EDITORIAL • OPEN ACCESS

Editorial essay: ERL focus issue on technology and global change

To cite this article: Charlie Wilson *et al* 2025 *Environ. Res. Lett.* **20** 120201

IOP Publishing Environ. Res. Lett. 20 (2025) 120201 https://doi.org/10.1088/1748-9326/ae2ac0

ENVIRONMENTAL RESEARCH
LETTERS

RECEIVED
13 November 2025

ACCEPTED FOR PUBLICATION
25 November 2025

PUBLISHED
23 December 2025

EDITORIAL

Editorial essay: ERL focus issue on technology and global change

Charlie Wilson[1,5,*], **Greg Nemet**[2], **Laura Diaz Anadon**[3], **Frank W Geels**[4], **Radhika Khosla**[1] **and Shonali Pachauri**[5]

[1] University of Oxford, Oxford, United Kingdom
[2] University of Wisconsin, Madison, United States of America
[3] University of Cambridge, Cambridge, United Kingdom
[4] University of Manchester, Manchester, United Kingdom
[5] IIASA, Laxenburg, Austria
[*] Author to whom any correspondence should be addressed.

E-mail: charlie.wilson@eci.ox.ac.uk

Abstract

The ERL Focus Issue on Technology and Global Change brings together 19 research articles, 4 perspectives, and 2 topical reviews on wide-ranging topics including innovation, policy, poverty alleviation, digitalisation, and modelling. Collectively, these 25 new articles help advance understanding of technology and global change, building on work 25 years ago by Arnulf Grübler whose system perspective in turn built on pioneering scholarship in evolutionary and institutional economics. In this editorial essay, we survey the 25 contributions to this Focus Issue and draw out some of the themes and ideas that define the research frontiers in this field.

1. Text

Over twenty five years ago, Arnulf Grübler's book 'Technology and Global Change' documented the paradoxical relationship of technology as both source and remedy of global environmental change (Grubler 1998). This study built on early thinking on innovation dynamics by fellow Austrian, Joseph Schumpeter (1934) and a subsequent body of pioneering work on evolutionary economics (Freeman 1974, Nelson and Winter 1982, Freeman and Perez 1988, Arthur 1989, Dosi *et al* 1990). Drawing both on this literature and a wealth of historical data, Grübler illustrated characteristic patterns of technological change that have remained remarkably stable across time periods, technologies, and contexts. These included drivers such as positive returns to scale and knowledge spillovers and resulting dynamics such as S-shaped diffusion curves and spatial diffusion patterns from core to periphery. He emphasised the dynamic, uncertain, systemic, and cumulative aspects of technology. The historical data he analysed also showed adoption processes that tended to be more gradual than might be expected.

Grübler also emphasised that technology's impact on the global environment had to be understood through the macroscopic lens of technological clusters rather than singular innovations: not solar PV, electric vehicles, and smartphones, but the interdependent systems of energy, transport, and communication of which they are part.

In the last decades of the twentieth century, the backdrop to Grübler's analysis, the prominent technological clusters for energy, transport and communication, industry, and consumer services respectively were: gas, electricity; roads, air transport, multimedia communication; alloys, specialty materials, environmental technologies, disassembly and recycling; leisure, vacation, custom-made products (table 4.1 in Grubler 1998). At the time, these clusters of technological systems were spreading out from their innovation centres (OECD) to peripheries (Asia), with global change impacts evident in patterns of land-use, urbanisation, air pollution, ozone depletion, and increasingly, greenhouse gases.

Much of these findings still resonate more than twenty-five years on. On one hand they explain the slowness of systems change that is at the centre of Grübler's work. Renewable electrification is accelerating, but in a fossil fuel-dominated global energy system, natural gas remains the most versatile 'bridging fuel' towards full decarbonisation. Despite the Covid-19 shock, patterns of road and air travel embedded in the spatial organisation of work, leisure, and domestic life make the transportation sector stubbornly resistant to structural change.

On the other hand, Grübler's view of clusters, which was inspired by Freeman and Perez (1988), helps explain the pervasive impacts of change. Digitalisation as a general-purpose technology continues to upheave routines and practices at home, in the office, and on the factory floor, while requiring quantities of previously exotic metals and minerals whose supply chains impose both geopolitical and environmental risks in addition to the longer standing and more substantive risks in the supply and use of fossil fuels. The inter-dependence of technology clusters across energy, transport, materials, industry and consumer products is also vividly clear in the low-carbon vision of a decentralised, renewable, smart, service-oriented, prosuming, accessible, and electrified future world that Grübler has been instrumental in advancing (Grubler *et al* 2018).

But much about technology and global change has also changed in the past twenty-five years. Several landscape-level shifts have affected research priorities. In particular, climate change and social justice issues are more prominent in global discourse. More recently, geopolitics, economic competitiveness, and economic resilience have emerged as other key dimensions of innovation and climate efforts. The UN Sustainable Development Goals have made explicit the breadth and magnitude of entwined social and environmental challenges, as well as the trade-offs and synergies in their pursuit. The core has steadily shifted from historical innovation centres in the US and Europe to China and other Asian economies. Innovation, industrial and climate policies seeking to direct the course of technological change have grown in abundance and diversity, enriching the evidence base on what works. Systems theories and analyses of technological change have brought social and institutional conditions more to the fore. Scenarios, simulation models, new types of data and other forward-looking analytical tools have also made progress in capturing Grübler's 'grand patterns of technological change'.

In this ever-growing and ever-branching body of scholarship on innovation and technological change applied to energy, climate, land use, and other global environmental issues, much progress has been made—but much still remains to do.

In this Focus Issue, we extend and enrich understanding of technology and global change, with a view to positively informing major contemporary challenges of climate change and sustainable development. Following Arnulf Grübler's precedent, we focus particularly on new empirical analyses of the grand patterns of innovation and technological change that help us understand how positive social and environmental impacts can be achieved at scale. As 'Technology and Global Change' concluded:

> *"The immediate challenge is to include the billions of people who have so far been excluded from the benefits of technology. The next challenge is to wisely use the power of technology to 'liberate' the environment from human interference" (*Grubler 1998, *p 364).*

2. Topics

To structure this Focus Issue, we identified a small number of topic areas in which we invited significant new contributions to policy-relevant scientific understanding on technological change and the environment. These topics are:

1. clean energy innovation and policy for poverty alleviation in developing countries
2. socio-technical transitions
3. digitalisation and demand-side transformation
4. innovation economics and policy for energy transitions
5. modelling technology and global change.

In this editorial essay, we provide a brief introduction and summary of the contributions in each topic area and invite the reader to explore further.

2.1. Clean energy innovation and policy for poverty alleviation in developing countries

Over a billion people worldwide still lack access to the benefits of technological change in the form of electricity, clean cooking fuels, sanitation, hygiene, motorised travel, and other prerequisites of decent living (Rao and Min 2017, Kikstra *et al* 2021). Innovating for poverty alleviation (including energy) and providing decent standards of living for all while minimising adverse impacts on human and planetary health is needed to enhance overall sustainability. Concepts such as appropriate innovation, inclusive innovation, and frugal innovation have been used to describe efforts to use local resources and ingenuity to deliver affordable services and opportunities that enhance wellbeing for the most disenfranchised and deprived groups in society (Prabhu 2017). Innovations are required not only in technology but also in financial and business models, service provisioning systems and social practices, and in finding ways to leverage grassroots innovations for global impact.

Four contributions in this Focus Issue explore this topic area.

Pachauri *et al* (2024) use a comparative case-study design to identify common factors explaining locally-adapted success stories of inclusive innovation in low-income regions of Africa. Their cases include solar irrigation in farming, solar-powered cold storage, and improved access to clean cooking fuels and stoves, spanning innovations in products, services, business models, and supply chains. Despite this variation, they find commonalities in the bundling of products and services responsive to users' needs alongside pay-as-you-go financing for affordability and digital payment options for flexibility. Accessibility for more marginalised communities is further enabled by piggybacking on local networks, distributors and service agents. Public policy as well as strong funding support from government donors or private investors was an important wider enabler (Pachauri *et al* 2024).

Falchetta *et al* (2023) take one of these cases—solar PV irrigation systems—and demonstrate its potential if deployed at scale. Using spatially explicit integrated modelling of 19 major crops in smallholder croplands in sub-Saharan Africa (SSA), they show how more than a third of unmet water crop requirements could be supplied by solar irrigation systems with payback periods for farmers under 20 years. Resulting benefits from improved yields, food security, and energy access significantly exceed upfront investment costs. Their analysis underscores the attractiveness of solar irrigation for both funders and farmers but also the importance of resource management policy to mitigate over-extraction risks (Falchetta *et al* 2023).

Colombo *et al* (2024) further integrate social dimensions into the evaluation of innovations for poverty alleviation. They propose a comprehensive framework for energy access planning that emphasises the integration of user needs, technical solutions, and delivery business models (Colombo *et al* 2024). Echoing Pachauri *et al* (2024), they also emphasise the importance of technical, procedural, and economic regulations that analysis of past innovation failures shows to be critical.

Shifting from agriculture and energy to transport, Butt *et al* (2024) take the policy and regulatory theme further using a technology innovation system approach to analyse mobility transitions in Pakistan. They find that policy played a catalytic role in the emergence of compressed natural gas as a lower-emission fuel alternative to petrol and diesel, but that policy also undermined further maturation to protect scarce local gas resources as attention shifted in the global mobility landscape towards electric vehicles. Their analysis shows how developing countries can build the institutional capacity to absorb global innovation opportunities (Butt *et al* 2024).

These new empirical, modelling, and conceptual studies in different low-income countries across Africa and Asia show the interdependence of entrepreneurial activity for widening access to more sustainable innovations and the policy environment necessary for underwriting business cases. The importance of locally-adapted innovation assessments and deployment strategies is another common theme.

2.2. Socio-technical transitions

Addressing climate change will require major transitions in socio-technical systems, involving changes in technologies, infrastructures, social practices, institutions, manufacturing, and cultural meanings (Geels *et al* 2017). While the socio-technical transitions literature has so far mostly focused on single systems, more attention is needed for multi-system interactions and technological clusters, including interactions between electricity, mobility, and heavy industry. This shift aligns closely with the arguments in Grubler (1998). These interactions may not be smooth or straightforward because actors in different systems may have different interests, views, and capabilities and because institutions may be mis-aligned. Five papers in the special issue directly address this topic.

Andres *et al* (2023) address one of the fundamental concepts in Grubler (1998), the substitution of an old technology by a new one. Those entities, companies or countries, with strong ties to the old technology will find transitions slower. Here, the authors operationalise these ideas with data on exports of established or 'brown' technologies. Their findings add nuance to these concepts by showing that concentration in exporting a small number of brown products makes transitions more difficult (Andres *et al* 2023). Variety in brown products can enable transitions.

Vinichenko *et al* (2023) analyse one of Grübler's core concepts, the speed of diffusion. Analysing historical data for nuclear, wind, and solar power, they find that solar and wind have diffused faster and more broadly than nuclear. They do however see a future role for nuclear power in Asia in scenarios consistent with Paris Agreement goals because of the rapid growth in energy needs there.

Nykamp *et al* (2023) apply the systemic perspective of Grübler in assessing the electrification in Norway of three case studies: marine transport, construction, and chemicals. While these three cases represent very different configurations of actors, they are all constrained by the same systemic issue: limited connections to the electricity grid.

Kern *et al* (2023) focus on discourse over a new energy cluster, hydrogen, in a case study of Germany. They focus on an element important to Grübler's work, shared expectations. They find that expectations on how and what role hydrogen infrastructure will play in Germany is highly varied and thus slows down the rise of hydrogen as a cluster within the energy system.

Rogge and Goedeking (2024) conduct a comparative case study of electrifying transportation in Germany and California. They conduct interviews in both places and identify a large set of barriers holding the transition back. Importantly, they argue that most of these barriers have to do with governance issues, both for how incumbent industries will fare in the new regime as well as on who benefits with the expansion of the new system.

2.3. Digitalisation and demand-side transformation

More than half the world's population has access to a smartphone, and over two thirds have access to the internet. Digitalisation is central to many of the technological clusters shaping life in the Anthropocene including as enabler of renewable energy integration in electricity networks and sharing economy platforms into transportation and retail systems. As well as its direct energy footprint, digitalisation has systemic implications for planetary boundaries (e.g. carbon emissions), human agency and governance (e.g. democratic institutions), and equity (within and between countries) (Creutzig *et al* 2022). Digitalisation is opening up opportunities for 'demand-side transformation' strategies that reduce the natural resources required to deliver appealing services to final users, while raising their living standards (Wilson *et al* 2023). Much of the focus in decarbonisation debates has been on energy-supply technologies like renewables and carbon capture, but the transformation of service provisioning systems towards step change improvements in resource efficiency is an important complementary strategy for '*liberating the environment from human interference*' (Grubler 1998).

Six contributions in this Focus Issue explore this topic area: two on digitalisation, three on transforming provisioning systems for mobility, and one on broader social innovation enablers.

Fouquet (2023) takes the long view by analysing trends in the communication intensity and energy intensity of the global economy since 1850. He finds that information (communication) has consistently substituted for energy as a factor of production, particularly in industrialised countries. However, given current marginal rates of substitution, this dynamic is set to slow or halt. From this macro-perspective, digitalisation cannot be relied upon to drive further decarbonisation. In the vein of Grübler's findings on the interdependence between transport and communication infrastructures for moving stuff and for moving information respectively (Grubler 1990), Fouquet's work shows the interdependence between energy and information technology clusters from a systems perspective (Fouquet 2023).

Bento (2023) goes from macro to micro on the digitalisation theme by analysing the potential for digital convergence in sharing economies to reduce environmental impacts. He defines digital convergence as the provision of multiple services by single multifunctional devices—the smartphone is an exemplar. In combination with digitally-enabled sharing platforms, he estimates convergence could reduce device and appliance ownership while increasing usage in all but 1 of 11 world regions. Together with improving efficiency per device, the net effect of digital convergence is a 55%–56% reduction in emissions, energy and materials by 2050 while ensuring decent living standards for all (Bento 2023).

Creutzig *et al* (2024) focus on shared pooled mobility (or ride-pooling) as a digitally-enabled innovation that efficiently bundles rides in cars and vans to increase their occupancy. This reduces the energy and other resources like road space and parking that are needed to provide the same levels of mobility service. In their perspective article, they comparatively analyse insights from nine different research traditions to draw up a programme of research and action for overcoming the economic, system design, and regulatory constraints inhibiting this potentially transformative demand-side strategy (Creutzig *et al* 2024).

In a complementary study, Arbeláez Vélez *et al* (2023) look empirically at shared mobility alongside digitalisation and electrification as drivers of change in passenger transport. They develop shared mobility scenarios to 2035 built off baseline travel data in 2019 for the US, Sweden, and The Netherlands. They then use a travel demand model to estimate direct emissions from vehicle fleets, with input-output modelling to capture indirect emission footprints (e.g. from manufacturing supply chains). Projected emissions reductions from shared mobility are amplified under assumptions of social transformation in users' travel behaviour and expectations (Arbeláez Vélez *et al* 2023).

Arnz and Krumm (2023) are also concerned with reducing energy demand for passenger transport but from a sufficiency rather than a shared mobility perspective. Like Arbeláez Vélez *et al* (2023) they develop scenario storylines linked to underlying drivers of change that they translate into parameters in a transport model, in this case for Germany. They estimate a potential 73% reduction in energy demand from concerted 'avoid' (less travel) and 'shift' strategies (different travel modes) with strong co-benefits for users around 'new fundamental principles of mobility: equity, health, and diversity' (Arnz and Krumm 2023). This is a common theme of the demand-side transformation literature dating back to Grubler *et al* (2018)'s influential global low energy demand study: dramatic reductions in resource consumption can go hand in hand with significant increases in wellbeing and living standards (Creutzig *et al* 2021).

Niamir *et al* (2024) use an innovation systems lens to flesh out the conditions under which technological interventions can be scaled up in line with this vision of a low-energy high-wellbeing future. They also focus on shared mobility but include additive manufacturing and solar prosumers as case studies from industrial and energy sectors. They identity a set of eight conditions which they term 'social enablers'. These include peer effects (inter-personal social influence), inclusive governance, finance and investment, and enabling policy environments (Niamir *et al* 2024). These enablers are recurring themes in many of the empirical studies in this Focus Issue.

2.4. Innovation economics and policy for energy transitions

Government actions have the potential to influence both the speed and direction of technological change. As Grübler called for in 1998:

> "Better knowledge is required on the effectiveness of different instruments to induce technological change in particular directions and how to craft evolutionary technology strategies that prepare us best for a wide range of future contingencies and potential surprises" (Grubler 1998, p 366).

A growing number of papers have analysed past and existing policies, as well as the potential for new policies to steer innovation toward favourable outcomes for global change (Peñasco *et al* 2021, Meckling *et al* 2022, Ma *et al* 2025). We have several papers in this Focus Issue that look at multiple policies simultaneously, some of which fall under the term industrial policy. Grüblerian concepts are highlighted throughout including policy experimentation and learning, alignment, knowledge spillovers, and clusters (Grubler and Wilson 2014). Policy analysis, patents, and large language models are put to work to arrive at the assessments in the papers that follow.

Burrage *et al* (2023) analyse federally-funded climate solutions research in the US and find that it is overwhelmingly directed toward engineering and the natural sciences. Further they see marginalisation of Tribal institutions, Historically Black Colleges and Universities, and Hispanic Serving Institutions, as evidenced by much lower funding per student. Consequently, they argue that improving equity in research funding is part of an equitable energy transition.

Taking a systemic view on policy, Victor and Carlton (2023) in their Perspective article look at the re-emergence of 'industrial policy' in multiple countries over the past several years. Industrial policy in many ways echoes the cluster-focus of Grübler's arguments. In a further similarity, the authors emphasise the large uncertainty that arises from combining a set of policies together. They raise the importance of experimental governance as an approach to policy-making for which learning about what works is built in.

Narassimhan *et al* (2023) also look at industrial policy, in this case focusing on electric vehicles. They take up a topic that Grübler emphasised, ensuring that the set of policies at play are aligned with each other. Empirically, for electric vehicles, they find that countries whose policies were aligned attained and maintained first-mover advantage. Further, misalignment favours incumbents.

In a third paper on industrial policy, Hart (2023) assesses the array of policies passed in the US directed at global change between 2020 and 2023. Following the framework of Grübler, Hart sees uncertainty as central, but also opportunities for learning and generation of new knowledge through the array of new funding mechanisms introduced in this period.

Because the policy related to technology and global change depends on understanding the patterns and incentives in those technologies, the special issue includes papers focused on some of these underlying drivers. Toetzke *et al* (2023) pick up on the uncertainties described in the papers on industrial policy above and aim for improving the timeliness of information about how policies are working. They argue that large language models can analyse unstructured data from websites and social media to provide policymakers with assessments in near real-time to help guide their efforts.

Peiseler *et al* (2024) aim to understand knowledge spillovers, a core Grüblerian concept. They look at Korean patents for lithium-ion batteries with inventors from both Korean and other countries listed on them. They find that patents with both Korean and Japanese inventors produced the most influential patents. Tacit knowledge—another key Grüblerian concept (Grubler and Nemet 2014)—seems to have been crucial because the most important inventor combinations involved companies from Korea hiring experienced engineers from Japan.

Finally, Wang *et al* (2024) also use patent data, in this case to assess how closely patents are related to each other. In their study of offshore wind turbine patents, they find that patents for foundations and maintaining offshore turbines are closely related to oil and gas industry while the turbine components are more closely related to onshore wind. Their results again echo the notion of clusters, in this case with some obvious connections, as well as less obvious ones.

2.5. Modelling technology and global change

How well do we model innovation and technological change? Inducing low-carbon innovation and deploying resulting technologies forms the backbone of national and international climate policy programmes. A range of simulation, optimisation, accounting, and agent-based modelling techniques are used to assess programme design *ex ante* or evaluate outcomes *ex post* (Sathaye and Shukla 2013). However, there are longstanding concerns on whether current modelling approaches adequately represent and reproduce the observed mechanisms of induced innovation within co-evolving innovation, industrial and consumer systems (Grubb *et al* 2021) and how uncertainty around the outcomes of innovation and policies introduced to shape it is modelled (Anadón *et al* 2017). Important debates also remain on whether models of technological change are built upon axioms as opposed to empirics (Meng *et al* 2021, Wilson *et al* 2021). Resolving these debates will impact how modelling analysis informs policy-making both on induced technological change and on the socio-economic impacts of a rapid zero-carbon transition.

In this Focus Issue, we include three contributions that explore this topic area: one looks back at how technological change has been modelled in recent decades, and two explore frontier issues—lifestyles and socio-politics—for future-oriented technoeconomic simulation models. Both these recognise the importance of human and institutional factors in low-carbon transitions.

Pasqualino *et al* (2024) set the scene by reviewing the models used to inform national and international climate policy including through the IPCC assessments (Guivarch *et al* 2022). Their concern is that mainstream modelling approaches assuming cost-optimal solutions or market equilibria fail to capture non-linear innovation dynamics. As an example, they find relatively few of the 24 they consider in detail have endogenous (within-model) representations of the positive returns to scale associated with learning-by-doing, network and spillover effects—elements of Grübler's grand patterns of technological change (Grubler 1996). To help policymakers select appropriate models for policy assessment they provide a helpful decision tree for matching model characteristics to task requirements. They argue that endogenously modelling induced innovation should enable a mission-oriented approach to policymaking that seeks opportunities to accelerate the low-carbon energy transition while avoiding the risks of inaction (Pasqualino *et al* 2024).

Dioha *et al* (2023) point to another omission in mainstream technoeconomic energy transition modelling—social and political institutions. They ask: why does modelling primarily focus on the techno-economic factors that support the energy transition, but not the socio-political factors that shape the transition? Although they recognise the complexity and data availability challenges for modelling socio-political factors, they argue their inclusion would improve modelling assessments' realism, impact, relevance and contributions to social justice. This would require new metrics, improved model structures, model coupling, and stronger interdisciplinarity (Dioha *et al* 2023).

Pettifor *et al* (2023b) contribute insights on a related weak spot in conventional techno-economic modelling of energy transitions—the representation of behaviours and lifestyles. However, in their case they go beyond critique to develop and apply a novel empirically-grounded approach for endogenously representing low-carbon lifestyle change (Pettifor *et al* 2023a). They demonstrate their approach by coupling their 'LIFE' model to a global integrated assessment framework, MESSAGE, widely used in IPCC assessments. Their results show how both lifestyle heterogeneity across different social groups give rise to lifestyle change dynamics in response to changing technoeconomic conditions and climate policy. This improves both model verisimilitude and model relevance to pressing policy concerns around equity and social acceptance (Pettifor *et al* 2023b).

3. Conclusions

Looking at the 25 articles in this Focus Issue together, one immediately sees the continued relevance of the arguments and conclusions in Grübler's 1998 book, Technology and Global Change, and from the field of evolutionary economics more generally. Key concepts such as clusters, learning, heterogeneity, and uncertainty loom large in this work conducted over 25 years later. Grübler's work is always situated on evidence, whether quantitative data sets or qualitative case studies. He draws on both, as do the papers in this issue. Even the quantitative-oriented papers necessarily reflect on qualitative explanations of the mechanisms at work. In part because Grübler emphasised systems, clusters, and interdependence, few data sets, even in combination, are up to the task of capturing all important components. The combination of quantitative and qualitative analysis that provides the evidence base for Grübler's claims, is front and centre in the papers in this Focus Issue as well.

Also because of his insightful and persistent focus on a systems perspective, Grübler's work is often characterised by the development of quantitative modelling. Whereas an empirical study can integrate both quantitative and qualitative evidence, modelling is restricted to the former. As a result, the three papers on modelling in this Focus Issue point to important characteristics of technological change often still missing in models—increasing returns, different innovation channels, institutions, and end-user behaviour. Thus, research continues on one of the hallmarks of Grübler's influence: the translation of case studies, thick explanations and complicated, interdependent phenomena into compact quantitative representations suitable for simulation and optimisation.

By setting out a framework capturing the most important aspects of technology and global change over 25 years ago, Grübler made important contributions to evolutionary economics and innovation studies, which continue to inspire a much larger community of scholars and practitioners working on these issues. That is surely one of his most significant and lasting legacies.

ORCID iDs

Charlie Wilson 0000-0001-8164-3566
Greg Nemet 0000-0001-7859-4580
Laura Diaz Anadon 0000-0002-2688-118X
Frank W Geels 0000-0001-8778-4757
Radhika Khosla 0000-0002-7730-8041
Shonali Pachauri 0000-0001-8138-3178

References

Anadón L D, Baker E and Bosetti V 2017 Integrating uncertainty into public energy research and development decisions *Nat. Energy* **2** 17071

Andres P, Mealy P, Handler N and Fankhauser S 2023 Stranded nations? Transition risks and opportunities towards a clean economy *Environ. Res. Lett.* **18** 045004

Arbeláez Vélez A M, Ivanova D and Stadler K 2023 Shared mobility and lifestyles as mechanisms to reduce environmental impacts from passenger transportation *Environ. Res. Lett.* **18** 084025

Arnz M and Krumm A 2023 Sufficiency in passenger transport and its potential for lowering energy demand *Environ. Res. Lett.* **18** 094008

Arthur B W 1989 Competing technologies, increasing returns, and lock-in by historical events *Econ. J.* **99** 116–31

Bento N 2023 The potential of digital convergence and sharing of consumer goods to improve living conditions and reduce emissions *Environ. Res. Lett.* **18** 124014

Burrage A, Goldstein A and Carter T 2023 Disciplinary and institutional diversity of federally funded academic research on climate solutions in the United States *Environ. Res. Lett.* **18** 114019

Butt M H, Roy J and Some S 2024 Policy as a catalyst in shaping mobility sector transition for developing countries *Environ. Res. Lett.* **19** 024039

Colombo E, Crevani G, Stevanato N and Mereu R 2024 Comprehensive energy solution planning (CESP) framework: an evidence-based approach for sustainable energy access projects in developing countries *Environ. Res. Lett.* **19** 054059

Creutzig F *et al* 2021 Demand-side solutions to climate change mitigation consistent with high levels of well-being *Nat. Clim. Change* **12** 36-46

Creutzig F *et al* 2022 Digitalization and the Anthropocene *Annu. Rev. Environ. Resour.* **47** 479–509

Creutzig F *et al* 2024 Shared pooled mobility: expert review from nine disciplines and implications for an emerging transdisciplinary research agenda *Environ. Res. Lett.* **19** 053004

Dioha M O, Montgomery M, Almada R, Dato P and Abrahams L 2023 Beyond dollars and cents: why socio-political factors matter in energy system modeling *Environ. Res. Lett.* **18** 121002

Dosi G, Pavitt K and Soete L 1990 *The Economics of Technical Change and International Trade* (Harvester Wheatsheaf)

Falchetta G, Semeria F, Tuninetti M, Giordano V, Pachauri S and Byers E 2023 Solar irrigation in sub-Saharan Africa: economic feasibility and development potential *Environ. Res. Lett.* **18** 094044

Fouquet R 2023 The digitalisation, dematerialisation and decarbonisation of the global economy in historical perspective: the relationship between energy and information since 1850 *Environ. Res. Lett.* **19** 014043

Freeman C 1974 *The Economics of Industrial Innovation* (The MIT Press)

Freeman C and Perez C 1988 Structural crises of adjustment, business cycles and investment behavior *Technical Change and Economic Theory* ed G Dosi, C Freeman, R Nelson, G Silverberg and L Soete (Pinter) pp 38–66

Geels F W, Sovacool B K, Schwanen T and Sorrell S 2017 Sociotechnical transitions for deep decarbonization *Science* **357** 1242

Grubb M *et al* 2021 Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO2 mitigation *Environ. Res. Lett.* **16** 043007

Grubler A 1990 *The Rise and Fall of Infrastructures, Dynamics of Evolution and Technological Change in Transport* (Physica-Verlag)

Grubler A 1996 Time for a change: on the patterns of diffusion of innovation *Daedalus* **125** 19–42 (available at: https://www.jstor.org/stable/20027369)

Grubler A 1998 *Technology and Global Change* (Cambridge University Press)

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 *Nat. Energy* **3** 515–27

Grubler A and Nemet G F 2014 Chapter 10: sources and consequences of knowledge depreciation *Energy Technology Innovation: Learning from Historical Successes and Failures* ed A Grubler and C Wilson (Cambridge University Press) pp 133–45

Grubler A and Wilson C 2014 *Energy Technology Innovation: Learning from Historical Successes and Failures* (Cambridge University Press) (https://doi.org/10.1017/CBO9781139150880)

Guivarch C *et al* 2022 Annex III: scenarios and modelling methods *Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* (Intergovernmental Panel on Climate Change (IPCC)) pp 1451–546

Hart D M 2023 Recent legislation in the United States: consequences for the US and global energy and climate innovation systems *Environ. Res. Lett.* **18** 091002

Kern F, Schmelzle F and Hummel M 2023 Hydrogen as a panacea for decarbonising everything? Exploring contested hydrogen pathways in Germany *Environ. Res. Lett.* **18** 114017

Kikstra J S, Mastrucci A, Min J, Riahi K and Rao N D 2021 Decent living gaps and energy needs around the world *Environ. Res. Lett.* **16** 095006

Ma C, Peñasco C and Anadón L D 2025 Technology innovation and environmental outcomes of road transportation policy instruments *Nat. Commun.* **16** 4467

Meckling J, Galeazzi C, Shears E, Xu T and Anadon L D 2022 Energy innovation funding and institutions in major economies *Nat. Energy* **7** 876–85

Meng J, Way R, Verdolini E and Diaz Anadon L 2021 Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition *Proc. Natl Acad. Sci.* **118** e1917165118

Narassimhan E, Myslikova Z and Gallagher K S 2023 Strategies for green industrial and innovation policy–an analysis of policy alignment, misalignment, and realignment around dominant designs in the EV sector* *Environ. Res. Lett.* **19** 014029

Nelson R R and Winter S G 1982 *An Evolutionary Theory of Economic Change* (Belknap Press)

Niamir L, Verdolini E and Nemet G F 2024 Social innovation enablers to unlock a low energy demand future *Environ. Res. Lett.* **19** 024033

Nykamp H, Andersen A D and Geels F W 2023 Low-carbon electrification as a multi-system transition: a socio-technical analysis of Norwegian maritime transport, construction, and chemical sectors *Environ. Res. Lett.* **18** 094059

Pachauri S, Coldrey O, Falchetta G and Pelz S 2024 Innovation in distributed energy services for sustainable development: case studies from sub-Saharan Africa *Environ. Res. Lett.* **19** 114090

Pasqualino R *et al* 2024 Modelling induced innovation for the low-carbon energy transition: a menu of options *Environ. Res. Lett.* **19** 073004
Peiseler L, Jun Y L, Schmid N, Waidelich P, Malhotra A and Schmidt T S 2024 Globalising innovation through co-inventions–the success case of the Korean lithium-ion battery industry *Environ. Res. Lett.* **19** 034025
Peñasco C, Anadón L D and Verdolini E 2021 Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments *Nat. Clim. Change* **11** 257–65
Pettifor H, Agnew M and Wilson C 2023a A framework for measuring and modelling low-carbon lifestyles *Glob. Environ. Change* **82** 102739
Pettifor H, Mastrucci A, Wilson C, van Ruijven B, Agnew M and Gallic T L 2023b Endogenous simulation of low-carbon lifestyle change in global climate mitigation pathways *Environ. Res. Lett.* **19** 014016
Prabhu J 2017 Frugal innovation: doing more with less for more *Phil. Trans. R. Soc. A* **375** 20160372
Rao N D and Min J 2017 Decent living standards: material prerequisites for human wellbeing *Soc. Indic. Res.* **138** 225–44
Rogge K S and Goedeking N 2024 Challenges in accelerating net-zero transitions: insights from transport electrification in Germany and California *Environ. Res. Lett.* **19** 044007
Sathaye J and Shukla P R 2013 Methods and models for costing carbon mitigation *Annu. Rev. Environ. Resour.* **38** 137–68
Schumpeter J A 1934 *The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle* 1st edn (Harvard University Press)
Toetzke M, Probst B and Feuerriegel S 2023 Leveraging large language models to monitor climate technology innovation *Environ. Res. Lett.* **18** 091004
Victor D G and Carlton E K 2023 Technology to solve global problems: an emerging consensus for green industrial policy? *Environ. Res. Lett.* **18** 091006
Vinichenko V, Jewell J, Jacobsson J and Cherp A 2023 Historical diffusion of nuclear, wind and solar power in different national contexts: implications for climate mitigation pathways *Environ. Res. Lett.* **18** 094066
Wang Y, Baker E and Goldstein A 2024 Leveraging patent analysis to measure relatedness between technology domains: an application on offshore wind energy *Environ. Res. Lett.* **19** 024045
Wilson C, Grubler A, Nemet G, Pachauri S, Pauliuk S and Wiedenhofer D 2023 The 'High-with-low' scenario narrative: key themes, cross-cutting linkages, and implications for modelling (No. WP-23-009) (International Institute for Applied Systems Analysis (IIASA)) (available at: https://pure.iiasa.ac.at/id/eprint/19036/1/WP-23-009.pdf)
Wilson C, Guivarch C, Kriegler E, van Ruijven B, van Vuuren D P, Krey V, Schwanitz V J and Thompson E L 2021 Evaluating process-based integrated assessment models of climate change mitigation *Clim. Change* **166** 3