

## Modeling Low Energy Demand Futures for Buildings

### Current State and Research Needs

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

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## Keywords

residential and commercial, climate change mitigation, scenarios development, energy demand transformation, megatrends, decent living standards

## 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 .....	763
2. BUILDING SECTOR MODELS .....	766
3. MODELING LOW ENERGY DEMAND TRANSFORMATIONS .....	767
3.1. Socio-Behavioral Intervention .....	768
3.2. Infrastructural Intervention .....	770
3.3. Technological Intervention .....	772
4. MODELING LOW ENERGY DEMAND MEGATRENDS .....	773
4.1. Digitalization .....	773
4.2. Sharing Economy .....	775
4.3. Circular Economy .....	776
5. MODELING DECENT LIVING STANDARDS .....	777
6. KEY MODELING GAPS .....	778
6.1. Spatiotemporal Resolution and Coverage .....	779
6.2. Granularity .....	780
6.3. Model Dynamics .....	780
6.4. System Boundaries .....	781
7. CONCLUSIONS .....	782

## 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).

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<sub>2</sub>e) 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

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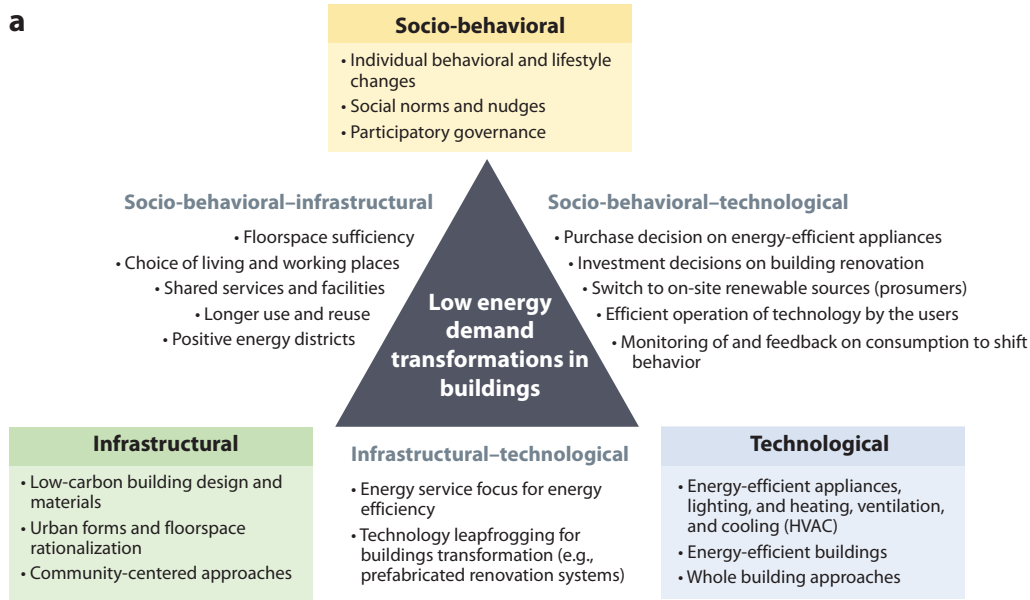
### Demand-side mitigation strategies:

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

---



**b**

**Low energy demand transformations in buildings**

		Socio-behavioral	Infrastructural	Technological
Megatrends	Digitalization	<ul style="list-style-type: none"> <li>• Teleworking</li> <li>• Smart meters</li> <li>• Demand–response</li> </ul>	<ul style="list-style-type: none"> <li>• Virtual community approaches</li> <li>• Building information modeling</li> <li>• 3D printing of buildings</li> </ul>	<ul style="list-style-type: none"> <li>• Smart homes and appliances</li> </ul>
	Sharing economy	<ul style="list-style-type: none"> <li>• Lifestyle changes toward sharing services and facilities</li> </ul>	<ul style="list-style-type: none"> <li>• Co-housing and co-working</li> <li>• Community-based services</li> </ul>	<ul style="list-style-type: none"> <li>• Centralization of equipment</li> <li>• Sharing of appliances</li> </ul>
	Circular economy	<ul style="list-style-type: none"> <li>• Circular practices and changes in behaviors</li> <li>• Longer use and reuse of appliances and facilities</li> </ul>	<ul style="list-style-type: none"> <li>• Low-carbon design and materials</li> <li>• Longer use, reuse, and repurposing of buildings</li> </ul>	<ul style="list-style-type: none"> <li>• Low-carbon materials and building systems</li> <li>• Lifetime extension</li> </ul>
Well-being support	Decent living standards	<ul style="list-style-type: none"> <li>• Sufficient housing floorspace</li> <li>• Adoption of clean technologies</li> </ul>	<ul style="list-style-type: none"> <li>• Access to adequate housing</li> </ul>	<ul style="list-style-type: none"> <li>• Access to clean and affordable technologies</li> <li>• Leapfrogging in provision of durable housing</li> </ul>

**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 1a): socio-behavioral, infrastructural, and technological interventions. In addition, we investigate three cross-cutting megatrends playing a key role as enablers of LED transformations (Figure 1b)—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,<sup>1</sup> 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

**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
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.

<sup>1</sup>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 2a**).

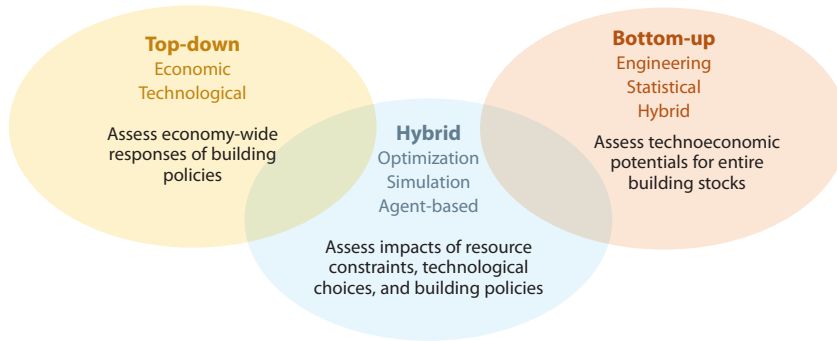
Top-down models represent the building sector at the aggregated level and are either economic or technological. They are used mostly to assess economy-wide policy responses (19) and are often limited in their ability to represent the impact of new technologies and disruptive changes, as they lack granularity (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).

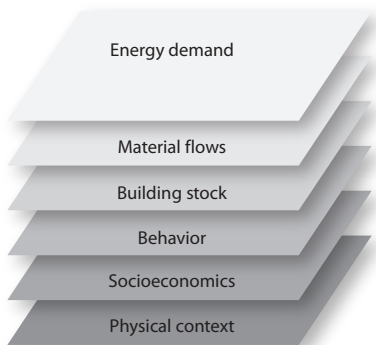
While most building sector models focus on energy demand, additional layers can support the representation of key determinants and dynamics (13), including physical context and climate, socioeconomics, stock turnover, and material flows, as well as behavior and practices (**Figure 2b**). Additionally, we identify four model features (**Figure 2c**) 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 2d**) 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.



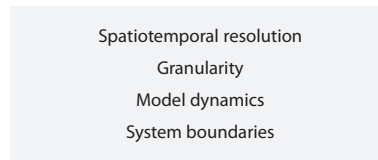
## a Building sector modeling traditions



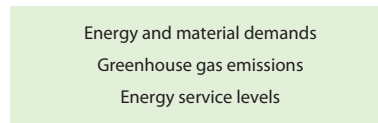
## b Model layers



## c Model characteristics



## d Model outputs



**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.

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).

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 1b**). 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.

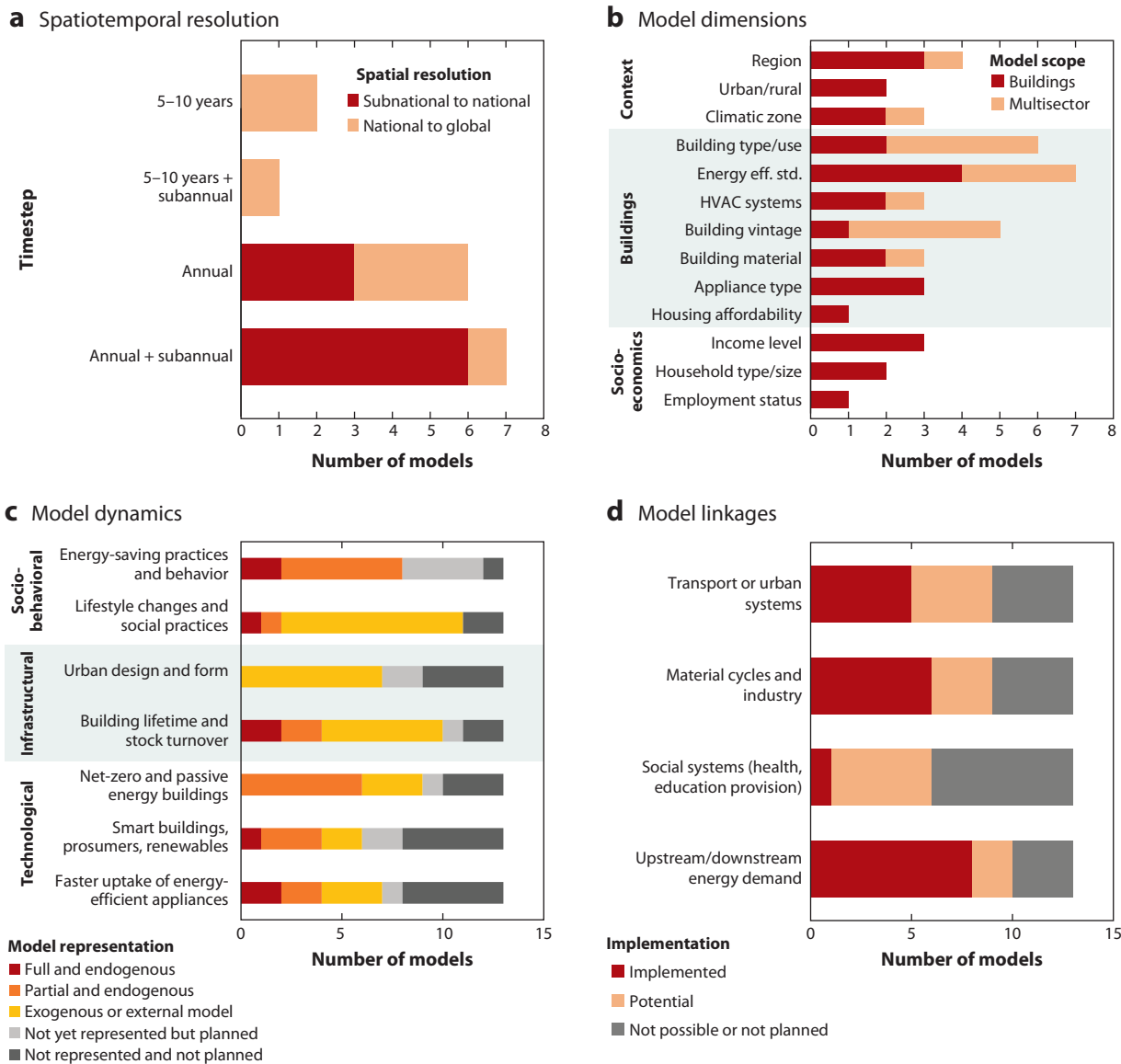
## 5. MODELING DECENT LIVING STANDARDS

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





**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 3a**). 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 sub-daily 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 3b**). 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 3c**). 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 3d), 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

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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## LITERATURE CITED

1. Fell MJ. 2017. Energy services: a conceptual review. *Energy Res. Soc. Sci.* 27:129–40
2. Kalt G, Wiedenhofer D, Görg C, Haberl H. 2019. Conceptualizing energy services: a review of energy and well-being along the Energy Service Cascade. *Energy Res. Soc. Sci.* 53:47–58
3. Rao ND, Min J. 2017. Decent living standards: material prerequisites for human wellbeing. *Soc. Indic. Res.* 138(1):225–44
4. Rao ND, Wilson C. 2021. Advancing energy and well-being research. *Nat. Sustain.* 5(2):98–103
5. Cabeza LF, Bai Q, Bertoldi P, Kihila J, Lucena AFP, et al. 2022. Buildings. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. PR Shukla, J Skea, R Slade, A Al Khouradajie, R van Diemen, et al. Cambridge, UK: Cambridge Univ. Press
6. IEA (Int. Energy Agency). 2019. *Global status report for buildings and construction 2019: towards a zero-emission, efficient and resilient buildings and construction sector*. Paris: IEA. <https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019>
7. UN Gen. Assem. 2015. *Transforming our world: the 2030 Agenda for Sustainable Development*, Oct. 21. UN Doc. A/RES/70/1. UN Gen. Assem., New York, NY. [https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A\\_RES\\_70\\_1\\_E.pdf](https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf)
8. Scrucca F, Ingrao C, Barberio G, Matarazzo A, Lagioia G. 2023. On the role of sustainable buildings in achieving the 2030 UN Sustainable Development Goals. *Environ. Impact Assess. Rev.* 100:107069
9. Creutzig F, Roy J, Devine-Wright P, Díaz-José J, Geels FW, et al. 2022. Demand, services and social aspects of mitigation. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group*

- III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. PR Shukla, J Skea, R Slade, A Al Khourdajie, R van Diemen, et al. Cambridge, UK: Cambridge Univ. Press
10. Creutzig F, Niamir L, Bai X, Callaghan M, Cullen J, et al. 2022. Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat. Clim. Change* 12(1):36–46
  11. Patt A, van Vliet O, Lilliestam J, Pfenninger S. 2019. Will policies to promote energy efficiency help or hinder achieving a 1.5°C climate target? *Energy Effic.* 12(2):551–65
  12. Grubler A, Wilson C, Bento N, Boza-Kiss B, Krey V, et al. 2018. A low energy demand scenario for meeting the 1.5°C target and Sustainable Development Goals without negative emission technologies. *Nat. Energy* 3:515–27
  13. Langevin J, Reyna JL, Ebrahimiagharehbaghi S, Sandberg N, Fennell P, et al. 2020. Developing a common approach for classifying building stock energy models. *Renew. Sustain. Energy Rev.* 133:110276
  14. Molnár G, Ürge-Vorsatz D, Chatterjee S. 2022. Estimating the global technical potential of building-integrated solar energy production using a high-resolution geospatial model. *J. Clean. Prod.* 375:134133
  15. Swan LG, Ugursal VI. 2009. Modeling of end-use energy consumption in the residential sector: a review of modeling techniques. *Renew. Sustain. Energy Rev.* 13(8):1819–35
  16. Chatterjee S, Stavarakas V, Oreggioni G, Süsler D, Staffell I, et al. 2022. Existing tools, user needs and required model adjustments for energy demand modelling of a carbon-neutral Europe. *Energy Res. Soc. Sci.* 90:102662
  17. Mahler AG. 2017. *Global South*. Oxford, UK: Oxford Univ. Press
  18. Hayward B, Roy J. 2019. Sustainable living: bridging the North-South divide in lifestyles and consumption debates. *Annu. Rev. Environ. Resour.* 44:157–75
  19. IPCC (Intergov. Panel Clim. Change). 2022. Annex III: scenarios and modelling methods. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. PR Shukla, J Skea, R Slade, A Al Khourdajie, R van Diemen, et al. Cambridge, UK: Cambridge Univ. Press
  20. Niamir L, Ivanova O, Filatova T. 2020. Economy-wide impacts of behavioral climate change mitigation: linking agent-based and computable general equilibrium models. *Environ. Model. Softw.* 134:104839
  21. Anderson K, Peters G. 2016. The trouble with negative emissions. *Science* 354(6309):182–83
  22. Di Giulio A, Fuchs D. 2014. Sustainable consumption corridors: concept, objections, and responses. *GALA Ecol. Perspect. Sci. Soc.* 23(3):184–92
  23. Burke MJ. 2020. Energy-sufficiency for a just transition: a systematic review. *Energies* 13(10):2444
  24. Lorek S, Spangenberg JH. 2019. Energy sufficiency through social innovation in housing. *Energy Policy* 126:287–94
  25. Leach M, Raworth K, Rockström J. 2013. Between social and planetary boundaries: navigating pathways in the safe and just space for humanity. In *World Social Science Report, 2013: Changing Global Environments*, pp. 84–89. Paris: UNESCO Publ.
  26. O'Neill DW, Fanning AL, Lamb WF, Steinberger JK. 2018. A good life for all within planetary boundaries. *Nat. Sustain.* 1(2):88–95
  27. Gilg A, Barr S, Ford N. 2005. Green consumption or sustainable lifestyles? Identifying the sustainable consumer. *Futures* 37(6):481–504
  28. Niamir L, Kiesewetter G, Wagner F, Schöpp W, Filatova T, et al. 2020. Assessing the macroeconomic impacts of individual behavioral changes on carbon emissions. *Clim. Change* 158(2):141–60
  29. Nyborg K, Anderies JM, Dannenberg A, Lindahl T, Schill C, et al. 2016. Social norms as solutions. *Science* 354(6308):42–43
  30. Cialdini RB. 2006. *Influence: The Psychology of Persuasion*. New York: Harper Collins
  31. Henry ML, Ferraro PJ, Kontoleon A. 2019. The behavioural effect of electronic home energy reports: evidence from a randomised field trial in the United States. *Energy Policy* 132:1256–61
  32. Jachimowicz JM, Hauser OP, O'Brien JD, Sherman E, Galinsky AD. 2018. The critical role of second-order normative beliefs in predicting energy conservation. *Nat. Hum. Behav.* 2(10):757–64
  33. Ito K, Ida T, Tanaka M. 2018. Moral suasion and economic incentives: field experimental evidence from energy demand. *Am. Econ. J. Econ. Policy* 10(1):240–67
  34. Karlin B, Zinger JF, Ford R. 2015. The effects of feedback on energy conservation: a meta-analysis. *Psychol. Bull.* 141:1205–27

35. Marangoni G, Tavoni M. 2021. Real-time feedback on electricity consumption: evidence from a field experiment in Italy. *Energy Effic.* 14(1):13
36. McKerracher C, Torriti J. 2013. Energy consumption feedback in perspective: integrating Australian data to meta-analyses on in-home displays. *Energy Effic.* 6(2):387–405
37. Szalek BZ. 2013. Some praxiological reflections on the so-called ‘Overton window of political possibilities’, ‘framing’ and related problems. *Real. Politics* 4:237–57
38. Schubert C. 2017. Green nudges: Do they work? Are they ethical? *Ecol. Econ.* 132:329–42
39. Thaler RH, Sunstein CR. 2009. *Nudge: Improving Decisions About Health, Wealth, and Happiness*. New York: Penguin Press
40. Ebeling F, Lotz S. 2015. Domestic uptake of green energy promoted by opt-out tariffs. *Nat. Clim. Change* 5(9):868–71
41. Janda KB, Parag Y. 2013. A middle-out approach for improving energy performance in buildings. *Build. Res. Inform.* 41(1):39–50
42. Hicks J, Ison N. 2018. An exploration of the boundaries of ‘community’ in community renewable energy projects: navigating between motivations and context. *Energy Policy* 113:523–34
43. Murakami S, Levine MD, Yoshino H, Inoue T, Ikaga T, et al. 2009. Overview of energy consumption and GHG mitigation technologies in the building sector of Japan. *Energy Effic.* 2(2):179–94
44. Hearn AX. 2022. Positive energy district stakeholder perceptions and measures for energy vulnerability mitigation. *Appl. Energy* 322:119477
45. Beckage B, Lacasse K, Winter JM, Gross LJ, Fefferman N, et al. 2020. The Earth has humans, so why don’t our climate models? *Clim. Change* 163(1):181–88
46. Farmer JD, Hepburn C, Mealy P, Teytelboym A. 2015. A Third Wave in the economics of climate change. *Environ. Resour. Econ.* 62(2):329–57
47. Krumm A, Süsler D, Blechinger P. 2022. Modelling social aspects of the energy transition: What is the current representation of social factors in energy models? *Energy* 239:121706
48. Stern N. 2016. Economics: Current climate models are grossly misleading. *Nature* 530(7591):407–9
49. Niamir L, Filatova T, Voinov A, Bressers H. 2018. Transition to low-carbon economy: assessing cumulative impacts of individual behavioral changes. *Energy Policy* 118:325–45
50. Jager W. 2021. Using agent-based modelling to explore behavioural dynamics affecting our climate. *Curr. Opin. Psychol.* 42:133–39
51. Moglia M, Podkalicka A, McGregor J. 2018. An agent-based model of residential energy efficiency adoption. *J. Artif. Soc. Soc. Simul.* 21(3):3
52. Rai V, Henry AD. 2016. Agent-based modelling of consumer energy choices. *Nat. Clim. Change* 6(6):556–62
53. Savin I, Creutzig F, Filatova T, Foramitti J, Konc T, et al. 2023. Agent-based modelling to integrate elements from different disciplines for ambitious climate policy. *WIREs Clim. Change* 14(2):e811
54. Kiesling E, Günther M, Stummer C, Wakolbinger LM. 2012. Agent-based simulation of innovation diffusion: a review. *Cent. Eur. J. Oper. Res.* 20(2):183–230
55. Gaspard A, Chateau L, Laruelle C, Lafitte B, Léonardon P, et al. 2023. Introducing sufficiency in the building sector in net-zero scenarios for France. *Energy Build.* 278:112590
56. Niamir L, Ivanova O, Filatova T, Voinov A, Bressers H. 2020. Demand-side solutions for climate mitigation: bottom-up drivers of household energy behavior change in the Netherlands and Spain. *Energy Res. Soc. Sci.* 62:101356
57. Creutzig F, Agoston P, Minx JC, Canadell JG, Andrew RM, et al. 2016. Urban infrastructure choices structure climate solutions. *Nat. Clim. Change* 6(12):1054–56
58. Lanau M, Liu G, Kral U, Wiedenhofer D, Keijzer E, et al. 2019. Taking stock of built environment stock studies: progress and prospects. *Environ. Sci. Technol.* 53(15):8499–515
59. Churkina G, Organschi A, Reyer CPO, Ruff A, Vinke K, et al. 2020. Buildings as a global carbon sink. *Nat. Sustain.* 3(4):269–76
60. Cabrera Serrenho A, Drewniok M, Dunant C, Allwood JM. 2019. Testing the greenhouse gas emissions reduction potential of alternative strategies for the English housing stock. *Resour. Conserv. Recycl.* 144:267–75

61. Gregory J, AzariJafari H, Vahidi E, Guo F, Ulm F-J, Kirchain R. 2021. The role of concrete in life cycle greenhouse gas emissions of US buildings and pavements. *PNAS* 118(37):e2021936118
62. Pauliuk S, Heeren N, Berrill P, Fishman T, Nistad A, et al. 2021. Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nat. Commun.* 12(1):5097
63. Yang X, Hu M, Tukker A, Zhang C, Huo T, Steubing B. 2022. A bottom-up dynamic building stock model for residential energy transition: a case study for the Netherlands. *Appl. Energy* 306:118060
64. Zhong X, Hu M, Deetman S, Steubing B, Lin HX, et al. 2021. Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. *Nat. Commun.* 12(1):6126
65. Mishra A, Humpenöder F, Churkina G, Reyer CPO, Beier F, et al. 2022. Land use change and carbon emissions of a transformation to timber cities. *Nat. Commun.* 13(1):4889
66. Erb K, Haberl H, Le Noë J, Tappeiner U, Tasser E, Gingrich S. 2022. Changes in perspective needed to forge ‘no-regret’ forest-based climate change mitigation strategies. *Glob. Change Biol. Bioenergy* 14(3):246–57
67. Li VC. 2019. *Engineered Cementitious Composites (ECC): Bendable Concrete for Sustainable and Resilient Infrastructure*. Berlin: Springer
68. Henrion L, Zhang D, Li V, Sick V. 2021. Built infrastructure renewal and climate change mitigation can both find solutions in CO<sub>2</sub>. *Front. Sustain.* 2:733133
69. Pessoa S, Guimarães AS, Lucas SS, Simões N. 2021. 3D printing in the construction industry - a systematic review of the thermal performance in buildings. *Renew. Sustain. Energy Rev.* 141:110794
70. Sakin M, Kiroglu YC. 2017. 3D printing of buildings: construction of the sustainable houses of the future by BIM. *Energy Procedia* 134:702–11
71. Levesque A, Pietzcker RC, Luderer G. 2019. Halving energy demand from buildings: the impact of low consumption practices. *Technol. Forecast. Soc. Change* 146:253–66
72. Berrill P, Hertwich EG. 2021. Material flows and GHG emissions from housing stock evolution in US counties, 2020–60. *Build. Cities* 2(1):599–617
73. Privitera R, Evola G, La Rosa D, Costanzo V. 2021. Green infrastructure to reduce the energy demand of cities. In *Urban Microclimate Modelling for Comfort and Energy Studies*, ed. M Palme, A Salvati, pp. 485–503. Cham, Switz.: Springer
74. Vadovics E, Boza-Kiss B. 2013. Voluntary consumption reduction - experience from three consecutive residential programmes in Hungary. Residential energy master as a new carrier? In *Bridging Across Communities and Cultures Towards Sustainable Consumption. SCORAI Europe Workshop Proceedings*, ed. J Backhaus, S Lorek, pp. 53–72. Istanbul: SCORAI. <https://d-nb.info/1079506993/34>
75. Sahakian M, Rau H, Grealis E, Godin L, Wallenborn G, et al. 2021. Challenging social norms to recraft practices: a living lab approach to reducing household energy use in eight European countries. *Energy Res. Soc. Sci.* 72:101881
76. Elgamal AH, Vahdati M, Shahrestani M. 2022. Assessing the economic and energy efficiency for multi-energy virtual power plants in regulated markets: a case study in Egypt. *Sustain. Cities Soc.* 83:103968
77. Boza-Kiss B, Bertoldi P, Della Valle N, Economidou M. 2021. *One-stop shops for residential building energy renovation in the EU*. EUR 30762 EN, Publ. Off. Eur. Union, Luxembourg. <https://publications.jrc.ec.europa.eu/repository/handle/JRC125380>
78. Pauliuk S, Heeren N. 2021. Material efficiency and its contribution to climate change mitigation in Germany: a deep decarbonization scenario analysis until 2060. *J. Ind. Ecol.* 25(2):479–93
79. Heeren N, Hellweg S. 2019. Tracking construction material over space and time: prospective and georeferenced modeling of building stocks and construction material flows. *J. Ind. Ecol.* 23(1):253–67
80. Deetman S, Marinova S, van der Voet E, van Vuuren DP, Edelenbosch O, Heijungs R. 2020. Modelling global material stocks and flows for residential and service sector buildings towards 2050. *J. Clean. Prod.* 245:118658
81. Haberl H, Wiedenhofer D, Schug F, Frantz D, Virág D, et al. 2021. High-resolution maps of material stocks in buildings and infrastructures in Austria and Germany. *Environ. Sci. Technol.* 55(5):3368–79
82. Marinova S, Deetman S, van der Voet E, Daioglou V. 2020. Global construction materials database and stock analysis of residential buildings between 1970–2050. *J. Clean. Prod.* 247:119146

83. Güneralp B, Zhou Y, Ürge-Vorsatz D, Gupta M, Yu S, et al. 2017. Global scenarios of urban density and its impacts on building energy use through 2050. *PNAS* 114(34):8945–50
84. Fishman T, Heeren N, Pauliuk S, Berrill P, Tu Q, et al. 2021. A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modeling. *J. Ind. Ecol.* 25(2):305–20
85. Millward-Hopkins J, Steinberger JK, Rao ND, Oswald Y. 2020. Providing decent living with minimum energy: a global scenario. *Glob. Environ. Change* 65:102168
86. Karlen C, Pagani A, Binder CR. 2022. Obstacles and opportunities for reducing dwelling size to shrink the environmental footprint of housing: tenants' residential preferences and housing choice. *J. Hous. Built Environ.* 37(3):1367–408
87. Edelenbosch O, Rovelli D, Levesque A, Marangoni G, Tavoni M. 2021. Long term, cross-country effects of buildings insulation policies. *Technol. Forecast. Soc. Change* 170:120887
88. Mastrucci A, van Ruijven B, Byers E, Pobleto-Cazenave M, Pachauri S. 2021. Global scenarios of residential heating and cooling energy demand and CO<sub>2</sub> emissions. *Clim. Change* 168(3–4):14
89. Grübler A. 1998. *Technology and Global Change*. Cambridge, UK: Cambridge Univ. Press
90. IEA (Int. Energy Agency). 2017. *Energy Technology Perspectives 2017 - Catalysing Energy Technology Transformations*. Paris: OECD/IEA. [https://iea.blob.core.windows.net/assets/a65879f-e56c-4b1d-96e4-5a4da78f12fa/Energy\\_Technology\\_Perspectives\\_2017-PDF.pdf](https://iea.blob.core.windows.net/assets/a65879f-e56c-4b1d-96e4-5a4da78f12fa/Energy_Technology_Perspectives_2017-PDF.pdf)
91. Zissis G, Bertoldi P, Ribeiro Serrenho T. 2021. *Update on the Status of LED-Lighting World Market Since 2018*. Luxembourg: Publ. Off. Eur. Union
92. Tetri E, Sarvaranta A, Syri S. 2014. Potential of new lighting technologies in reducing household lighting energy use and CO<sub>2</sub> emissions in Finland. *Energy Effic.* 7(4):559–70
93. Alborzi F, Schmitz A, Stamminger R. 2017. Consumers' comprehension of the EU energy label for washing machines. *Tenside Surfactants Deterg.* 54(4):280–90
94. Boyano A, Espinosa N, Villanueva A. 2017. *Follow-up of the preparatory study for Ecodesign and Energy Label for household washing machines and household washer dryers*. Tech. Rep. EUR 28807 EN, Eur. Comm., Joint Res. Cent., Ispra, Italy
95. Brockway PE, Sorrell S, Semieniuk G, Heun MK, Court V. 2021. Energy efficiency and economy-wide rebound effects: a review of the evidence and its implications. *Renew. Sustain. Energy Rev.* 141:110781
96. Slorach PC, Stamford L. 2021. Net zero in the heating sector: technological options and environmental sustainability from now to 2050. *Energy Convers. Manag.* 230:113838
97. Shimoda Y, Taniguchi-Matsuoka A, Inoue T, Otsuki M, Yamaguchi Y. 2017. Residential energy end-use model as evaluation tool for residential micro-generation. *Appl. Thermal Eng.* 114:1433–42
98. Milcarek RJ, Ahn J, Zhang J. 2017. Review and analysis of fuel cell-based, micro-cogeneration for residential applications: current state and future opportunities. *Sci. Technol. Built Environ.* 23(8):1224–43
99. Sadineni SB, Madala S, Boehm RF. 2011. Passive building energy savings: a review of building envelope components. *Renew. Sustain. Energy Rev.* 15(8):3617–31
100. Manzano-Agugliaro F, Montoya FG, Sabio-Ortega A, García-Cruz A. 2015. Review of bioclimatic architecture strategies for achieving thermal comfort. *Renew. Sustain. Energy Rev.* 49:736–55
101. Dequaire X. 2012. Passivhaus as a low-energy building standard: contribution to a typology. *Energy Effic.* 5(3):377–91
102. Ürge-Vorsatz D, Khosla R, Bernhardt R, Chan YC, Vérez D, et al. 2020. Advances toward a net-zero global building sector. *Annu. Rev. Environ. Resour.* 45:227–69
103. Brown D, Kivimaa P, Sorrell S. 2019. An energy leap? Business model innovation and intermediation in the 'Energiesprong' retrofit initiative. *Energy Res. Soc. Sci.* 58:101253
104. Mata É, Korpál AK, Cheng SH, Jiménez Navarro JP, Filippidou F, et al. 2020. A map of roadmaps for zero and low energy and carbon buildings worldwide. *Environ. Res. Lett.* 15(11):113003
105. Gaur A, Balyk O, Glynn J, Curtis J, Daly H. 2022. Low energy demand scenario for feasible deep decarbonisation: whole energy systems modelling for Ireland. *Renew. Sustain. Energy Transit.* 2:100024
106. Nemet G, Greene J. 2022. Innovation in low-energy demand and its implications for policy. *Oxf. Open Energy* 1:oiac003
107. Wilson C, Grubler A, Bento N, Healey S, De Stercke S, Zimm C. 2020. Granular technologies to accelerate decarbonization. *Science* 368(6486):36–39



108. Saunders HD, Roy J, Azevedo IML, Chakravarty D, Dasgupta S, et al. 2021. Energy efficiency: What has research delivered in the last 40 years? *Annu. Rev. Environ. Resour.* 46:135–65
109. Giraudet L-G, Guivarch C, Quirion P. 2012. Exploring the potential for energy conservation in French households through hybrid modeling. *Energy Econ.* 34(2):426–45
110. WBGU. 2019. *German Advisory Council on Global Change (2019): Towards Our Common Digital Future*. Berlin: WBGU. [https://www.wbgu.de/fileadmin/user\\_upload/wbgu/publikationen/hauptgutachten/hg2019/pdf/WBGU\\_HGD2019\\_S.pdf](https://www.wbgu.de/fileadmin/user_upload/wbgu/publikationen/hauptgutachten/hg2019/pdf/WBGU_HGD2019_S.pdf)
111. Kelly K. 2016. *The Inevitable: Understanding the 12 Technological Forces that Will Shape Our Future*. New York: Viking
112. Creutzig F, Acemoglu D, Bai X, Edwards PN, Hintz MJ, et al. 2022. Digitalization and the Anthropocene. *Annu. Rev. Environ. Resour.* 47:479–509
113. Wilson C, Kerr L, Sprei F, Vrain E, Wilson M. 2020. Potential climate benefits of digital consumer innovations. *Annu. Rev. Environ. Resour.* 45:113–44
114. Royal Society. 2020. *Digital Technology and the Planet: Harnessing Computing to Achieve Net Zero*. London: Royal Society
115. Hook A, Court V, Sovacool BK, Sorrell S. 2020. A systematic review of the energy and climate impacts of teleworking. *Environ. Res. Lett.* 15(9):093003
116. Larson W, Zhao W. 2017. Telework: urban form, energy consumption, and greenhouse gas implications. *Econ. Inq.* 55(2):714–35
117. O'Brien W, Yazdani Aliabadi F. 2020. Does telecommuting save energy? A critical review of quantitative studies and their research methods. *Energy Build.* 225:110298
118. Shimoda Y, Yamaguchi Y, Kawamoto K, Ueshige J, Iwai Y, Mizuno M. 2007. *Effect of telecommuting on energy consumption in residential and non-residential sectors*. Presented at the 10th Conference of the International Building Performance Simulation Association, Beijing, July 27–30. [http://www.ibpsa.org/proceedings/bs2007/p653\\_final.pdf](http://www.ibpsa.org/proceedings/bs2007/p653_final.pdf)
119. Hargreaves T, Wilson C. 2017. *Smart Homes and Their Users*. Cham, Switz.: Springer
120. Al-Obaidi KM, Hossain M, Alduais NAM, Al-Duais HS, Omrany H, Ghaffarianhoseini A. 2022. A review of using IoT for energy efficient buildings and cities: a built environment perspective. *Energies* 15(16):5991
121. Yang H, Lee W, Lee H. 2018. IoT smart home adoption: the importance of proper level automation. *J. Sens.* 2018:1–11
122. Brown D, Hall S, Davis ME. 2019. Prosumers in the post subsidy era: an exploration of new prosumer business models in the UK. *Energy Policy* 135:110984
123. Park E, Kim S, Kim Y, Kwon SJ. 2018. Smart home services as the next mainstream of the ICT industry: determinants of the adoption of smart home services. *Univ. Access Inf. Soc.* 17(1):175–90
124. Galperova E, Mazurova O. 2019. Digitalization and energy consumption. In *Proceedings of the VIth International Workshop 'Critical Infrastructures: Contingency Management, Intelligent, Agent-Based, Cloud Computing and Cyber Security' (IWCI 2019)*. Berlin: Springer Nature
125. Frenken K. 2017. Political economies and environmental futures for the sharing economy. *Philos. Trans. R. Soc. A* 375(2095):20160367
126. Pouri MJ. 2021. Eight impacts of the digital sharing economy on resource consumption. *Resour. Conserv. Recycl.* 168:105434
127. Zhang Z, Fu RJC. 2020. Accommodation experience in the sharing economy: a comparative study of Airbnb online reviews. *Sustainability* 12(24):10500
128. Fremstad A, Underwood A, Zahran S. 2018. The environmental impact of sharing: household and urban economies in CO<sub>2</sub> emissions. *Ecol. Econ.* 145:137–47
129. Ivanova D, Barrett J, Wiedenhofer D, Macura B, Callaghan M, Creutzig F. 2020. Quantifying the potential for climate change mitigation of consumption options. *Environ. Res. Lett.* 15(9):093001
130. Wiedenhofer D, Smetschka B, Akenji L, Jalas M, Haberl H. 2018. Household time use, carbon footprints, and urban form: a review of the potential contributions of everyday living to the 1.5°C climate target. *Curr. Opin. Environ. Sustain.* 30:7–17
131. Ivanova D, Büchs M. 2020. Household sharing for carbon and energy reductions: the case of EU countries. *Energies* 13(8):1909

132. Klint E, Peters G. 2021. Sharing is caring - the importance of capital goods when assessing environmental impacts from private and shared laundry systems in Sweden. *Int. J. Life Cycle Assess.* 26(6):1085-99
133. Gill B, Moeller S. 2018. GHG emissions and the rural-urban divide. A carbon footprint analysis based on the German Official Income and Expenditure Survey. *Ecol. Econ.* 145:160-69
134. Poom A, Ahas R. 2016. How does the environmental load of household consumption depend on residential location? *Sustainability* 8(9):799
135. Ghisellini P, Cialani C, Ulgiati S. 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114:11-32
136. Hossain MdU, Ng ST, Antwi-Afari P, Amor B. 2020. Circular economy and the construction industry: existing trends, challenges and prospective framework for sustainable construction. *Renew. Sustain. Energy Rev.* 130:109948
137. Haas W, Krausmann F, Wiedenhofer D, Lauk C, Mayer A. 2020. Spaceship earth's odyssey to a circular economy - a century long perspective. *Resour. Conserv. Recycl.* 163:105076
138. Korhonen J, Honkasalo A, Seppälä J. 2018. Circular economy: the concept and its limitations. *Ecol. Econ.* 143:37-46
139. Cullen JM. 2017. Circular economy: theoretical benchmark or perpetual motion machine? *J. Ind. Ecol.* 21(3):483-86
140. Ghisellini P, Ripa M, Ulgiati S. 2018. Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *J. Clean. Prod.* 178:618-43
141. Pauliuk S. 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resour. Conserv. Recycl.* 129:81-92
142. Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, et al. 2020. Embodied GHG emissions of buildings - the hidden challenge for effective climate change mitigation. *Appl. Energy* 258:114107
143. Hertwich EG. 2021. Increased carbon footprint of materials production driven by rise in investments. *Nat. Geosci.* 14(3):151-55
144. Volk R, Müller R, Reinhardt J, Schultmann F. 2019. An integrated material flows, stakeholders and policies approach to identify and exploit regional resource potentials. *Ecol. Econ.* 161:292-320
145. Cao Z, Liu G, Zhong S, Dai H, Pauliuk S. 2019. Integrating dynamic material flow analysis and computable general equilibrium models for both mass and monetary balances in prospective modeling: a case for the Chinese building sector. *Environ. Sci. Technol.* 53(1):224-33
146. Schiller G, Gruhler K, Ortlepp R. 2017. Quantification of anthropogenic metabolism using spatially differentiated continuous MFA. *Change Adapt. Socio-Ecol. Syst.* 3:119-32
147. Tanikawa H, Fishman T, Okuoka K, Sugimoto K. 2015. The weight of society over time and space: a comprehensive account of the construction material stock of Japan, 1945-2010: the construction material stock of Japan. *J. Ind. Ecol.* 19(5):778-91
148. Ajayebi A, Hopkinson P, Zhou K, Lam D, Chen H-M, Wang Y. 2020. Spatiotemporal model to quantify stocks of building structural products for a prospective circular economy. *Resour. Conserv. Recycl.* 162:105026
149. Arora M, Raspall F, Cheah L, Silva A. 2020. Buildings and the circular economy: estimating urban mining, recovery and reuse potential of building components. *Resour. Conserv. Recycl.* 154:104581
150. Buffat R, Froemelt A, Heeren N, Raubal M, Hellweg S. 2017. Big data GIS analysis for novel approaches in building stock modelling. *Appl. Energy* 208:277-90
151. Knöri C. 2015. *Agent-based modelling of transitions towards sustainable construction material management: the case of Switzerland*. PhD Diss., Univ. Zürich
152. Daioglou V, Mikropoulos E, Gernaat D, van Vuuren DP. 2022. Efficiency improvement and technology choice for energy and emission reductions of the residential sector. *Energy* 243:122994
153. Pauliuk S, Arvesen A, Stadler K, Hertwich EG. 2017. Industrial ecology in integrated assessment models. *Nat. Clim. Change* 7(1):13-20

154. Hertwich EG, Ali S, Ciacci L, Fishman T, Heeren N, et al. 2019. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. *Environ. Res. Lett.* 14(4):043004
155. UN Habitat. 2014. *The right to adequate housing*. Fact Sheet 21/Rev.1 Nairobi: UN-Habitat
156. Behr DM, Chen L, Goel A, Haider KT, Singh S, Zaman A. 2021. *Introducing the Adequate Housing Index : a new approach to estimate the adequate housing deficit within and across emerging economies*. Policy Res. Work. Pap. 9830, World Bank, Washington, DC
157. Berto R, Cechet G, Stival CA, Rosato P. 2020. Affordable housing versus urban land rent in widespread settlement areas. *Sustainability* 12(8):3129
158. Courmède B, Ziemann V, De Pace F. 2020. *The future of housing: policy scenarios*. OECD Econ. Dep. Work. Pap. 1624, OECD Publ., Paris
159. Mete S, Xue J. 2021. Integrating environmental sustainability and social justice in housing development: two contrasting scenarios. *Prog. Plann.* 151:100504
160. Kikstra JS, Mastrucci A, Min J, Riahi K, Rao ND. 2021. Decent living gaps and energy needs around the world. *Environ. Res. Lett.* 16(9):095006
161. Cumming O, Elliott M, Overbo A, Bartram J. 2014. Does global progress on sanitation really lag behind water? An analysis of global progress on community- and household-level access to safe water and sanitation. *PLOS ONE* 9(12):e114699
162. Martínez-Santos P. 2017. Does 91% of the world's population really have “sustainable access to safe drinking water”? *Int. J. Water Resour. Dev.* 33(4):514–33
163. Pelz S, Pachauri S, Rao N. 2021. Application of an alternative framework for measuring progress towards SDG 7.1. *Environ. Res. Lett.* 16(8):084048
164. Rao ND, Min J, Mastrucci A. 2019. Energy requirements for decent living in India, Brazil and South Africa. *Nat. Energy* 4:1025–32
165. Kikstra JS, Vinca A, Lovat F, Boza-Kiss B, van Ruijven B, et al. 2021. Climate mitigation scenarios with persistent COVID-19-related energy demand changes. *Nat. Energy* 6:1114–23
166. Pachauri S, Poblete-Cazenave M, Aktas A, Gidden MJ. 2021. Access to clean cooking services in energy and emission scenarios after COVID-19. *Nat. Energy* 6:1067–76
167. Poblete-Cazenave M, Pachauri S, Byers E, Mastrucci A, van Ruijven B. 2021. Global scenarios of household access to modern energy services under climate mitigation policy. *Nat. Energy* 6:824–33
168. Cameron C, Pachauri S, Rao ND, McCollum D, Rogelj J, Riahi K. 2016. Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nat. Energy* 1(1):15010
169. Howard G, Calow R, Macdonald A, Bartram J. 2016. Climate change and water and sanitation: likely impacts and emerging trends for action. *Annu. Rev. Environ. Resour.* 41:253–76
170. Khosla R, Miranda ND, Trotter PA, Mazzone A, Renaldi R, et al. 2021. Cooling for sustainable development. *Nat. Sustain.* 4(3):201–8
171. IEA (Int. Energy Agency). 2018. *The Future of Cooling*. IEA: Paris
172. Falchetta G, Mistry MN. 2021. The role of residential air circulation and cooling demand for electrification planning: implications of climate change in sub-Saharan Africa. *Energy Econ.* 99:105307
173. Mastrucci A, Byers E, Pachauri S, Rao ND. 2019. Improving the SDG energy poverty targets: residential cooling needs in the Global South. *Energy Build.* 186:405–15
174. Pavanello F, De Cian E, Davide M, Mistry M, Cruz T, et al. 2021. Air-conditioning and the adaptation cooling deficit in emerging economies. *Nat. Commun.* 12(1):6460
175. Khosla R, Agarwal A, Sircar N, Chatterjee D. 2021. The what, why, and how of changing cooling energy consumption in India's urban households. *Environ. Res. Lett.* 16(4):044035
176. Zhang Y, Hu S, Yan D, Guo S, Li P. 2021. Exploring cooling pattern of low-income households in urban China based on a large-scale questionnaire survey: a case study in Beijing. *Energy Build.* 236:110783
177. Poblete-Cazenave M, Pachauri S. 2021. A model of energy poverty and access: estimating household electricity demand and appliance ownership. *Energy Econ.* 98:105266
178. Kar A, Pachauri S, Bailis R, Zerriffi H. 2020. Capital cost subsidies through India's Ujjwala cooking gas programme promote rapid adoption of liquefied petroleum gas but not regular use. *Nat. Energy* 5:125–26
179. Grabher HF, Rau H, Ledermann ST, Haberl H. 2023. Beyond cooking: an energy services perspective on household energy use in low and middle income countries. *Energy Res. Soc. Sci.* 97:102946

180. Prayas (Energy Group). 2021. *PIER: modelling the Indian energy system through the 2020s*. Pune, India: Prayas (Energy Group)
181. Prayas (Energy Group). 2020. *Energy consumption patterns in Indian households: insights from Uttar Pradesh and Maharashtra*. Pune, India: Prayas (Energy Group)
182. Balaras CA, Dascalaki EG, Droutsas KG, Kontoyiannidis S. 2016. Empirical assessment of calculated and actual heating energy use in Hellenic residential buildings. *Appl. Energy* 164:115–32
183. Bhan M, Gingrich S, Roux N, Le Noë J, Kastner T, et al. 2021. Quantifying and attributing land use-induced carbon emissions to biomass consumption: a critical assessment of existing approaches. *J. Environ. Manag.* 286:112228
184. Sola A, Corchero C, Salom J, Sanmarti M. 2020. Multi-domain urban-scale energy modelling tools: a review. *Sustain. Cities Soc.* 54:101872
185. Creutzig F, Lohrey S, Bai X, Baklanov A, Dawson R, et al. 2019. Upscaling urban data science for global climate solutions. *Glob. Sustain.* 2:e2
186. Peled Y, Fishman T. 2021. Estimation and mapping of the material stocks of buildings of Europe: a novel nighttime lights-based approach. *Resour. Conserv. Recycl.* 169:105509
187. Milojevic-Dupont N, Creutzig F. 2021. Machine learning for geographically differentiated climate change mitigation in urban areas. *Sustain. Cities Soc.* 64:102526
188. Biljecki F, Chew LZ, Milojevic-Dupont N, Creutzig F. 2021. Open government geospatial data on buildings for planning sustainable and resilient cities. arXiv:2107.04023 [cs]
189. Lanau M, Liu G. 2020. Developing an urban resource cadaster for circular economy: a case of Odense, Denmark. *Environ. Sci. Technol.* 54(7):4675–85
190. Li R, Crowe J, Leifer D, Zou L, Schoof J. 2019. Beyond big data: social media challenges and opportunities for understanding social perception of energy. *Energy Res. Soc. Sci.* 56:101217
191. Pauliuk S, Fishman T, Heeren N, Berrill P, Tu Q, et al. 2021. Linking service provision to material cycles: a new framework for studying the resource efficiency-climate change (RECC) nexus. *J. Ind. Ecol.* 25(2):260–73
192. Kim B, Yamaguchi Y, Kimura S, Ko Y, Ikeda K, Shimoda Y. 2020. Urban building energy modeling considering the heterogeneity of HVAC system stock: a case study on Japanese office building stock. *Energy Build.* 207:109590
193. Department for Business, Energy and Industrial Strategy. 2017. *National Household Model*. United Kingdom Gov., London. <https://data.gov.uk/dataset/957eadbe-43b6-4d8d-b931-8594cb346ecd/national-household-model>
194. Kumar P, Natarajan R, Ashok K. 2021. Sustainable alternative futures for urban India: the resource, energy, and emissions implications of urban form scenarios. *Environ. Res. Infrastruct. Sustain.* 1(1):011004
195. Taniguchi-Matsuoka A, Shimoda Y, Sugiyama M, Kurokawa Y, Matoba H, et al. 2020. Evaluating Japan's national greenhouse gas reduction policy using a bottom-up residential end-use energy simulation model. *Appl. Energy* 279:115792
196. Chatterjee S, Kiss B, Ürges-Vorsatz D, Teske S. 2022. Decarbonisation pathways for buildings. In *Achieving the Paris Climate Agreement Goals*, ed. S Teske, pp. 161–85. Cham, Switz.: Springer
197. Fraunhofer ISI. 2022. *FORECAST FOREcasting Energy Consumption Analysis and Simulation Tool*. Fraunhofer ISI, Karlsruhe, Ger. <https://www.forecast-model.eu/forecast-en/index.php>
198. RTE France. *Energy pathways to 2050: key results*. Réseau de Transport d'Electricité (RTE), Paris. [https://assets.rte-france.com/prod/public/2022-01/Energy%20pathways%202050\\_Key%20results.pdf](https://assets.rte-france.com/prod/public/2022-01/Energy%20pathways%202050_Key%20results.pdf)
199. Zhou N, Khanna N, Feng W, Ke J, Levine M. 2018. Scenarios of energy efficiency and CO<sub>2</sub> emissions reduction potential in the buildings sector in China to year 2050. *Nat. Energy* 3:978–84
200. EPRI (Electr. Power Res. Inst.). 2020. *US-REGEN model documentation*. Rep. 3002016601, EPRI, Palo Alto, CA. <https://www.epri.com/research/products/3002016601>

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# Contents

## I. Integrative Themes and Emerging Concerns

- 30×30 for Climate: The History and Future of Climate  
Change–Integrated Conservation Strategies  
*L. Hannab and G.F. Midgley* ..... 1
- Exploring Alternative Futures in the Anthropocene  
*Steven Cork, Carla Alexandra, Jorge G. Alvarez-Romero, Elena M. Bennett,  
Marta Berbés-Blázquez, Erin Bohensky, Barbara Bok, Robert Costanza,  
Shizuka Hashimoto, Rosemary Hill, Sohail Inayatullah, Kasper Kok,  
Jan J. Kuiper, Magnus Moglia, Laura Pereira, Garry Peterson, Rebecca Weeks,  
and Carina Wyborn* ..... 25
- Plastics and the Environment  
*I.E. Napper and R.C. Thompson* ..... 55
- Toward Zero-Carbon Urban Transitions with Health, Climate  
Resilience, and Equity Co-Benefits: Assessing Nexus Linkages  
*Anu Ramaswami, Bhartendu Pandey, Qingchun Li, Kirti Das, and Ajay Nagpure* ..... 81

## II. Earth’s Life Support Systems

- Harmful Cyanobacterial Blooms: Biological Traits, Mechanisms, Risks,  
and Control Strategies  
*Lirong Song, Yunlu Jia, Boqiang Qin, Renhui Li, Wayne W. Carmichael,  
Nanqin Gan, Hai Xu, Kun Shan, and Assaf Sukenik* ..... 123
- Pushing the Frontiers of Biodiversity Research: Unveiling the Global  
Diversity, Distribution, and Conservation of Fungi  
*Tuula Niskanen, Robert Lücking, Anders Dahlberg, Ester Gaya,  
Laura M. Suz, Vladimir Mikryukov, Kare Liimatainen, Irina Druzhinina,  
James R.S. Westrip, Gregory M. Mueller, Kelmer Martins-Cunha, Paul Kirk,  
Lebo Tederso, and Alexandre Antonelli* ..... 149
- Soils as Carbon Stores and Sinks: Expectations, Patterns, Processes,  
and Prospects of Transitions  
*Meine van Noordwijk, Ermias Aynekulu, Renske Hijbeek, Eleanor Milne,  
Budiman Minasny, and Danny Dwi Saputra* ..... 177

Understanding Fire Regimes for a Better Anthropocene <i>Luke T. Kelly, Michael-Shawn Fletcher, Imma Oliveras Menor, Adam F.A. Pellegrini, Ella S. Plumanns-Pouton, Pere Pons, Grant J. Williamson, and David M.J.S. Bowman</i> .....	207
---	-----

### III. Human Use of the Environment and Resources

Deforestation-Free Commodity Supply Chains: Myth or Reality? <i>Eric F. Lambin and Paul R. Furumo</i> .....	237
Great Green Walls: Hype, Myth, and Science <i>Matthew D. Turner, Diana K. Davis, Emily T. Yeh, Pierre Hiernaux, Emma R. Loizeaux, Emily M. Fornof, Anika M. Rice, and Aaron K. Suiter</i> .....	263
Mapping Industrial Influences on Earth's Ecology <i>James E.M. Watson, Erle C. Ellis, Rajeev Pillay, Brooke A. Williams, and Oscar Venter</i> .....	289
Mitigation of Concurrent Flood and Drought Risks Through Land Modifications: Potential and Perspectives of Land Users <i>Lenka Slavíková and Anita Milman</i> .....	319
Surveying the Evidence on Sustainable Intensification Strategies for Smallholder Agricultural Systems <i>Meba Jain, Christopher B. Barrett, Divya Solomon, and Kate Gbezzi-Kopel</i> .....	347
Brine: Genesis and Sustainable Resource Recovery Worldwide <i>Chenglin Liu, Tim K. Lowenstein, Anjian Wang, Chunmiao Zheng, and Jianguo Yu</i> .....	371
Groundwater Quality and Public Health <i>Xianjun Xie, Jianbo Shi, Kunfu Pi, Yamin Deng, Bing Yan, Lei Tong, Linlin Yao, Yiran Dong, Junxia Li, Liyuan Ma, Chunmiao Zheng, and Guibin Jiang</i> .....	395
The Global Technical, Economic, and Feasible Potential of Renewable Electricity <i>Nils Angliviél de La Beaumelle, Kornelis Blok, Jacques A. de Chalendar, Leon Clarke, Andrea N. Habmann, Jonathan Huster, Gregory F. Nemet, Dhruv Suri, Thomas B. Wild, and Inês M.L. Azevedo</i> .....	419
The State of the World's Arable Land <i>Lennart Olsson, Francesca Cotrufo, Timothy Crews, Janet Franklin, Alison King, Alisher Mirzabaev, Murray Scown, Anna Tengberg, Sebastian Villarino, and Yafei Wang</i> .....	451

## IV. Management and Governance of Resources and Environment

Environmental Decision-Making in Times of Polarization <i>Madeline Judge, Yoshibisa Kashima, Linda Steg, and Thomas Dietz</i> .....	477
Implications of Green Technologies for Environmental Justice <i>Parth Vaishnav</i> .....	505
The Commons <i>Arun Agrawal, James Erbaugh, and Nabin Pradhan</i> .....	531
Governance and Conservation Effectiveness in Protected Areas and Indigenous and Locally Managed Areas <i>Yin Zhang, Paige West, Lerato Thakholi, Kulbushansingh Suryawanshi, Miriam Supuma, Dakota Straub, Samantha S. Sithole, Roshan Sharma, Judith Schleicher, Ben Ruli, David Rodríguez-Rodríguez, Mattias Borg Rasmussen, Victoria C. Ramenzoni, Siyu Qin, Deborah Delgado Pugley, Rachel Palfrey, Johan Oldekop, Emmanuel O. Nuesiri, Van Hai Thi Nguyen, Noubou Ndam, Catherine Mungai, Sarah Milne, Mathew Bukhi Mabele, Sadie Lucitante, Hugo Lucitante, Jonathan Liljeblad, Wilhelm Andrew Kiwango, Alfred Kik, Nikoleta Jones, Melissa Johnson, Christopher Jarrett, Rachel Sapery James, George Holmes, Lydia N. Gibson, Arash Ghoddousi, Jonas Geldmann, Maria Fernanda Gebara, Thera Edwards, Wolfram H. Dressler, Leo R. Douglas, Panayiotis G. Dimitrakopoulos, Veronica Davidov, Eveline M.F.W. Compaoré-Sawadogo, Yolanda Ariadne Collins, Michael Cepek, Paul Berne Burow, Dan Brockington, Michael Philippe Bessike Balinga, Beau J. Austin, Rini Astuti, Christine Ampumuza, and Frank Kwaku Agyei</i> .....	559
Sustainability Careers <i>Christopher G. Boone, Erin Bromaghim, and Anne R. Kapuscinski</i> .....	589
Three Decades of Climate Mitigation Policy: What Has It Delivered? <i>Janna Hoppe, Ben Hinder, Ryan Rafaty, Anthony Patt, and Michael Grubb</i> .....	615
Overheating of Cities: Magnitude, Characteristics, Impact, Mitigation and Adaptation, and Future Challenges <i>Jie Feng, Kai Gao, H. Khan, G. Ulpiani, K. Vasilakopoulou, G. Young Yun, and M. Santamouris</i> .....	651
Risks to Coastal Critical Infrastructure from Climate Change <i>Indrajit Pal, Anil Kumar, and Anirban Mukhopadhyay</i> .....	681
US Legal and Regulatory Framework for Nuclear Waste from Present and Future Reactors and Their Fuel Cycles <i>Sulgiye Park and Rodney C. Ewing</i> .....	713



## V. Methods and Indicators

### Metrics for Decision-Making in Energy Justice

*Erin Baker, Sanya Carley, Sergio Castellanos, Destenie Nock,  
Joe F. Bozeman III, David Konisky, Chukwuka G. Monyei,  
Monisha Shah, and Benjamin Sovacool* ..... 737

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

*Alessio Mastrucci, Leila Niamir, Benigna Boza-Kiss, Nuno Bento,  
Dominik Wiedenhofer, Jan Streeck, Shonali Pachauri, Charlie Wilson,  
Souran Chatterjee, Felix Creutzig, Srihari Dukkupati, Wei Feng,  
Arnulf Grubler, Joni Jupesta, Poornima Kumar, Giacomo Marangoni,  
Yamina Sabeel, Yoshiyuki Shimoda, Bianka Shoai-Tebrani, Yobei Yamaguchi,  
and Bas van Ruijven* ..... 761

### Advances in Qualitative Methods in Environmental Research

*Holly Caggiano and Elke U. Weber* ..... 793

### Attribution of Extreme Events to Climate Change

*Friederike E.L. Otto* ..... 813

## Indexes

Cumulative Index of Contributing Authors, Volumes 39–48 ..... 829

Cumulative Index of Article Titles, Volumes 39–48 ..... 838

## Errata

An online log of corrections to *Annual Review of Environment and Resources* articles may  
be found at <http://www.annualreviews.org/errata/environ>