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Perspective

Conceptualizing demand-side technological and social innovations in modeling pathways to carbon neutrality

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ABSTRACT

Achieving mid-century carbon neutrality goals requires drastic energy and carbon dioxide (CO_2) emissions reductions that can be enabled by transformative demand-side technological and social innovations. These innovations can significantly reduce energy demand and related emissions to achieve global low energy demand (LED) pathways that rely less on uncertain CO_2 removal technologies to meet climate targets. Many existing decarbonization pathway studies focus more on supply-side innovations with less attention on LED innovations, and those that do often have limited focus on industry, freight transport, and broader cross-sector strategies. In this perspective, we apply the "avoid-shift-improve" framework to assess the technical potential and deployment feasibility (in terms of adoption, implementation and response) barriers of demand-side innovations. We observed that smart, integrated building systems improve energy performance, with further reductions possible through design, occupant behavior changes, and social interactive programs. Improved design processes, higher quality products, and circular economy strategies can reduce material demand and associated industrial energy use. Shared mobility systems face uncertain net energy impacts, but smart freight and logistics, and aviation to rail shift can be deployed quickly. Sustainable food, fashion and lifestyle changes are needed beyond technological transformations. Our work illuminates potential impacts and factors that affect realization of the technical potential of individual LED innovations to support their inclusion in future global and national LED scenarios and climate policy development. Additional research is needed to ensure successful integration of LED innovations into a broader mix of climate actions to provide greater flexibility, speed, and lower costs for decarbonization.

1. Introduction

In support of the Paris Agreement, many countries have pledged to significantly reduce their greenhouse gas emissions (GHGs) through 2030 or later as part of their Nationally Determined Contributions (NDCs) or revised NDCs. In addition, over 130 countries have also committed to achieving net zero emissions or carbon neutrality by mid-century [1]. The timing and realization of these climate goals are crucial, as the latest Intergovernmental Panel on Climate Change (IPCC) analysis [2] found that immediate, rapid, and large-scale reductions in GHG emissions are needed in the next two decades if limiting global temperature rise to 1.5 °C or even 2 °C is to remain within reach. To achieve this ambitious climate target, drastic emissions reductions will require not only the development and deployment of more efficient and cleaner technologies and processes but also additional transformative societal changes to complement technological advances. The IPCC's *Global Warming of 1.5 °C* Special Report [3] identified key characteristics of 1.5 °C-compatible pathways of limiting temperature increase to 1.5 °C above the pre-industrial levels that included: rapid and profound near-term decarbonization of energy supply, greater mitigation efforts to reduce demand, increased electrification, adoption of mitigation options aligned with sustainable development goals, and deploying carbon dioxide removal (CDR) at scale before 2050.

Integrated Assessment Models (IAMs) are commonly used to evaluate different climate mitigation strategies – including technological, economic, social, and policy changes – to inform decision-makers. In many 1.5 °C-compatible scenarios modeled in IAMs, carbon neutrality goals cannot be achieved without substantial CDR deployment through options such as carbon capture and storage (CCS), bioenergy, renewable hydrogen, afforestation and reforestation [3]. These options are not yet

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commercially available or widely deployed, and face myriad implementation barriers as well as concerns about sustainability implications. Recognizing CDR's potential deployment challenges, an emerging field of research focuses on achieving very low energy demand (LED) pathways through demand-side measures and broader societal transformations through technological and social innovations that already exist today, beyond traditional energy efficiency or conservation [4–8]. Pathways with lower energy demand have the greatest synergies and lowest number of trade-offs with the Sustainable Development Goals and would reduce dependence on the use of CDR [3,9].

The recent LED studies highlight that certain emerging technological and social innovations may provide alternative pathways to significantly reduce overall energy demand and related emissions [4–8]. Technological innovations include novel technologies that are either newly introduced to the market, or still have relatively low market adoption rates that affects how energy is consumed. Social innovation is a relatively new concept as related to energy policy, but can refer to different innovative social phenomena such as social organizations and configurations, and relations or practices that may include new forms of governance, supportive policies and regulations, and new business models that contribute to the low-carbon energy transition [10]. The conceptualization of social innovation in this context is similar to climate change "mitigation initiative" used in other literature [11 – 13], with a more nuanced emphasis on novelty in terms of years since introduction or limited market share. Technological and social innovations are often, but not always, linked and complementary to one another, and may exist independently.

The quantitative modeling of energy demand and related emissions impacts of technological and social innovations is fairly new, but broader lifestyle changes have generally been conceptualized and modeled through improved efficiency to meet the same level of demand, technological substitution or shifts, and lifestyle changes or achievement of sufficiency that reduces consumption [14,15]. Technological and social innovations to reduce energy demand have been captured in IAMs through three main approaches [14]. The most commonly used approach is to change existing narratives or storylines to exogenously represent these innovations, based on qualitative research on consumer behavior change. Energy demand changes as a result of innovations can also be modeled endogenously within certain IAMs by adjusting modeling parameters to represent dynamic behavior change in technological and social learning. The last but most difficult approach is to explicitly model demand changes due to innovations through an endogenous module that fully captures dynamic interactions between lifestyle changes with other modules [14].

To our knowledge, most IAMs do not comprehensively account for demand reductions from these emerging innovations, particularly social innovations, in their deep decarbonization scenarios due to the lack of data with relatively aggregated representations of energy end-use technologies, and inherent methodological challenges with model structures focused on interactions between economics and biophysical systems with limited representation of social complexity beyond purely economic behavior [14,16] While IAMs effectively help identify cost-optimal pathways for climate change mitigation, it is less effective in capturing the more complex social drivers and social impacts of climate change due to simplified representation of the world as limited number of rational agents that optimizes decisions based on social-economic welfare [16]. IAMs also face challenges in balancing the uncertainties surrounding the economic quantification of climate mitigation benefits, particularly in terms of human lives and ecosystems, and around the extent of expected damages [17]. An additional limitation of modeling such disruptive innovations in global IAMs is shortcomings in reflecting rapid and non-linear real-world transformations outside the scope of a tractable model [7,18].

As a result, only a few global energy modeling studies have explicitly focused on addressing measures that can be considered technological and social innovations needed for energy demand reduction across multiple sectors [6,14,19–21]. At the global level, the findings of these few studies emphasize that a lower demand scenario for 1.5 °C climate mitigation can result in greater flexibility and speed for both end-use and supply-side decarbonization, as well as lower pollution and reduced system costs [6,19].

Some prominent global energy outlook studies have begun incorporating specific instances of technological and social innovations to reduce demand across multiple sectors in recent scenarios [22–24]. Even so, most existing studies have focused heavily on innovations and strategies for reducing demand in the passenger transport and building sectors, with very little consideration for demand reduction in industry, freight transport, and either through direct measures or indirect impacts from broader strategies such as circularity or sustainable consumption [14]. Only two recent studies have explicitly modeled potential demand reductions in industry and cross-sectoral applications such as circular economy and sustainable consumption [6,20]. Country or region-specific scenario analysis capturing the impacts of technological and social innovations that can help inform policy development is also lacking, with the exception of some studies conducted for Europe [20].

In this perspective, we provide a review and assessment of emerging technological and social innovations that can reduce energy demand using a conceptual framework. The framework and analysis help highlight their potential significant contributions to enabling LED pathways for both energy modelers as well as climate policy decision-makers. This perspective builds on existing reviews that assessed the potential impacts of digitalization innovations [25], household-level consumption options [26], technological and behavioral disruptions considered for the United Kingdom [27], and demand-side mitigation options with high levels of well-being [9]. It aims to provide a broader scope in terms of innovations covered by focusing on freight transport and industry-specific innovations, with additional consideration of key factors of what we consider "deployment feasibility" based on a recently developed framework for feasible climate mitigation [11–13] that influence when and to what extent individual innovations can be adopted to enable a global LED transition. By assessing technology or market readiness level that informs barriers to adoption, areas of uncertainties for energy demand reduction related to implementation and responsiveness, and the types of barriers to widescale deployment, we offer a conceptual framework for assessing and incorporating technological and social innovations into the development of global and national LED scenarios.

First, we introduce a conceptual framework for understanding different social and technological innovations that exist today for reducing, shifting, and improving different energy demand end-uses in transport, residential and commercial buildings, industry, food, and consumption. We then analyze and quantify, where feasible, the technical potential impact of technological and social innovations on reducing energy demand, including examples of prefabrication, digitalization, artificial intelligence, and the sharing economy using end-use sector-specific and cross-sectoral examples. We further assess and emphasize the key barriers that affect three key steps of deployment feasibility – adoption, implementation and responsiveness - of these innovations in the path to fully realizing energy reductions as climate mitigation measures. This assessment provides the basis for a synthesis of sector-specific and cross-sectoral findings on the technical potential and deployment feasibility of scaling up demand sector innovations. The final section discusses remaining research gaps and potential ways to address challenges with accounting for demand-side innovations in pathways to mid-century carbon neutrality.

2. A conceptual framework for incorporating demand-side innovations that reduce, shift, and/or improve energy use into energy models

Rapid technological advancements and the transformative societal changes enabled by new technologies have the potential to drastically change how people use energy to meet their daily needs, as exemplified by significant shifts towards telecommuting and e-commerce during the Covid-19 global pandemic shutdowns. In this paper, we conducted literature review to identify and assess technological and social innovations that can reduce energy demand. More specifically, to provide a consistent scope of technological innovations across sectors, we adopted the selection criteria used in Rogers 2003 [28] and Wilson et al. 2020 [25] of <~10 years since market introduction and/or <~15 % market share in their conceptualization of early adopters and digitalization innovations, respectively. Social innovations complement technological innovations by reflecting different social phenomena such as social organizations, relations or practices related to changes in energy systems. Specific examples in the energy realm include innovative business models, energy sufficiency or savings practices, to energy games and green nudging [29]. While social innovations are more difficult to define in terms of the two selection criteria for technological innovations, we aimed to ensure consistency in scoping by focusing on social innovations that have emerged recently and/or have relatively low adoption rates.

The “avoid, shift, and improve” analytical framework used to evaluate sustainable transport options is now increasingly being used to describe broader changes in consumer behavior related to the use of energy and other natural resources [14,25,30]. We apply this analytical framework to highlight how different emerging technological and social innovations can affect energy demand across the demand sectors of buildings, industry, and transport and at the cross-sectoral level. We characterize each innovation based on their main impact on changing energy demand, through: 1) avoiding or reducing consumer demand for a service provided through energy consumption, 2) shifting to a cleaner form of energy demand provision (e.g., fuel switching for technologies or switching to cleaner service-provisioning systems including transport modes and sharing systems), or 3) improving the technical energy efficiency of existing technologies. Although selected innovations could potentially fall into multiple categories, grouping each innovation into one of these three main categories under this general framework can help decision-makers more easily understand the main impact of each innovation on energy consumption.

Table 1 summarizes the emerging innovations we reviewed and assessed for each sector as well as cross-sector applications under this avoid, shift, and improve framework.

In a recently proposed framework for improving climate change mitigation analysis, Nielsen et al. 2020 [11] argues for the need to better incorporate factors that affect feasibility beyond technical and economic factors in climate change mitigation analysis. Stern, et al. 2022 [12] and 2023 [13] further differentiate elements of feasibility analysis from proposed to actual mitigation based on three key steps in the process: the adoption of mitigation initiative, its implementation after adoption, and the responsiveness (or behavioral plasticity) of the intended responder, to provide insight on improving the effectiveness of mitigation initiatives. We focused on two key aspects for assessing the potential impact of individual innovations in reducing energy demand based on this work. These two aspects include the technical potential for reducing energy demand and the deployment feasibility, which aligns with the three steps of feasibility in Stern et al.’s latest work - adoption, implementation and response - that determine the feasibility of deployment to achieving full technical potential [12,13].

For technical potential, we focused on evaluating the potential for reducing energy demand as a result of adopting an innovation and fully realizing its theoretical potential impact on reducing energy demand. In this context, the technical potential we identified follows the same conceptualization as other studies [11,26,31] and the concept of “mitigation potential” used in Stern et al. 2022 [12] in representing the reduction in the drivers of an environmental change (i.e., specifically energy demand in this case) that would result if “a mitigation opportunity was completely realized or an initiative fully achieved its objectives.” We chose to focus on the mitigation of energy demand, rather than on CO_2 or GHG emission reductions, as those can depend heavily on region-specific factors such as electricity emission factors.

To characterize and assess the feasibility of achieving full technical potential, we then focused on each innovation’s deployment feasibility based on the steps of moving from potential to actual mitigation [12,13] and categories of key barriers to widescale deployment of the innovations. While technological innovations face the technology-to-market process of moving from research and development concepts to commercially viable and available products, both technological and social innovations face the additional need for market transformation and large-scale adoption. We followed the U.S. Department of Energy’s technology-to-market process [32], which includes market scaling levels that are also applicable for social innovations, in assessing the relative market readiness level of each innovation. This provides context for understanding the current market status of adoption of a given innovation, and existing barriers that hamper full adoption. In addition to market readiness and acceptance needed to enable adoption, innovations also face additional barriers in the other two steps of implementation and responsiveness of the intended user. These barriers are similar to those that have been studied in their inhibition of energy efficiency adoption, and which require policy actions to overcome [33–35]. These range from technological, economic or market, institutional, to sociocultural barriers. We used literature review to identify key types of barriers, aligning with the categorization used in IPCC 2022 and the associated step from the feasibility analysis for each innovation [36]. The unpacking and categorization of key barriers that exist in each of the three main steps on the path from proposed to actual mitigation in our deployment feasibility assessment help shed light on the level of policy and programmatic support needed to address these barriers, and the speed and scale with which they can be fully deployed in integrated energy and climate modeling. Together, the assessment of both the technical potential and the deployment feasibility analysis provide quantitative and qualitative inputs to understanding how to model the reasonably achievable energy demand reductions (based on Reasonably Achievable Emissions Reduction [31,37] and Reasonably Achievable Mitigation [12] from these innovations.

The detailed assessment results of each innovation’s technical potential, market or technology maturity level, and existing barriers that impact deployment feasibility are discussed in the Supplementary Material Tables S1 and S2. Table 2 presents selected sectoral examples of innovations and the elements of deployment feasibility assessed.

Below we synthesize the key findings of the innovation assessment for the building, industry and transport sectors and at the cross-sectoral level.

3. Insights on the technical potential and deployment feasibility of scaling up demand sector innovations

3.1. Building sector

Technological innovations are transforming building energy systems by lowering energy use with improved performance, while changes in design and occupant behavior can further avoid or reduce energy demand. In particular, advances in building technologies and construction techniques allow for reduced energy use in buildings, with many countries and regions now adopting “net zero energy buildings” as targets to decarbonize their building sector (see Fig. 1) [38]. Achieving net zero energy requires advanced building envelope systems to achieve good thermal integrity and high-performance building wall assembly with good insulation that can effectively reduce heat loss from buildings [39]. Prefabrication of building construction panels and modules represents an innovative approach to deliver net-zero integrated system solutions faster, at lower costs, and with reduced material requirements and thus lower embodied emissions, compared to conventional construction approach [40]. Novel insulation materials also demonstrate good heat resistance values using low global warming potential (GWP)

Table 1
Technological and social innovations for avoid/reduce, shift, and improve energy demand.

	Residential and Commercial Buildings	Transport	Industry	Cross-Sector
Avoid	• Passive house and net zero energy buildings • Personal space conditioning technologies • Smart (tiny) house movement and co-housing	• Digitalization • E-commerce	• Additive manufacturing • Post-tensioning • By-product synergy • Cement production: Alternative fuels • Steel production: Improving product manufacturing yields • Extend building and product lifetime • Cross-cutting: integrative design • Component reuse • Cement/concrete: reduce overdesign • Cement/concrete: recycling • Cement/concrete: reduce construction wastes • Steel: remanufacturing and reuse • Intensified use of existing building stocks • Smart manufacturing	• Urban form • Sustainable fashion • Food waste reduction
	• Innovative behavioral programs • Innovative financing models for energy efficiency			
Shift	• Prefabrication • Coal/gas to electric heating	• Internet of Things/Mobility as a Service • Multi-modal last-mile logistics • Bike-sharing • Motorized ride-sharing • Aviation to rail • Active mobility	• Cement/concrete: Clinker substitution • Cement/concrete: Material substitution • Cement/concrete: Alternative cement chemistries • Steel: Lightweight materials	• Dietary change • Telecommuting
Improve	• Smart building control technologies • Artificial Intelligence • High performance building fenestration system • Lighting and plug loads	• Autonomous cars and trucks (platooning) • Smart freight and logistics improvement • Passenger vehicle right-sizing and increased occupancy	• Cement/concrete: Improving concrete quality	

Note: grey color denotes overlap between sectors and/or between how innovations affect energy demand.

materials with lower non-CO_2 emissions compared with traditional insulation materials using hydrofluorocarbons (HFCs) [41]. Smart fenestration systems transmit visible daylight into buildings and shade solar heat gain which reduces cooling and artificial lighting energy use [42]. Greater integration of building fenestration systems with building control systems allows smart windows and shading devices to be controlled together with building lighting and HVAC systems to create good indoor illuminance and thermal comfort performance while producing maximum savings [43].

Energy savings in buildings is also dependent on the engagement of building occupants. Living in small rooms and housing units (e.g., "tiny housing" movement) and co-housing is one way to avoid unnecessary space conditioning energy use and reduce ecological footprint of residents, however, the saving potentials could potentially be offset if these houses are located in remote areas and residents have to rely on fossil fuel vehicles for daily mobility – indicating a high uncertainty to quantify its energy impacts. Passive energy saving measures including natural ventilation and daylighting also require building occupants' active engagement such as opening and closing windows or shades. Behavioral changes can lead to 10–25 % energy savings through reducing domestic hot water, plug loads, lighting, and HVAC energy demand [44]. Some occupant behaviors can be activated through advanced artificial intelligence. Smart building automation systems and thermostats can gradually learn occupant behaviors and adjust room temperatures remotely to avoid energy waste [45]. Occupant behaviors can be further activated through social innovations, such as providing real-time energy use and/or cost, normative peer comparison, gamification. Dietz et al. 2009 showed that behavioral programs have potential to reduce U.S. emissions by 7.4 % with little or no impact on household well-being, however, the context in which these behavioral studies are conducted is important and highly uncertain, including the climate, building types, timing, and personal preferences [31].

The use of technologies can be more efficient through technical improvements. The proliferation of light-emitting diode lighting technologies has greatly reduced lighting energy use in buildings. HVAC system efficiency has also improved and many countries have developed plans to improve cooling system efficiency. District heating and cooling can scale up single building HVAC system efficiency and also enable transactive heating/cooling tariffs to encourage occupants to save energy [46].

Many countries and regions are shifting from traditional fossil-fuel based heating technologies towards electric resistant heating technologies which enables buildings to utilize clean electricity from renewable energy generation [47]. Energy efficient buildings can be achieved by switching from fully relying on energy technologies to utilizing passive and active measures of daylighting and natural ventilation. Case studies show that buildings that integrate such measures can effectively reduce building energy operation by 60 % within the same climate region [48]. Building power distribution systems are also changing from the current alternating current (AC) systems for most building end-use technologies to direct current (DC). Renewable energy and battery storage are natively DC and the use of DC in buildings' power distribution has shown a 4–15 % reduction in power conversion losses with improved electrical system safety [49].

3.2. *Industry sector*

Many current models have identified supply-side and carbon removal technologies for decarbonizing the industrial sector such as bioenergy with carbon capture and storage and direct air carbon capture and storage. These emerging technologies can have significant energy, water, land, and resource requirements with uncertain potential [50–53]. In contrast, improved design processes, higher quality products, alternative materials, circular economy strategies, and other innovative technologies and practices can reduce material demand and associated industrial energy use. For example, innovative technologies and practices for reducing material demand and associated industrial energy use are available today (see Fig. 2 and Table S2) and typically cost-effective. However, they currently face a multitude of deployment barriers in terms of adoption, implementation and response (Table S1). If deployed successfully, material demand can be reduced through many existing and emerging industrial practices. For example, improving the design process by reducing unnecessary corrosion protection for indoor parts, using the correct mix, and adopting customized elements can lead to a 20 % cement demand reduction in structural elements [54]. Using higher quality materials and better construction methods such as multiscale fiber reinforcement, steel with improved corrosion resistance, advanced chemical admixtures to improve the rheology of fresh concrete, self-healing concrete, and ultra-lightweight cement composites with low thermal conductivity, can improve building lifetime [55]. A 50 % increase in building lifetime can result in a 14 % decrease in cement demand [56]. Circular economy is another key strategy to avoid production of new materials and the associated industrial energy demand. Reusing modular components for new construction projects that are based on reversible or circular design can potentially save 68 % of concrete use in new construction [56]. Reuse, repair, refurbish, or remanufacture can also significantly reduce material and energy demand. Studies have found that remanufacturing of a diesel engine would reduce 90 % of the energy demand and save 69 % of the embodied emissions [57–59].

Advanced technologies and measures can shift material demand to more efficient and lower energy-using processes. New supplementary cementitious materials, such as kaolinite-rich calcined clay, can replace clinker in cement by 30 %, while producing concrete that is as strong as using Portland cement [60]. Some alternative cement products, such as belite clinker or belite calcium sulphoaluminate, use different raw materials and/or raw mixes that can reduce both process CO_2 emissions and energy use [61]. Substituting conventional concrete in mid-rise buildings with mass timber such as glue-laminated beams, nail-laminated timber, dowel-laminated timber, and cross-laminated timber, can reduce concrete use by 25–42 % [62–64]. However, some of these innovations are still in earlier stages of market maturity and face greater barriers in increased adoption (Fig. 2).

Innovative technologies and practices such as additive manufacturing and integrative design can improve material efficiency, save energy, reduce waste, and provide other non-energy benefits. For example, additive manufacturing can reduce the weight of a single aircraft engine by about 500 kg, reduce material needs by 90 % and energy use by 75–98 %, and reduce fabrication time and increase design flexibility [63]. By adopting holistic integrative design principles that

Table 2
Selected sectoral innovations and assessment of deployment feasibility.

Sector	Innovation type	Innovation	Market maturity	Barriers to deployment feasibility		
				Adoption	Implementation	Response
Buildings	Technological: Improve	Prefabricated buildings	Deployment	I: Lack of consistent building codes and unfavorable zoning requirements (especially in the US)	Ec: High capital costs	I: Firms lack incentives/ initiative to minimize energy usage in construction
				Sc: Negative public perception regarding quality, value, and aesthetics	Sc: Lack of skilled workforce	Sc: Consumer design preference and operation behavior may influence energy savings outcome
				Sc: Labor union opposition (in the US)	T: Lack of technological “know how”	
				I: Inconsistent or inflexible permitting laws and product standards	T: material transportation and logistical concerns	
				Sc: Skewed or misinformed view of impact on labor market		
Transport	Technological: Improve	Shared autonomous private passenger vehicles	Deployment	I: lack of uniform vehicle safety standards, public opinion	Ec: higher capital, operation and maintenance costs	T: Consumer access to AVs
				T: technological development of autonomous capabilities	Sc: safety and liability concerns	Sc: rebound effects and substitution choices
				Sc: public acceptance		
Industry	Technological: Avoid	Improve design to reduce material demand	Deployment	I: system inertia for builders and contractors to adopt innovative practices	Ec: low cost cement compared to high costs of implementation and tailor-designed building elements	Sc: design preferences by architects and engineers
				I: regulations requirements on specific types of concrete and other material products can be used.	Sc: requires coordinated efforts of multiple stakeholders, e.g., designers, engineers, constructors, developers, and general public.	
Cross-sector	Social: Shift	Dietary changes to animal free protein and/or away from resource intensive food products	Market Transformation	I: Difficulty in attaining government food health and safety approval	Sc: Health & nutrition considerations	I: Misleading labeling and/ or overstated sustainability commitments (e.g. “Greenwashing”)
				I: Prioritization of animal protein in national dietary guidelines & nutrition recommendations (in some countries)	Ec: Potential higher costs to consumers	Sc: Personal preferences may not align with plant-based foods
					Ec: Requires supply chain shifts and increased production costs	Sc: Misalignment with cultural traditions & negative sociocultural perception
					Sc: Potential disruptions to family life & convenience.	Sc: Lack of social and environmental awareness

Note: Market Maturity level corresponds to U.S. Department of Energy’s Technology-to Market process levels [32]; Deployment Feasibility steps from potential to actual mitigation taken from Stern et al. 2023 [13]; Categorization of barriers and enabling factors needed are based on IPCC, 2022 and includes I: Institutional; Sc: Sociocultural; Ec: Economic and T: Technological [36].

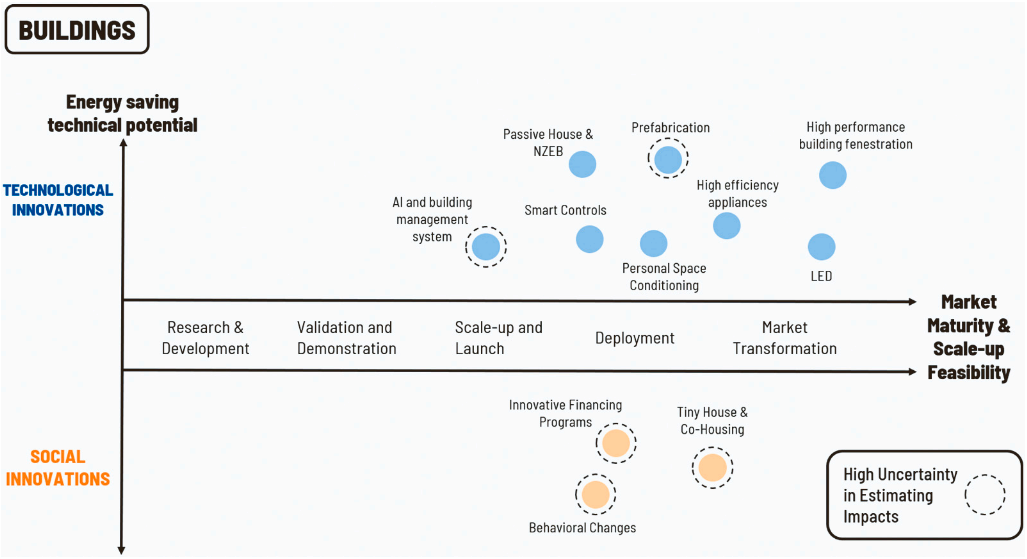

Fig. 1. Technical energy reduction potential, market maturity and deployment feasibility factors for building innovations.

emphasize design changes, whole systems, right-sizing and optimally combining individual energy-efficiency technologies, energy savings of 30–60 % and 40–90 % with lower capital costs could be achieved in existing and new industrial facilities, respectively [64].

Industry has traditionally prioritized costs, production reliability, and safety in the choice of technologies and practices, but transformation to meet carbon neutrality goals is possible with new technological and social innovations that can reduce energy demand. Targeted policy interventions to promote material-efficient strategies and practices and overcome regulatory and market barriers are needed to accelerate the research, development, and deployment of these innovative technologies in industry.

3.3. Transport sector

A number of impactful innovations related to transport demand reduction and mode shifting can be deployed quickly but will require institutional support and new societal norms to overcome existing implementation and response barriers (Table S1). Many of the newest and most discussed transport innovations have significant technical potential to avoid or reduce mobility demand through substitution and shift from private car transport to shared mobility systems, including digitalization, e-commerce, Internet of Things/Mobility as a Service, vehicle ride-sharing with autonomous vehicles or carpooling, and bike sharing [65–68]. However, the estimated impact on energy demand for most of these innovations could be positive or negative, depending on a number of underlying factors (see Fig. 3) [65,67–69]. Besides uncertainties about adoption given the transformative nature of these innovations, the net impact of innovations that shift transport energy demand including Mobility as a Service, bike-sharing, and motorized ride-sharing is sensitive to the mode of transport being replaced by shared mobility systems (see Table S1). Rebound and substitution effects from how users respond to these innovations directly influence the net actual impacts of avoid/reduce innovations as well as some shift innovations, including digitalization, e-commerce, and ride-sharing. To address these uncertainties, modelers have used stylistic scenario storylines such as “Selfish Digitalization” versus “Responsible Digitalization” based on consistent assumptions about rebound and substitution

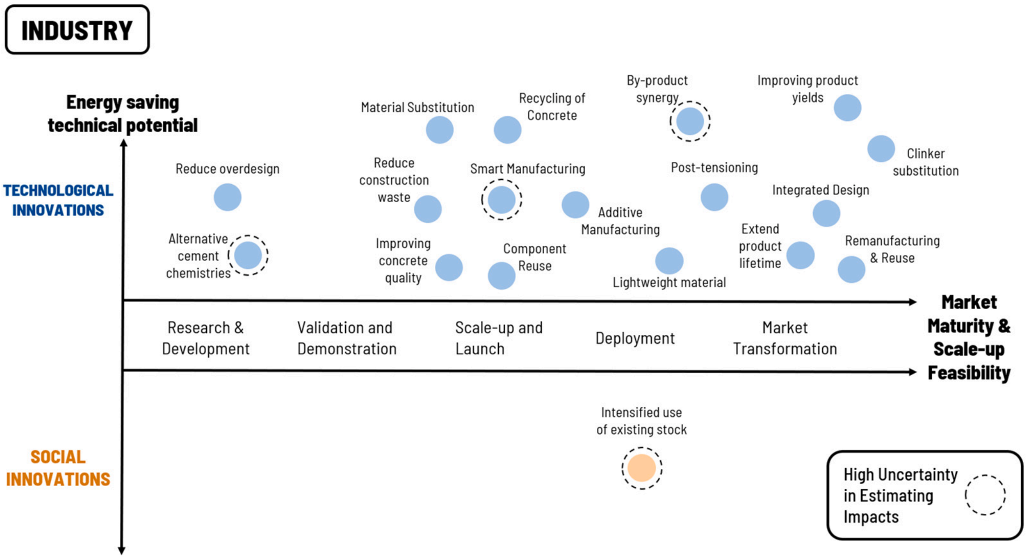

Fig. 2. Technical energy reduction potential, market maturity and deployment feasibility factors for industry innovations.

effects from digitalization and shared mobility, finding a wide range from 25 % net reduction to 20 % increase in transport energy demand [65]. Better understanding of the factors that influence the net actual impact of these innovations – the drivers behind rebound and substitution effects and mode shifting – and documenting successful case studies can reduce uncertainties and improve estimates of their energy impacts.

Smart freight technological innovations and logistics improvement measures such as automated truck platooning, route optimization, and improved vehicle utilization or loading all have the technical potential to reduce baseline trucking energy consumption by 5–20 % [69,70]. Multi-modal last-mile logistics such as urban consolidation centers can also contribute to reduced vehicle activity and related emissions in urban centers through bundling that achieves a high load factor, high density of delivery points, and use of clean fleet where feasible [68]. These innovations face less uncertainty in their potential impact on reducing energy demand with lower techno-economic barriers than other transport innovations, but still faces key deployment challenges in adoption and implementation barriers. Successful individual case studies with documented energy and emission reductions exist for these innovations, but more market, institutional and policy support are needed to scale-up deployment [68,71,72].

Other social innovations such as right-sizing vehicles and increasing vehicle occupancy and mode shifting from aviation to rail have higher technical potential and lower costs but face greater sociocultural and institutional barriers to successful adoption, implementation and response [22,69]. These options require significant changes in individual behavior and longer societal changes in norms, such as changing societal preferences for flying versus rail, for driving large sports utility vehicles versus compact cars in some regions, or regulatory policy changes such as bans on short-distance flights where rail is available, feebates that discourage large vehicles, or carbon prices to internalize air travel externalities [24].

3.4. *Cross-sector*

In addition to technological transformations, deep and widespread sustainable consumption and lifestyle changes will be needed to achieve carbon neutrality. Cross-cutting technological and social innovations can have direct and indirect impacts on energy use and GHGs emissions in the transportation, buildings, and industry sectors. The nature of these innovations is complex but could have significant implications for deeper GHG mitigation if implemented on a large scale (see Fig. 4). Our purpose is to call for inclusion of these strategies in future modeling work. Research to better understand their impacts and uncertainties in the context of end-use energy is needed.

Urban form refers to the spatial pattern and density of urban physical objects, such as buildings, streets, vegetation, and open space [73]. Ewing et al. (2008) [74] argue that compact development has the potential to reduce vehicle-miles traveled (VMT) per capita by 20 to 40 % over that of sprawling development. The implications of urban form on buildings are mostly related to building geometry and surroundings, and the urban island heat effect [75]. Rode et al. (2014) [76] estimates that heat-energy efficiency can differ up to a factor of six depending on the urban form. Urban form is not just about compactness; the physical urban forms could be sprawling but include well-networked public transport systems, such as many suburban areas that are found in Japan [77]. Modeling urban form impacts is challenging because most urban areas have been developed, with extremely high uncertainty given the intertwined nature of urban attributes. Attention could be paid to regions with rapid urbanization such as China, countries in southeast Asia, and Africa.

Telecommuting has gained wider acceptance since the COVID-19 pandemic but the impacts on economy-wide energy use are not straightforward. A review confirmed that 26 out of 39 studies show energy reduction - by as much as 77 % - from teleworking, while 8 studies suggest that teleworking increases or has a neutral impact on energy use [78]. The uncertainties include transportation modes and behavioral impacts, such as non-work travel and occupant home energy use [79]. Greater impact uncertainty may exist for multiple-day telecommuting options; Hook et al. (2020) [80] found part-week teleworking could lead to a net increase in energy consumption, mainly because part-time teleworkers are able to live further away from their offices.

At the basic level, lifestyle includes four elements of clothes, food, housing, and transport. Beyond innovations in the building and transportation sectors addressed earlier, sustainable fashion and sustainable diet are two additional lifestyle innovations. In 2018, the fashion sector accounted for 2.1 $GtCO_2eq$ of GHG emissions, about 4 % of the global total [81]. Around 21 % of accelerated abatement potential is directly related to consumer actions in the use and end-of-use phases, enabled by

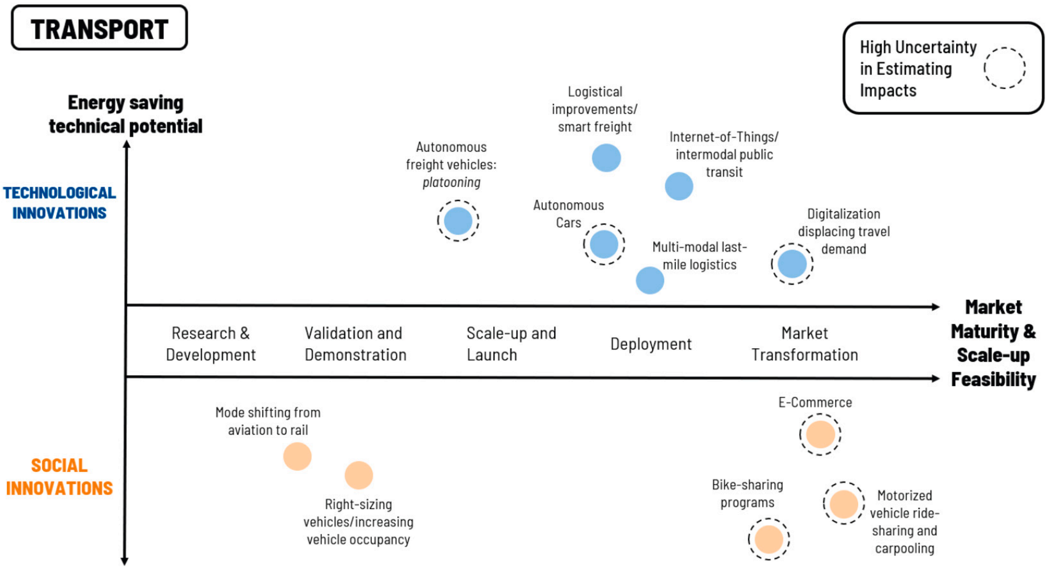

Fig. 3. Technical energy reduction potential, market maturity and deployment feasibility factors for transport innovations.

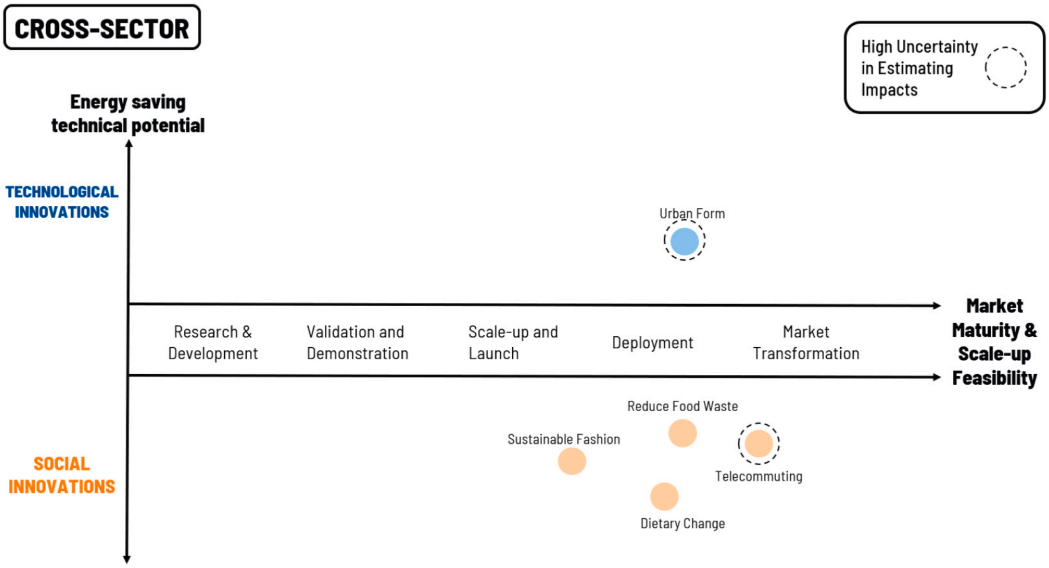

Fig. 4. Technical energy reduction potential, market maturity and deployment feasibility factors for cross-sector innovations.

conscious consumption and new industry business models. Another area of sustainable consumption is food waste reduction and dietary change. The Food and Agriculture Organization of the United Nations quantified the carbon footprint of global food wastage as 3.6 $GtCO_2eq$ emissions in 2011, which excluded 0.8 $GtCO_2eq$ of deforestation and managed organic soils associated with the food wastage [82]. Aleksandrowicz et al. (2016) [83] reviewed 210 scenarios in 63 studies and found that GHG emissions reductions associated with dietary pattern change could be as high as 70–80 %, assuming average population-level intakes as the baseline diet.

Lifestyle is a personal choice, and subject to socioeconomic constraints that are highly related to income, age, education, family size, and other factors. Research communities should aim to account for the population heterogeneity in modeling the impacts of sustainable consumption, by recognizing the social and environmental disparity among populations and between developed and developing countries.

4. Conclusions

Demand-side technological and social innovations have the potential to significantly lower global energy demand across all end-use sectors by avoiding or reducing demand for energy services, shifting to cleaner or more efficient forms, and improving technical energy efficiency. Deep energy demand reductions enabled by these innovations can provide greater flexibility for alternative paths to meeting a global 1.5 °C climate goal with reduced CDR, based on the findings highlighted in this paper at the sectoral and cross-sectoral levels.

Technological innovations under demonstration and deployment are transforming building energy systems by improving energy performance, while changes in design and occupant behavior can further reduce energy demand. In industry, improved design processes, higher quality products, alternative materials, circular economy strategies, and other innovative technologies and practices can all reduce material demand and industrial energy use. Emerging innovations for reducing private passenger transport through smart and shared mobility systems have more uncertain net energy impacts, but innovations in smart freight, increased vehicle utilization and rail to aviation mode shifting have greater potential for reducing transport energy use. Deep and widespread sustainable consumption of food and fashion and lifestyle changes including urban form changes and telecommuting will be needed to achieve carbon neutrality in addition to technological options for transformation. Many of these demand-side technological and social innovations are already in demonstration and deployment stages on the market, but face uncertainties in terms of energy impacts and varying levels of barriers to scaled up deployment. Nearly all of these innovations still face multiple barriers that need institutional, policy, and market support as well as new societal norms to ensure wider adoption. This paper attempts to shed more light on the potential impacts of these demand-side innovations, as well as factors that affect the feasibility of scaled up deployment to achieve full technical potential, to support their inclusion in climate mitigation analysis and policy development.

While this paper provides a LED conceptualization framework and initial assessment of selected innovations, however, much more needs to be done to address the inherent uncertainties and challenges with realizing the full energy demand reductions in terms of informing modeling and policy development. Current global studies and IAMs lack more localized consideration of factors that could affect the adoption and diffusion of technological or social innovations, such as different socioeconomic growth trajectories and patterns and cultural/societal barriers [83,84]. Some studies make simplifying assumptions at the regional level such as by dividing the world into Global North and South to represent the diffusion of these innovations in countries with different patterns of development [85]. Yet regionalized modeling studies of the potential energy impacts of adopting multiple innovations informed by national socioeconomic conditions and cultural norms are lacking beyond location-specific case studies of the adoption of single innovation such as shared autonomous vehicles or personal thermal comfort technologies. The EU and the United Kingdom include some of these innovations in their assessments of climate neutral roadmaps, but this analysis is missing in other regional assessments of 1.5 °C compatible pathways, especially in rapidly growing countries such as China and India [20,85]. Conducting more empirical studies focused in these regions can help inform the development of quantifiable patterns that can be integrated into modeling [15]. Developing effective interactions among modelers and stakeholders (“change agents”) can provide greater insight into local needs, opportunities and obstacles that determine the deployment feasibility of demand-side innovations [13].

Recognizing and improving the assessment of the potentially significant contributions of transformative innovations to reduce energy demand can help reduce reliance on uncertain and costly CDR technologies and measures in global carbon neutrality pathways. Additional research is needed to ensure successful integration of these demand reduction innovations into a broader mix of climate actions can provide greater flexibility, speed, and lower costs for decarbonization. For example, at a regional or national level, better understanding of socio-economic factors that determine how individual innovations can affect net energy demand and detailed case studies of effective policies for reducing consumption or promoting social innovations can help guide policy developments to support adoption of these innovations. This can be achieved by integrating multiple research disciplines and communities such as between energy modelers, social scientists, and political economists, and through the complementary use of both qualitative and quantitative methods to inform modeling. Interdisciplinary and innovative approaches to modeling will be critical to maximizing the adoption and subsequent energy reduction impacts of technological and social innovations by enabling broader changes in societal norms to achieve near-term reductions and carbon neutrality by mid-century.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nina Khanna reports financial support was provided by Research Institute of Innovative Technology for the Earth under Contract No FP00012358.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.103115.

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