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Social innovation enablers to unlock a low energy demand future

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Abstract

We initiate the process of developing a comprehensive low energy demand (LED) innovation narrative by applying the framework 'Functions of Innovation Systems' (FIS) and identifying the key conditions under which technology interventions can be improved and scaled up over the next three decades to contribute to climate change mitigation. Several studies have argued that the potential for LED-focused mitigation is much larger than previously portrayed and have shown that adopting a wide variety of energy-reducing activities would achieve emissions reductions compatible with a 1.5 C temperature target. Yet, how realistic achieving such a scenario might be or what processes would need to be in place to create a pathway to a LED outcome in mid-century, remain overlooked. This study contributes to understanding LED's mitigation potential by outlining narratives of LED innovation in three end-use sectors: industry, transport, and buildings. Our analysis relies on the FIS approach to assess three innovations in these sectors. A key insight is that the distinct characteristics of LED technology make enabling social innovations crucial for their widespread adoption. Finally, we identify a set of eight social enablers required for unlocking LED pathways.

1. Introduction

The low energy demand (LED) scenarios (Grubler *et al* 2018) quantitatively showed that LED technologies and behaviors could reduce emissions over the next 30 years compatible with a 1.5 C target. They used detailed estimates of how low energy use could become across the whole economy and then used integrated assessment modeling (IAMs) to evaluate mid-century impacts on greenhouse gas emissions and other social indicators. It built on earlier efforts going back to the 1970s, for example Soft Energy Paths (Lovins 1976), as well as the International Energy Agency's longstanding work on energy efficiency (IEA 2022), but is distinct because of its low temperature target. The LED results are important because they showed that the scope of emissions savings through lower energy use is vast, to the extent that they enabled the Paris Agreement targets to be achieved without relying on technological carbon removal. These insights arose from the authors' distinct focus on energy services and whence energy demand arises–particularly in the context of increasing access to energy services in developing countries.

The original LED paper had a substantial impact on the climate community. For example, its insights were prevalent in the IPCC AR6 chapter on energy demand (Creutzig *et al* 2022b). However, one prominent critique is that while the paper calculated careful estimates of energy savings, it did not make claims about how realistic achieving those savings might be (Keyßer and Lenzen 2021). While (Grubler *et al* 2018) compared energy use in today's world to that in the LED future through IAMs scenario runs, it did not explicitly characterize how behavioral and social dynamics would enable the transition to a low-energy world (Cordroch *et al* 2022). For example, it provided only an overarching view of how digital technologies may impact energy demand from industry and adopted a quite specific focus on energy savings due to the increasing role of services in meeting consumer choices. This set of mechanisms is particularly important given the LED scenario's emphasis on energy end-use, the role of consumers, and especially how they interact with each other. The extent to which LED approaches are taken seriously as credible complements to other mitigation efforts depends on understanding whether a LED world can be realistically attained over the next three decades; this in turn depends on a better characterization of the mechanisms for a transition to an LED world, which we describe here as LED innovation.

In this paper, we initiate the process of building a comprehensive narrative on LED innovation that describes how LED technologies can improve and be scaled up to become widely adopted. Following (Nemet and Greene 2022), LED innovations are defined as 'any effort to improve the level and structure of energy demand', 'including LED technologies and LED services.' This broad definition allows us to depart from a purely technological focus towards the inclusion of human behavior and business models. We rely on the 'Functions of Innovation Systems' (FIS) framework (Bergek *et al* 2008) to identify innovation dynamics and adoption timelines consistent with overall LED scenarios. This allows us to identify conditions and key enablers for the successful development and deployment of LED innovation in the context of five key drivers of change that condition innovation in LED (Grubler *et al* 2018): higher living standards, urbanization, digitalization, novel services, and prosumers. This paper thus represents a first step towards the generation of narratives characterized by a comparative systemic perspective through both quantitative indicators and qualitative descriptors to appropriately capture the many ways LED futures could unfold, given the distinct characteristics of LED innovations (Nemet and Greene 2022).

2. Methodology and scope

2.1. Analytical approach

Following Grubler *et al* (2018), we focus on three key high-level sectors—buildings, transport, and industry—because they provide a useful taxonomy congruent with the structure of IAMs. Essential improvements in terms of LED and decarbonization also arise when these sectors are coupled, such as vehicle-to-grid applications (Noel *et al* 2021). In addition, general purpose technologies with pervasive effects across sectors also play a key role, e.g. digitalization (Wilson *et al* 2020b, Creutzig *et al* 2022a).

Our comparative case study analysis of innovations relevant in the context of a LED[5] follows the approach of (Hekkert *et al* 2007), which identifies seven key FISs: knowledge development, knowledge diffusion, the guidance of search, resource mobilization, entrepreneurial activities, market formation and creation of legitimacy. We conceptualize how the development from nascent adoption to widespread diffusion of three innovations—which differ in innovation stage and maturity—may support the achievement of LED with a specific focus on the relevance of the different functions, and the role that key actors will play in LED scenarios in various sectors. While other innovations are also relevant in the context of LED, the three examples we discuss here are both relevant for their impact on energy demand, and widely discussed in both academic and business circles. A main insight from this comparative approach is that successful LED innovations involve substantial contributions from, and interactions among, technological, social, and business model innovation. This ultimately leads us to identify and discuss key enablers and conditions for further development and widespread uptake relevant for modelling LED pathways.

2.2. Distinct characteristics of LED innovations

A set of characteristics makes LED innovations distinct from many other types of innovation (Nemet and Greene 2022). In our context, these can be summarized as follows:

1. LED innovations favor a movement from a traditional economy based on goods towards the provision of ***Services.*** However, more efficient service provision can stimulate more utilization through short-term and longer rebound effects. Yet, typically, rebound takes back only some of the energy savings but not all (Gillingham *et al* 2016).
2. In contrast to supply-side approaches, LED adoption involves the successful and widespread application across billions of heterogeneous ***Adopters*** with diverse preferences for services (Niamir *et al* 2020b, Nemet and Greene 2022). Individual energy-related decisions, adopting new technology or services, are influenced by peer effects, norms and values (Devine-Wright 2011,

[5] LED innovations encompass all endeavors aimed to improve the level and structure of energy demand, including advancements in LED technologies and associated LED services. This broad definition expands the system boundaries of our analysis: from a purely technological focus towards the inclusion of human behavior and business models; from a pure focus on energy to consideration of material use impacts; and from a mere focus on monetary indicators (e.g. GDP) towards inclusive well-being. Our working assumption is that successful LED innovations are likely to involve substantial contributions from, and interactions among, technological innovation, social innovation, and business model innovation.

Table 1. Summary characteristics of the case studies.

Case study	Additive manufacturing (AM)	Sharing mobility (SM)	Solar prosumers (SP)
Sector	Industry	Transport	Buildings
Innovation focus	Technical, business model	Infrastructural, technical, business model, regulation	Technical, infrastructural, business model, regulation
Innovation stage[a]	Market adoption and scale-up in niche markets for specialized applications. Fundamental science and technology exploration to prototyping for other applications.	From prototype to market adoption and scale-up, depends on the mobility mode and geographical context (e.g. urban/rural, developing/developed countries)	Technology mature. Consumer adoption nascent.
Distinct characteristics	Services: change from traditional production to made-on-demand, customized products. Adopters: firms Technology: 3D printing	Services: sharing mobility infrastructure and business (e.g., GoGet, Lime micro-mobility) Adopters: citizens Technology: the mobile applications	Services: renewable electricity Adopters: citizens Technology: solar PVs, batteries, electric grid
Key demand reduction	AM reduces material and energy demand in prototyping and customized applications. Potential reduction in energy demand varies by sector, ranging from 4 to 27%.	Studies show sharing mobility can reduce GHG emissions by up to 50% by 2050	Production close to consumers and without combustion reduces wasted energy. Prosumers, who both produce and consume energy, may be more energy conscious also.
Existing and potential public policy instruments	Public support for R&I. AM included in industrial strategies. Yet, specific policies, including standards, are missing	Pricing /taxation schemes Subsidies on shared mobility Nudges and social movements	Subsidies. But many regulations hinder adoption
Concerns	Rebound effects, over-consumerism resulting from customization	Cyber security Finance in LMI countries	Financing in LMI countries, grid integration

[a] Innovation stage: research (fundamental science and technology exploration), Prototype, Demonstration, Early adoption, Market adoption and scale-up (Gallagher *et al* 2006).

Hicks and Ison 2018, Niamir *et al* 2020c, Creutzig *et al* 2022b).

3. LED ***Technologies*** are typically small in unit size and thus characterized by (a) strong potential for cost reductions and customization through iterative modification and adaptation, (Sweerts *et al* 2020, Wilson *et al* 2020a) and (b) amenable to new business models in the circular economy. Importantly, general purpose technologies such as digitalization can pervasively enhance LED services (Wilson *et al* 2020b).

2.3. Case study selection

Among the many possible cases, we selected one for each sector, which has potential to contribute to LED. Table 1 provides an overview of the main characteristics of the three case studies: additive manufacturing (AM), which has the potential to revolutionize the production of goods within the industrial sector; sharing mobility (SM) as a cutting-edge service within the transportation sector; and household energy users producing electricity with rooftop solar to become solar prosumers (SP) in the realm of building infrastructure. These cases exhibit distinct characteristics, including the nature of the services, adopters, and technologies. They also represent varying stages of innovation, while all three hold significant promise for reducing energy demand. Another vital factor guiding our selection process was the need to illustrate the diverse roles of enabling conditions in expediting adoption by end-users.

3. Three LED innovation case studies

For each of the three case studies, we summarize the context within which the innovation is emerging, its potential demand reduction, and the health of its innovation system functions. For more on the case study FIS analysis, please see SI1-3.

3.1. Case 1. AM

AM, or 3D printing, is a production method based on a process of joining materials to make objects from 3D model data, usually layer upon layer (Aboulkhair *et al* 2019). Plastics, nylon, metals, and ceramics can be used. Initially developed for rapid prototyping, AM could have great potential for larger-scale (rapid) manufacturing and, consequently, industrial energy demand reductions and associated emissions (see tables 1 and SI.1). Its biggest advantages are: (1) the manufacture of geometrically complex structures in a single-step process (Reis 2013); (2) major cost advantages in sectors where products need to be adapted to customers' needs (Aboulkhair *et al* 2019).

1. *Knowledge development:* maturity of AM varies greatly by sectors; in no sector is it applied for large-scale manufacturing (AMFG 2019). Universities are a main source of codified knowledge, but patenting is dominated by the private sector (Peña *et al* 2014). Innovation in new materials and methods for AM is progressing (Ngo *et al* 2018).
2. *Knowledge diffusion*: collaboration among different actors required for large-scale application of AM (Lavoie and Addis 2018). Ngo *et al* (2018).
3. *Guidance of search*: many governments consider AM a technology of interest for industrial policy, but their strategies differ significantly, ranging from targeted public R&D funding (Peña *et al* 2014, McKinsey 2017, Samford *et al* 2017) to fostering synergies with existing local industrial strengths (Peña *et al* 2014, McKinsey 2017, Samford *et al* 2017).
4. *Resource mobilization*: early-stage financing for AM innovation and funds for further development came both from private and public sources. (Peña *et al* 2014), including the automotive and aerospace, military, cement, and metal sectors (Vora and Sanyal 2020).
5. *Entrepreneurial activities*: private firms, mostly located in the US, were active in early technology development. Multiple major material manufacturers and key universities are engaging with AM technologies, establishing partnerships (McKinsey 2017).
6. *Market formation*: in 2017 the market for AM products and services was over $7 billion. (Thompson *et al* 2016). Yet, the penetration of AM technologies is estimated at only 8%, indicating untapped potential (Vora and Sanyal 2020). However, unit costs do not exhibit economies of scale, indicating limits to large-scale diffusion (Sculpteo 2014, Baumers *et al* 2017, Steenhuis and Pretorius 2017).
7. *Creation of legitimacy:* governments and the education sector generate legitimacy for AM technologies (e.g. inclusion of AM-relevant and specific training as part of undergraduate and graduate curricula) (Reis 2013). Yet, large-scale adoption of AM is inhibited by technical hurdles and lack of universal guidelines for metrology, inspection, and standardization, leading to concerns about IP protection and vulnerability to cyberattacks.

3.2. Case 2. Shared mobility (SM)

SM, characterized by asset sharing (e.g. a bicycle, e-scooter, vehicle) and facilitated by information technology (e.g. apps and the internet), holds promise for emission reduction and climate change mitigation (Creutzig *et al* 2022b). Four business models have been identified (Santos *et al* 2018): peer-to-peer platform (Ballús-Armet *et al* 2014); short-term rental managed and owned by a provider (Enoch and Taylor 2006, Bardhi and Eckhardt 2012, Schaefers *et al* 2016); Uber-like service (Wallsten 2015); and shared ride where private vehicles shared by passengers to a common destination (Liyanage *et al* 2019, Shaheen and Cohen 2019). Studies show that SM, mainly shared automated electric vehicles, cuts GHG emissions by one-third and 63%–82% per mile compared to a privately owned hybrid vehicle in 2030, 87%–94% lower than a privately owned, gasoline-powered vehicle in 2014 (Greenblatt and Saxena 2015). Berlin and Lisbon studies demonstrate that SM could reduce the number of cars by more than 90%, also saving valuable street space for human-scale activity (Bischoff and Maciejewski 2016, ITF 2016, Martinez and Viegas 2017, Creutzig *et al* 2019). The impacts depend on sharing levels—concurrent or sequential—and the future modal split among public transit, automated electric vehicle fleets, and shared or pooled rides.

1. *Knowledge development*. SM-related services and technology have reached the developed stage (PBOT 2011, van der Zee 2016). However, improvement in service design and deeper integration of digitalization is needed (Creutzig *et al* 2019).
2. *Knowledge diffusion*. As users and shared mobility providers/business models interact, a reciprocal flow of insights occurs, shaping the design, functionality, and future iterations of shared mobility solutions (Ruhrort 2020). This iterative learning process, often referred to as 'learning by using,' nurtures innovation by incorporating direct user feedback into the R&D cycle (Hekkert *et al* 2007). Consequently, the network's role transcends traditional knowledge exchange to become

a conduit for collaborative innovation, where the user's experience not only informs but actively shapes the direction of shared mobility evolution (Coretti Sanchez *et al* 2022, Li 2023).

3. *Guidance of search*. Private car ownership, fuel, and parking space taxation; shared mobility choice architecture and subsidies, and saving citizens useful time, particularly in big cities, raised awareness and motivated individuals to take up these LED services (Weschke *et al* 2022, Roca-Puigròs *et al* 2023). Using these strategies, service providers and inventors can customize their efforts to not only meet current needs but also predict and serve changing preferences and services. This promotes a more adaptable and customer-focused approach to developing shared mobility.
4. *Resource mobilization*. Both governments and the private sector (businesses) are investing in designing shared mobility infrastructure and services in various ways worldwide (Heinitz 2022).
5. *Entrepreneurial activities*. SM has become widespread globally as an innovative service business model (Ma *et al* 2018, Casprini *et al* 2019, Chaudhuri *et al* 2022). Many small, medium, and big businesses actively invest in designing and providing services (Ma *et al* 2018, Gilibert and Ribas 2019, Turoń 2022).
6. *Market formation*. Markets are currently at the stage of scaling up, improving, and designing new services and also over space (Casprini *et al* 2019, Mouratidis 2022).
7. *Creation of legitimacy*. SM is already being adopted by individuals; however, social and data security improvement is key to more widespread adoption (Affia and Matulevičius 2022). Despite the vast potential for new business opportunities, authorities grapple with the challenge of effectively regulating and structuring SM and its associated data.

3.3. Case 3. Residential solar energy prosumers (SP)

Residential SP, who both consume and produce energy services (Rathnayaka *et al* 2012), have strong potential for energy savings because transmission losses are avoided and waste heat is not generated (Lee and Song 2021). In addition, awareness of energy use associated with adopting solar can lead to energy saving behavioral changes. In large markets such as the US, Germany, and China, less than 5% of households have solar installed so the energy reduction potential of rooftop solar is an untapped resource (Denholm and Margolis 2008, Michaels and Parag 2016, Gagnon *et al* 2018) and the global potential is vast (Creutzig *et al* 2017, Haegel *et al* 2019). The global mitigation potential of solar energy is 2–7 GT CO_2/year in 2030, among the highest of all mitigation options (Babiker *et al* 2022), with rooftops providing a substantial share. Technologies enabling SP are mature (O'Shaughnessy *et al* 2018a), the challenge being their integration in the grid, a form of infrastructure design. Therefore, social innovations and behavioral changes, especially peer effects, have a large role to play. The proliferation of household energy storage, either standalone or in electric vehicles, combined with digitalization, especially connectivity to the grid, would facilitate a larger role for SP (Denholm and Margolis 2016). This combination of development in social drivers and novel technical innovations is an important aspect within this innovation system.

1. *Knowledge development*. All technologies enabling SP are mature: solar panels, energy storage, electric vehicles, smart meters, and power systems (O'Shaughnessy *et al* 2018a). Grid integration at high levels of solar adoption has been demonstrated in some areas.
2. *Knowledge diffusion*: components and know-how are widely available and transferring grid integration experience from areas with high solar adoption is now a focus (Heptonstall and Gross 2021).
3. *Guidance of search*: public policy such as renewables obligations, subsidies, as well as information programs (like Solsmart in the US) raise awareness and orient expectations of growth. Solar is very popular (Roddis *et al* 2019, Hazboun and Boudet 2020).
4. *Resource mobilization*. Solar technologies benefit from massive investment globally, but a key issue is access to finance and investment in low-to-moderate income (LMI) countries (Schmidt *et al* 2019).
5. *Entrepreneurial activities*. Small businesses play an active role, e.g. there are many small local installers in Germany (Neij *et al* 2017) and over 10 000 installers in the US (O'Shaughnessy *et al* 2018b). New business models, especially software, for managing and marketing power at local levels will be important as well providing finance in LMI countries (Egli *et al* 2022).
6. *Market formation*: adoption has gone beyond early adopters to more mainstream consumers (Haegel *et al* 2019). Grid integration is key challenge as the share of prosumers increases. Market development depends on continued cost reductions, particularly in developing and LMI countries.
7. *Creation of legitimacy*. Market growth has conferred legitimacy, such that it is now part of the policy regime (Horstink *et al* 2021) although in some jurisdictions growth has stalled or has been thwarted by opposing actors. An inclusive governance approach to regulation and policies would help establish legitimacy. Peer-to-peer energy trading, the logical next step for prosumers (Luo *et al* 2014), has not yet achieved legitimacy

and strong political forces use extant regulations and natural monopolies to bar the inception of neighbors buying and selling electricity.

4. Unlocking LED technological innovations pathways

To maximize their potential, LED innovation necessitates coordinated efforts from individuals, businesses, cities, regions and countries (also see SI.4) (Stern *et al* 2007, Grubler *et al* 2018, Schot and Kanger 2018). While a substantial focus is placed on the development and widespread adoption of new LED technologies, social aspects such as behaviors, lifestyle shifts, and more broadly the social dimension, are also vital components of LED solutions (Creutzig *et al* 2016, Niamir *et al* 2020a). By intertwining technological advancements with behavioral change efforts, LED pathways can lead to more effective and long-lasting results in mitigating climate change. While social dimensions are encompassed in FIS, here we explore them in greater depth. We discuss eight sets of key social enablers that can facilitate the scaling up technological innovation in support of LED, contingent on their distinct characteristics (also see tables SI5.1–3):

1. ***Behavior and lifestyle changes*** play a pivotal role as enabler conditions in the transition to LED. By influencing individual and collective choices, these changes contribute significantly to shaping consumption patterns and reducing overall energy needs. As apparent from all three case studies, the successful development and deployment of technology in a LED scenario needs to go beyond the pure deployment of new technology and be accompanied by, and favor, meaningful change in individual behaviors and lifestyle.
2. ***Peer effects*** are central to accelerating innovation and spreading the adoption of LED solutions. Social and cultural processes play an important role in shaping what actions people take on climate mitigation, interacting with individual, structural, institutional and economic drivers (Thaler and Sunstein 2003).
3. ***Inclusive governance*** plays a crucial role in the deployment of LED innovations to achieve societal goals. Addressing climate change and improving human well-being requires an inclusive, equitable, and all-of-society approach. Multi-level governance and effective institutions can enable LED pathways by prioritizing inclusive decision-making, enhancing equitable access to finance, infrastructure and technology, setting targets and priorities, and mainstreaming climate actions across sectors and actors (Niamir and Pachauri 2023). This approach fosters collaboration and cooperation among government bodies, businesses, communities, and individuals, ultimately contributing to a more effective and holistic response to the challenges energy demand.
4. ***Infrastructure design and availability*** matter for effective LED measures since there are systematic interconnections between infrastructure design and practices (Cass *et al* 2018). For example, in urban transport, infrastructure design and services provision contribute to higher uptake of LED options (Goodman *et al* 2014, Song *et al* 2017).
5. ***Finance and investment*** are crucial because LED measures tend to be capital intensive, i.e., they involve up-front costs and generate savings and benefits over time and require significant infrastructure to be successfully deployed. Therefore, access to finance is essential in adopting LED measures in low- and middle-income countries where the potential is very large but where access to capital remains a constraint (Egli *et al* 2022).
6. ***Market development and cost reductions*** can occur concurrently via learning effects. The granularity of many LED technologies makes them amenable to mass production and rapid learning. Social interactions, such as peer effects, can accelerate learning (Neij and Nemet 2022).
7. ***Regulations and policies*** are needed so that LED technologies are further developed and deployed in a sustainable way and in accordance with mitigation and other sustainable development goals. For example, under emissions regulation (Porter and Kramer 2006) are accessible to, and for scale-up LED innovations, and benefits all, not just the wealthy who could afford it early on, both within developed and extended to developing countries. They include investment in social innovations, behavioral and lifestyle changes through education, new norms, and mindsets.
8. ***Business models***. Business will need to part of the solutions, as business models will have to adapt to a new way of providing goods and services (Markard 2018, O'Shaughnessy *et al* 2020). Importantly, investment patterns will change. For example, the insurance industry might be affected by its role as an insurer of third-party liability.

4.1. LED narratives

We offer illustrative LED narratives for the case studies of AM, SM and SP to highlight the crucial roles that the eight enablers can play in optimizing the potential of LED technological innovation (see figure 1). Because of the distinct characteristics of these cases, in addition to context and scale, all or only a few of these enablers may be applicable. Even though each case is at a different level of maturity, they are all at an early stage in their development relative to the level required to achieve 1.5 C.

AM LED narrative. By 2050 it is plausible that AM technologies will have significantly increased their

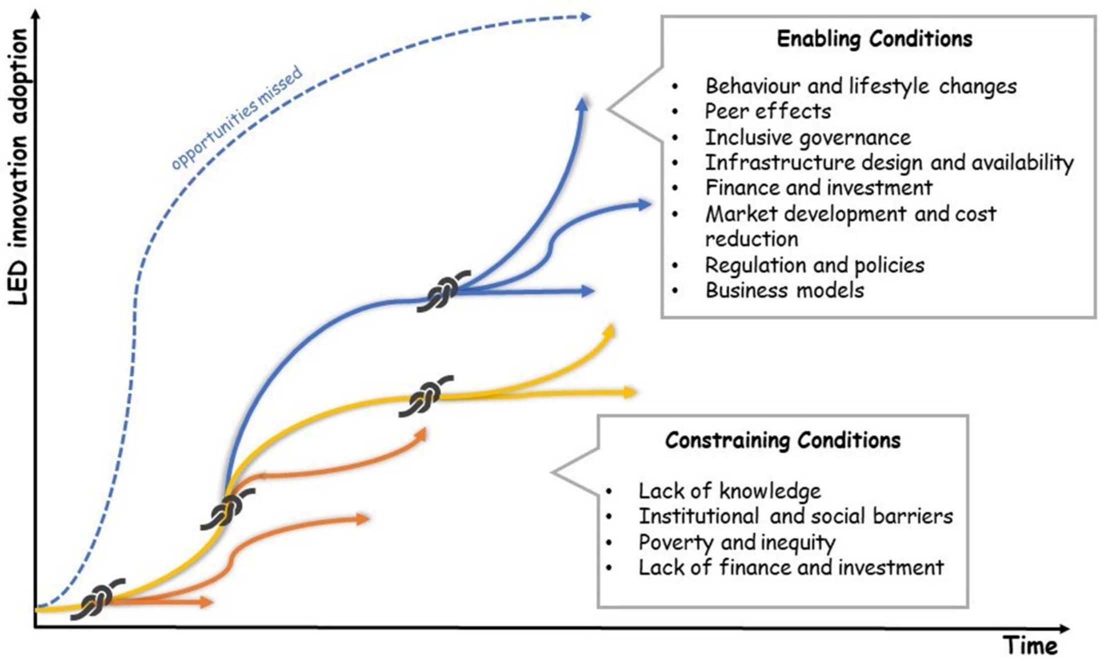

Figure 1. Illustrative LED innovation pathways. Lines indicate the cumulative adoption of an LED innovation over time, with key junctures indicated by knots. Diverging LED innovation pathways (orange to blue) illustrate that interacting choices and actions by diverse actors—government, business, and civil society—can enable LED innovation adoption. Pathways and opportunities for action are shaped by the innovation stage, distinct characteristics, and previous actions (or inactions and opportunities missed) and enabling and constraining conditions. Social innovations can create enabling conditions allowing for steeper adoption pathways (blue pathways). At the same time, lack of knowledge, finance and investment, institutional and social drivers as well as poverty and inequity, halt the process (orange pathways). {The concept of the visualization of illustrative pathways is derived from figure SPM.6 (IPCC 2023)}.

penetration rate, but their potential to contribute to LED varies by sector: AM could reduce total primary energy supply in aerospace fuels by between 9 and 35%, from aerospace manufacturing by between 8 and 19% and in the sectors of medical equipment and tools by between 5 to 19%, and 3%–10%, respectively (Gebler *et al* 2014). Three critical junctures exist in the AM narratives. A first is whether the **technology** will mature and proof-of-concept will be achieved for large-scale manufacturing. Achievement of proof-of-concept in several key areas—such as metal-based AM or AM based on recycled inputs—hinges on public support for innovation in the form of technology-push policies, including R&D investments and subsidies. Application of AM technologies in other sectors and their relevance for decarbonization is dependent on lifestyle changes and developing a culture of sufficiency which would avoid material and energy rebound. A second is whether new **business models** will be fostered to move away from traditional linear manufacturing and towards on-demand production. Network effects and changes in business models are necessary to promote the scale-up and give rise to learning-by-using dynamics, including increased technology efficiency and lower costs. Access to finance and investment needs to be granted to promote adoption among producers and service providers. A third is whether governance will promote the necessary **behavioral change**, mindsets, and targeted policies to ensure AM achieves deep emission reductions, circularity, and sufficiency as well as economic benefits. Tailored public policies, including regulation and the development of industry standards, are needed to promote a paradigm shift from linear and subtractive manufacturing to AM consistent with a deep sustainability transition.

SM LED narrative. Shared mobility innovation demonstrates various levels of development and adoption linked to the economic, social, institutional, and financial contexts. For example, traditional micro-mobility like cycle rickshaws thrive in developing countries, while bike- and scooter-sharing systems flourish in developed countries. Drawing from the literature, several social enablers are relevant and have the potential to significantly influence the transition toward realizing the full LED innovation potential. Specifically, these enablers include **design and access to technology and infrastructure**, exemplified by carsharing's global expansion and shared electric vehicles' emission reductions (ITF 2017, 2019, 2020). Well-designed, safe and accessible infrastructure provides the necessary support to be effectively utilized and integrated, encouraging individuals and organizations to embrace and benefit from the advancements (Goodman *et al* 2014, Song *et al* 2017, Creutzig *et al* 2022b). **Policy packages** such as social and behavioral intervention, like nudges, can influence individuals' choices in favor of SM usage, e.g. 'walk cycle ride' campaign (Rojas López and Wong 2017), while carbon pricing mechanisms can affect incentives (Eliasson and Mattsson 2006, Richardson *et al* 2010). **Social movements and peer effects** exist in that individuals are often motivated by collective sentiments and the behaviors of their peers when embracing new services and lifestyles (Burghard and Dütschke 2019, Whittle *et al* 2019). Another enabler, **business models**, includes expanding service offerings, fostering collaborative partnerships, and optimizing pricing, as well as **providing adequate finance and investment support** to ensures the development and expansion of SM infrastructure and services, making them more accessible and attractive to the public.

SP LED narrative. Rooftop solar is mature and growing rapidly, but at less than 2% of global electricity supply, its future potential remains large, and the extent to which that potential is realized depends highly on social innovations and behavioral change in particular. Two key junctures in the rooftop PV narrative are 1) whether growth in adoption continues in existing markets, especially in East Asia, Europe, and North America, and 2) whether adoption proliferates in emerging low- and middle-income countries. If both occur, we will see rooftop PV take the upper pathway to reach well above 10% of the global electricity supply, perhaps accounting for half of all PV, which could account for half of electricity supply. That pathway depends on key social innovations. Existing market growth depends on **governance and regulation**, particularly supportive electric rate structures, credit for energy storage, and incentives for reducing demand and would be bolstered by the proliferation of peer-to-peer electricity trading, which itself requires modification of **infrastructure** design. The latter would give consumers more control and would take full advantage of the granularity that rooftop solar provides; **peer effects** combined with network effects could catalyze further adoption of rooftop solar. Emerging market growth depends on all the above, as well as a fundamental change in **finance and investment**, particularly credit access, which is central to improving costs and market development. Financing for rooftop solar remains much more expensive than in existing markets, which in combination with lower median incomes, limits adoption. **Business model** innovations that can provide credit at rates like those in existing markets would help put rooftop solar on the upper pathway. One can also imagine a scenario where none of these supporting social innovations take hold, and adoption grows at a rate that only grows with overall demand leaving its share unchanged. While many middle pathways exist, an especially problematic one has supporting social innovations take hold in both existing and emerging markets, but access to finance remains a constraint in emerging markets. That would lead to a tremendous, wasted opportunity both for the global impact and distribution of the access to benefits that rooftop solar can provide.

5. Conclusion and directions for further work

This paper examines three pertinent innovations in LED through the lens of the FIS framework: AM, shared mobility, and SP. Furthermore, it discusses key enablers to unlock their LED potential and demonstrates ways for scaling them up to widespread adoption. We highlight that technological innovation is not the sole driver of LED. Rather, realistically achieving LED requires a range of crucial non-technological, non-cost aspects of technology diffusion, such as changing behaviors, social norms, and governance, all in the context of heterogeneous agents and the development of local knowledge. Consequently, this study underscores the need for additional bottom–up qualitative and quantitative research and analysis. This approach can offer a more in-depth understanding of the complexities and, potentially, serve as a valuable complement to addressing the challenges posed by large-scale IAMs.

To present feasible LED scenarios, capture key enablers and explore (non-linear) solutions, current scenario modelling needs three key shifts. First, large-scale IAMs and energy system models could be complemented with modelling approaches which can more realistically capture heterogeneous effects and the role of peer effects in technology development and diffusion. This is the case, for instance, for agent-based modelling, which has the potential to play an increasing role in informing large-scale modelling exercises (Niamir *et al* 2020a, Edelenbosch *et al* 2022). Second, the key role of non-technological drivers in LED innovation points to the importance to develop more detailed LED narratives to ground and justify model results—that is, provide rationales for specific model constraints to account for changes in lifestyle, norms, and beliefs. Finally, available IAMs are extremely limited in their ability to depict different policy instruments and mixes. This surely represents an interesting area of further model development and is a particularly important one in the context of LED pathways.

To improve our understanding of LED innovation and narratives alongside our modelling tools, there are two complementary fruitful avenues of future work. On the one hand, detailed empirical data and analysis on LED innovation development and adoption, particularly in LMI countries, is needed to characterize the intersections between institutional, political, environmental, social, and economic factors which contribute to LED innovation development and adoption at different scales in different geographies (Beckage *et al* 2020, Rubiano Rivadeneira and Carton 2022). On the other hand, future research should inform and complement IAMs by distilling specific insights regarding policy instrument and mixes in support of LED innovation. This includes valuable insights on establishing and promoting policy motivations, addressing innovation system failures, improving technologies and services, facilitating behavioral change and LED innovation adoption, enabling new business models, and addressing adverse consequences of successful adoption—e.g., material or energy rebound or distributional repercussions. Attention should be given to the role of local context both in adoption and policy, especially in LMI countries and to the combination, timing and strategic sequencing of policy instruments. Pursuing this comprehensive research agenda can help unlock the potential of LED scenarios in the context of urgent deep decarbonization.

Data availability statement

No new data were created or analysed in this study.

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