation by 2020. At the same time, Brazil's wind industry developed rapidly, with more than a hundred firms in the supply chain, employing 150,000 people.[9]

In the UK, deployment subsidies, first as a premium subsidy added to the market price, and later as fixed-price contracts allocated by auction, were critical to the growth of **offshore wind power**. As the market grew, costs fell by 70% within the decade, from several times the (wholesale) market price of electricity to below the wholesale market price.

Offshore wind is the UK's biggest renewable energy resource, and the industry now supports more than 30,000 jobs and forms a central role in the UK's decarbonisation plans.[10]

A common factor across these case studies was that the policies most central to their success were those that targeted investment towards the new technologies – whether through subsidies, cheap finance, or bulk public procurement. They were not the policies most often recommended by economic theory: public R&D funding along with carbon pricing.

A second commonality was that the most widely used economic framework for public policy appraisal – cost-benefit analysis – did not recommend the use of any of these critically important policies. Because the new technologies were expensive at first, there were many cheaper ways to reduce a tonne of emissions at that moment in time, such as improving the efficiency of coal power plants, using biomass for power or planting trees to offset emissions. But when major change is required, 'current least cost' is misleading given the dynamics of positive feedbacks for new technologies (Box 2).

For both these reasons, the policies central to these outstanding successes were generally implemented despite, not because of, the predominant economic analysis and advice. These reflections imply an approach to policy appraisal (and techniques) more suitable for a major, purposive and structural transition.

---

[8] EEIST (2021) - Appendix 3: Transforming lighting efficiency in India, Chaudhury (2024) and Malhotra et al. (2021)

[9] EEIST (2021) - Appendix 1: Wind Energy in the UK and Brazil

[10] Norris (2022)

Box 2: The dynamics of positive feedbacks

The success of the targeted investment policies can be understood in terms of their effect on feedbacks in the development and diffusion of the new technologies. New technologies often benefit from reinforcing feedbacks, which include:

- learning-by-doing (experience leads to better technologies)
- economies-of-scale (expanded production and delivery systems make it cheaper)
- the emergence of complementary technologies (growing use stimulates development of other technologies that make it more useful, more widely)
- and the feedback between rising investment, falling cost, growing confidence (reducing financing costs) and growing demand.

Targeted investment directly stimulates these feedbacks, creating a self-amplifying effect. Early in the transition, policies focused on taxing incumbent technologies may not stimulate such self-amplification.

Scale takes time, and progress may seem modest at first. The dynamics typically unfold as a phase of exponential growth, during which the contributions at first seem small with little impact on the dominant system (or emissions) – but then developing as an 'S-curve' dynamic displacing the older technologies, or simply offering new options in the course of economic development.

The potential for policies to drive cost reduction is often missing from cost-benefit analysis. The cheapest way to cut emissions at a moment in time is not necessarily the cheapest way to cut them over time. Moreover, these policies had positive effects in many dimensions beyond cutting emissions – in many cases creating jobs, improving energy security, increasing access to electric lighting, and reducing air pollution. Such effects were rarely quantifiable in advance.

Source: EEIST (2021), Grübler et al. (2012) in GEA (2012) and Meng et al. (2021).

3. Principles for policy design, development and appraisal

Principles are used to determine what detailed analysis should be undertaken, or, in the context of deep uncertainty, to inform decisions in the absence of extensive evidence. The dynamics of major transitions in technologies and sectoral structures imply different approaches to policy compared to traditional economic policy prescriptions. Using the case studies, combined with dynamic theories of economic development and innovation as reviewed in EEIST (2021), we derived principles for policy design, development and appraisal for energy transitions in EEIST (2022). This EEIST 2022 report explains that these ten principles complement, and, in many cases, stand in contrast to, traditional principles typically taught in economics.

Five of these principles focus on aspects of policy design for energy transitions:

1. **Technology choices need to be made.** Existing structures and policies intended to be neutral can have a de facto bias towards incumbent technologies and businesses, and incremental change. In a context of innovation and structural change, policies will almost always advantage some technologies more than others. Existing structures may impede the adoption of better technologies (as with many aspects of energy efficiency), and it is better to support innovation, particularly in options which enhance efficiency or low-carbon technologies and businesses, and which draw on large low-carbon resources like wind and solar, and the corresponding system requirements for storage and networks.
2. **Invest and regulate to bring down costs.** Innovation and deployment are not economically separate processes, but are intertwined.[11] 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. This can strengthen reinforcing learning-by-doing feedbacks in technology development, deployment and diffusion.
3. **Actively manage risks to crowd-in investment.**[12] 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 or underwriter, can reduce the risk and financing costs of low-carbon technologies and greatly increase rates of investment and deployment.
4. **Target tipping points.**[13] A dynamic perspective underlines that technologies and systems can develop in different directions, and sometimes modest interventions can open up new avenues. Well-targeted interventions can activate tipping points in technology competitiveness, consumer preference, investor confidence or social support for transitions, where a modest input leads to a large change in possibilities and direction. This can inform the targeting and level of subsidies and taxes, and the stringency of regulations.
5. **Combine policies for better outcomes.** A combination of policies will be needed to drive each low-carbon transition, and the appropriate combination will change over time. Since 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 and have an effect that is 'greater than the sum of the parts' (see section 4).

The dramatic transition in UK electricity, and the cost of offshore wind energy in particular, offers one illustration of these principles (Box 3).

---

[11] IPCC (2022, Chapter 16) and Systematic Review of Grubb et al. (2021)

[12] For example, renewables investment in most competitive electricity markets faces the risks associated with uncertain fossil fuel prices, whereas fossil fuel investors are largely self-hedged because they set the price. Internationally also, whereas major fossil fuel investments typically sell into international markets, in US$, renewables tend to sell power in local currency so international investors face currency risks. Hence in both cases, the markets as currently organised contain structural imbalances against renewables investment. At the macro level, other risks such as those associated with critical mineral supply need to be considered; this may create bottlenecks or price spikes for investment in renewables or batteries (for a recent concise review see Ekins (2023), Chapter 8), a possible risk to construction costs but not operation. Fossil fuel investors also do not generally yet carry the risks associated with climate change.

[13] Farmer et al. (2019), Sharpe and Lenton (2021)

Box 3: The UK transition in electricity generation

The UK electricity 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 CO2 emissions reduced by around 45% between 1990 and 2022,[14] with an average rate of decarbonisation faster than anywhere else in the G20 between 2000-2020.[15] At the same time, energy consumption reduced by 13% while GDP grew by 71%. Seen as a European laggard in renewable energy until early this century, the UK became one of the world's leading countries for offshore wind energy, and the contribution of renewables to its electricity generation has soared from well under 5% to over 40% during the past 20 years.[16]

Around two-thirds of CO2 reductions in the UK over this period have been delivered by a decarbonising power sector.[17]

Technology choices. After a decade of 'technology-neutral' policies to foster renewable energy in general, it was recognised that subsidies were flowing to the most-developed and lowest-risk options. A decision to amplify incentives to develop offshore wind – which is the UK's biggest physical resource – was a major step.

Invest and regulate. The efforts included direct investment in R&D, including a government-funded Offshore Wind Accelerator to foster industrial collaboration between companies, and large-scale investment in deployment subsidies, along with regulatory measures around standardisation, seabed leasing and offshore transmission.

Actively manage risks to crowd-in investment. These efforts established offshore wind as a viable technology, but costs initially remained high, in part because investors faced not only technology risks, but major revenue risks from the volatile electricity wholesale market. Contracts for Difference offered fixed electricity prices, procured through competitive auctions, enabling bank financing at a much lower cost-of-capital. With a 'virtuous circle' between induced R&D, learning-by-doing, scale economies and lowered cost of capital, the cost of offshore wind fell sharply – in real terms, from over £200/MWh to around £50-60/MWh in less than a decade.

Targeting tipping points. The UK had built up capacity of gas generators, but coal remained the baseload. A carbon floor price scheduled to rise over time (later, a top-up on the EU ETS price) made it plain there would be no future for new coal, and tipped the economics to ensure gas ran before existing coal.

Policy packages. Many other policies served to secure the transformation of UK electricity. Standards and company obligations for energy-efficient appliances and lighting turned the historic growth of electricity demand into a decline. Squeezed between gas and rapidly rising renewables, there was then little need for coal, except for backup, and a Capacity Market ensured that the UK has sufficient capacity to cover for days with little wind energy, including increasing amounts of storage and other firm and flexible power options.

Sources: EEIST (2021) Annex 1: Wind energy in the UK and Brazil

From the combination of analysis and experience with engagement and national policy debates, we derived five more principles for policy development and appraisal:

6. **Policy should be adaptive.** There are many paths along which the economy can develop over time, and with constant learning. It is often impossible in practice to identify the 'best' in terms of public goals, or even 'least cost' economically, so there may be no knowable and enduring 'optimal' policy choice. Policy should be designed to be adaptive, so that it can more easily respond to unforeseen changes, incorporate learning, exploit opportunities and manage risks. In all five regions of the EEIST project, the most effective policies were those that built upon the capacity and learnings associated with earlier policies, understood their limitations as technologies evolved and expanded, and adapted policies accordingly.
7. **Put distributional issues at the centre.** Low-carbon transitions inevitably involve transfers of economic resources. Distributional issues should be central to policy analysis, since they are important for environmental, economic and social goals, and are likely to have a strong bearing on social support for the transition[18]. Distributional dimensions are highlighted both by international modelling and a focused study on the challenges facing Chinese coal production (Box 4).

---

[14] DESNZ (2023)

[15] PWC (2021)

[16] UK Government (2023)

[17] BEIS & ONS (2022)

8. **Coordinate internationally to grow clean technology markets.** Given scale economies and the potential for specialisation in different parts of value chains, the transition will be accelerated if countries coordinate internationally to grow clean technology markets, in each of the emitting sectors of the global economy. This can lead to faster innovation and larger economies of scale, accelerating the cost reduction of clean technologies, with benefits for all countries.
9. **Assess opportunities and risks.** Policy appraisal should consider risks and opportunities, not just costs and benefits, when unquantifiable or very uncertain factors are likely to be important. Where the aim is transformational change, appraisal should consider the effects of policies on processes of change in the economy, alongside their expected outcomes.
10. **Know your biases.** The construction of economic models (and mindsets) unavoidably involves many choices that will influence their outputs. This was a strong finding also of our studies of the role of models in European policy appraisal.[19] We should be aware of our biases, make model choices transparently, and where possible, compare a range of models, with different theoretical assumptions, instead of a single one.

Box 4: Anticipating and addressing distributional concerns: China and Global

Economic appraisal tends to focus on aggregate outcomes (e.g. overall GDP or global cost), but there are both ethical and pragmatic reasons for policymakers to be deeply concerned with distributional impacts. This applies at both national and international levels.

Chinese coal. Perhaps the world's biggest single national challenge of 'just transition' will be that of coal in China. Between 2014 and 2020, the total number of jobs supported by mines servicing Chinese coal plants halved, from 5.3m to 2.7m workers. This occurred along with an 8%-per-year increase in labour productivity, modernising its coal mining and closing down small and inefficient coal mines.

Our analysis suggests that the trend of declining coal industry employment will continue, but inevitably will be faster in the context of Chinese decarbonisation. Provinces with smaller, more efficient workforces will experience less impact than large and highly labour-intensive ones. The coal-producing provinces of Inner Mongolia, Shanxi, Shaanxi and Xinjiang will face particular challenges in managing localised effects and retraining workers for other more productive sectors.

There will be significant fiscal effects. At present, total tax revenues associated with the coal industry amount to more than CNY 300bn (£40bn), and are shared between provincial and central government. However, subsidies to the thermal coal industry are even larger, we estimate at around CNY 480bn (£60bn) (before accounting for the uncosted impacts of coal on health, environment and climate change). The overall net effect of accelerated transition is likely to be positive for public finances, but managing the distributional fiscal changes – including between different provinces, and between provinces and central governments – will be challenging.

International disparities. Like climate change itself, the low-carbon transition will have widely varying socio-economic impacts. Inevitably, there will sectoral shifts as low-carbon industries grow and displace carbon-intensive ones. Our analyses also show that impacts on national employment and trade balances will vary widely between different countries and regions, and may be more dramatic, both positively and negatively, than economy-wide metrics suggest.

This structural change could represent significant economic upsides, particularly for countries with net fossil fuel imports, where decarbonisation improves the trade balance, but regions with large carbon-intensive industries risk post-industrial decline. Transformative economic policies, where appropriate, supported by international finance for 'just transitions', will be key to diversifying local economies, improving their resilience and enabling them to gain a stake in international low-carbon value chains.

Sources: Clark et al. (2023) and Lynch et al. (2023)

---

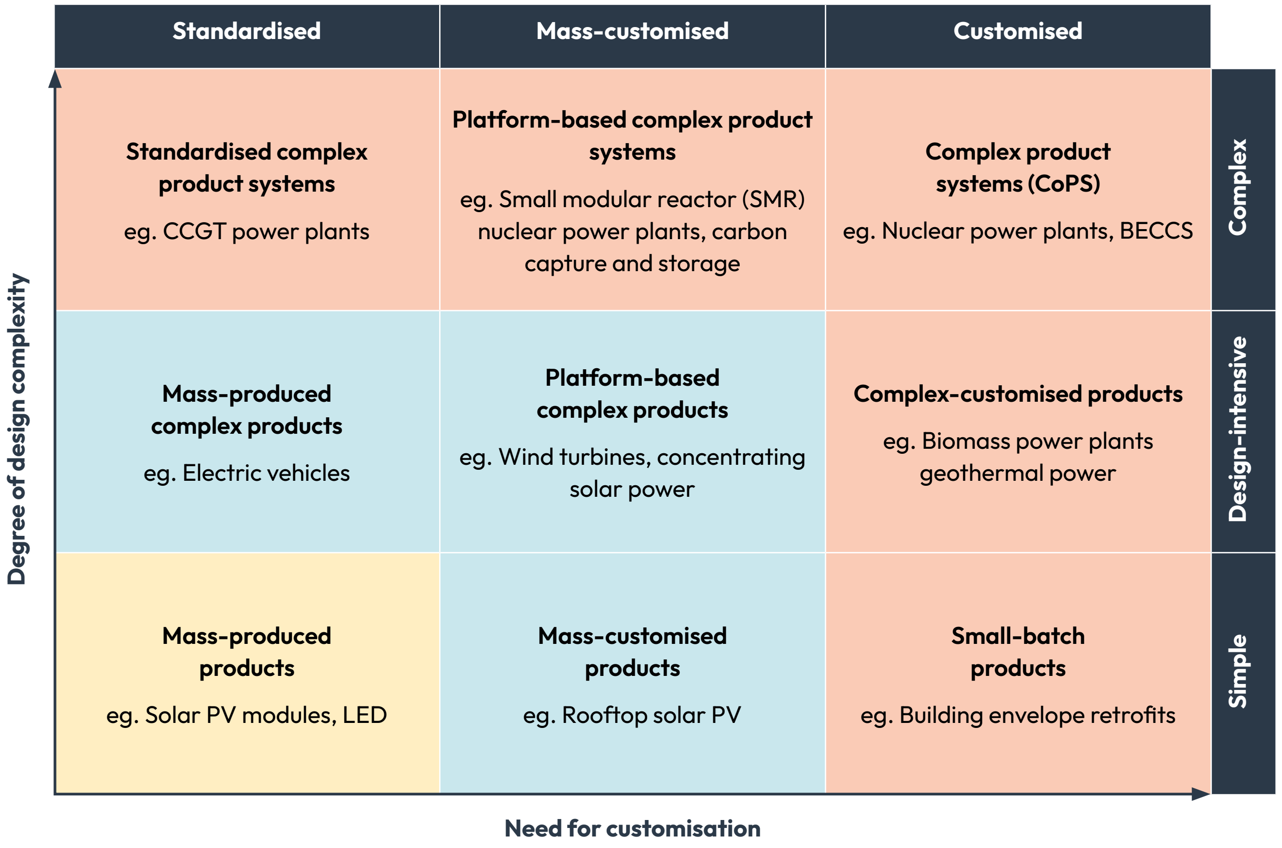
[18] Peñasco, Anadón and Verdolini (2021)

[19] Royston et al. (2023)

On the last of the 10 principles, a particular source of bias concerns cost projections.[20] It is well known that complex projects often exceed their estimated costs – sometimes, hugely. In the UK, public servants are taught to beware of 'optimism bias'. The history of renewable energy over the past 20 years has seemed the opposite – costs have declined more than almost anyone expected.[21] This illustrates the need for a more nuanced understanding of potential biases, and ways of mitigating them.

One useful approach is summarised in Figure 1. Technologies that are larger and inherently complex, and which require customisation for each site or context (top right), tend to learn slowly and indeed have large potential for cost overruns. Conversely, however, technologies which are quite simple to assemble and distribute at massive scale (bottom left) – though they may utilise sophisticated components – seem to exhibit rapid learning and industry-scale economies.

Figure 1: Potential for cost reductions based on high-level technology characteristics



Standardised	Mass-customised	Customised	
Standardised complex product systems eg. CCGT power plants	**Platform-based complex product systems** eg. Small modular reactor (SMR) nuclear power plants, carbon capture and storage	**Complex product systems (CoPS)** eg. Nuclear power plants, BECCS	**Complex**
Mass-produced complex products eg. Electric vehicles	**Platform-based complex products** eg. Wind turbines, concentrating solar power	**Complex-customised products** eg. Biomass power plants geothermal power	**Design-intensive**
Mass-produced products eg. Solar PV modules, LED	**Mass-customised products** eg. Rooftop solar PV	**Small-batch products** eg. Building envelope retrofits	**Simple**

Note: From Malhotra and Schmidt (2020), who describe these as Type 1 (yellow), Type 2 (blue) and Type 3 (red) technologies respectively (see text). For further discussion see source, and EEIST (2021).

This approach can aid understanding of long-standing observations about different 'learning rates' (% cost reduction associated with doubling of scale). Notwithstanding fluctuations, the long-run trend of observed cost reductions seem persistent for a given technology; previous trends generally prove a good guide to future potentials for continued 'learning rate' cost reductions.[22] 'Design complexity' and 'need for customisation' warrant careful definition to place technologies along these axis (ie. within the matrix of Figure 1). Nevertheless, in combination with other research,[23] this stylised mapping can offer both an explanation of why observed learning rates differ between technologies, and a first insight to likelihood of future cost reductions – or overruns – for emerging or proposed technologies with limited track records.

---

[20] Another common bias, not explored in EEIST, has been a tendency to over-project energy demand as economies mature beyond the stage of basic industrialisation.

[21] Meng et al. (2021)

[22] Way et al. (2022)

[23] Basnet and Magee (2017), Wilson et al. (2020)

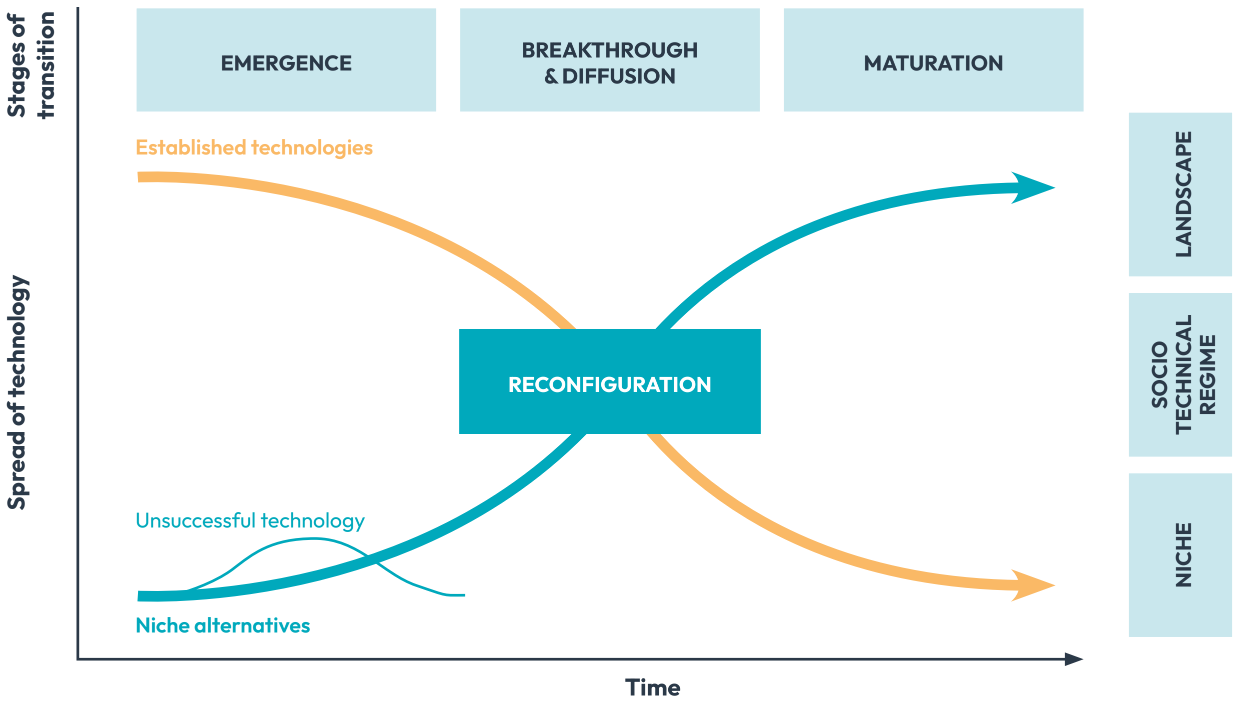
4. Effective policy packages for the transition

Economies are dynamic, imperfect, diverse and complex.[24] Deep decarbonisation will involve changes in technologies, business models, markets, infrastructure and institutions. The IPCC describes this process as 'rapid and far-reaching system transitions' in energy, land, transport, buildings and industrial systems. The policy approach developed in the EEIST project differs fundamentally from the common economic recommendation. Traditionally, economics has framed the problem in terms of balancing the benefits of reduced climate change against an assumed additional cost of cutting emissions – a 'marginal abatement cost'. Climate impacts are a market failure 'externality', and the prescription is to internalise these in market transactions through a carbon price (to create incentives for incurring the assumed additional cost of cutting emissions).[25]

In reality, deep decarbonisation involves competition between two investment streams: high and low-carbon ways of generating, and using, energy. Within the mainstream economics literature, formalised mathematical models have begun to emerge which represent this directly, rather than through an assumed 'abatement cost'.[26] Their representation of policy remains mostly confined to R&D and broad economy-wide incentives.[27] But with technology learning embodied, such models were the first in mainstream economics to acknowledge that low carbon could become cheaper than high carbon (even more so when damage costs are included).

This simple but profound shift moves attention to the dynamics of energy innovation and transition from high to low-carbon technologies. After a period of technology emergence, a typical bell-curve pattern of adoption results in new technology market share growing in an 'S-curve' of (i) market emergence, (ii) breakthrough and diffusion, and (iii) maturation – with corresponding impacts on incumbent technologies (Figure 2).

Figure 2: Stylised S-curve dynamic: 3 stages of technology growth and displacement



Source: As depicted in IPCC (2022), Tech. Summary and Chapter 1 (Figure 1.7). Innovative technologies or practices if successful, typically emerge from niches into an S-shaped dynamic of exponential growth. The diffusion stage often involves new infrastructure and reconfiguration of existing market and regulatory structures. During the phase of more widespread diffusion, growth levels off to linear, then slows as the industry and market matures. The processes displace incumbent technologies/practices, which decline, initially slowly, but then at an accelerating pace. Many related literatures identify three main levels with different characteristics, most generally termed micro, meso and macro.

---

[24] Stern (2018)

[25] This approach has long been challenged from other disciplines (such as climate science, engineering and philosophy) and indeed by some leading economists, most notably the well-known arguments of Nick Stern, including as brought together in his book Why Are We Waiting (Stern, 2016).

[26] Namely, Acemoglu et al. (2012) and Golosov et al. (2014). The former suggested that the combination of R&D and relatively modest carbon taxes could lead to a wholesale change of the system; the latter noted that "the costs of inaction are particularly sensitive to the assumptions regarding the substitutability of different energy sources and technological progress" – factors to which much of the prior economics literature had paid inadequate attention, but which formed a major focal point of the EEIST project.

[27] Such models have still tended to equate innovation with R&D, or generalised rather than technology/sector-specific learning-by-doing, and assume that cheaper technologies will automatically and promptly dominate once developed, which empirical studies covered by EEIST show is not generally the case.

The IPCC Mitigation Report[28] sought to integrate this approach with developments in social science 'multi-level perspectives' to understanding the nature of transitions. This includes emphasising the role of niches from which new technological systems can emerge, and the typical need to reconfigure the 'socio-technical regimes' through which existing market structures tend to favour incumbents and raise obstacles to transitions (This also informs the diagrammatic representation of how policy combinations may evolve in the course of transitions shown in Figure 3 below).[29]

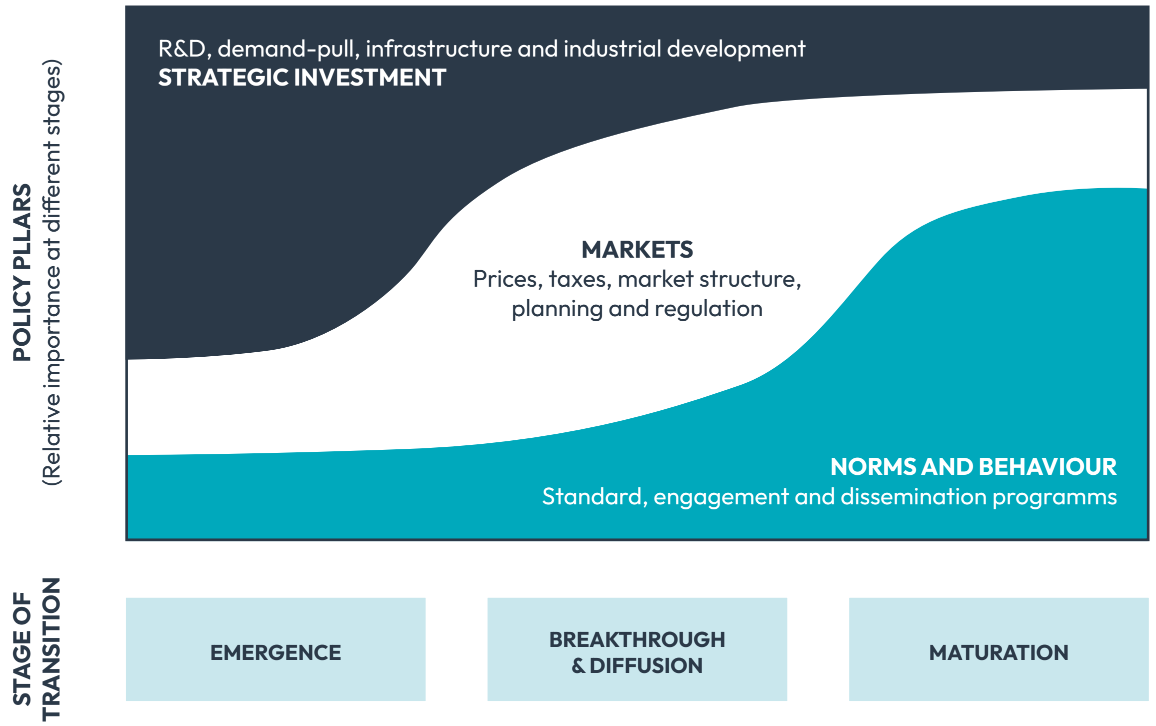
Coupled with the practical experience noted in Section 2, and the theoretical and modelling approaches presented in Part B of this synthesis report, this underpins our recommendations to focus attention on:

1. the technologies that matter for deep decarbonisation
2. the scale-investment and regulation required to bring down their costs
3. the shifting of investor risks away from emergent low-carbon industries to the established but damaging incumbent fossil fuel systems
4. Identification of potential 'tipping points' towards cleaner energy systems.

Figure 2 depicts the transition process in a way to illustrate that the rise of one technology leads to another's decline. Transitions lead to winners and losers (hence also our second principle for design and implementation: **to put distributional issues at the centre**). The scale of the challenge – among the much wider literature on 'just transitions' – is illustrated in the EEIST research identifying the dramatic decline in mining jobs (and tax revenues) as part of the socio-economic impacts of coal transition in China (Box 4).[30]

All this informs our fifth principle, that such **major, purposive transitions require a mix of policies.** There is no single 'optimal policy mix', but rather, combinations of policies – often, sector and context specific – which need to evolve through the course of a transition. A simple structured approach helps to categorise the roles of different policies, and thus also understand where and how they may be complementary (Box 5).

Figure 3: Indicative evolution of policy mix over the course of transition



Source: EEIST (2021), Figure 9; also depicted in IPCC (2022), Tech. Summary and Chapter 1 (Figure 1.7, upper panel). Indicates how the relative emphasis on different 'pillars of policy' may vary according to the stage of the transition.

Box 5: A dynamic 'three pillar' approach to transition policy

For technologies that are still underdeveloped and in evolution, policies beyond R&D itself need to harness the positive feedbacks identified (Box 1) so as to support the typical 'S-curve' evolution of transition (Figure 3):

1. Early in the transition process, the priority is to improve the new zero-emission technologies and bring them to the market. Targeted investment policies (like subsidies or procurement) are likely to achieve this most cost effectively, which may include anticipatory investment in necessary infrastructure.
2. In the middle of the transition, the priority is to spread the new technologies quickly through markets and society, displacing fossil fuels. Consumer demand for the new cleaner technologies can play an important role, if market structures facilitate this. Along with market reforms, support may evolve towards broader policies on emissions pricing or regulation, in combination to make clean technologies cheaper than the fossil fuel alternatives. Regulations or mandates can be used to reallocate industry investment towards the clean technology, accelerating diffusion and cost reduction. Which specific policies or policy combinations are most effective will depend on the sector, the country and the context.
3. In the mid-to-late stages of the transition, deeper redesigning of markets, and overcoming remaining barriers for adoption at scale, including widespread social acceptance and associated norms, assume greater importance. In this stage, links to other sectors and complementary technologies may also be crucial to fully realising the potential – as with electric vehicles or heat storage in well-insulated houses – to integrate as part of an overall more efficient and cleaner energy system.

Each of these diverse 'pillars of policy' can be anchored in foundational economic literatures, and can be mutually reinforcing.[31]

This approach also reflects the first of our principles for designing and implementing policies: that **policy should be adaptive** (EEIST 2022). Direct strategic investment in low-carbon technologies can accelerate their developments while governments seek to reform markets and strengthen appropriate pricing – but the duration of support, and the timing of stronger use of market competition, regulation and carbon pricing can adapt to the progress secured.

Indeed, even where technologies are already clearly known, available and economic, they may not be adopted at scale, or rapidly. Hence the potential value of targeted policies to accelerate diffusion, which need to be grounded in an understanding of the behavioural and structural impediments, which may be diverse. This, in fact, is the case for many energy-efficient technologies, such as with efficient buildings, appliances, lighting and heating systems.

Thus, effective policy packages for transition are complex and country/time specific, and a rapidly growing field of research is emerging to establish the best overall approaches.[32] The IPCC Sixth Assessment underlined the need for policy mixes, and emphasised the corresponding importance of governance approaches and enabling conditions to help countries manage the energy transition.[33] We add the need for corresponding developments in analytic approaches and capabilities, to which the rest of this Synthesis now turns.

---

[28] IPCC (2022), Chapter 1

[29] As pioneered through numerous articles by Geels et al., and applied recently specifically to low-carbon transitions as The Great Transformation (Geels and Turnheim, 2022)

[30] Clark et al. (2023)

[31] Grubb et al. (2023)

[32] Key references for this emerging literature include the results of research programmes carried in Special Issues led by Rogge and colleagues at the UK's Science Policy Research Unit (Rogge, Kern and Howlett, 2017; Rogge and Song, 2023) and analysis of sustainability transitions policy as reviewed by EEA (2019)

[33] IPCC (2022), especially chapters 4 and 13.

PART B: Analytic approaches and insights

5. New approaches for shifting needs

The last 15 years have seen an important but rarely remarked-upon change in analysts' climate change responses: from technology and economic assessment of whether and how much to act (and debating appropriate carbon price level and design), to needing to understand how to implement effective sector-focused and economically beneficial policy.

Engagements through our Communities of Practice (Box 6) underlined that climate change has moved internationally beyond an issue of relevance mainly to environment ministries: it now involves the broad policy and planning functions of government, including energy, transport, housing, industry, finance and economy ministries, as well as regulatory functions such as central banks and financial regulation. Governments around the world are no longer debating whether to do something, but are designing detailed sector-focused policy, in the context of strategic goals which span multiple ministries.

Box 6: Communities of Practice

Policies are developed and implemented by governments, not by researchers. They are developed in a context of contested claims, under the influence of strong interest groups, and in specific institutional structures. They can involve struggle between entrenched ideas, innovative thinking and technological change – at multiple levels from the local to the global – within complex and sometimes volatile political contexts.

Consequently, useful economic and policy research needs to be informed by, and engaged with, policy processes within country contexts. While implemented by a consortium of research institutes in relevant countries, **the EEIST project engaged with governments in the UK, China, India and Brazil to ensure the work was relevant to policy.**[34]

Through the project partners, the project followed a structured approach to develop Communities of Practice (CPrs) to engage policy analysts and decision makers in articulating issues of concern, and reactions to initial research.[35] Early engagement served to clarify the nature of current decision-making processes, and national approaches regarding the pros and cons of formal appraisal processes.[36]

The engagements across the CPrs also informed relevant case studies on how the technology breakthroughs observed involved international developments, with different countries playing different roles as technologies developed (as reported in the separately published Annexes to our first report (EEIST, 2021) and case studies in our second report (EEIST 2022). CPrs thus informed research on the priorities of the governments in each of the partner countries, and widened familiarity with new economic thinking and related capacity. In total, there were almost 20 CPr events, spread across the five regions/countries.

A culminating conference (Brown, Hinder and Hobgin, 2023) held small workshops on three key sectors (electricity, transport and industry) and identified five cross-cutting themes for policy-engaged research on the energy transition, which inform this Synthesis report.

In industry, the same shift has been seen. Where businesses once considered climate change (if at all) as an issue of corporate social responsibility, they now understand the need to make strategic decisions to position their business for success as the low-carbon transition reshapes global markets and supply chains. Similarly, investors have gone from ignoring climate in the early 2000s, to needing to understand their exposure to climate and transition risk.

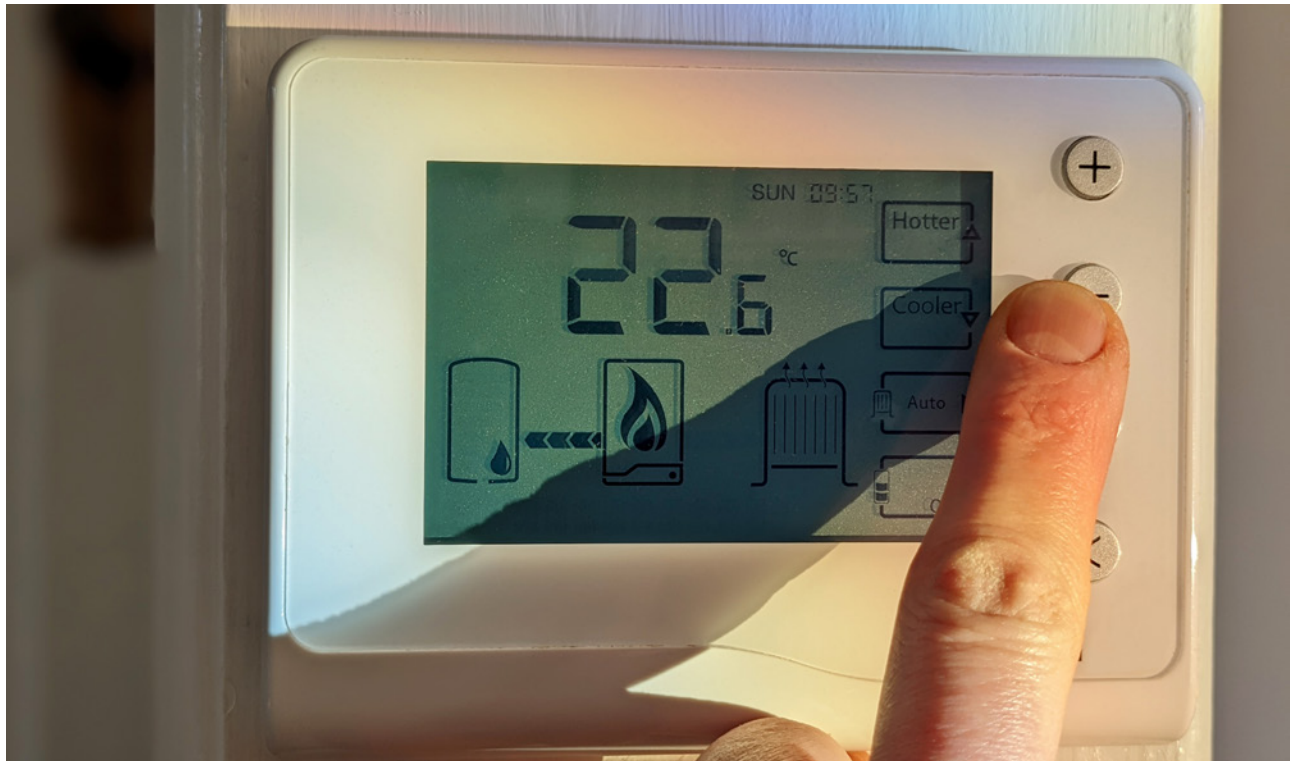
Without the capacity and analytics to match these needs, policy and industry ambition risks being dissipated ineffectively instead of being used to achieve rapid, structural change.

International discourse on the economics of decarbonisation has been largely framed by global Integrated Assessment Models (IAMs) that shape IPCC scenarios in projecting 'least-cost' technology pathways. In the most recent IPCC Assessment, most IAMs updated their assumptions to include the much lower cost of renewables, which already informs assessment of progress being made towards lower global temperature increases (due to lower projected 'reference' emissions and/or mitigation costs) than previously projected.

Only a few (about seven) of these IAMs substantially model induced innovation.[37] Some have become highly sophisticated in such representations, but remain quite aggregated and rely on economy-wide indicators or policies (principally, marginal cost and implied carbon prices) combined with R&D. They can explore aspirational technology pathways that meet climate targets, but have limited representation of the complex realities of current markets, the actual dynamics of change, or – crucially – the range of potential policies available. Put more bluntly, **they have become much better at meeting the former needs of decision makers.**

As noted, literature spanning hundreds of papers over many decades has established the reality of 'technology experience curves' – how the cost of technologies tend to fall by a relatively constant fraction with each doubling of global deployment, although for some technologies the variability in the learning rate over time is greater than for others.[38]

Our analysis (note 6) supports both the apparent long-term continuation of such 'experience curves' and their systematic differences between technology types (as illustrated in Figure 1). It is also not surprising if newer technologies have more scope for learning and cost reduction. In contrast to solar, wind, LEDs and batteries (and most IT-related technologies), the delivered price of fossil fuels, nuclear energy and biomass power generation shows no sustained trend of falling costs. Projecting forward, using stochastic techniques derived from past variations in cost trends/learning rates to account for uncertainties, this suggests a rapid global transition to clean technologies could save many trillions of dollars by 2050, compared to continuing the use of fossil fuels, and that the savings would be less from a slower transition.[39]



---

[34] Work in the three major emerging economies was supported by a grant from the UK Department of Business, Energy and Industrial Strategy. The work on CPrs in the EU and UK was supported by a grant from the Children's Investment Fund Foundation (CIFF).

[35] Despite the limitations of the COVID-19 pandemic, key stakeholders were identified and interviewed starting from the first CPr events, building one-to-one relationships, to support engagement in the country and ground analysis in the specific context of the legal and policy systems; see note 5. Launch of the major reports at international policy events, and a conference at Wilton Park, served to mainstream some of the core messages of EEIST.

[36] Qin et al. (2023)

[37] Grubb, Wieners and Yang (2021)

[38] See the Systematic Review on induced innovation (Grubb et al., 2021) conducted for input to the IPCC Sixth Assessment, covering hundreds of papers and methodologies including an Annex summarising findings from more than 70 papers estimating learning curves.

[39] Way et al. (2022)

6. Decision-making frameworks: risk-opportunity analysis and modelling foundations

Innovation, by definition, involves uncertainties – even more so when expanded to encompass transitions in complex systems. This led the EEIST project to promote an approach of **risk-opportunity analysis** (ROA).

Responsible public policy analysts seek actions with expected social benefits exceeding the costs. Over the years and in many countries this principle has been translated into a technocratic expectation to quantify overall (i.e. aggregated) expected benefits and costs, so they can be compared on a common basis, generally in terms of monetary equivalence. The resulting formalised approach to cost-benefit analysis (CBA) is deployed extensively and, in some countries, is legally required to support governmental decisions.[40]

Such formalised, monetised CBA best suits situations in which the major costs and benefits can be plausibly measured, quantified and compared. This is most feasible when assessing challenges and short-term changes of modest scale – in economic terms, 'marginal' to the economic system overall.

Crucially, the associated underlying set of economic principles, models and decision-making frameworks often **implicitly separate public policy for innovation** from the main workings of the economic system, thus neglecting large-scale changes to technologies and whole sectors. They are therefore typically grounded in theories of equilibrium (Box 7) which poorly represent the real economics of innovation and transitions.

For larger changes and longer periods, traditional CBA struggles not just because of multiple – and fundamental – uncertainties, but because the opportunities are less well known than up-front costs and therefore involve larger uncertainties. It follows that attempts to monetise everything in practice tends to contain an inbuilt bias against the opportunities arising from innovation, structural and behavioural change.

Aggregate CBAs are also often blind to distributional impacts, on the assumption that public authorities would address distributional concerns through other means (e.g. tax structures or fiscal compensation), which may be much more problematic for major transitions over extended periods.

Box 7: Limitations of equilibrium theory and modelling

Much economic theory and modelling is based on the concept of equilibrium – an underlying, stable balance of costs and benefits, for example in the production and consumption of goods. Standard general-equilibrium theory focuses on conditions of equilibrium across an economy, rather than the dynamics of change. This also applies to classical literatures and models in which growth is modelled based on the accumulation of resources (labour, capital, etc), in which productivity gains – often associated with innovation – were traditionally assumed to originate from processes external to the main economy.

General Equilibrium (GE) theory does not in fact imply any long-term and unique least-cost pathway for an economic system, based on rational foresight. Indeed, extensive economic literatures probing 'endogenous innovation' and other approaches illustrate the opposite. A major concern in modelling low-carbon economics is that fundamental GE theory has often been extrapolated to models which assume equilibria are global (not just local), and multi-period, with perfect foresight and coordination across all actors, no transition costs and no other market failures. Such models take the underlying idea of GE and extrapolate it ad absurdum, but they may still inform economic and policy mindsets about 'optimal' policy.

The dynamics of transition in complex economies are about as far from such a 'global least- cost/ equilibrium' as an economic problem can be. Models which assume a stable, optimal 'baseline' based on current systems and technology data will struggle to help decision makers understand the potential opportunities and risks of different policies or strategies in this context, as illustrated not only by the way the solar revolution occurred, but how it completely upended previous modelling analyses (Box 1). Finance is also crucial and financial literature (and experience) illustrates that global finance is also far from a far-sighted, optimising system.

In practice, theories of equilibrium, and of complex dynamical systems, offer views of economics which can be complementary. Which perspective is most useful depends upon what we seek to measure and the questions we seek to answer. Our economic systems – the technologies, institutions, physical and social infrastructures on which they rest – evolve. Crucially, as Stern (2018) notes, 'The economic response [to climate change] has to be very large, involve dynamic increasing returns, changed economic and urban organisation and design, and the avoidance of potential lock-ins' but **'we have seen models predominate where these elements, the guts of the story, are essentially assumed away'.**

Source: Substantially abridged from EEIST (2021), Box 5

---

[40] In practice, our engagement found that all countries used multicriteria analysis (MCA) - with roles for different types of information aside from the monetary calculations from CBA - but only in China was the additional 'multicriteria' information considered more influential than CBA. This research found that "Practitioners understand CBA and its limitations well but also value its usability and the perception of robustness. Across all countries, political considerations can outweigh appraisal findings; respondents suggested this can be negative, in the sense that appraisal results are sometimes ignored, but can also be positive in the sense that other objectives are considered. Existing approaches present several limitations, particularly regarding transformational change, which could hamper progress to formulate and implement effective climate and energy policy."(Royston et al., 2023). See also Qin et al. (2023) for analysis on how Climate Policies are assessed in Developing Countries, showing how legally influential CBA is.

In a dynamic context of transition, a more useful framework is Risk-Opportunity Analysis (ROA), which seeks to offer a structured way to help policy appraisal navigate the uncertainties.[41] This has three main differences from CBA, with a focus on assessing:

1) The likely effects of policies on processes of change in the economy, instead of assessing expected outcomes at fixed points in time. (Appropriate where the context or aim is structural change, not marginal change).
2) Opportunities and risks that cannot be reasonably quantified, not limiting the analysis to quantifiable costs and benefits. (Appropriate where variables that are important to policy goals are fundamentally uncertain.)
3) Outcomes in multiple dimensions, instead of converting all outcomes into one metric, so that the relative value of different outcomes can be considered explicitly instead of assumed implicitly. (Appropriate when policies are likely to significantly affect diverse interests, for example costs, jobs, energy security, competitive advantage, the distribution of income, and environmental damage).

Figure 4: Methodological approaches in context of marginal and non-marginal change

	Where the aim or expectation is **marginal change**	Where the aim or expectation is **non-marginal change/ transformation**	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/neutral innovation	Market shaping / purposive innovation	Over periods or scales of concern, existing markets are changing, or new ones emerge, so that optimal states cannot be reliably identified; support investment and innovation that tackles, not exacerbates, public problem
Appropriate analysis	Cost-benefit analysis	Risk-opportunity analysis	Fundamental uncertainty makes precise expected future costs and benefits unknowable
Most directly relevant model types	Equilibrium/optimising	Dynamic (Disequilibrium) / simulating	Need to assess effect of policy on processes of change, not just on destination
Theoretical basis	Equilibrium/welfare economics	Complex systems, evolutionary economics	Need theory that can explain non-marginal, irreversible and transformational change where relevant

Source: EEIST (2021)

---

[41] Mercure et al. (2021)

ROA can be considered a generalisation of CBA, because it is appropriate for use in contexts where change is structural, uncertain and affecting diverse interests; whereas CBA is applicable in the special circumstances of more marginal change, where uncertainty is modest or symmetric, and interests are homogenous or easily compensated.

A five-step approach to ROA is outlined in EEIST (2021). Our engagement programmes indicated that ROA fits with the kind of thinking that governments need to support their work, reflected in the widespread use of multicriteria analysis (MCA: note 40) , which is broader than CBA but tends to be more static than ROA, and focused more on trade-offs than potential opportunities. Policy analysts intuitively understand the essence of ROA; what remains is to build capacity with systems thinking, to help shift decision making beyond MCA to build in dynamics and to better synthesise information across disciplines.

7. Technology mixes, costs and investment in comparative national scenarios

The EEIST project included model comparison studies with each of the participating countries, comparing the insights of different national models, as published separately for Brazil,[42] China[43] and India,[44] alongside scenarios from national modules of the E3ME-FTT econometric-technology-simulation model for each country. The emphasis that emerges is not to pursue a 'best' model, but to use insights from model comparisons to illuminate key issues, determinants and choices.

Model comparisons themselves are now established practice, but often involve comparing the impact of different assumptions in models that are based on similar theoretical approaches. Our national studies offer insights from embodying different structural approaches to the dynamics of transitions, and/or expand to encompass macro-economic dimensions of the transition. Our complementary study of the role of models in EU decision making[45] emphasises the need to diversify not just models, but the types of models used, to represent better the complexity of transition processes and the diversity of information of interest to policymakers.

Comparing the results of national scenarios in this way illustrates both commonalities and differences, beyond projected least-cost pathways.

Centrality and uncertainty in electricity demand growth. The comparative studies focused particularly on electricity, finding that demand increases in all models and in each country, but to widely varying degrees, especially for India. While in China, both models project that electricity demand will almost double in 30 years (from 7500 TWh in 2020 to 14300TWh by 2050), in India projected demand varies substantially already by 2030, and by 2050 ranges from 5400 TWh to 9400TWh (with a third model between these two). In absolute terms, this in itself drives large variations in many other results for India. Brazilian studies (next section) also illustrate the impact of industrial structure and trade on demand, and the scope for innovation to accelerate energy efficiency, along with the contributions of such demand-side changes to low-carbon development.[46]

Renewables dominate over time... All models project that renewables will dominate the growth in generation needed to meet demand in each of the countries, and indeed find that renewables overall account for more than half of power generation by 2050 in all cases. Building on the established base of solar PV, the FTT model extrapolates growth and experience-curve cost reductions such that PV remains the cheapest option in Brazil, China and India, even while accommodating the assumed costs of storage, given the simultaneous continuing and induced reductions in battery costs. Consequently, in this model PV growth continues to exceed official forecasts, and e.g., eclipses wind energy by 2030 in Brazil (Figure 5a) and to account for almost two-thirds of generation in India, and about half in China, by 2050.

...but the composition varies widely. In contrast, a very different mix emerges from Tsinghua University's detailed REPO optimising model of China's electricity system, with wind continuing to contribute more than PV throughout; this also reflects the regional detail and transmission requirements in the model, contrasting with the national aggregation of E3ME-FTT. In India, the two other models employed (MARKAL and the Energy Policy Simulator (EPS)

---

[42] Pasqualino et al. (2023) Case Study: Pasqualino, R., Vercoulen, P., Sharpe, S. and Nijsse, F.J.M.M. 'Power sector technology choices and economic outcomes: a comparative analysis using optimising and simulating models'.

[43] Miller-Wang et al. (2024)

[44] Chaudhury et al. (2024)

[45] Royston et al. (2023)

[46] Energy demand was not a major focus of EEIST research, and remains a strongly contested arena of academic studies, with widely varying views and projections. See in particular IPCC (2022), Chapter 5, and some of the key analyses and reviews which fed into the debate (e.g. Creutzig et al. (2018) and Grubler et al. (2018))

system dynamics model[47]) concur on a power mix even more dominated by variable renewables (almost 80%), but relatively balanced between solar and wind in 2050 (c. 45% and 35% respectively). The Brazilian studies in turn suggest a need to actively balance the mix of wind and solar investment over time, given the very low starting point of PV in Brazil and the higher cost of capital. A more detailed model of distributed solar finds that most of the PV could sensibly come from distributed, rather than utility-scale, generation.

Storage and transmission needs are crucial, but are varied and challenging to fully assess. The dominance of variable renewables implies that electricity storage on varied timescales, and enhanced transmission capacity, are vital. In FTT, the induced cost reductions in batteries support the dominance of PV, however the modelling of longer-duration storage remains rudimentary. The Chinese REPO model, with its more extensive modelling of storage, finds a rapid growth in compressed air storage from the mid-2030s to handle the growing need for long duration storage, while maintaining a sizeable role for thermal plants. The Indian models handle storage in varied ways, but it emerges as less of a challenge given the greater intensity and constancy of the renewable resources (including much lower winter heating needs), and also greater model integration with transport and hydrogen (see also next section). Storage needs in Brazil are also less of a determinant than in China, given its geography and resource endowment including existing hydro and biomass resources. Storage technologies overall are an area of numerous options in which dynamic innovation interacts with regional and temporal complexities of their role and markets, so that combinations of deep power systems modelling with induced innovation are a pressing need.

Options among a range of complementary technologies are influenced by diverse national factors. As noted, the studies all suggest an inversion over time from variable renewables being marginal to becoming the core of electricity generation, such that other technologies increasingly play a complementary role. The models (and geographies) vary hugely in this area. Alongside its 10-fold increase in variable renewables by 2050, the Chinese REPO model projects a large growth in nuclear (to five times its current size by 2050) and a rapid surge in CCS from the mid-2030s, initially retrofitting coal and subsequently integrated into both gas and biomass (BECCS), reaching more than double the projections of FTT. By contrast, in India, all three models find that the dominance of variable renewables, as least-cost along with batteries, renders bulk 'baseload' in any form substantially uneconomic – across all three models, just 10-15% of power by 2050 comes from the combination of nuclear, gas and coal (with or without CCS). On the shorter time horizon of the Brazil comparative study, complementarity is provided by the existing hydro, combined with batteries in the FTT model.

System cost is not the issue! Over recent decades, huge modelling effort and political debate has centred on the cost of decarbonisation. A striking finding of the EEIST project is the relative insignificance of decarbonisation on overall system costs, indeed with ambiguity as to the sign, along with significant questions around the relationship of costs and prices, as indicated in the next section. The Chinese REPO model projects a negligible increase in unit costs of electricity in its net zero scenario (just 4% over the 30 years from 2020 to 2050: Figure 5b). This is despite this being combined with the almost-doubled scale of the power system and – in common with most optimising models – a steeply rising carbon price to drive decarbonisation (particularly for widespread CCS across coal, gas and biomass from the mid-2030s). The rising carbon price only applies to a rapidly diminishing volume of carbon emissions, and is offset by the reduced cost from the growing volume of cheaper renewables. In India, the optimising model (MARKAL) and EPS find that a modest implicit carbon price[48] rising to US$50/tCO2 price by 2050 in the emerging Indian carbon pricing system suffices to drive the small amount of CCS required to finalise power sector decarbonisation by that date.

In all three countries, the E3ME-FTT model finds that average unit electricity costs decline slightly in the case of balanced high-renewables scenarios, due to their lower costs, along with declining battery costs (Figure 5b). However, the international scope of FTT[49] also underlines that costs in one country are influenced by the deployment policy decisions of other countries, thus indicating (as with our empirical case studies (section 2)), the potential importance of international collaboration to accelerate the global transition.

---

[47] Swamy et al. (2021)

[48] The MARKAL model, in common with many optimising models, measures the marginal cost of a carbon constraint at each point in time, which in such modelling is frequently (if incorrectly) equated with an implied carbon price. India is currently transforming its existing PAT scheme to become a carbon pricing system, and the models decarbonise the power sector by 2050 as a necessary precursor to delivering the 2070 decarbonisation of the whole economy. Our Brazilian scenarios to 2035 do not include carbon pricing, though such a system has recently been legislated, which will take some years to come into effect.

[49] Mercure (2012), Nijsse et al. (2023)

Nor do the models find significant impacts on GDP or aggregate employment… In aggregate by 2050, these impacts – given a relatively smooth transition – appear negligible in these country studies. The E3ME-FTT model finds a small, long-term increase in GDP if the declining average cost of electricity feeds through to power prices (an effect boosted in Brazil if policies accelerate PV deployment from its relatively low levels). In this macro-econometric model, without an explicit finance sector, high-renewable scenarios also give a short-run boost to GDP, arising from the enhanced investment over the next decade (in contrast with a relative near-term decline in the more fossil fuel-based scenarios). In India, the EPS model also finds a macroeconomic boost from decarbonisation, and (along with the E3ME model, which finds a stronger employment boost from the enhanced investment this decade), a small net increase in jobs, but cautions about the strong distributional impacts between sectors (Figure 5c). Ultimately also, the impact on electricity prices – key to the long-run macroeconomic impacts – depends upon the pricing structure of the sector.

…but finance is crucial. However, these positive results hinge upon financing. As noted in numerous publications, the low-carbon transition requires substantial up-front investment. Estimates in the EEIST national studies are consistent with the global estimates totalling trillions of dollars annual average investment over the next decade, and the terms of finance is key. Availability and cost of finance in China is not a major impediment; in India, it is central. Brazil also faces abnormally high interest rates, which impede market-led investment at the scale required, and indeed, threaten a return to fossil fuel investments as the Brazilian power sector moves beyond hydro, making efficient low-carbon financing key. Despite finance not being modelled explicitly in either traditional optimising models, nor in the econometric E3ME model – they implicitly make opposite assumptions. The former assumes that finance is already optimal, so any increased investment comes at a GDP cost; the latter, that viable investments can attract finance, and potentially boost GDP, allowing repayment in due course without any impact on interest rates.[50]

---

[50] This dichotomy of finance, as reflected in different types of models, is noted in the IPCC Finance Chapter 15 (Box 15.6) drawing in particular upon Mercure et al. (2019)

Figure 5(a) Wind and solar deployment in different models (example: Brazil)

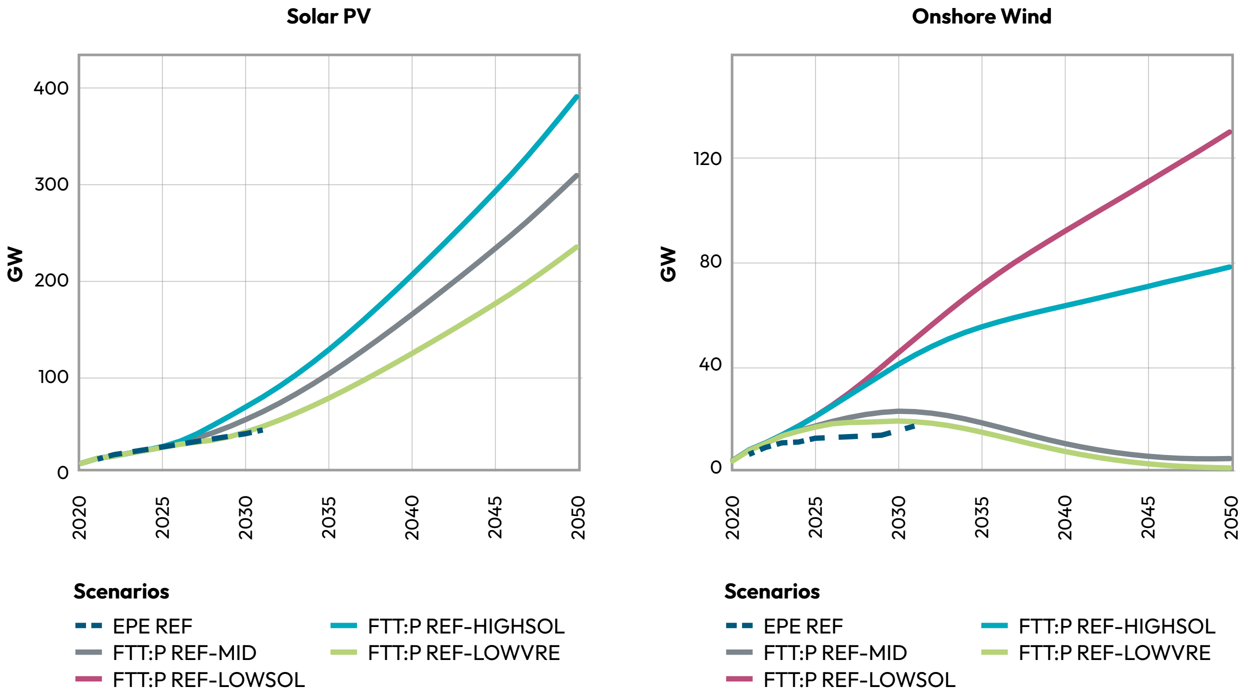
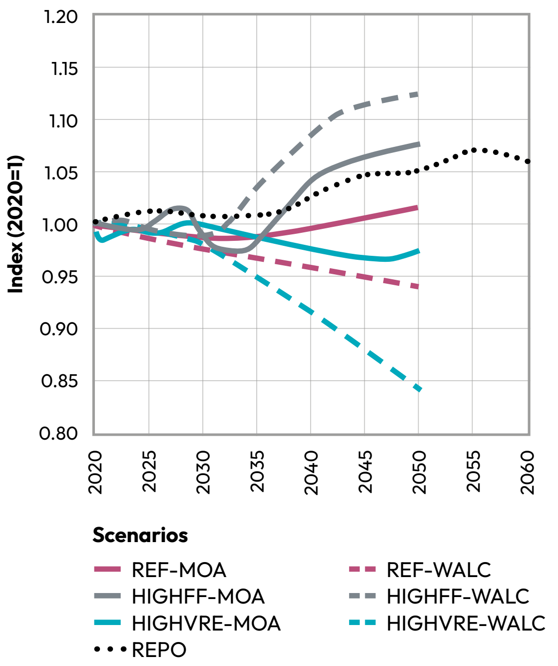


Figure 5(a) illustrates for Brazil the extent to which the dynamics of endogenous cost reduction through innovation and learning accelerate solar photovoltaics (PV) deployment, contrasting with a cost-optimising model in which technology cost projections are an input. The FTT model projects an acceleration of renewables (especially solar PV) this decade even in a "base case", well beyond the more linear projections from the government EPE model; penalties on solar PV would be required to lower deployment to the EPE projection. The government models however give more attention to distributed solar PV, with low volumes of grid-connected. The FTT model also projects higher wind (right-hand panel), but suggests some trade-off impact of high solar PV on wind deployment. Similar differences between models are observed in the other countries studied, with accelerating divergence to 2050.

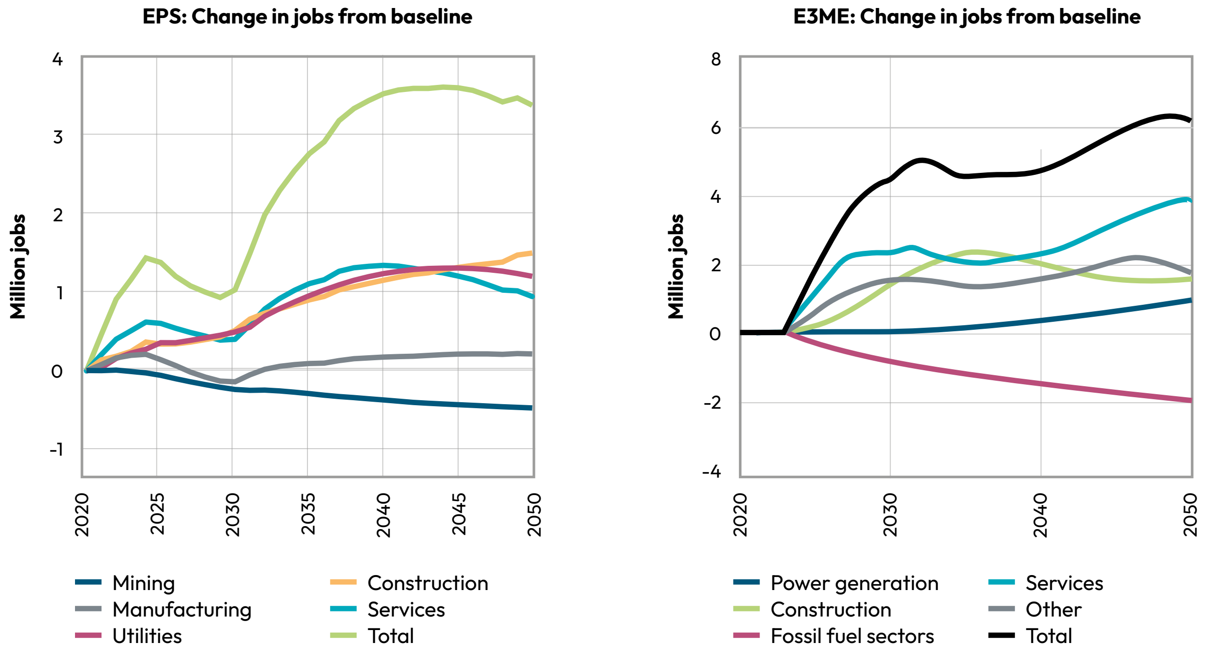
Figure 5(b): Electricity system costs and prices: example China to 2050



Ref = reference scenario
High FF = high fossil fuels scenario
High VRE = high variable renewable energy scenario
MOA = merit order approach with marginal cost pricing
WALC = weighted average levelised cost used as basis of electricity price

Figure 5(b) illustrates for China the modest impact on electricity system costs and prices, of +5% by 2050 for the cost of net zero electricity in the Chinese REPO model, and +2% from the reference case of the FTT model. The latter model can however show much wider variation in prices, which are projected to be higher (/lower) in more (/less) fossil-fuel-intensive scenarios, but also depend strongly on whether the electricity market design facilitates passing through the projected lower cost of renewables cost to final consumer prices ("average cost pricing").

Figure 5(c): Two models of impact on employment by sector: example India to 2050



Note: Change in direct and indirect jobs excluding the agriculture sector

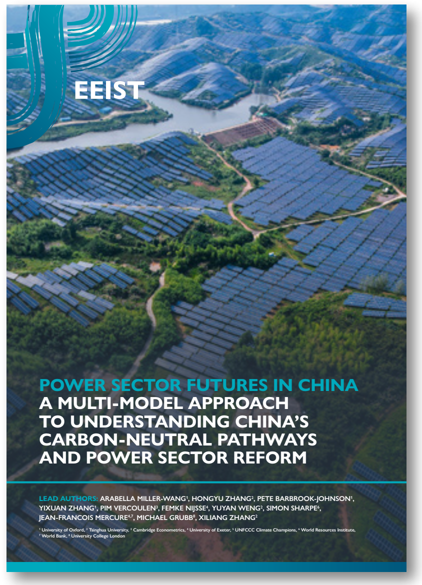
Figure 5(c) indicates results for India that the transition to a low-carbon economy can create net gains in employment, relative to the baseline. Both models – the EPS and the E3ME – identify electricity utilities, construction, and services as the three major sectors that will create new jobs. However, fossil fuel and mining sectors see a relative decline in employment, implying that mining and coal dependent states will face the need to diversify their economies and retrain workers to enable them to transition to new jobs in emerging sectors.


EEIST

ENERGY TRANSITION IN BRAZIL:
INNOVATION, OPPORTUNITIES
AND RISKS

LEAD AUTHORS: ROBERTO PASQUALINO, ANDREA CABELLO, MARCELO C. PEREIRA, CARLOS EDUARDO F. YOUNG, ANDREA ROVENTINI, ANNA CAROLINA MARTINS, MATTEO CORONESE, JIN QIN, CORMAC LYNCH, PETE BARBROOK-JOHNSON, FEMKE NIJSSE, SIMON SHARPE.

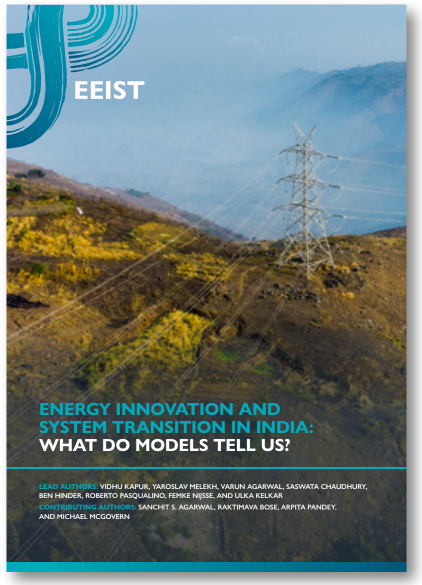
CONTRIBUTING AUTHORS TO CASE STUDIES: GUSTAVO ANDREAO, ESTHER DWECK, KAIO G. VITAL DA COSTA, LUCAS A. N. COSTA, FELIPE CORNELIO, MATHEUS T. VIANNA, JOSÉ MARIA F.J. DA SILVEIRA, MIGUEL VAZQUEZ, PIM VERCOULEN.


EEIST

POWER SECTOR FUTURES IN CHINA
A MULTI-MODEL APPROACH
TO UNDERSTANDING CHINA'S
CARBON-NEUTRAL PATHWAYS
AND POWER SECTOR REFORM

LEAD AUTHORS: ARABELLA MILLER-WANG[1], HONGYU ZHANG[2], PETE BARBROOK-JOHNSON[1], YIXUAN ZHANG[1], PIM VERCOULEN[3], FEMKE NIJSSE[4], YUYAN WENG[2], SIMON SHARPE[6], JEAN-FRANCOIS MERCURE[4,7], MICHAEL GRUBB[8], XILIANG ZHANG[2]

[1] University of Oxford, [2] Tsinghua University, [3] Cambridge Econometrics, [4] University of Exeter, [5] UNFCCC Climate Champions, [6] World Resources Institute, [7] World Bank, [8] University College London


EEIST

ENERGY INNOVATION AND
SYSTEM TRANSITION IN INDIA:
WHAT DO MODELS TELL US?

LEAD AUTHORS: VIDHU KAPUR, YAROSLAV MELEKH, VARUN AGARWAL, SASWATA CHAUDHURY, BEN HINDER, ROBERTO PASQUALINO, FEMKE NIJSSE, AND ULKA KELKAR

CONTRIBUTING AUTHORS: SANCHIT S. AGARWAL, RAKTIMAVA BOSE, ARPITA PANDEY, AND MICHAEL MCGOVERN

8. Policy insights from the broader modelling toolkit

The EEIST project represents a significant effort to deploy a new cohort of modelling approaches that can meet the needs of policymakers, drawing upon the evidence and theories documented in EEIST (2021). There is still much to be done to achieve both greater adoption and influence of such models, as well as methodological improvement. Increasingly, decision makers need climate-economy modelling which can:

- Represent technological progress in well-validated ways so as to inform a variety of policies to drive clean technology innovation, cost reduction and sectoral transitions.
- Represent a diverse range of policy options and their implementation in detail, instead of representing all climate policy in terms of a marginal cost, typically equated with a carbon price.
- Model the economy as dynamic and evolving, to inform the choice of policies at different stages in each transition.
- Better explain and predict the effect of the low-carbon transition on jobs, economic growth, finance and trade.

Applying such ideas and evidence in formal modelling is, of course, necessarily complex, and many paths can be taken to address a variety of specific aspects and questions. Modelling the complexity of economic systems and transitions can be seen in the spirit of the adage that 'it is better to be approximately right than precisely wrong' – particularly if simpler models risk misleading in their apparent precision of charting 'optimal responses', which turn out to be anything but. Our online Appendix, drawing upon a major academic review of modelling approaches to induced innovation, offers a method to classifying the range of models emerging.[51]

The case studies contained in EEIST project modelling reports show how a diverse range of analytical tools can be used to inform an equally diverse range of policy questions.[52] These illustrate new approaches to probe the potential impact of dynamic processes globally and in our partner countries; in the different sectors (renewable energy; zero emission vehicles; hydrogen for fuels and industry; and agriculture); and across varied policy-related questions (carbon pricing design, policy packages to reach 'tipping points', competitiveness opportunities, and jobs and skills). Here we briefly give a few examples of those findings.

Policies for electric vehicles… FTT modelling of the transition to zero emission vehicles (ZEVs) indicates that some combinations of subsidies, taxes, efficiency regulations and ZEV mandates achieve more than the sum of their parts, while other combinations achieve less than the sum of their parts.[53] Applied to China, India, the EU and the US, the model finds that regulatory policies aligned with a rapid transition (ZEV mandates and energy efficiency regulations) are likely to outperform incentive policies (subsidies and taxes) across outcomes including cost-effectiveness of both deployment and emissions reduction, reduction in cost of electric vehicles, and overall reductions in energy use and emissions.[54]

…and business energy efficiency. In Brazil, extending current trends of firm-led efficiency improvements could enhance national energy efficiency by 2050 by about 15%. Dynamic analysis with heterogenous agents simulates the possible impact of innovation to accelerate this further, which in turn greatly increases the emissions impact of low-carbon power investment.[55]

Policy combinations for renewables: An agent-based modelling study of the power sector in Brazil[56] shows that public financing in combination with auctions can be far more effective in supporting increased investment in solar and wind power than either can when applied in isolation. Whereas auctions in the early 2000s were seen to be ineffective, the analysis indicates that using the two policies in combination could achieve significantly more than the sum of their individual effects.

---

[51] Pasqualino et al (2024) summarise a typology of varied models of induced innovation engaged with the EEIST programme, organised through a decision tree identifying six main categories. Another important dimension concerns modelling treatments of finance, where there is a basic dichotomy reflected in different types of models; the IPCC Finance Chapter 15 (Box 15.6), drawing in particular upon (Mercure et al, 2019), notes that different approaches to representing finance can generate directly opposite results concerning the impact of enhanced low carbon investment on GDP over time.

[52] Report 'New Economic Models of Energy Innovation and Transition', and three country reports: 'Energy Transition in Brazil: Innovation, Opportunities, and Risks'; 'Power Sector Futures in China'; and 'Energy Innovation and System Transition in India: What do models tell us?'. Available at eeist.co.uk.

[53] Lam, Mercure and Sharpe (2023).

[54] EEIST (2023) Case study: Lam, A., Vercoulen, P., Mercure, J.-F. and Sharpe, S. 'Activating EV Tipping Points in China, India, Europe and the US'., and Published Policy Brief: Lam, Mercure and Sharpe (2023).

[55] Pasqualino et al. (2023) Case Study: Vianna, M.T., Dweck, E., Young, C.E. 'Firm-led innovations in energy efficiency and its contributions to carbon emissions in Brazil'.

[56] Pasqualino et al. (2023) Case Study: Andreao, G., da Silveira, M. J., Vazquez, M. and Pasqualino, R. 'Positive nonlinear change from combining low-carbon energy policies from a polycentric governance perspective: An agent-based analysis'.

[57] EEIST (2023) Case Study: Sharpe, S., Wang, H., Liu, J., Wu, T., Kang, Z., Han, Z., Jones, A., Natalini, D. and Barbrook-Johnson, P. 'What is the Most Cost-Effective Form of Carbon Pricing? Modelling emissions trading and a carbon tax in general and in China'.

Carbon pricing design… A system mapping exercise and agent-based modelling studies of carbon pricing in the power sector in China and in general[57] shows that the dynamics of a carbon tax are different from those of an emissions trading scheme, and their relative effectiveness will depend significantly on the structure of the markets to which they are applied.

…and impacts: An integrated-assessment agent-based model of the global economy suggests that a combination of green subsidies, regulation and moderate carbon taxes is likely to be most effective for achieving decarbonisation while maintaining economic growth and financial stability and limiting increases in public deficits.[58] In contrast, the study finds that, if carbon pricing is used alone, it will either be insufficient to limit temperature rise to 2°C, or, if set at a level high enough to achieve this goal, it could lead to economic instability, with a surge in unemployment, bankruptcies and recession.

Electricity market design: Simulation of the power sector transition in China, India and Brazil[59] illustrates how electricity prices may be determined by the interaction of technology choices and market design choices. Solar and wind are expected to have an increasing cost advantage compared to coal and gas. Whether this passes through into electricity prices depends on whether and how market design reflects costs (short-run marginal costs or long-run average system costs) as well as on the finance-efficiency of investment (interest rates as affected by perceived risks). The E3ME macro-econometric model suggests that the technology and market design choices that lead to the lowest electricity prices are also likely to have the most positive outcomes for employment and GDP.

Infrastructure strategy: An energy systems model combined with modelling of technology costs, system resilience and the interface between the power and industry sector enables a comparison of two approaches to infrastructure for green hydrogen and ammonia in India.[60] This finds that connecting hydrogen and ammonia production plants to the electricity grid can lower their production costs, reduce needs for solar and wind power capacity, and improve energy security and resilience to weather variations, compared to an 'islanded' approach where hydrogen and ammonia production plants are connected only to industrial off-takers.

At a national level, the EPS model (note 47) concludes that a combination of technology and policy choices (including mandates for industrial electrification, hydrogen production, zero emission electricity and vehicles, material efficiency and early retirement of coal power) could potentially achieve an economy-wide low-carbon transition in India with positive effects on aggregate employment, GDP and tax revenues.

Tax policy: A microsimulation study of the transition away from coal use in China[61] finds that, while the net effect on public finances at a national level may be positive, as the reduction in coal subsidies more than offsets the loss of tax revenues, the impact on provincial government finances will be highly varied. This suggests a redistribution of revenues between provinces, managed by central government, could be an important enabler of the transition.

The study of policy options for the transport transition (note 53) shows that, early in the transition, a small tax on sales of petrol cars can fund a large subsidy for the purchase of electric vehicles: a revenue-neutral way to achieve cost-parity between the clean technology and the fossil fuel technology.

Trade policy: A structural decomposition analysis based on input output data[62] finds that Brazil's exports are significantly more carbon intensive than its domestic consumption, that exports have driven up Brazilian emissions disproportionately and, in recent years, accounted for about a third of national emissions – but only 16% of gross output. This suggests that Brazil has a strong interest in coordinating with other countries to establish conditions in global markets that would allow its export industries to remain competitive while eliminating emissions from their production processes.

---

[58] EEIST (2023) Case Study: Lamperti, F. and Roventini, A. 'Policy Options for Rapid, Smooth Decarbonisation and Sustainable Growth', published Policy Brief: Clark et al. (2023), and Wieners C., Dosi, G., Lamperti, F. and Roventini, A. (2024). 'Macroeconomic policies for rapid decarbonization, steady economic transition and employment creation'. LEM Working Papers.

[59] EEIST (2023) Case Study: Vercoulen, P., Nijsse, F., Sharpe, S. and Mercure, J-F. Unstoppable Renewables and Marginal Pricing in China, India and Brazil.

[60] Cesaro et al. (2023)

[61] EEIST (2023) Case Study: Clark, A. and Zhang, W. 'China and the Social Consequences of the Coal Transition'.

[62] Pasqualino et al. (2023) Case Study: Vital da Costa, K., Costa, L. and Frickmann Young, C. E. Identifying the sources of structural changes of greenhouse gas emissions in Brazil: An input-output analysis from 2000 to 2020.

[63] EEIST (2023) Case Study: Bücker, J., Andres, P., Ives, M., Mealy, P., Tang, K., Urban, M., McCarten, M., Srivastav, S. and Hepburn, C. 'The Green Complexity and Competitiveness of China's Exports'.

Industrial strategy… Economic complexity analysis, which maps the network structure that relates different products in the economy to each other based on trade patterns, can be used to predict new areas in which a country may be able to gain industrial competitiveness. An application of this analysis to China[63] finds that its competitiveness in clean technologies exceeds its overall competitiveness in manufacturing, its competitiveness in electric vehicles is increasing, and that other areas in which it could increase its competitiveness include environmental monitoring technologies.

…including jobs and skills policy: The EPS modelling of the economy-wide low-carbon transition in India and the E3ME macro-econometric model[64] finds that the transition is likely to create jobs in sectors including services, power generation and construction, while causing loss of jobs in the fossil fuel and mining sectors. An agent-based model of the labour market (Berryman et al.)[65] simulates the way in which skills may constrain people's ability to move from sectors where jobs are being lost to those where they are being created, highlighting where unemployment is most likely to arise and where skills policies could most usefully be targeted.

Land use strategy: An agent-based model of agriculture and land use[66] finds that, without significant policy intervention, competition between farmers for short-term profitability and market share is likely to lead to soil degradation, causing serious risks to food security in the long term. It shows that policies such as giving farmers better access to information about sustainable practices and incentivising their uptake of new technologies are more likely to be effective if they are introduced early in the transition. If left too late, the divergence of technological development may make it impossible to avoid a lock-in to unsustainable agricultural practices.

---

[64] EEIST (2023) Case Study: McGovern, M., Vercoulen, P., Nijsse, F. and Mercure, J-F. 'Economics Impacts of Net Zero in India by 2070'.

[65] EEIST (2023) Case Study: Berryman, A., Bücker, J., De Moura, F. S., Barbrook-Johnson, P., Hanusch, M., Mealy, P., Rio-Chanona, M. D. and Farmer, J. D. 'Modelling Labour Market Transitions: The case of productivity shifts in Brazil', and Published Working Paper: Berryman et al. (2023)

[66] EEIST (2023) Case Study: Coronese, M., Occelli, M., Lamperti, F. and Roventini, A. 'Supporting Sustainable Agriculture Intensification: A system-wide agent-based modelling approach'.

Conclusions

9. The transition in economic thinking and modelling in context

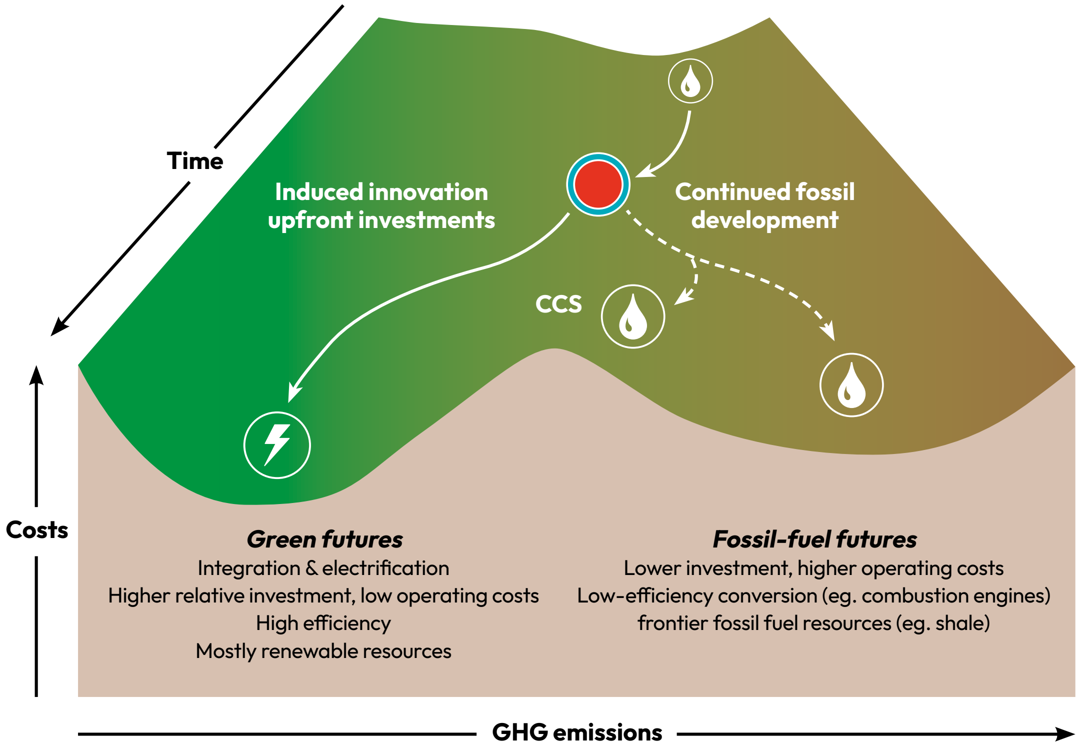
It is almost a quarter of a century since a seminal paper argued, on the basis of global energy systems modelling with induced innovation, that low-carbon systems over this century need not be more expensive than high carbon ones.[67] Today, it is obvious, and charted extensively in the sectoral chapters of the IPCC Mitigation Report, that many low and zero-carbon solutions are, or have the potential to become, competitive with fossil fuels, even more so as the accumulating damages begin to be acknowledged in markets in some regions, through carbon pricing. They may also yield co-benefits.

Low-carbon systems are not higher-cost versions of the fossil fuel economy; they are quite different. They herald new economies of energy, transport, buildings, industry, agriculture and land-use. So the economists' traditional 'marginal abatement cost curve' has to be replaced by a recognition of varied future possibilities, which evolve along different paths into futures which differ in multiple ways. Moreover, common sense suggests that new technological systems have more potential for cost reductions than long-standing incumbents.

There is a catch, however. Though many mainstream models now illustrate the potential to move from a 'high-carbon equilibrium' to a low-carbon one, through combinations of innovation and carbon pricing, most say little about the transition process (e.g. policy factors which determine the pace). The new emphasis on innovation through learning-by-doing and scale economies also involves varied path dependencies – in which the incumbent systems, by definition, have advantage, creating hurdles to be overcome.

Figure 6 illustrates conceptually these diverging possible pathways – with a ridge in between. Moving from entrenched fossil fuel-based systems to a low-carbon economy requires both up-front investment and sustained effort. A muddled and half-hearted response is likely to be more expensive (as well as more environmentally damaging) compared to a determined shift on to low-carbon development pathways.

Figure 6: The diverging pathways of green versus fossil fuel-based energy futures



---

[67] Gritsevskyi and Nakicenovic (2000)

The further economies develop along the fossil fuel valley, the more difficult and expensive it may become to change to the other – as needs must, in the end. As summarised in Part A (sections 2-4), from the evidence of 'what has worked' and theories of economic dynamics as presented in EEIST (2021), the project has offered 10 principles of policy to achieve the transition cost-effectively (EEIST, 2022). The needs of policymaking have developed and accelerating implementation requires new approaches to appraisal, based on analysis of risks and opportunities (sections 5-6). Consequently, economic modelling needs to move beyond not just illustrating future possibilities through innovation, but illuminating more realistically the actions required to 'cross the ridge' – and quickly.

Fundamentally, the energy transition requires an intellectual transition in economics, from a focus on the static costs of abatement, to the dynamic economics of accelerating investment in zero-carbon systems (both supply and end-use technologies) – and the opportunities as well as the risks that arise.

The EEIST project has demonstrated the use of some models and analytical tools that can help policymakers navigate the transition; there is an urgent need for these to be further developed, diversified and made more widely available. Priorities for development include:

- **Sector-specific models** that simulate the technology transition in each of the greenhouse gas-emitting sectors of the global economy, with country-specific resolution, to compare the costs and effectiveness of deployment policy options individually and in combination:

  - For many small-scale and end-use options, representing the behavioural and structural obstacles to enhanced take-up

  - For industrial and agricultural sectors, where trade is likely to strongly affect the transition, simulating the interacting effects of policies in different countries, with or without some form of international coordination.

- Given the wide variations in the availability and cost of finance for low-carbon investment internationally, **finance sector models** to assess national and international policies to mobilise finance for the transition, as well as to assess the risks of possible financial instability arising from the transition. These will be useful for central banks and international financial institutions, as well as for governments.

- Given the structural implications of the transition, **models of the macroeconomy** that simulate the effects of low-carbon transition policies and strategies on growth, jobs and trade. As many countries have macroeconomic models; the challenge is for these to embody the specific sectoral characteristics and investment needs of the sectors, to be able to represent the macroeconomic effects of realistic policy options.

- Given the political imperatives around jobs and distributional impacts, **labour market models** that show how the transition could affect jobs and employment in different sectors and regions, informing policies on skills, social security, gender and regional development, along with analysis of **household income** impacts of funding strategies and price-based instruments.

Not just one model: Multiple models are needed to better assess each of these challenges. That is not only because of the diversity of interests and circumstances across countries and sectors, but also because all models have their limitations, and key insights can be gained from comparisons. Our online Appendix presents an approach to classification of model types.

Not just models: Analytical tools such as system mapping, economic complexity analysis and the analysis of network structures in labour markets and supply chains can be useful to inform policy, alongside formal models. Governments would benefit from these tools being further developed and diversified.

Not just economics: The low-carbon transition is, ultimately, a social and political endeavour. Economic analysis can never provide all the answers, nor determine the choices. It may provide better insights into the sectors, industries, communities and places that policies are likely to affect but, ultimately, the choices of people and politics – as informed by the 'mental models' they develop of the transition – will determine our collective futures.

Appendix

Risk opportunity analysis in five steps

Step 1: Establish objectives, options, key system characteristics and system feedbacks.

- Define the objective within the target system (e.g. improving a specific technology within a given sector).
- Decide if the option being examined is 'mission-critical' to this objective.
- Establish the main characteristics, feedbacks and boundaries of the system and identify models available for analysing the system.

Step 2: Identify the impacts of policy options on processes of innovation and system change.

- Consider how policy options might affect innovation, infrastructure or other factors which may strengthen, weaken, create or eliminate reinforcing or balancing feedbacks, and whether or how this might change structural relationships between components of the system.
- Where historical data are available, assess the outcome of related past initiatives to inform the evidence based on system dynamics.

Step 3: Assess risks and resilience.

- Stress test the resilience of the system and the influence of the proposed policies regarding extreme, if unlikely, circumstances.
- Probe the most important ways in which the system could fail and the potential consequences with attention to cascading failures and tipping points, and the existence of low-likelihood, high-impact outcomes.

Step 4: Assess innovation and opportunity creation.

- Explore the ability of the policy to create or enhance options that could help the system evolve towards the goals established, in ways that capture economic and other opportunities.
- Large-scale programmes may also assess trade impacts, productivity improvements and resources and institutional implications.

Step 5: Engage decision makers concerning the impacts and uncertainties in multiple dimensions.

- Impacts, degrees of uncertainty or confidence, and resilience estimates for each of the metrics adopted in Step A can inform decisions, with specific reference to strategic goals of the overarching policy and legal frameworks.
- The preferred strategy is determined by the appropriately appointed decision maker

Source: EEIST report, The New Economics of Innovation and Transition: Evaluating Opportunities and Risks.

References

Note: As a Synthesis report of the EEIST project, the references in this report are principally to other EEIST reports and related academic publications, which in turn contain hundreds of references to the underlying academic and other literatures. Some other publications are cited here, where they are of direct central relevance.

Where not separately published:

- empirical case studies are indicated in the text footnotes as appropriate in relation to EEIST (2021) Annexes, and boxes in the policy report EEIST (2022)
- modelling studies are detailed in footnotes with reference to the source reports, namely EEIST (2023) and the three country reports.

The Annex to this report summarises a typology of varied models of induced innovation engaged with the EEIST programme, organised through a decision tree identifying six main categories, based on an extensive review; see Pasqualino et al (2024).

Acemoglu, D. et al. (2012) 'The environment and directed technical change', American Economic Review, 102(1), pp. 131–166. Available at: https://doi.org/10.1257/aer.102.1.131.

Basnet, S. and Magee, C.L. (2017) 'Artifact interactions retard technological improvement: An empirical study', PLOS ONE, 12(8), p. e0179596. Available at: https://doi.org/10.1371/journal.pone.0179596.

BEIS & ONS (2022) Final UK greenhouse gas emissions national statistics 1990-2020. London.

Berryman, A. et al. (2023) Modelling labour market transitions: the case of productivity shifts in Brazil. Oxford Institute for New Economic Thinking. Available at: https://www.inet.ox.ac.uk/publications/no-2023-21-modelling-labour-market-transitions-the-case-of-productivity-shifts-in-brazil/ (Accessed: 21 December 2023).

Brown, C., Hinder, B. and Hobgin, J.-A. (2023) Economics of Energy Innovation and System Transition (EEIST) Wilton Park Meeting Report. EEIST. Available at: https://eeist.co.uk/wp-content/uploads/Wilton-Park-Report-PDF.pdf.

Cesaro, Z. et al. (2023) The role of green hydrogen and ammonia in a low-cost, resilient power system in India: national grid connection versus energy islands 2023. EEIST. Available at: https://eeist.co.uk/wp-content/uploads/2023IIB081-EEIST-India-Policy-Brief-AW.pdf (Accessed: 19 December 2023).

Chaudhury, S. et al. (2024) India Country Report - What do models tell us? EEIST (to be Published). Available at: https://eeist.co.uk/eeist-reports/ (Accessed: 17 January 2024).

Clark, A. et al. (2023) Socio-economic impacts of coal transition in China - a regional challenge. Available at: https://eeist.co.uk/wp-content/uploads/2023IIB082-EEIST-China-Policy-Brief-AW.pdf.

Creutzig, F. et al. (2018) 'Towards demand-side solutions for mitigating climate change', Nature Climate Change [Preprint]. Available at: https://doi.org/10.1038/s41558-018-0121-1.

DESNZ (2023) Provisional UK greenhouse gas emissions national statistics 2022, GOV.UK. Available at: https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2022 (Accessed: 29 September 2023).

ECB (2010) Reflections on the nature of monetary policy non-standard measures and finance theory, European Central Bank. Available at: https://www.ecb.europa.eu/press/key/date/2010/html/sp101118.en.html (Accessed: 6 December 2023).

EEA (2019) Sustainability transitions: policy and practice — European Environment Agency. Publication 09/2019. European Environment Agency. Available at: https://www.eea.europa.eu/publications/sustainability-transitions-policy-and-practice (Accessed: 10 December 2023).

EEIST (2021) The New Economics of Innovation and Transition: Evaluating Opportunities and Risks. EEIST: Economics of Energy Innovation and System Transition. Available at: https://eeist.co.uk/eeist-reports/the-new-economics-of-innovation-and-transition-evaluating-opportunities-and-risks/ (Accessed: 6 October 2023).

EEIST (2022) 'Ten Principles for Policymaking in the Energy Transition: Lessons from Experience'. Available at: https://policycommons.net/artifacts/2675495/untitled/3698608/ (Accessed: 6 October 2023).

EEIST (2023) New economic models of energy innovation and transition: Addressing new questions and providing better answers. Available at: https://eeist.co.uk/eeist-reports/new-economic-models-of-energy-innovation-and-transition/ (Accessed: 21 December 2023).

Farmer, J.D. et al. (2019) 'Sensitive intervention points in the post-carbon transition', Science, 364(6436), pp. 132–134. Available at: https://doi.org/10.1126/science.aaw7287.

GEA (2012) Global Energy Assessment – Towards a Sustainable Future. Cambridge, New York and Laxenburg, Austria: Cambridge University Press and IIASA, pp. 1665–1744.

Geels, F.W. and Turnheim, B. (2022) 'The Great Reconfiguration: A Socio-Technical Analysis of Low-Carbon Transitions in UK Electricity, Heat, and Mobility Systems'. Available at: https://doi.org/10.1017/9781009198233.

Golosov, M. et al. (2014) 'Optimal Taxes on Fossil Fuel in General Equilibrium', Econometrica, 82(1), pp. 41–88. Available at: https://doi.org/10.3982/ECTA10217.

Gritsevskyi, A. and Nakicenovi, N. (2000) 'Modeling uncertainty of induced technological change', Energy Policy [Preprint]. Available at: https://doi.org/10.1016/S0301-4215(00)00082-3.

Grubb, M. et al. (2021) 'Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO2 mitigation', Environmental Research Letters, 16(4), p. 043007. Available at: https://doi.org/10.1088/1748-9326/ABDE07.

Grubb, M. and Newbery, D. (2018) 'UK Electricity Market Reform and the Energy Transition: Emerging Lessons'. Available at: https://doi.org/10.5547/01956574.39.6.mgru.

Grubb, M., Wieners, C. and Yang, P. (2021) 'Modeling myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation', WIREs Climate Change, 12(3), p. e698. Available at: https://doi.org/10.1002/wcc.698.

Grubb, M., Poncia, A., Drummond, P., Neuhoff, K. and Hourcade, J.-C. (2023). 'Policy complementarity and the paradox of carbon pricing'. Oxford Review of Economic Policy, 39 (4), pp. 711–730. doi: 10.1093/oxrep/grad045.

Grübler, A. et al. (2012) 'Chapter 24 - Policies for the Energy Technology Innovation System (ETIS)', in Annual Review of Environment and Resources, pp. 137–162. Available at: https://www.annualreviews.org/doi/10.1146/annurev-environ-060311-133915 (Accessed: 12 January 2024).

Grubler, A. et al. (2018) 'A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies', Nature Energy, 3(6), pp. 515–527. Available at: https://doi.org/10.1038/s41560-018-0172-6.

IPCC (2022) Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the IPCC Sixth Assessment Report. Available at: https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/ (Accessed: 13 May 2022).

Jennings, T. et al. (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. Available at: https://prod-drupal-files.storage.googleapis.com/documents/resource/public/Policy-innovation-offshore-wind-report-2020.pdf (Accessed: 6 October 2023).

Lam, A., Mercure, J.-F. and Sharpe, S. (2023) Policies to pass the tipping point in the transition to zero-emission vehicles. EEIST. Available at: https://eeist.co.uk/wp-content/uploads/2023IIB078-EEIST-EV-Policy-Brief-AW-1.pdf (Accessed: 19 December 2023).

Lynch, C. et al. (2023) Hidden disparities on the road to net-zero. Identifying areas of opportunity and risk. Available at: https://eeist.co.uk/policybriefs/ (Accessed: 10 January 2024).

Malhotra, A. et al. (2021) 'Building institutional capacity for addressing climate and sustainable development goals: achieving energy efficiency in India', Climate Policy, pp. 1–19. Available at: https://doi.org/10.1080/14693062.2021.1984195.

Malhotra, A. and Schmidt, T.S. (2020) 'Accelerating Low-Carbon Innovation', Joule, 4(11), pp. 2259–2267. Available at: https://doi.org/10.1016/J.JOULE.2020.09.004.

Meng, J. et al. (2021) 'Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition', Proceedings of the National Academy of Sciences, 118(27), p. e1917165118. Available at: https://doi.org/10.1073/pnas.1917165118.

Mercure, J.-F. (2012) 'FTT:Power : A global model of the power sector with induced technological change and natural resource depletion', Energy Policy, 48, pp. 799–811. Available at: https://doi.org/10.1016/j.enpol.2012.06.025.

Mercure, J.-F. et al. (2019) 'Modelling innovation and the macroeconomics of low-carbon transitions: theory, perspectives and practical use', Climate Policy, 19(8), pp. 1019–1037. Available at: https://doi.org/10.1080/14693062.2019.1617665.

Mercure, J.-F. et al. (2021) 'Risk-opportunity analysis for transformative policy design and appraisal', Global Environmental Change, 70, p. 102359. Available at: https://doi.org/10.1016/J.GLOENVCHA.2021.102359.

Miller-Wang, A. et al. (2024) Power sector futures in China: A multi-model approach to understanding China's carbon-neutral pathways and power sector reform. EEIST (to be Published). Available at: https://eeist.co.uk/eeist-reports/ (Accessed: 16 January 2024).

Nemet, G. (2019) How Solar Energy Became Cheap: A Model for Low-Carbon Innovation, How Solar Energy Became Cheap: A Model for Low-Carbon Innovation. Available at: https://doi.org/10.4324/9780367136604.

Nijsse, F.J.M.M. et al. (2023) 'The momentum of the solar energy transition', Nature Communications, 14(1), p. 6542. Available at: https://doi.org/10.1038/s41467-023-41971-7.

Norris, R. (2022) 'New report shows jobs in UK offshore wind industry to grow to 100,000 - RenewableUK', renewableUK. Available at: https://www.renewableuk.com/news/608235/New-report-shows-jobs-in-UK-offshore-wind-industry-to-grow-to-100000.htm (Accessed: 19 December 2023).

Pasqualino, R. et al. (2023) Energy Transition in Brazil: Innovation, Opportunities and Risks > EEIST. Available at: https://eeist.co.uk/new-report-energy-transition-in-brazil-innovation-opportunities-and-risks/ (Accessed: 19 December 2023).

Pasqualino, R. et al. (2024) 'Modelling induced innovation for low-carbon energy transition: a menu of options', forthcoming in Environmental Research Letters.

Peñasco, C., Anadón, L.D. and Verdolini, E. (2021) 'Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments', Nature Climate Change, 11(3), pp. 257–265. Available at: https://doi.org/10.1038/s41558-020-00971-x.

PWC (2021) Net Zero Economy Index 2021: Code Red To Go Green, PwC. Available at: https://www.pwc.co.uk/services/sustainability-climate-change/insights/net-zero-economy-index/2021.html (Accessed: 11 January 2024).

Qin, J. et al. (2023) 'How are climate policies assessed in emerging economies? A study of ex-ante policy appraisal in Brazil, China, and India', Climate Policy, 0(0), pp. 1–17. Available at: https://doi.org/10.1080/14693062.2023.2283174.

Rogge, K. and Song, Q. (2023) 'Policy Mixes for Addressing Environmental Challenges: Conceptual Foundations, Empirical Operationalisation, and Policy Implications', in Routledge Handbook of Environmental Policy. Routledge.

Rogge, K.S., Kern, F. and Howlett, M. (2017) 'Conceptual and empirical advances in analysing policy mixes for energy transitions', Energy Research & Social Science, 33, pp. 1–10. Available at: https://doi.org/10.1016/j.erss.2017.09.025.

Royston, S. et al. (2023) 'Masters of the machinery: The politics of economic modelling within European Union energy policy', Energy Policy, 173, p. 113386. Available at: https://doi.org/10.1016/j.enpol.2022.113386.

Sharpe, S. and Lenton, T.M. (2021) 'Upward-scaling tipping cascades to meet climate goals: plausible grounds for hope', Climate Policy, pp. 1–13. Available at: https://doi.org/10.1080/14693062.2020.1870097.

Stern, N. (2018) 'Public economics as if time matters: Climate change and the dynamics of policy', Journal of Public Economics, 162, pp. 4–17. Available at: https://doi.org/10.1016/j.jpubeco.2018.03.006.

Stern, N. (2016).' Why Are We Waiting?: The Logic, Urgency, and Promise of Tackling Climate Change'. The MIT Press. Available at: https://www.jstor.org/stable/j.ctt17kk7g6.

Swamy, D. et al. (2021) 'Pathways for Decarbonizing India's Energy Future: Scenario Analysis Using the India Energy Policy Simulator'. Available at: https://www.wri.org/research/pathways-decarbonizing-indias-energy-future-scenario-analysis-using-india-energy-policy (Accessed: 21 December 2023).

The Economist (2014) 'Sun, wind and drain', The Economist. Available at: https://www.economist.com/finance-and-economics/2014/07/29/sun-wind-and-drain (Accessed: 16 January 2024).

UK Government (2023) UK energy in brief 2023. Available at: https://www.gov.uk/government/statistics/uk-energy-in-brief-2023 (Accessed: 19 December 2023).

Way, R. et al. (2022) 'Empirically grounded technology forecasts and the energy transition', Joule, 6(9), pp. 2057–2082. Available at: https://doi.org/10.1016/j.joule.2022.08.009.

Wilson, C. et al. (2020) 'Granular technologies to accelerate decarbonization', Science, 368(6486), pp. 36–39. Available at: https://doi.org/10.1126/science.aaz8060.

EEIST

Economics of Energy Innovation and System Transition

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change. By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

University of Exeter

All documents can be found online here: eeist.co.uk/downloads

UCL THE BARTLETT INSTITUTE FOR SUSTAINABLE RESOURCES
UNIVERSITY OF CAMBRIDGE
a.r.u.
OXFORD MARTIN SCHOOL
UNIVERSITY OF OXFORD
University of Exeter Global Systems Institute
北京師範大學 BEIJING NORMAL UNIVERSITY
cambridge econometrics clarity from complexity
Universidade de Brasília
UNICAMP
Sant'Anna School of Advanced Studies – Pisa
WRI INDIA
UFRJ
CLIMATE Strategies
ENERGY RESEARCH INSTITUTE OF NDRC
teri
CIFF CHILDREN'S INVESTMENT FUND FOUNDATION
HM Government
Funded by UK Government
Department for Energy Security & Net Zero