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Modeling Low Energy Demand Futures for Buildings: Current State and Research Needs

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Abstract

Buildings are key in supporting human activities and well-being by providing shelter and other important services to their users. Buildings are, however, also responsible for major energy use and greenhouse gas (GHG) emissions during their life cycle. Improving the quality of services provided by buildings while reaching low energy demand (LED) levels is crucial for climate and sustainability targets. Building sector models have become essential tools for decision support on strategies to reduce energy demand and GHG emissions. Yet current models have significant limitations in their ability to assess the transformations required for LED. We review building sector models ranging from the subnational to the global scale to identify best practices and critical gaps in representing transformations toward LED futures. We focus on three key dimensions of intervention (socio-behavioral, infrastructural, and technological), three megatrends (digitalization, sharing economy, and circular economy), and decent living standards. This review recommends the model developments needed to better assess LED transformations in buildings and support decision-making toward sustainability targets.

Contents

1. INTRODUCTION

Buildings support human activities by providing important services, such as shelter, thermal comfort, and illumination, to their occupants (1). These services are key contributors to several aspects of human well-being, including health and life satisfaction (2, 3). For example, adequate building design, materials, and heating, ventilation, and cooling (HVAC) systems contribute to the thermal comfort of occupants and reduce health risks due to exposure to pollution, extreme temperatures, and humidity. At the same time, the demand for services in buildings drives significant energy consumption and greenhouse gas (GHG) emissions both directly, in building operation (e.g., for heating and cooling spaces), and indirectly, in service and product supply chains (e.g., for producing building construction materials) (4).

Demand-side mitigation strategies: climate change mitigation measures associated with individual behavior, lifestyle changes and social practices, infrastructure design and use, and technology adoption, potentially reducing energy consumption and GHG emissions

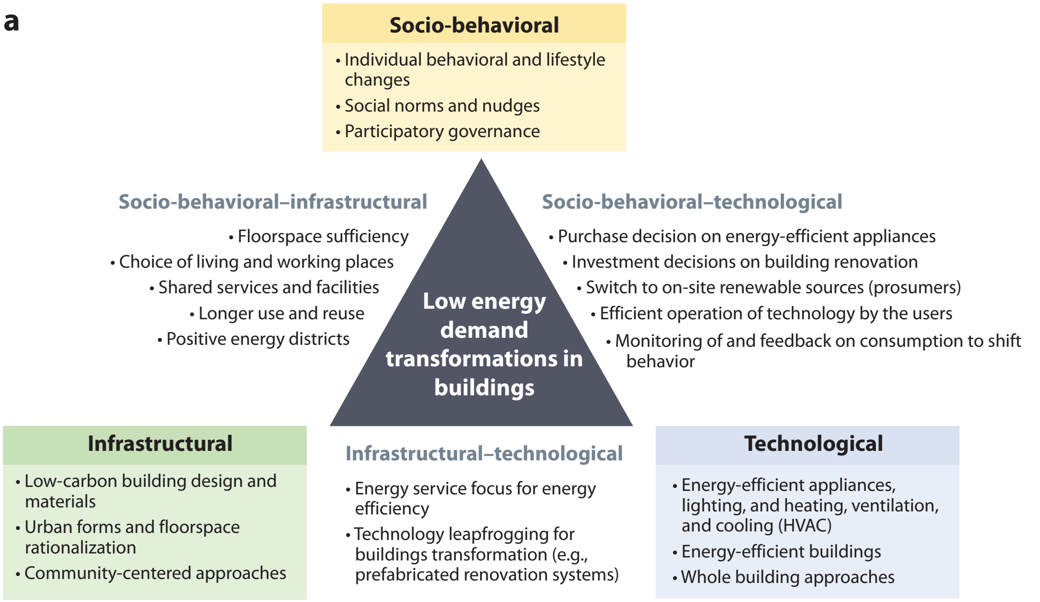
Building sector model: computer-based tool to support the analysis of energy demand, GHG emissions, and other quantities related to buildings at the sector level

At the global level, the building sector accounted for 21% of GHG emissions in 2019, including direct and indirect emissions and emissions from the use of steel and cement (5). Buildings play a key role in reaching climate mitigation targets (6) and many of the Sustainable Development Goals (SDGs) (7) due to their crucial contribution to economic growth, social progress, and environmental protection (8). Improving the way services are provided in buildings while reducing energy demand during their life cycle is key for supporting the well-being of populations and reducing burdens on the environment. Several strategies to reduce the energy demand, also termed demand-side mitigation strategies, were investigated in recent scenario analyses for buildings, including socio-behavioral (e.g., social practices in energy savings, behavioral and lifestyle changes), infrastructural (e.g., compact cities, living floorspace rationalization, architectural design), and technological (e.g., energy efficiency solutions, shift to renewables) interventions (5, 9). Demand-side mitigation strategies could technically reduce GHG emissions of buildings by 78% (6.8 $GtCO_2e$) by 2050 (10) and make the transition to renewables much faster and more cost-effective (11).

The low energy demand (LED) scenario (12) shows that drastic reductions in energy demand (at least 40% from 2020 to 2050) would be possible with social and technological change consistent with demand-side strategies (LED transformations), leveraging digitalization, sharing, and circular economy megatrends while delivering higher standards of living. The LED scenario narrative assumes higher levels of end-use services (e.g., thermal comfort, consumer goods, mobility, and food) with stark reductions in energy inputs to reach climate change mitigation and sustainable development targets without relying on uncertain supply-side large-scale negative emissions.

To support effective decision-making and to provide quantitative evidence on the effect of demand-side mitigation strategies, computer-based modeling has become an essential tool (13–15). Most of the existing building sector models used to project future energy demand and GHG emissions, however, focus on specific strategies and lack a comprehensive view on the broader transformations, enablers, and requirements to reach low levels of energy demand while supporting well-being. Representing LED transformations requires shifts in modeling practices (16), placing energy services (1) in the foreground, accounting for social and technological heterogeneity, and addressing relevant drivers, which currently are not part of most models used to assess climate change mitigation scenarios. Despite the large literature on building sector models (Section 2), a mapping of the current tools in relation to key gaps and model development needs for representing LED transformations in future scenarios (LED futures) is currently not available.

This article aims to address this gap by reviewing building sector models ranging from the subnational to the global scale to identify best practices and critical issues in representing LED transformations. In particular, we identify (*a*) the components of LED transformations already represented in models and how they are implemented; (*b*) the current critical modeling gaps for understanding LED futures; (*c*) the key drivers and elements that need improved representation; and (*d*) how these models and research efforts need to be developed further. To a



b

Low energy demand transformations in buildings

		Socio-behavioral	Infrastructural	Technological
Megatrends	Digitalization	• Teleworking • Smart meters • Demand–response	• Virtual community approaches • Building information modeling • 3D printing of buildings	• Smart homes and appliances
	Sharing economy	• Lifestyle changes toward sharing services and facilities	• Co-housing and co-working • Community-based services	• Centralization of equipment • Sharing of appliances
	Circular economy	• Circular practices and changes in behaviors • Longer use and reuse of appliances and facilities	• Low-carbon design and materials • Longer use, reuse, and repurposing of buildings	• Low-carbon materials and building systems • Lifetime extension
Well-being support	Decent living standards	• Sufficient housing floorspace • Adoption of clean technologies	• Access to adequate housing	• Access to clean and affordable technologies • Leapfrogging in provision of durable housing

Figure 1

Overview of low energy demand (LED) transformations in buildings. (*a*) Examples of interventions for the three dimensions of LED transformations (*triangle corners*, *colored boxes*) and transversal strategies (*triangle sides*). (*b*) Examples of interventions for three megatrends and well-being support, and their relationships with LED transformations.

present the LED scenarios coherently, we focus on three key dimensions of LED transformations, as conceptualized in the most recent Intergovernmental Panel on Climate Change (IPCC) report (9) (**Figure 1*a***): socio-behavioral, infrastructural, and technological interventions. In addition, we investigate three cross-cutting megatrends playing a key role as enablers of LED transformations (**Figure 1*b***)—digitalization, sharing economy, and circular economy—and the provision of higher living standards for all, using the concept of decent living standards (DLS) as a benchmark of material conditions for human well-being (3, 9).

We use a multimethod approach combining a literature review, a survey of model features, and their comparative analysis, as well as expert elicitation and appreciation (see Section 1 in the **Supplemental Text**) to tackle the complexity of LED transformations in building sector modeling. The selected literature ranges from subnational to global in geographical scope, covers both the Global North and the Global South,[1] and consists of both impact assessment and forward-looking scenario studies using building sector–specific or multisectoral models. We conduct a detailed survey and comparative analysis of 16 models representative of a diversity of solution algorithms and features and geographical coverage (**Table 1**). We use a dedicated questionnaire (see the **Supplemental Questionnaire**) in combination with interviews with

Supplemental Material >

Table 1 Overview of the surveyed building demand models

Sector coverage	Geographical coverage	Model name	Approaches	Reference(s)
Buildings	Subnational or local to national	BENCH	Agent-based modeling	28, 49
		JCBSEM	Simulation, agent-based modeling	192
		NHM	Simulation	193
		SAFARI	Hybrid	194
		TREES	Simulation, agent-based modeling	195
	National to regional or global	ACCESS-E-USE (MESSAGEix-Buildings)	Simulation, optimization or minimization, partial equilibrium	167
		EDGE-Buildings	Simulation, optimization or minimization	87
		HEB	Other	196
		STURM/CHILLED (MESSAGEix-Buildings)	Simulation	88
Multisectoral	Subnational or local to national	FORECAST	Simulation, other	197
		PIER	Optimization or minimization, accounting	180
		RTE model	Simulation, accounting	198
	National to regional or global	DREAM	Simulation, accounting	199
		POTEnCIA	Simulation, partial equilibrium	192
		RECC	Simulation, system dynamics, hybrid	191
		US-REGEN	Simulation, optimization or minimization, partial equilibrium, hybrid	200

Abbreviations: BENCH, Behavioral change in ENergy Consumption of Households; DREAM, Demand Resources Energy Analysis Model; EDGE, Energy Demand Generator; FORECAST, Forecasting Energy Consumption Analysis and Simulation Tool; HEB, High Efficiency Building model; JCBSEM, Urban Building Energy Model for Japanese Commercial Building Stock; NHM, UK National Household Model; PIER, Perspectives on Indian Energy based on Rumi; POTEnCIA, Policy Oriented Tool for Energy and Climate Change Impact Assessment; RECC, Resource Efficiency–Climate Change mitigation framework; RTE, Réseau de Transport d'Electricité model; SAFARI, Sustainable Alternative Futures for India; STURM/CHILLED, Stock TURnover Model of global buildings/Cooling and Heating gLobaL Energy Demand model; TREES, Total Residential End-use Simulation; US-REGEN, US Regional Economy, Greenhouse Gas, and Energy model.

[1]Here, the Global North and Global South follows the definition given by intergovernmental development organizations, referring to economically disadvantaged nation-states (17), that is mostly used in regional and global building sector energy modeling studies. This definition differs from the social designation (rather than geographical) provided to Global North and Global South in other works focusing on sustainable living (18).

expert modeling teams to investigate the scope, features, and potential of existing models to capture the future dynamics and impacts of LED transformations. Finally, we summarize the results emerging from our literature review, comparative model analysis, and expert elicitation workshops to identify modeling gaps, needs, and best practices.

In the following sections, we first give an overview of the current and emerging building sector models (Section 2). We then introduce the rationale, key interventions, best practices, and challenges in modeling LED transformations (Section 3), LED megatrends (Section 4), and DLS (Section 5). Finally, we discuss key modeling gaps (Section 6) and future developments in building demand modeling and our conclusions (Section 7).

2. BUILDING SECTOR MODELS

Building sector models (19) have become essential tools for developing and assessing potential strategies to reduce energy demand and GHG emissions of buildings. While there is a long tradition of energy demand models for single buildings, modeling the energy demand and GHG emissions of buildings at the sector level (from subnational to national, from regional to global) has emerged only in the past few decades. Building sector models can be grouped as top-down, bottom-up, or hybrid (13, 15, 19) (**Figure 2*a***).

Top-down models represent the building sector at the aggregated level and are either economic or technological. They are used mostly to assess economy-wide policy responses (19) and are often limited in their ability to represent the impact of new technologies and disruptive changes, as they lack granularity (level of detail). For example, an aggregated model might not distinguish buildings in the stock by their characteristics, failing to properly assess the effect of new technology uptake (e.g., heat pumps or deep renovations) on different building types.

Bottom-up models represent individual buildings or subsystems in detail and subsequently aggregate results at the system level. They include engineering, statistical (including machine learning), and hybrid approaches. Bottom-up models can explicitly represent key dynamics of energy use, building heterogeneity, and the aggregate effect of changes from individual buildings (13) and are used to estimate the technoeconomic potentials at the stock level (19). Hybrid models combine the two approaches and are used to explore the impacts of resource constraints, technological choices, and building policies (19). They use optimization and simulation approaches, including agent-based modeling (ABM) (20).

While most building sector models focus on energy demand, additional layers can support the representation of key determinants and dynamics (13), including physical context and climate, socioeconomics, stock turnover, and material flows, as well as behavior and practices (**Figure 2*b***). Additionally, we identify four model features (**Figure 2*c***) that are crucial for evidence synthesis (Section 6). Spatiotemporal resolution and coverage refer to the smallest unit of analysis (resolution) and scope (coverage) in space and time. Granularity indicates the level of detail in the model concerning, for example, buildings, agents, and technologies, and strongly relates to the ability of a model to represent heterogeneities (see the example above in this section). Model dynamics describe the evolution of the modeled system over time and are characterized by exogenous or endogenous variables depending on whether they represent influences external or internal to the model. For instance, the building renovation rate can be modeled either exogenously, by assuming externally given renovation rates, or endogenously, by modeling the decision process of renovations within the model on the basis of other external variables. System boundaries define the scope of the modeled system (e.g., which sectors or subsectors are represented). Typical model outputs of building sector models (**Figure 2*d***) include GHG emissions, energy and material demands, and energy service or activity levels, such as floorspace (the surface area of floors in a building) commonly used as an indicator of service levels for shelter and thermal comfort.

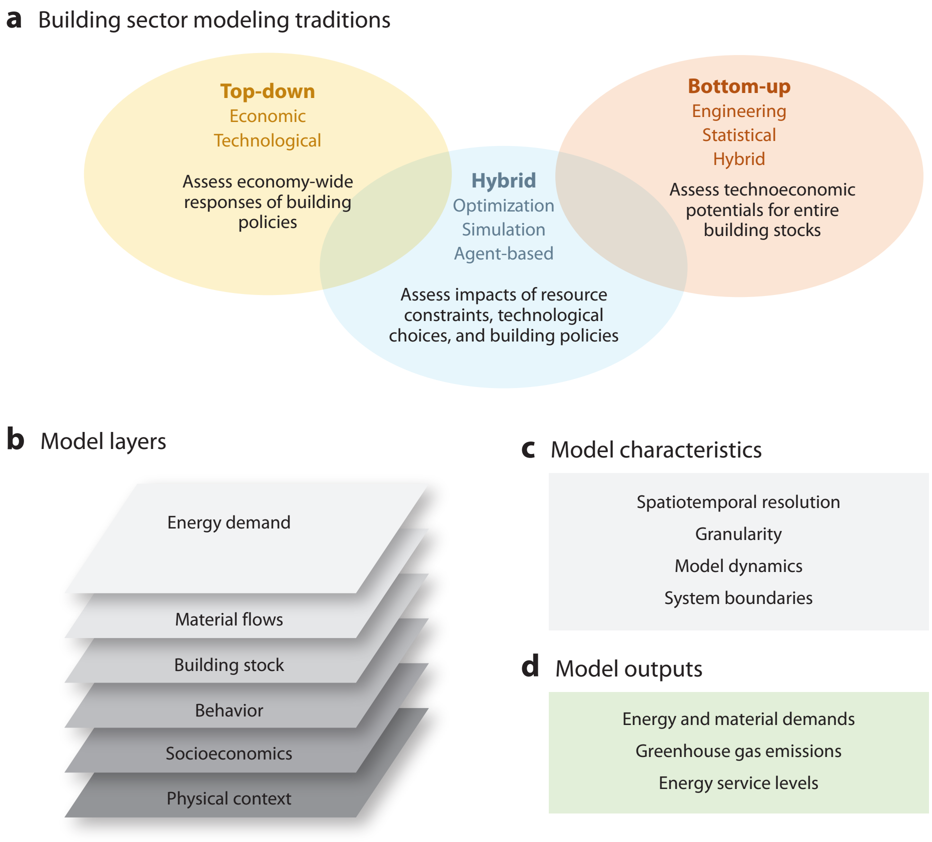


Figure 2

Overview of building sector modeling for energy demand and greenhouse gas (GHG) emission assessments. (*a*) Modeling traditions. (*b*) Model layers. (*c*) Model characteristics. (*d*) Model outputs. Part of the data is from References 13 and 19.

In this review, we focus on bottom-up and hybrid building sector models using a variety of different approaches to project future energy and material demands and associated GHG emissions. We disregard top-down building sector models due to their limitations in representing demand transformations. Nevertheless, we discuss the key linkages with more aggregated large-scale and economy-wide models [e.g., integrated assessment models (IAMs)] extensively used in the analysis of climate change mitigation scenarios. We include models whose geographical coverage ranges from subnational to global and that cover the individual building sector or multiple sectors.

3. MODELING LOW ENERGY DEMAND TRANSFORMATIONS

The LED scenario (12) assumes radical changes on the demand-side as a major driver of mitigating climate change and providing higher living standards without relying on risky negative emissions in the future (21). The LED scenario narrative is similar to other long-standing discourses on sustainable consumption corridors (22), energy efficiency and sufficiency (23, 24), planetary boundaries and human well-being (25, 26), and sustainable lifestyles (27). The LED narrative focuses on long-term drivers of energy end use, including higher quality of life, rapid urbanization, novel energy services, diversified end-user roles, and information innovation. For each of the three dimensions of change (9)—socio-behavioral, infrastructural, and technological—we introduce here the rationale, relevance for LED scenarios, and key interventions, and we review existing modeling gaps and best practices.

3.1. Socio-Behavioral Intervention

Social practices in energy saving and behavioral and lifestyle changes, such as adaptive heating and cooling by changing indoor temperature, can contribute approximately 15% to GHG emissions reduction in the building sector by 2050 (9). Socio-behavioral mitigation strategies in the building sector involve individuals' choices, social norms and nudges, and participatory governance.

3.1.1. Individual behavioral and lifestyle changes. Individual energy decisions and behavioral and lifestyle changes include changing energy-use habits (e.g., adjusting the set-point temperature for heating, saving hot water); investing in energy-efficient appliances, buildings (e.g., thermal insulation), and on-site renewable sources [e.g., photovoltaic (PV) panels]; and switching to better services (e.g., green energy providers). Individual energy decisions can be motivated by market and nonmarket forces (e.g., regulations and policies, social norms, structural factors) and can reduce energy demand directly and indirectly. Demand-side policies can use various behavioral tools that complement regulations and monetary policies (e.g., subsidies and taxes). The provision of targeted information, social advertisements, and the influence of trusted in-group members and role models can be used to create better climate change knowledge and awareness (20, 28). Behavioral interventions such as communicating changes in social norms can accelerate behavior change by creating tipping points (29).

3.1.2. Social norms and nudges. Each individual's energy behavior is influenced by the perception of what other people commonly think, do, or expect (30). For instance, moral values and political ideology influence human beliefs and the effectiveness of one's actions. Several studies provide strong empirical support for social comparison interventions (31, 32) and information feedback (33–36), with energy and GHG emissions reductions between 0.8% and 2.6% for the former and between 1% and 12% for the latter. The feedback mechanism becomes more effective when combined with goal setting or external incentive interventions such as pricing. Social movements (e.g., advocating behavioral change) can open up windows of opportunity to unlock behavioral and structural changes (37). Behavioral nudges promote behavior change, such as investments in energy efficiency actions. Policymakers have various tools, including prohibitions, mandates, taxes, fees, subsidies, and nudges, to influence individual energy decisions and consumption (38, 39). Nudges include choice-preserving interventions such as information, warnings, reminders, uses of social norms, and default rules (40).

3.1.3. Participatory governance. Professionals, such as building managers, landlords, energy efficiency advisers, and technology installers, influence patterns of energy consumption by acting as middle actors in providing building services (41). Professionals can enable or obstruct improvements in efficient service provision or shifts toward low-carbon technologies (e.g., heat pumps, solar hot water, underfloor heating). Collective action has the potential to enable or constrain societal shifts in emissions reduction. For instance, community energy initiatives can improve energy efficiency, ensuring a decent standard of living and increasing renewable energy uptake while building on existing social trust (42). The famous Japanese behavioral change campaign Cool Biz recommended office workers increase the temperature to 28°C during summer while relaxing the dressing code (43). The campaign was a huge success thanks to the widespread acceptance of the comfortable image of light clothing. The Positive Energy District (PED) innovation introduces the next generation of energy-efficient buildings with high coverage of renewables integration (Sections 3.2 and 3.3). Bottom-up engagement, cooperation, and participatory governance are crucial for implementing PEDs. Despite several successful cases, more consideration should be given to the social dimension (e.g., energy poverty and energy justice) for new PED creation (44) (Section 5).

3.1.4. State of the art and challenges in modeling. Building sector models still lack a proper representation of socio-behavioral interventions as effective drivers of future energy conservation opportunities. Due to the complex nature of human behavior and social dynamics, current models (Section 2) mostly overlook heterogeneous individual behavior and diverse social and institutional settings (28, 45–47). This comes mostly from insufficient model granularity to enable explicit characterization of heterogeneous actors and individuals and an inability to adequately represent complex human behavioral (decision-making process) and social dynamics and learning. Most of the surveyed models (see **Supplemental Figure 1**) can integrate behavioral strategies only through simplified exogenous assumptions, including changes in floorspace and energy-saving practices (e.g., temperature set-points, telecommuting) (Sections 3.2 and 4.2) and improving heating and cooling systems (Section 3.3). Some simulation and optimization models (EDGE-Buildings, FORECAST, RTE model, STURM/CHILLED, TREES) have partial endogenous coverage on specific aspects, such as energy-efficient appliances and technology adoption, buildings renovation decisions, or rebound effects (Sections 3.2, 3.3, and 5), mostly via dedicated discrete choice models or probability functions. Only two of the surveyed models (BENCH and POTEnCIA) fully cover energy-saving practices endogenously, and only one (BENCH) covers behavioral changes and social norms using ABM.

Supplemental Material >

In reality, people make energy decisions in buildings on the basis of their diverse preferences, socioeconomic conditions, behavioral and lifestyle biases, social peer influence, and technology and infrastructure availability. Thus, new models are needed to reflect these complex decision environments (48). One promising approach is ABM, which can represent heterogeneous individual energy choices, behaviors, and lifestyles that fully reflect socioeconomic, behavioral, social, infrastructural, and institutional settings, along with the spatial context. ABM is a frontrunner, as it is designed to account for heterogeneous agents (e.g., individuals, firms), different lifestyles, bounded rationality (heterogeneous rationalities and decision rules), and social influences (48–53), going beyond the classical rational choice perspective, where homogeneous, perfectly rational individuals act in a perfect market with complete information (54).

Various socio-behavioral interventions are already covered by building sector models (**Supplemental Table 6**). Sufficiency is an emerging concept that refers to measures that avoid the demand for energy and materials over the life cycle of buildings and appliances and related GHG emissions driven by nontechnological solutions (5, 55). Sufficiency scenarios are captured by translating qualitative lifestyle changes (e.g., sharing facilities) into quantified model parameters (e.g., surface per capita and number of appliances per household) (Sections 3.2 and 4.2). The community would benefit from more studies of sufficiency for both the Global North and the Global South and of how sufficiency measures compare to minimum requirements to provide DLS (Section 5). Other models capture behavioral and lifestyle changes and energy efficiency interventions, from simple energy-saving practices to investment in solar PVs and building insulation (Section 3.3). Yet to better understand the impact of social norms on energy decisions and energy reduction potentials, it is critical to capture heterogeneity. Households' heterogeneities in sociodemographic characteristics (e.g., income, age, education), building characteristics (e.g., type, size), energy consumption patterns, behavioral factors (e.g., awareness, beliefs), social factors (e.g., social norms, culture), and institutional settings influence household occupants' energy decisions and behavioral and lifestyle changes (56). Social norms have an essential role in shaping behavioral and lifestyle changes. For example, to inform demand projections on the basis of smart meter data (Sections 3.3 and 4.1), to better characterize elasticity to prices on the basis of previous experiments, and to introduce network effects on virtuous behaviors will be vital to offering a complete assessment of available policy instruments for energy efficiency. It is also useful to incorporate a plurality of perspectives on plausibility and desirability through iterative participatory engagement and worldview-based scenario exploration. Finally, it is also valuable to make projected futures more tangible and experiential so that diverse societal actor groups can understand and genuinely engage with them.

3.2. Infrastructural Intervention

Buildings are an important part of the built environment, constituting the backbone of modern societies, underpinning human activities and well-being (57), and driving material and energy consumption (58). Key infrastructural interventions for low energy and material demands range from the individual building to the city scale and include low-carbon building design and materials, compact urban forms and floorspace rationalization, and community-centered approaches. Infrastructural interventions have the potential to reduce buildings' GHG emissions by approximately 20% (9).

3.2.1. Low-carbon building design and materials. Building characteristics, design, and size drive energy and material demands in all phases of a building's life cycle. Material production associated with the construction of new buildings and infrastructures can become a major source of GHG emissions under future growth and urbanization (59). Various material strategies (i.e., material substitution, lifetime extension, longer use and reuse, renovation, and more intensive use) (Sections 3.1, 3.3, 4.2, and 4.3) have been investigated on the demand-side (60–64). Engineered wood has been proposed as a substitute for high-emitting mineral-based structural materials and as a potential carbon sink (59). This option has a high mitigation potential but requires expansion of timber plantations (65), resulting in complex trade-offs with other land uses for food, feed, and fuels as well as ecosystem conservation (66). Novel materials, particularly engineered cementitious composites, open a new avenue to make use of captured carbon dioxide for enhanced infrastructure durability (67) and simultaneously address embodied carbon and maintenance emissions (68). Advances in construction processes enabled by digitalization (Section 4.1), including building information modeling (BIM), automated construction, and 3D printing (69, 70), offer novel opportunities to lower the environmental impact of building construction and stimulate circularity practices (Section 4.3).

3.2.2. Compact urban forms and floorspace rationalization. Urban form strategies play a critical role in reducing energy and material demands. Compact designs translate into lower average floorspace and correspondingly lower energy and material demands (10). Floorspace reduction (71) can be driven by new business models for house sharing and co-living initiatives; building reuse and repurposing (Section 4.2); financial constraints and housing prices; and land-use and urban policies to manage the expansion of cities and regulate their densities, such as a shift toward multifamily housing and reducing the average size of new single-family housing (72). Related to urban design, nature-based solutions, such as green roofs and green facades, and urban green infrastructures can substantially reduce the operational energy demand of buildings while contributing to climate change adaptation strategies and reducing the urban heat island effect (73).

3.2.3. Community-centered approaches. Communities are key in enabling systemic changes toward LED (74), as they can concentrate activities, thus leading to economies of scale, access to services, and faster diffusion of knowledge. Community-based energy services improve the efficiency of demand and small-scale supply solutions, for example, through co-purchasing and sharing (Section 4.2). Virtual communities go beyond the traditional system boundaries for transformation and foster positive reinforcement (75). For example, virtual power plants are innovative business models that aggregate decentralized, small-scale energy production with energy and saving potentials (76) (Section 4.1). One-stop shops, offering assistance in the energy renovation supply chain, can bridge the gap between individual households and the construction supply-side and therefore increase the rate and speed of renovation (77). Communities can help upscale and roll out demand-side mitigation strategies through peer pressure, example setting, demanding solutions, and replication (Section 3.1), thus making these solutions more available and cheaper (74).

3.2.4. State of the art and challenges in modeling. Several detailed bottom-up models evaluate potential future trajectories of building stocks, focusing on materials and operational energy demand (61–63, 78). Many of those studies model buildings with an increasing number of archetypes, achieving up to global coverage. Other studies focus on building-by-building modeling (79), however, usually only for a single country. Comprehensive building sector modeling for the whole globe, with regional resolution (62, 64), enables matching system boundaries across countries and time, although at the expense of detail. Despite recent efforts to characterize national and global building material stocks (80–82), challenges remain in representing heterogeneous building materials and construction types, including informal buildings (Section 5), and building lifetimes and reuse (Section 4.3).

Representation of urban forms and urban-related strategies is currently limited in building sector models (83), as they focus mostly on individual buildings while overlooking the broader urban context. Our survey (**Supplemental Figure 1**) confirms that urban form–related aspects are only partially represented in bottom-up models and mainly exogenously, for example, via per-capita floorspace assumptions (HEB, STURM/CHILLED, RECC) or representation of different building types (STURM/CHILLED, RECC, TREES). While data-driven floorspace projections dependent on income and urban density are common in building sector models, only a few studies consider floorspace reduction scenarios by introducing per-capita caps or convergence to normative values (12, 55, 71, 84, 85). Most of these projections are assumption based and overlook the underlying dynamics, acceptability, and feasibility of reducing floorspace, which require further empirical evidence (86). Considering floorspace heterogeneity across housing, household types, and different building functions (including vacant buildings) is critical to further assess the potential of sufficiency (Section 3.1) while ensuring minimum DLS (Section 5) and of floorspace rationalization strategies, for example, by repurposing and reusing vacant buildings (Section 4.2).

Supplemental Material >

More detailed representation of urban strategies is challenging, as they strongly depend on local conditions, context, complex dynamics, and interlinkages with other sectors. It is critical for models at scale to capture system-wide effects, bridging scales from individual buildings to mesoscale (neighborhood, city) and large scale (country, global). Recent linkages of detailed global building sector models with IAMs (87, 88) enable explicit consideration of building stock turnover and demand-side interventions in combination with energy supply system transformations. However, IAMs are still limited in accounting for material cycles (Section 4.3) and complying with thermodynamics, requiring more developments to properly integrate the stock–flow dynamics of buildings into the overall social metabolism. More linkages with other sectoral models are required to adequately represent transformation at the urban scales and community-centered approaches (Section 6).

3.3. Technological Intervention

Technology is a means to do things, consisting of technical artifacts (hardware) and a disembodied element of knowledge (software) (89). The adoption of energy-efficient technologies and small-scale renewables can contribute to 30–70% of the GHG emissions reduction potential in buildings (9). The LED scenario narrative assumes a rapid and radical rollout of selected existing low-demand technologies only possible with a systemic approach (12). Here, we review technological LED interventions and their modeling representation, including energy-efficient appliances, lighting, HVAC systems, energy-efficient buildings, and whole-building approaches.

3.3.1. Energy-efficient appliances, lighting, and HVAC systems. Accounting for one-third of the energy consumed in buildings (90), appliances are among the fastest-growing energy end uses in buildings. Many appliance types, such as refrigeration and lighting technologies (91), have undergone major maturation and efficiency improvement in recent decades (92). However, these have been counterbalanced by rapid adoption, increased size, and user behavior in the Global North (93, 94), often resulting in rebound effects (95), and an insufficient penetration increase in the Global South, which often relies on less-energy-efficient appliances. Continuous upgrading of energy efficiency standards for appliances and HVAC technologies is a critical cost-effective approach to achieve LED globally. Heat pumps (96) and fuel cells (97, 98) are among the promising decentralized technologies for decarbonization and integration of intermittent renewable energy. While the adoption of high-efficiency HVAC systems is growing, penetration is slower due to critical barriers related to costs, burden of renovations, clarity of decisions for homeowners, and lack of reliable information. Further energy reduction is foreseen in LED through further electrification (12), digital convergence (Section 4.1), sharing and centralization (Section 4.2), and dematerialization (Section 4.3).

3.3.2. Energy-efficient buildings. Energy efficiency improvements of building envelopes are key to reducing the energy demands of buildings. Passive strategies (99), as opposed to active strategies, do not require the use of mechanical systems and additional energy use and include building insulation, thermal mass, air tightness, advanced fenestration technologies, passive solar systems, natural ventilation, and bioclimatic design (100). Passive strategies adapted to the local climate and context can entail significant energy savings for thermal comfort. Passive houses (101) require very low energy for space conditioning while providing high standards for thermal comfort. In the Global North, the potential for energy demand reduction relies largely on the renovation of older and inefficient buildings (87, 102). Both acceleration in renovation rates (up to 2–3% yearly) and increased depth of renovation are needed to meet climate targets (6). One promising direction is the wider rollout of prefabricated systems for new construction and renovation (103) (Section 3.2). These measures could lead to an LED-relevant energy transformation leap and decrease the complexity of the technological solution while reducing the time and investments needed to renovate homes or nonresidential buildings (77).

3.3.3. Whole-building approaches. A whole-building passive or energy-plus building design combines both demand-side and supply-side solutions (104), including renewable energy sources, with a focus on user comfort while making the user an active energy system player (prosumer) (102). Given the automatization required in highly efficient buildings, smart buildings, and building systems, these changes are closely linked to digitalization (Section 4.1). Leaping to at least an average passive design for new buildings is a key LED element. Previous studies (102) have shown that it is possible to achieve high-efficiency performance in most building types and climates with already existing technologies and skills and without major extra costs. However, significant barriers still exist, limiting their penetration and thus requiring further policy interventions.

3.3.4. State of the art and challenges in modeling. For modeling LED transformations, it is critical to interpret the features of technological advancement that lead to major reductions in energy demand beyond the direct or stylized representation of the individual technologies (105). Doing so requires a shift in modeling practices to include an energy service perspective, development and innovations, technology adoption, and user interaction (106, 107).

First, building sector models should represent access to and demand for energy services as opposed to demand for energy in itself. Therefore, efficiency in buildings should be understood as the input of energy, materials, or other resources to lead to a unit energy service, such as shelter, thermal comfort, or lighting. Many of the surveyed models already represent energy services via activity-related indicators (e.g., floorspace as an indicator for shelter and thermal comfort) (Section 3.2). More interdisciplinary research is needed to understand what end users value for their well-being and business benefits beyond the technologies and activity levels (such as floorspace) and how these values can be provisioned in ways that require less energy input, in consideration of historical and cultural contexts. In addition, modeling the relation between innovative technologies and the changed activity levels can lead to more realistic LED-type scenarios, including rebound effects (Sections 4.1–4.3).

Second, technology is dynamic and cumulative and follows nonlinear technological innovation and readiness curves in its rollout (89, 108). Rapid technology development and uptake can happen on a short diffusion timescale in a multiplicative and self-generating process (107). Due to their modularity, more granular energy technologies are likely to develop faster and scale up faster than lumpy technologies (107). Current models often use exogenous technology learning functions but are limited in modeling disruptive technologies and leapfrogging, which are critical for LED scenarios. Some of the more detailed bottom-up models already include fine technological resolution and can endogenize technological learning, among other factors.

Third, the spread and operation of demand-side technologies are tightly linked to user knowledge and interaction, possibility of adoption, and the underlying socioeconomic and institutional contexts. In current models, the uptake of advanced energy-efficient solutions (e.g., passive buildings or deep renovations) is often modeled via exogenous adoption rates. Although effective for showing the potential of technology uptake, this approach does not adequately represent the underlying dynamics, barriers, and enablers, including policy levers and financing. Some of these dynamics, particularly the investment decisions of households, have been represented by enriching bottom-up approaches with microeconomic mechanisms (109) and increasing technological and socioeconomic granularity. Many building sector models now represent technology-rich bottom-up dynamics (e.g., POTEnCIA, RTE model, FORECAST), and other models represent buildings or appliances in a largely heterogeneous way through lifetime distribution (e.g., RECC, HEB, MESSAGE-Buildings, JCBSEM, EDGE-Buildings) and are supported by data-driven approaches (ACCESS-E-USE). Agent-based models (e.g., BENCH) could further contribute to enriched representation of technology adoption, accounting for social and behavioral aspects (Section 3.1).

4. MODELING LOW ENERGY DEMAND MEGATRENDS

Megatrends are tendencies that are transversal to the main dimensions surveyed in the LED transformations (**Figure 1*b***). We focus here on three main megatrends: digitalization, the sharing economy, and the circular economy. In the following, we detail the contributions of these trends to LED transformations and the state of the art in building sector models.

4.1. Digitalization

Digitalization refers to the widespread embedding of digital capabilities in appliances, homes, workplaces, and utility infrastructures so that daily life becomes data rich with increasing potential for automation. Digitalization centers on information and communication technologies and related applications such as cloud computing, data analytics, artificial intelligence, smart Internet-connected technologies, and on-demand platforms and services (110). Collectively, these technologies open up new services and possibilities across all domains of economic and social activity (111). Digitalization is important for LED scenarios for three reasons (112). First, it is a pervasive force shaping daily life, including the provision and consumption of energy services in buildings. Second, digital services, platforms, and applications offer clear and significant energy and GHG emissions reduction potential (113). Third, if left ungoverned and unchecked, digitalization can lead to rebound effects that undermine LED future developments (114).

The influence and uncertain impact of digital solutions are demonstrated by the analysis of trends in telecommuting during the COVID-19 pandemic. Studies quantifying the impacts of energy and GHG emissions across demand sectors, and accounting for rebound effects (115–117), found that telecommuting does not greatly affect net energy consumption due to offsetting effects between increased household energy use and decreased transportation and commercial building energy use. Studies of urban areas (116, 118) showed that the energy implications of telecommuting are also uncertain, due to potential increases in housing unit size and home energy consumption, and that energy reductions in office buildings are possible only if space is shared among telecommuters.

Digitalization can support reductions in energy demand in buildings by two main mechanisms: control and integration. First, smart technologies and the Internet of things (IoT) provide new control functionality with possibilities for algorithms or automated routines to manage heating, lighting, or appliances to reduce bills or support the electricity and gas networks during times of peak demand (119). Either by automatization and optimization or by supporting user decisions and behavior change, these approaches can offer saving potentials between 10% and 40% for electricity, heating, and cooling (120, 121). Second, digitalization also enables distributed generation (e.g., rooftop solar systems) and distributed storage (e.g., electric vehicle batteries) to be integrated into electricity networks, so buildings can provide flexibility, trading, and balancing services back to the grid (122). Real-time or marginal cost pricing during peak periods is one mechanism by which electricity network operators can incentivize buildings and their occupants to reduce or shift demand, avoiding the need for costly fossil fuel supply infrastructure (123). Besides operational energy demand, digitalization offers new opportunities to reduce the environmental impact of building construction through BIM, automated construction, and 3D printing (Sections 3.2 and 4.3).

Current building sector models rarely represent the adoption of digital technologies and their effect on energy demand, requiring new methodological developments (124). Some aspects related to digitalization, such as telecommuting and related lifestyle changes, could be addressed by current bottom-up models (e.g., EDGE-Buildings, JCBSEM, RECC), although only by using simplified approaches such as exogenously changing floorspace levels in housing and offices, occupancy profiles, and building energy system operation levels. To do this, researchers need more supporting data, for instance, to recalibrate sociodemographic parameterizations and energy demand functions, for example, by drawing on high-resolution smart meter data (71). Models with higher temporal granularity that address electricity load profiles and renewable supply (e.g., TREES) can represent various changes induced by digitalization by exogenously modifying the parameters related to building activities and appliance ownership and operation. Other bottom-up models can readily represent smart appliances (e.g., FORECAST), demand-side flexibility (e.g., RTE model), and related energy consumption reduction potentials.

Modeling digitalization endogenously poses several challenges, requiring model structure changes and further empirical backup, due to the uncertainty about the dynamics affecting lifestyles, operation, and technology use. Model improvements may also lead to showing the diffusion of new technologies at the household level for both demand (e.g., smart metering) and supply (e.g., PV panels), given the potential network and social norm effects as well as the policy incentives in place. Digitalization also leads to more vector coupling and sector coupling (e.g., between electricity, transport, and heat), which has been considered in some multisectoral models (POTEnCIA) but is a major challenge for sector models in general. Future building sector models will need to properly represent the changes in demand as more users become better informed on and engaged in demand–response programs, dynamic pricing, and other types of economic incentives and nudges that promote energy conservation or load shifting (Section 3.1). Modeling complex systemic changes due to, for example, the wider spread of IoT is challenging and requires further methodological developments (124).

4.2. Sharing Economy

Sharing refers to the case in which assets, such as vehicles, houses, or devices, are used by multiple people as opposed to their ownership for exclusive individual consumption. The sharing economy is at the crossroads of three more general trends: access over ownership, the circular economy, and peer-to-peer exchange (125). Giving access to assets increases the use of underutilized devices owned by an individual. Moving from owning to sharing presents several benefits, such as more intensive use of the good or service and the minimization of waste (circular economy) and material needs (dematerialization) (Section 4.3). Peer-to-peer online platforms are at the core of many sharing activities (126), such as short-term lodging (127).

Co-living and co-working are other types of flexible usage, encouraging the sharing of amenities such as space heating and cooling, living spaces, appliances, and other equipment (128–130). Appliances and services sharing (rather than owning) and centralization of building equipment (e.g., space and water heating, ventilation) reduce the number of devices required to serve the same energy needs (e.g., lighting, entertainment, hygiene) and have the potential to reduce embodied energy (129). In addition, devices can be used at a higher load factor, increasing efficiency and lowering energy consumption and cost.

A long-standing line of research repeatedly shows the potentials of sharing in terms of economies of scale at the household and urban levels using empirical methods (128, 130–132). Adding one person to a one-member household can significantly reduce energy consumption and material footprint; however, the marginal gains of further increases become much smaller and may exhaust after some threshold. On the other hand, more densely populated and compact urban areas tend to offer more opportunities for sharing resources between households (133). But urban areas also attract wealthier populations (134), which live in smaller size households (131), and this might counterbalance the effects of density. Several empirical studies show lower potential for further household economies of scale in urban contexts compared with rural areas, though with lower emissions per capita in cities (128). We were unable to find estimates of carbon reduction potentials obtained by sharing equipment, for example, heating and cooling or laundry rooms, compared with owning. Moreover, flexible usage of buildings and synergies between commercial and residential sectors have been largely overlooked in building sector models.

Despite these limitations, our survey results highlight that several models could represent aspects of the sharing economy, albeit in a simplified way. Having per-capita floorspace among the main drivers, many of the surveyed models (RECC, TREES, STURM/CHILLED, JCBSEM, EDGE-Buildings, FORECAST, RTE model) could represent space sharing in residential and commercial buildings by exogenously providing modified floorspace projections. Part of these models allows for introducing additional building archetypes, and their projected share in the stock, to represent buildings with hybrid functions or shared spaces. Another way to represent co-living would be to adapt projections of household size (TREES, RTE model). Other models could readily represent appliance and equipment sharing via modified appliance usage and ownership (FORECAST, RTE model). However, challenges remain for available data to inform and support such exogenous model parameterizations and more endogenous representations of aspects of the sharing economy.

4.3. Circular Economy

The circular economy is an increasingly important concept for the construction industry and in society (135, 136). Circularity measures aim to narrow, slow, and close material loops within socioeconomic systems and also within ecological systems (137). These measures aim to reduce overall resource use and conserve energy and emissions, although thermodynamic and biophysical limits to circularity within environmental limits have to be understood (138), as there can be no perpetual motion machine (139). For buildings, circularity measures address all life cycle stages of the material stocks and flows that cater to the demand for building services, making circularity highly relevant for LED scenarios.

To model circularity potentials for buildings, established methods and data are insufficient to fully capture the benefits of circularity, but they do show inevitable trade-offs and problem shifts (58, 136, 140, 141). To fully capture the benefits of circularity, it becomes necessary to dynamically model the life cycle of the materials and components that constitute a building, for the entire building stock at scale, to assess the upstream and downstream life cycle energy and emissions implications of circularity measures for industry and energy supply, vis-à-vis operational energy requirements of buildings (58, 140, 142). Importantly, this requires comprehensive system boundaries on the GHG emissions due to material cycles across all life cycle stages of a building, as well as intertemporal assessments of socioeconomic and natural carbon stocks and resulting net emissions, for example, due to timber construction (136, 140, 142). The current life cycle literature usually is too narrow and selective (136, 140), while most material stock–flow analyses are focused on modeling the building material stock at scale (58). Tackling this modeling challenge is increasingly being done by combining prospective life cycle assessment, BIM, and dynamic material stock–flow analysis.

State-of-the-art prospective modeling covers various supply- and demand-side circularity measures (Section 3.2). A recent bottom-up stock-driven study using the RECC model showed that circularity measures can reduce global cumulative GHG emissions from the residential building life cycle from 2016 to 2050 by 14–22% (62). These measures can make an important contribution to reducing emissions from material production, which in 2015 were responsible for 23–35% of global total GHG emissions (143). This finding might become even more important, as future buildings such as passive houses require slightly more and different materials (102, 142).

Moving beyond biophysical modeling, some studies focus on the monetary costs and benefits of circularity strategies (60, 61, 87), assess explicit policy variations (87), represent decisions and effectiveness of measures with ABM of stakeholders and users (144), and either use results from IAMs (64) or are coupled to these models themselves (88, 145), the latter of which enables the evaluation of sectoral emissions, capital accumulation, and labor implications.

However, areas for further improvement include the following research frontiers. Spatially explicit modeling is increasingly important, as many studies (58) (Section 3.2) conducted at the national to global scales have assumed that circularity strategies can occur within the modeled geographic boundaries (e.g., RECC), effectively ignoring transport constraints for large volumes of construction materials. Recent efforts have started to explicitly model potential materials supply from deconstruction and demolition in a spatially explicit or highly regionalized manner to understand region-specific demand potentials for secondary circulated materials (72, 146, 147).

The aspect of spatiality is crucial for waste management planning, accounting for transport implications, and considering the full life cycle of GHG emissions from recycled secondary materials.

Detailed modeling of individual building structures at the subnational, national, and global scales, for example, via BIM, would be required to accurately assess more ambitious circularity strategies (e.g., more efficient design and component reuse instead of recycling), but this currently is challenging on large scales. The modeling of building components (148, 149) in turn could inform these circularity strategies about project-specific smaller scales (79, 150). The integration of spatially explicit, high-resolution building-by-building modeling with large-scale national to global assessments therefore constitutes an important research frontier.

Best-practice biophysical models like RECC primarily model high-potential circularity measures such as more intensive use, lifetime extensions, refurbishment, or recycling via exogenously given changes in model parameters. Thus, they do not answer questions about the (policy) instruments that can incentivize behavioral changes for uptake of these circularity measures. For this, efforts to integrate the biophysical layer with socioeconomic layers such as stakeholders (144), agents (151), and costs (61, 87) are required.

While the field of building sector modeling is rapidly expanding, its biophysically and thermodynamically correct integration into larger-scale macroeconomic modeling or IAMs is still in its infancy (80, 82, 87, 88, 152). Currently, larger system models and IAMs lack consistent representations of material cycles (153, 154).

Overall, more research is needed to assess which level of detail provides the best compromise between the required modeling efforts, data availability, and resulting accuracy, specifically in regard to representation of granular building types, coverage of materials, components, and material quality, yielding more refined insights into reuse and recycling potentials. This would provide important insights into model result uncertainty and future integration into large-scale assessments.

5. MODELING DECENT LIVING STANDARDS

Quality of life, referring to the push for higher living standards, clean local environments, and accessible services and end-use technologies, is a key driver of long-term change in energy demand (12). DLS have been defined as a set of material conditions to support well-being (3), overlapping with many SDGs. Several dimensions of DLS are closely related to buildings and the services they provide, including shelter, thermal comfort, food preparation and storage, water, and sanitation.

The 1948 Universal Declaration of Human Rights already recognized a right to adequate housing for all. More recently, the SDGs included targets on safe and affordable housing (SDG 11) and universal access to critical amenities within a house (SDGs 6 and 7). Access to adequate shelter is an important prerequisite for well-being (3). Important elements of adequate housing that relate to the structure of a habitat include sufficient space, durable housing materials and good structural quality, and security of tenure (155). Approximately 1.26 billion people in emerging nations are estimated to live in inadequate housing, and this number will rise to 3 billion people by 2030 (156). Among the approaches to model access to housing or shelter, demographic variables, such as household formation, or economic variables, including aspects of housing markets and affordability, are typically considered important drivers of changes in housing stocks and flows over time (157–159). Recent studies (160) showed that provision of durable housing for all could result in considerable energy footprints, even if the increase in energy provision for basic decent living does not pose, in itself, a threat to climate change mitigation (160).

The provision of universal access to critical amenities within the house are also considered key aspects of adequate housing. These amenities include sustainable and affordable access to natural and common resources; clean drinking water; energy for cooking, heating, cooling, and lighting; sanitation and washing facilities; food storage facilities; refuse disposal; site drainage; and emergency services. Recent research has assessed populations lacking access to these amenities, as well as global and regional gaps (161–164). Other research has assessed how access to these services might improve, under either baseline scenarios of socioeconomic and demographic change or normative scenarios that aim to provide universal access, and has estimated the associated investments required, as well as the consequent energy and emissions for specific subsets of these services (85, 165–167). Finally, some nascent research has analyzed how access to these basic services might be affected under alternative climate change futures and has estimated the distributional consequences of climate mitigation policies on access to these services (168, 169).

Cooling needs have been drawing attention as an important energy service and adaptation measure to protect people's health from an increasingly warmer climate (170). The global energy use for space cooling is predicted to triple by 2050 (171), with nearly 70% of the increase from the residential sector and the Global South. Recent literature investigated current and future gaps in access to cooling, related energy demand, and vulnerability to thermal discomfort and heat-related health threats using mostly empirically based methods for different regions and globally (172–174). Fewer empirical studies investigated the cooling pattern of households in specific countries (175, 176). More empirical work in different contexts is needed to support improved representation of household preferences and cooling behavior in building sector modeling (177).

A large literature exists on residential cooking fuel transitions in the context of modern energy access in the Global South. Recent studies (178, 179) found that connections to clean cooking fuels such as liquified petroleum gas (LPG) do not translate to sustained use due to issues related to affordability, availability, and other perceived co-benefits and energy services of traditional fuels. In India, 40% of residential energy needs may still be met from solid biomass in 2030 (180), with serious implications for household health and quality of life. Households that have shifted to LPG for cooking might still be using biomass for water heating (181), and in urban areas LPG might still be used even if electric or solar water heaters are available due to issues of reliability and affordability.

Supplemental Material >

Only a few of the surveyed models represent aspects related to DLS (**Supplemental Figure 1**). National models for India (SAFARI and PIER) have detailed representation of access to household energy services, linked to energy and material demands (SAFARI). STURM/CHILLED accounts for access to shelter and to thermal comfort globally via empirically based models. In ACCESS-E-USE, access to appliances and clean cooking, and associated final energy demands, is modeled endogenously using structural econometrics and capturing heterogeneities in households and housing characteristics. More broadly, existing approaches that relate aspects of adequate housing to energy and emissions have been top-down and aggregated, with fewer studies accounting for population and spatial heterogeneities. Thus, less is known about inequalities in access to adequate housing and associated amenities within nations, particularly in the Global South. Furthermore, aspects related to quality of services are less explored. Finally, in addition to energy requirements, the material demands needed to provide these services are not well understood.

6. KEY MODELING GAPS

The analysis of current and emerging building sector modeling practices allowed us to identify key gaps in representing LED transformation, megatrends, and DLS (Sections 3 and 4). Supported by the literature review, survey of model features (**Figure 3**), and expert elicitation process, we discuss four main areas of critical modeling gaps that need to be addressed by future research, based on four key model features (Section 2; **Figure 2**): spatiotemporal resolution and coverage, granularity, model dynamics, and system boundaries.

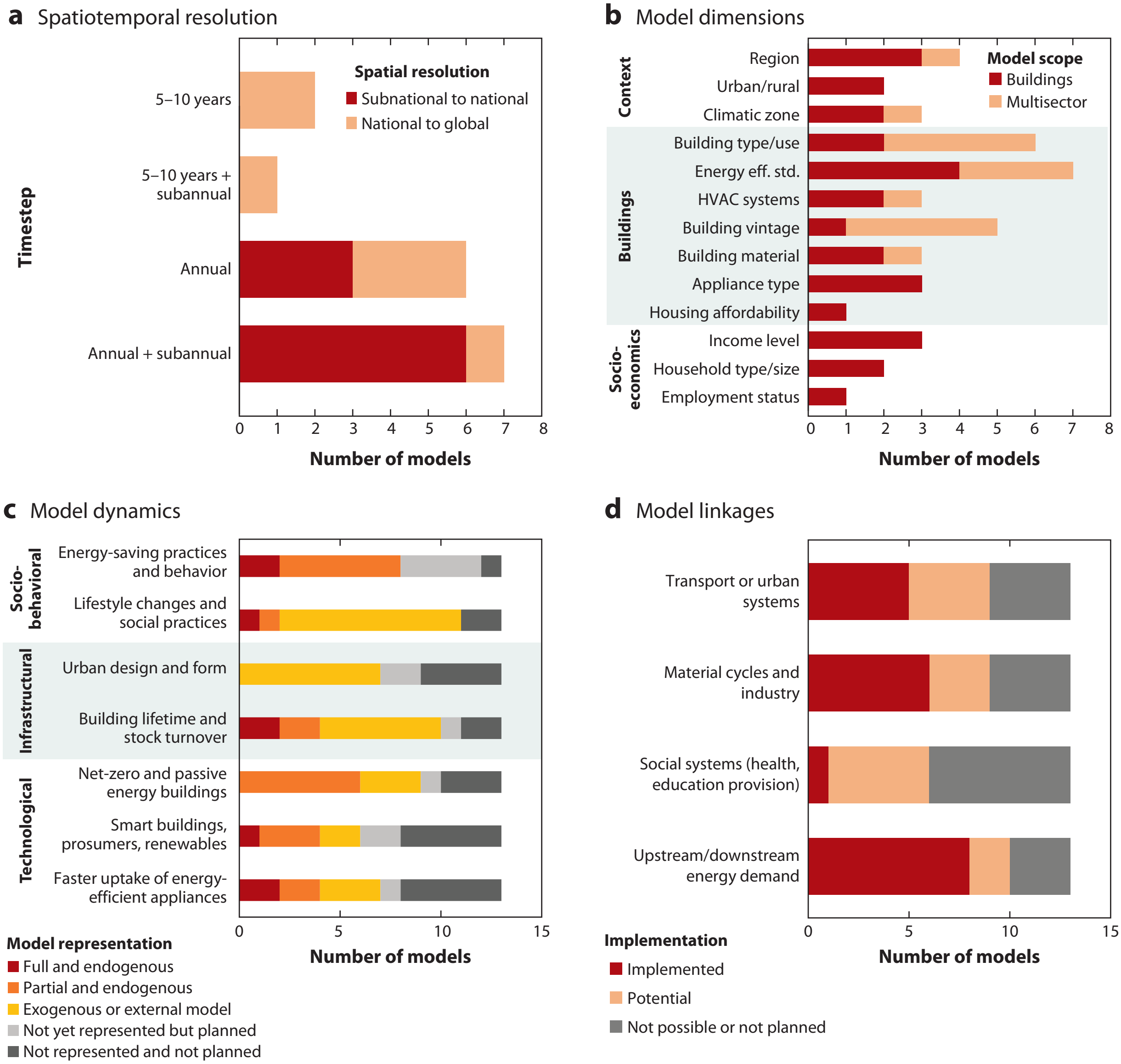


Figure 3

Results from surveyed building sector models. (*a*) Spatiotemporal resolution. (*b*) Model dimensions considered in building sector and multisectoral models. (*c*) Representation of model dynamics related to the three dimensions of low energy demand (LED) transformations. (*d*) Implementation of cross-sectoral linkages. Results in panel *a* are based on 16 survey responses received. Results in panel *b* are based on 11 survey responses available. Results in panels *c* and *d* are based on 13 survey responses received. Data are from our own survey of building sector model features (see Section 1.2 in the **Supplemental Text**). The underlying data are available in Section 2.1 of the **Supplemental Text**. Abbreviations: energy eff. std., energy efficiency standard; HVAC, heating, ventilation, and cooling.

6.1. Spatiotemporal Resolution and Coverage

Spatiotemporal resolution and coverage are important aspects of building sector modeling, influencing the ability of a model to represent LED transformations. Geographical resolution in the surveyed models broadly varies from subnational to national and global (**Table 1**). Models with

Supplemental Material >

global coverage (EDGE-Buildings, HEB, STURM/CHILLED, RECC) often rely on simplified regional or country representation, depending on available input data. More granular spatial resolution is necessary to further represent LED transformation, including changes in urban form and decentralized service provision (Section 3.2), and spatial matching of demand–supply to evaluate the transport implications of circularity measures (Section 4.3). Coarse aggregation could risk masking aspects related to climate variability, available fuels, and economics, with higher uncertainty (16). In terms of geographical coverage, some regions are still not adequately represented in current building sector models. While an increasing number of models focus on developing countries, either from a national (PIER, SAFARI) or global (HEB, ACCESS-E-USE, STURM/CHILLED) perspective, data gaps still represent a challenge for modeling the building sector and its dynamics in the Global South (88), particularly in rural areas, and DLS (Section 5).

Building sector models used for long-term energy demand scenarios at scales larger than national have mostly annual or multi-annual temporal resolution (**Figure 3*a***). Subannual timesteps (5 minutes to hourly) are already used in several subnational and national level models but are less used in larger-scale modeling. Finer temporal resolution is needed to capture seasonal and subdaily variations and to adequately represent LED transformations, including demand–response management and prosumers (Section 3.3) and behavior profiles (Section 3.1). Combining long-term projection of energy demand with finer temporal resolution is challenging due to intensive data and computation requirements and data availability.

6.2. Granularity

The building sector is characterized by large heterogeneity in characteristics of both the building stock and the actors involved in its development and operation. Capturing these dimensions of heterogeneity is critical for representing LED transformations but also challenging due to both data availability and limitations in model granularity.

The potential to represent these heterogeneities is strongly related to modeling approaches, modeling units and granularity, and underlying data structures. Recent model developments have substantially broadened the range of dimensions of heterogeneity that are considered (**Figure 3*b***). Bottom-up engineering approaches typically have more granular representation of building characteristics and technologies, enabling improved representation of heterogeneities in building types, vintage, energy efficiency standards, and technical systems that are essential for assessing technological and infrastructural LED interventions. Other bottom-up approaches, including economic models and ABM, have enhanced socioeconomic granularity, which is necessary to represent different actors of change and household types that are critical for socio-behavioral LED interventions and megatrends. Accounting for combined buildings, technological and socioeconomic heterogeneity is important to further represent distributional aspects key to DLS and other LED megatrends (Sections 4 and 5). Gaps persist in representing the socioeconomic heterogeneities and actors of change (e.g., individuals, households, businesses, governments) and in mapping with infrastructural and technological heterogeneities for improved accounting of dynamics of transformation and effects of policies. Differences also exist between subsectors, with the commercial sector significantly underrepresented compared with the residential sector and often at an aggregated level despite even larger heterogeneities, for example, in building functions, characteristics, and actors of change.

6.3. Model Dynamics

Existing building sector models can already account for some components of LED transformations, captured by a series of model dynamics and variables (**Figure 3*c***). However, model implementations are diverse and often rely on simplified methods or assumptions. Dynamics and variables can be exogenously or endogenously represented depending on the model research questions and assumptions. Regarding socio-behavioral interventions, most of the surveyed models can represent lifestyle changes (Section 3.1), though only partially and using mostly exogenous parameters or via linkage with external models. One key example concerns reduction of building size, where changes are commonly represented via exogenous floorspace projections (Section 3.2) rather than the underlying dynamics. Conversely, energy-saving practices and behavior are covered by a smaller number of models but are mostly endogenously represented. Enhancing the modeling of behavioral aspects could improve the accuracy of modeled energy demands and reduce discrepancies with energy consumption levels observed in the real world (102, 182), especially for low-energy buildings.

Infrastructural changes related to building lifetime and stock turnover (Section 3.2) are largely covered, partly represented by dedicated turnover models, but in most cases are exogenously assumed. Urban form–related infrastructural interventions are covered by a smaller number of building sector models and only exogenously, for instance, by imposing different shares of building types in future scenarios. Most models cover either endogenously or exogenously technological interventions related to energy-efficient new construction and renovations (Section 3.3). However, there is a gap in the coverage of smart buildings and the switch to renewables, as well as technological innovation and business models.

6.4. System Boundaries

LED transformations are not contained in a certain sector, such as buildings, because LED scenarios incorporate restructuring of servicing systems throughout the entire economy, whereas different sectors are integral parts. Thus, it becomes inevitable to understand and model cross-sectoral linkages (**Figure 3*d***), specifically with the energy supply systems, industry, and transportation. Linkages with urban systems and social systems are also key and are further reviewed below. Linking the energy demand-side and supply-side is critical for representing LED transformations. Some of the building sector models in this study have been designed to link with large energy system models. For example, STURM/CHILLED and ACCESS-E-USE are linked with MESSAGEix-GLOBIOM, EDGE-Buildings can be linked with REMIND and WITCH, and UK Household Model is linked with UK TIMES. These linkages respond to the demand for a more detailed representation of demand-side mitigation strategies in the context of IAMs, which traditionally focus more on the supply-side (87).

Assessment of upstream and downstream energy demand and emissions requires improved representation of material cycles and interlinkages with industry (Section 4.3). While building sector models have been focusing largely on the operational energy assessment, an increasing number of models consider material aspects. In particular, bottom-up engineering-based models have been increasingly combined with industrial ecology methods, such as life cycle assessment and material flow analysis, to assess all stages of the building life cycle, stock turnover dynamics, and material aspects (EDGE-Buildings, STURM/CHILLED, SAFARI). Interlinkages with raw material–producing sectors (mining, forestry, agriculture) are also important for LED transformation and insufficiently considered. For instance, substituting standard construction materials with timber or other renewable resources needs to be assessed carefully vis-à-vis mounting pressures on land systems and trade-offs with food, feed, fuel, natural carbon sinks, and biodiversity (137, 183).

Linkage with urban systems has been partially represented via exogenous floorspace and building type projections, relating to different urban forms (Section 3.2). Some multisectoral models already incorporate linkages between buildings and transportation by considering vehicle-to-grid applications (POTEnCIA), common behavior models (TREES), and consistent definitions of demand levels across sectors (SAFARI, RTE model). This is in line with urban-scale energy modeling, assessing new strategies for urban development planning, energy supply–demand, and distribution network stability (184). More fundamental linkages would be required to adequately represent the implications of different urban forms on both building and transportation infrastructure and operation, and associated energy and emission, in a more consistent way.

Finally, a clear gap exists in linking building sector models with social systems, including education and health. Most of the surveyed models, except ABM (BENCH), currently cannot readily represent such aspects. Linkages between building sector models and approaches offering richer details on socio-behavioral dynamics (e.g., ABM) (Section 3.1) are currently limited.

7. CONCLUSIONS

In this article, we reviewed current practices in building sector modeling and contrasted them with the transformations required to achieve LED futures, in consideration of three megatrends (digitalization, the sharing economy, and the circular economy) that will mark the coming decades, and DLS. In an LED future, higher levels of end-use services (such as thermal comfort and mobility) can be provided with at least 40% lower final energy input than today while also reaching climate mitigation and sustainable development targets without relying on large-scale negative emissions. We used literature reviews, model surveys, and expert elicitation to describe the state of the art and to identify best practices and key modeling gaps.

We found that modeling practices significantly vary across different LED transformations. Current building sector models mostly lack appropriate representation of socio-behavioral interventions as effective drivers of future energy conservation opportunities. Infrastructural interventions are often represented with simplified approaches and exogenous projections, while in some cases more detailed industrial ecology methods have been integrated for modeling the stock turnover and life cycle of buildings. Technological interventions are more commonly assessed in current building sector models, yet a shift toward modeling at the energy services level and a revision of how technological development, drivers, and user interactions influence technology are required to assess LED futures. Dynamics related to the three megatrends and DLS are mostly not well integrated because of the complexity compared to current practices and methodologies. Future improvements will require methodological developments and empirical data support to advance modeling beyond exogenous representation of key dynamics.

Key gaps toward modeling LED transformations, megatrends, and DLS include insufficient spatiotemporal resolution and coverage, granularity and heterogeneity, model dynamics, and cross-sectoral linkages. To achieve more robust results, spatially explicit representation and connecting to existing building databases via geo-location are at the cutting edge of recent approaches (79, 81, 185). Recent advances in using remote sensing (186–188), cadastral data (189), and modeling of building components (148) could make building-by-building and spatially explicitly modeling more feasible in the future. Improved data availability is critical for supporting consideration of heterogeneities, including distributional aspects and equitable access to energy. In addition to empirical data, newly available big data, such as social media (190), and machine learning techniques (187) have the potential to greatly improve the representation of building heterogeneity at regional or larger scales and their spatial and temporal resolutions.

More empirical research and availability of microdata are needed to support the endogenous representation of LED transformations, megatrends, and DLS in building sector models, providing improved understanding of the role of different agents as drivers of change in combination with technological innovation and infrastructure evolution, and of the impact of buildings and cross-sectoral policies and regulations, as well as business models. While endogenization allows for representation of the underlying dynamics of specific interventions, it is usually not possible or desirable to fully endogenize all aspects of LED transformations in a single model, nor should it be a modeling aim. Linkages between models can offer an alternative to full endogenization. Linkages of building sector models with the energy supply-side (e.g., via IAMs) were demonstrated by recent studies. As the energy transition advances, it becomes increasingly important to account for the whole life cycle of buildings and appliances, as energy use and impacts shift toward upstream and downstream. Coupling with industrial ecology models is promising to better represent buildings–industry linkages and has been demonstrated in recent work (191). More research is needed to fill current gaps and better assess linkages with industry, urban systems, and social systems. These modeling advancements could provide improved evidence of LED transformations and their impacts to better support decision-making toward climate and sustainability targets.

SUMMARY POINTS

1. Modeling low energy demand (LED) transformations in the building sector is essential to provide evidence for strategies to reduce greenhouse gas emissions in line with climate targets while supporting human activities and well-being.
2. More knowledge and data on social and behavioral interventions, including individual behavioral and lifestyle changes, social energy-saving practices, and participatory governance, are required in LED transformation modeling for the building sector.
3. Infrastructural interventions related to low-carbon building design, urban form and floorspace rationalization, and community-centered strategies are represented mostly with simplified approaches and exogenous projections, often overlooking the underlying dynamics.
4. Demand-side technologies, from energy-efficient appliances to low-energy or passive buildings, became an integral part of building sector modeling; however, a focus on energy services and improved representation of technology development, drivers, and user interactions are needed to properly assess LED futures.
5. Dynamics related to megatrends, including digitalization, the sharing economy, and the circular economy, and decent living standards (DLS) are not yet well understood in relation to building sector modeling.

FUTURE ISSUES

1. Increased availability of datasets on sociodemographics, building characteristics, and energy consumption patterns and behaviors, including spatiotemporally explicit datasets, is necessary for bridging gaps in representing the Global South, rural areas, and nonresidential buildings, enabling appropriate modeling of LED transformations in building sector models.
2. Improved socioeconomic and technological granularity and heterogeneity are critical for adequately modeling LED transformations, megatrends, and DLS, including distributional aspects and equitable access to energy, in building sector models.

3. More empirical research and availability of microdata are needed to support the endogenous representation of LED transformations, megatrends, and DLS in building sector models, providing improved understanding of the role of different agents as drivers of change in combination with technological innovation and infrastructure evolution, and of the impact of policies and regulations.
4. Model interlinkages can support more systemic assessments of LED transformations across the whole life cycle of buildings, bridging across different sectors and dimensions, including energy-supply, industry, transportation, and social systems.

DISCLOSURE STATEMENT

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