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Perspective

Closing the gap: Integrating behavioral and social dynamics through a modular modelling framework for low-energy demand pathways

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ABSTRACT

Demand-side pathways play a key role in achieving the 1.5-degree target and enhancing human well-being. Achieving this requires establishing a systematic bridge between social sciences and climate-energy-economy assessment tools, such as models. The IPCC's sixth assessment report faced challenges in providing robust demand-side scenarios, primarily due to the intricate nature of this challenge and existing knowledge gaps. Nevertheless, it emphasizes the urgent need for a more thorough examination of demand-side pathways. Policymakers and stakeholders are in dire need of improved decision support tools capable of anticipating demand-side interventions, especially behavioral and social interventions, and guide the planning of low-energy demand pathways. In this perspective, we comprehensively assess the drivers of change in the transition toward low-energy demand. We categorize these drivers into behavioral and socio-cultural factors, technological and infrastructural design and adoption, and institutional settings. Moreover, we propose a modular architecture and a complementary modelling framework that facilitates nuanced, policy-relevant scenario exploration. Such exploration is essential for translating scientific insights into actionable measures. Additionally, we call for a comprehensive community effort to co-create and co-develop this modular and complementary modelling platform.

1. Toward low energy demand pathways

Recent insights from the social sciences underscore the significance of human behavior and lifestyle changes, service provisioning, and choice architecture in energy demand management and the mitigation of climate change. These insights advocate for concurrent shifts toward transdisciplinary and bottom-up approaches to support climate mitigation efforts worldwide [1–4]. The IPCC SR1.5 identifies "behavioral and lifestyle changes" as a crucial climate change mitigation strategy, complementary to technological measures [5]. In line with this perspective, the IPCC's sixth assessment report includes, for the first time, a dedicated chapter on "demand, services, and social aspects of mitigation [6]. Other studies show that demand-side contributions to mitigation are as promising as supply-side contributions because they allow individuals to select the best way to further their wellbeing, making tradeoffs across sectors and technologies that best suit their needs and contexts [7–9].

Mitigating climate change with demand-side solutions is an *interdisciplinary effort*, specifying strategies that target technology choices, consumption, behavior, lifestyles, coupled production-consumption infrastructures and systems, service provision, and associated socio-technical transitions. Disciplines vary in their approaches and in the research questions that they take to solve global environmental problems. For example, traditional economists often discuss how carbon pricing and other fiscal instruments can trigger changes [10], while psychologists and sociologists examine the behavioral and social factors, cognitive biases, nudges, socio-economic inequality, and wellbeing [3,11–14], anthropologists tend to explore the influence of culture and social structure [15], and natural scientists and engineers investigate aspects such as works on technology, efficiency, affordability and effectiveness [16–18].

Mitigating climate change with demand-side solutions also requires *transdisciplinary approaches* (Fig. 1). To design robust climate-energy mitigation policies, policymakers and stakeholders rely on scientific

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insights and decision support tools (models) to navigate intricate shifts in social dynamics and markets across temporal and spatial dimensions. These tools facilitate the scrutiny of nonlinear transitions and aid into anticipating of forthcoming alterations in climate, energy and the overarching economy [19]. Through the active involvement of policymakers, a dynamic learning process takes shape. The focus should transcend specific modelling intricacies, centering instead on fostering engagement and knowledge exchange [20]. Integrating stakeholders and adopting and systems thinking are crucial for imagining sustainable futures and designing pathways toward achieving them. As an important strategy to address climate change, the exploring and exploiting opportunities in transition low energy demand pathways require stakeholder involvement, inclusive public engagement, and communication [1,21–24]. Through stakeholder engagement and communication, modelers are better able to identify priorities and shortcomings, drivers and barriers of change, and also explore plausible strategies. In addition, through stakeholders' engagement, scientists would be able to share good practices and increase public knowledge awareness.

As a result, our study undertakes a comprehensive evaluation of the factors influencing the shift toward reduced energy consumption. Acknowledging the significance of inter- and trans-disciplinary collaboration and recognizing the key drivers of change, we present a modular architecture and complementary modelling framework. Implementation of this framework necessitates a concerted effort from the community to co-create and co-develop.

2. Drivers of energy demand

To gain a deeper understanding of the systems, processes, and pathways underlying socio-technical changes, it is essential to incorporate relevant theories from various disciplines. Social scientists, for instance, have developed various theoretical frameworks that span from individual behavior process [3,25–29] to broader theories of lifestyle [30–32] and technology acceptance [33–35]. Context-specific factors influencing these changes including, attitudes and beliefs, attitudes, beliefs, values and meaning, relations, social norms, and peer effects [4,12,35,36]. Table S1 presents 20 different identified energy demand modelling frameworks applied to various specific sectors and scope of analysis. The most recent IPCC assessment categorized key drivers of energy demand into behavioral and socio-cultural on the one hand, and technological and infrastructural on the other hand, embedded into institutional context [37]. Here we build on this IPCC assessment, categorizing factors into the corresponding three main areas: (1) *behavioral and social factors* (including individual choices, attitudes, beliefs, collective actions, values, and social norms), (2) *technological and infrastructural options* (such as infrastructure design, choice architecture, and technology), all situated within the broader (3) *institutional* context (Figure2-A). The relative significance of these drivers may vary on the specific sector, type of energy behavior or action, state of infrastructure and technological development, and socio-economic circumstances. Consequently, based on research objectives and knowledge requirements, modelers/researchers can identify and prioritize the most relevant factors for analysis.

Heterogeneity and disparities in consumption patterns, behaviors, lifestyles, climate risk perception, motivation, and intention to act are triggered by various internal and external factors, including socio-demographic characteristics (such as age, education, and income), psychological factors (such as personal experiences, attitudes, and beliefs), diffusion of information (e.g., through climate campaigns, social norms), geographical and political factors (e.g., weather, ideologies, culture, and governance), and available services and infrastructures (e.g., walking and cycling paths, green spaces). This clearly highlights the

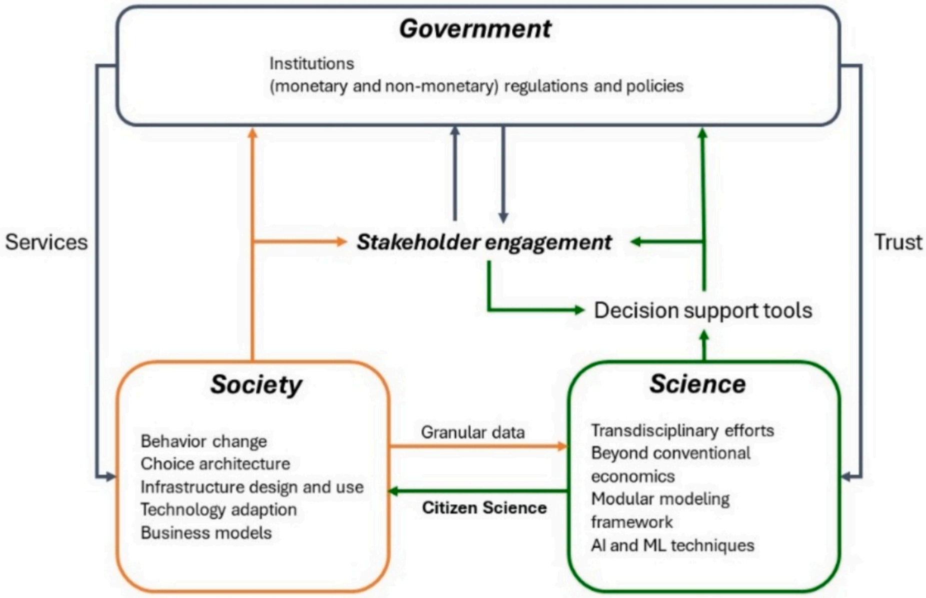

Fig. 1. Modelling of demand-side solutions requires a transdisciplinary understanding that includes not only societal dynamics as an object of analysis but also recognizes social actors are contributors to designing plausible futures. In this context, stakeholder engagement emerges as a critical component for both enhancing model specifications and ensuring effective result implementation. Establishing trust in models as decision support tools is essential for policymakers to develop realistic and impactful policy packages. However, this trust is often undermined by concerns regarding the models complexity, data limitations, or uncertainty in assumptions, and perceived opacity. By integrating stakeholders engagement as a central element of this framework, these challenges can be mitigated. Engaging policymakers from the early stages of model development through to implementation promotes collaboration, improves transparency, and fosters confidence in the modelling process, ultimately bridging the gap between scientific insights and policy action. Meanwhile, citizen science can play a vital role in modelling by engaging the general public in scientific research and data collection. By involving citizens in data gathering and analysis processes, models can benefit from a broader and more diverse dataset, leading to improved accuracy and reliability. Stakeholders' (e.g. civil society, policymakers, scientists) engagement helps to understand the needs/challenges of change better and shed light on unforeseen innovation narratives. By embracing this approach, we cultivate a strong sense of ownership and empowerment among participants, fostering a deeper comprehension of scientific concepts and encourage their active engagement in addressing real-world challenges.

inevitable and robust relationship between individual energy behavior, socio-cultural dynamics, technology and infrastructure availability, and institutional frameworks. For instance, when choosing a place of residence, a household may take into account various factors, including rental or mortgage costs relative to their income, neighborhood layout, community and neighbor interactions, proximity to workplace, schools, daycare facilities, or grandparents' homes. Additionally, consideration may include the building's structure (e.g., heating/cooling systems, insulation levels, energy sources, and associated costs), neighborhood amenities, such as green spaces, playgrounds, supermarkets, sports facilities, and healthcare services.

2.1. Behavioral and social factors

Behavioral change, whether occurring at an individual or collective level, is influenced by a variety of psychological, social, institutional, infrastructural, and other factors (See Tables 1 and 2.). Such change necessitates both motivation and capacity, including awareness of available options for change and the resources to consider, initiate, and sustain change. Understanding individuals' energy consumption practices and patterns and the factors that trigger or inhibit changes in energy behavior is crucial for effective policymaking. However, current models and decision support tools for policymakers often overlook these aspects of human behavioral change and their pertinent implications for environmental policy [38–40]. Notably, lifestyle modelling allows to seamlessly connect different aspects of energy demand and behavior across sectors and situated in daily life routines [41].

2.2. Technological and infrastructural options

Technological improvement and infrastructural options shape individual behavioral change and social practices (See Table 2). The innovation and design of these technologies and infrastructures are essential for facilitating effective behavioral and lifestyle change. For instance, the development and implementation of dedicated cycling and walking lanes, as well as related facilities such as bike parking and pedestrian-friendly pathways, actively promote a car-free lifestyle by making active transportation more accessible and convenient [79–82]. Advancements in technology and ICT have enabled teleworking, reducing commuting, lowering emissions, and promoting a sustainable, healthier urban living lifestyle [83,84]. There are interconnections between infrastructures and individual behavioral change and social practices [85]. For example, a new design electricity system to meet emerging low energy demand based on intermittent renewable can change consumption habits and adopt lifestyles compliant with more power supply interruption [86]. As an innovative technology, solar panels were

Table 1
Behavioral and social key indicators in low energy demand pathways.

Key indicators	Explanation
Attitudes, beliefs, and personal norms[1]	An individual energy behavioral change is influenced by the interaction between intrapersonal factors (e.g., attitudes, values, beliefs), socio-cultural factors (e.g., social network and peer effects, social comparisons, social norms), and external factors (e.g., institutional setting, financial incentives). Awareness (through education and communication), personal norms, and perceived behavioral control predict willingness to change energy behavior above and beyond traditional socio-demographic and economic predictors [3,43], as do perceptions of self efficacy [44]. However, such motivation for change is often not enough, as actors also need capacity for change and help to overcome individual, institutional and market barriers [45–47]. For instance, while a household might be inclined to make the shift by enhancing the insulation of the building, in most cases, the requirement of property ownership also arises as a prerequisite for implementing these changes.
Individuals' collective action[2]	Collective action plays a dual role in emissions reduction, acting as both an enabler and a constraint on societal shifts. For instance, movements that influence social norms can create tipping points toward decarbonisation [48] and low-carbon lifestyles, such as the rise of veganism [49–51]. Conversely, some groups, like landscape conservation organizations, have resisted onshore wind turbine deployment in parts of Europe [52,53]. Collective decisions by individuals, as both consumers and producers, depend on various factors and have uneven impacts on different groups [54,55]. For example, "just transition" movements link workers' interests (e.g., jobs and workplace safety) with consumer concerns (e.g., well-being and reduced climate risks), creating an interdisciplinary framework for inclusive climate and energy policies [56–59]. Similarly, the "Yellow Vest" movement in France underscores how collective action can arise in response to perceived inequities in climate and energy policies, emphasizing the critical need to integrate social and economic fairness to secure public support for emissions reduction initiatives [60,61]. The "FridaysForFuture" movement, on the other hand, has raised awareness and motivated climate actions, especially among youths, while pressuring policymakers to declare a climate emergency. Thus, by shaping collective values and social norms, such movements influence voting, politics, and decisions across the private and informal sectors, driving faster societal change.
Conscious consumption and behavioral contagion	All of us as individuals can make a difference in climate through our choices on energy. Each individual small step toward lowering carbon footprint creates cascading changes in social behavior and consequently mitigates climate change [62]. Behavioral contagion could be a crucial policy tool in transitioning to low energy demand. Social influence occurs when an individual's behaviors or beliefs change to become similar to those of its network contacts; this means that individuals update their beliefs based on the beliefs that their contacts hold [63]. For example, the degree to which friends and neighbors adopt solar panels and energy-efficiency technologies and practices is a powerful predictor of whether an individual adopts them [19,62]. Behavioral interventions like communicating changes in social norms can accelerate behavior change by creating tipping points [64–66]. When changes in energy demand decisions (e.g., adopting heat pumps, electric two or four wheelers, or prosumer solar panels) are motivated by creating and activating a social identity [67] consistent with this and other behaviors, positive spillover can accelerate behavior change [68], both within a domain or across settings.
Culture	Culture significantly influences individuals' perceptions of emissions-related services and their expectations, impacting climate outcomes directly and indirectly [69,70]. Intangible cultural heritage, such as traditional land and water management, traditional architecture and building materials, and traditional food security practices, often (but not alwayssupports climate mitigation and adaptation. Cultural energy practices, local and endogenous knowledge, and natural heritage sites can also serve as valuable assets for addressing climate change mitigation and adaptation, reconciliation and recovery [71–73]. Lifestyles rooted in cultural context explain variations in behavior across countries or cultures. Religion, a central element of many cultures, interacts with climate change in diverse ways [68,69]. For example, White Evangelical Christians in the U.S. are often linked to climate change denial, while their Swedish and Dutch counterparts tend to support progressive climate policies [74–76].
Role models and professional actors.	Role models, such as public figures and celebrities, could have a significant impact on individuals' awareness and behavior as an "influencer", "encourager", and even "investor". Professional actors, such as building managers, landlords, technology installers, car dealers, and energy advisers, could play an important role in individuals' energy consumption and patterns by acting as "middle actors" [77] or "intermediaries" in the provision of building or mobility services [78].

[1] These indicators refer to the individual's sense of self-ethical obligation to perform an action (e.g., consuming green electricity, shifting to walking and cycling), a kind of self-expectation, and they reflect the individual's sense of responsibility for implementing specific actions [25,26,42]

[2] This indicator could be part of formal social movements or informal lifestyle movements.

Table 2
Technological and infrastructural key indicators in low energy demand pathways.

Key indicators	Explanation
Infrastructure design and use	Education, health care, water, energy, and other service provisions are essential for wellbeing and a good life [7,92]. They are all manifested in spatially explicit arrangements in cities and human settlements via the built environment road networks and supply chains. The role of the spatial built environment (and thus infrastructures) has been correspondingly recognized in its importance for demand-side management [93]. There is also a broad understanding that urban form structures mobility and energy choices [94] and that economy-wide mission reductions interact with (transport) infrastructures and mobility lifestyles [95]. Grid congestion and lack of storage emerges as relevant barrier to the expansion of renewables [96,97]. It will become increasingly important to jointly take an urban planner and climate change economist perspective to devise infrastructures in agreement with climate change mitigation goals.
Choice architectures and nudges	Changing decision environments and choice architectures is a primary tool to provide opportunities for low-carbon lifestyles [98]. To influence individual energy-related decisions and consumption, policy-makers have an assortment of tools, including prohibitions, mandates, taxes, fees, subsidies, and "nudges" [99], defined to include such choice-preserving interventions as information, warnings, reminders, uses of social norms, and default rules, such as automatic enrolment in "green energy," such as wind or solar [100]. A meta-analysis of various behavioral interventions in the residential sector demonstrates that interventions are most effective if combined, and especially if monetary instruments are included, allowing for saving up to 8 $GtCO_2$ globally between 2020 and 2040 [101]. These results highlight the importance of considering information, economic incentives, and social dynamics within one modelling context.
Digitalization	Digitalization adds a new (virtual) infrastructure that shapes behavior, social interaction, and lifestyles. While digitalization itself adds energy use and GHG emissions at the scale of 1–2 % at global levels [102,103], its significant impact is via the change and modification in everyday behavior, habits, and patterns. Artificial intelligence is expected to accelerate technology development and provide more efficient climate solutions at all levels [104]. However, the indirect impact of digitalization on GHG emissions and climate change mitigation on a systemic structural level rather than on a specific technological level has not yet been explored and would require explicit modelling of behavioral responses to digital nudges and structures [105].

strongly taken up by individuals [87]. This technology evolution has driven large-scale cost reduction and increased deployment worldwide. Based on the political, social, and geographical context, various drivers have played a role; however, observation is individuals have consistently played a key role in multiple countries (e.g. Germany). In the global south, the shift from LPG to electricity (through induction stove) for cooking has been another successful case of technology adoption toward sustainable, reliable, low energy demand [88–91]. It is important to mention that access to end-use technologies, infrastructure, and services is distributed extremely inequitably worldwide. This means that while many regions of the world should lower energy demand through various mitigation options, in some places, people might require additional energy and resources for their wellbeing.

2.3. *Institutional settings and regulations*

The impact of institutional rules on individuals' energy behavior and decisions is inevitable, as confirmed by several studies [106,107]. Institutions play a crucial role in driving the transformation toward low energy demand, shaping policies and determining how various instruments interact [108]. These institutions include both formal rules, such as laws and regulations, and informal norms, which collectively create the incentive structures that guide individual and collective decisions.

Institutions indirectly influence energy demand by setting regulatory norms, financial incentives, and market frameworks that encourage efficient energy use. For example, feed-in tariffs, a formal policy instrument, enable citizens to participate in energy transitions as prosumers, thereby promoting the widespread adoption of renewable energy and facilitating the shift toward more sustainable energy systems [109]. Performance-based regulations align utilities' incentives with clean energy goals, driving investments in energy-efficient technologies [110]. Incentive-based demand response programs also shape consumer behaviors by encouraging electricity usage during off-peak hours, enhancing grid flexibility and reducing peak demand [111]. Similarly, energy efficiency codes for buildings significantly reduce energy consumption by enforcing compliance with high-performance standards [112]. Additionally, carbon pricing mechanisms, such as emissions trading schemes, penalize high-carbon activities while incentivizing low-energy-intensive practices, reshaping organizational strategies for energy management [113]. This highlights how institutional frameworks not only govern energy markets but also encourage behavioral changes that support broader climate and energy goals.

The allocation of political power to incumbent actors and coalitions has contributed to the lock-in of specific institutions, stabilizing the interests of these incumbents through networks that include policymakers, bureaucracies, advocacy groups, and knowledge institutions. This process can impede progress by reinforcing existing power structures. However, institutional flexibility is crucial in preventing such policy lock-in, e.g., through power struggles and lobbying, allowing for the rapid adoption of context-specific mitigation policies [114,115].

Through regulations, governments can establish targets for reducing emissions, mandate energy efficiency standards, and promote the adoption of renewable energy sources. Institutional settings, such as energy agencies or regulatory bodies, play a vital role in facilitating coordination among stakeholders and ensuring compliance with established policies. Moreover, they stimulate innovation by incentivizing research and development in this field. Effective institutional settings and regulations create an environment conducive to informed decision-making by businesses and individuals, thereby contributing to the reduction of energy consumption and the mitigation of climate change.

3. Modular and complementary modelling framework

Current computational models used for policy analysis are inadequate in capturing the complexity of human behavior and social dynamics. While popular models like Computable General Equilibrium (CGE) and Integrated Assessment Models (IAMs) inform policy decisions, they often overlook the diverse preferences, socio-economic conditions, and behavioral biases that influence individual choices. Improved models are necessary to better reflect these complexities and support effective climate-energy policy assessments. Several studies attempt to integrate social aspects, particularly finance and governance, into the climate-energy modelling. Battiston et al. (2021) point out the absence of financial system considerations in current models like IAMs and propose an integrated framework to address this gap [116]. Lamperti et al. (2019) explore how climate-related damages affect global banking stability using a macroeconomic agent-based model [117]. Moore et al. (2022) highlight the need to include socio-politico-technical processes in climate-earth models and present a stylized model simulating various policy and emissions trajectories [118]. Brutschin et al. (2021) assess low-carbon scenarios through ex-post analysis but note a focus on individual social aspects rather than comprehensive integration [119]. Thus far, all efforts have been focused on integrating one social aspect, e.g., finance and banking, as an input/output model integration, a stand-alone model, or a broad economic-energy-climate scenario ex-post analysis. What is missing is a modelling framework that systematically allows for studying behavioral and social dynamics. Specifically, there are four areas for improvement:

First, models should be geared toward representing the main dimensions of energy demand, including behavioral and social dynamics, infrastructural and technological, and institutional settings (Figure2-A). Second, a representation of these dimensions will require a modular modelling framework that includes models at different resolutions, considering behavioral economics and bounded rationality, and also macro-economic equilibrium dynamics, investigating both sectoral mitigation to the economy-wide reduction in greenhouse gas emissions reduction. Such a modular framework also represents heterogeneous individuals and their socio-economic, behavioral and social, infrastructural, and spatial contexts while enabling a study of spatially and contextually explicit policies and their dynamic potential to reduce greenhouse gas emissions (Figure2-B,D). This knowledge gap has been recognized, and efforts have been initiated, particularly within the socio-technical energy transition community, across various scales and domains [40,64,120–122]. Third, models have a structural path dependence both in terms of model structure and parameters. Engagement of modelers with stakeholders can allow for more flexibly incorporating key dynamics previously underrepresented. Engagement and communication help to understand priorities and shortcomings, drivers and barriers of change, and to explore plausible strategies, but also to share good practices, increase public knowledge awareness and enable active learning by doing. Policymakers and stakeholders are rarely perfect decoders and recipients of scientific information; instead, they deserve a more active role on the information/scenario exploration side, promoting active mutual learning. Forth, modelling should consider policy dynamics in their institutional embedding. Rather than only considering policies only from an optimal social planner perspective (which remains crucial as a normative benchmark), models should allow flexibility in considering political dynamics and existing discourses (Figure2-C).

Addressing these improvements will help decision-makers and communities obtain answers to policy-relevant questions on the ground. For example, policymakers may ask: what are the environmental and social effects of subsidizing solar panels rooftop installations across diverse neighborhoods? [1,123,124] What are the socio-cultural (non-financial) drivers, and to what extent could they trigger climate change mitigation over various spatial and time scales? [19,125–127] What building regulations and retrofit strategies interact beneficially with regional demographic change? [128,129] What are the systematic impacts of street space transformation? [130,131] These are dimensions not considered in integrated assessment models. But answers to these questions are not only important for decision-makers but also have repercussions for global-scale models. More granular models are hence needed.

Here, we introduce a model architecture that comprehensively incorporates local behavioral and social dynamics, structural context, and global mitigation pathways. Its central feature lies in the modular design of model interactions spanning various spatial and socio-economic scales. This architecture facilitates the development of implementable policies geared toward fostering sustainable and resilient societies, while accommodating spatial heterogeneity and uncertainties related to behavior, social dynamics, and service provisioning. Aligned with the science-policy-society meta-frame (Fig. 1) and the concept of human behavior modelling, the modular architecture and complementary modelling[1] framework are devised (Fig. 2). Its primary characteristic is the modular organization of models and techniques across different scales, ranging from behavioral economics and bounded rationality to macroeconomic equilibrium dynamics, and from sectoral mitigation to economy-wide greenhouse gas emission reduction. This modelling architecture allows for the representation of diverse individual energy decisions, fully capturing socio-economic, behavioral, social, infrastructural, institutional settings, and spatial contexts. The proposed computational framework facilitates the explicit consideration of policies in specific spatial and contextual settings, along with their dynamic potential for reducing greenhouse gas emissions.

3.1. *Multi-level micro-models: High resolution, high granularity, interactions and learning*

How can researchers account for *heterogeneous individuals* and *behavioral, social, and structural* uncertainty when designing policies? Currently, there is a big gap between what the current assessment tools can do and what social science highlights as pro-environmental behavior and lifestyle changes in climate change mitigation movements. Social scientists and behavioral economists focus on the emotional and cognitive biases in the decision-making process. Namely, psychology theories investigate motivation for individual behavior change; behavioral studies demonstrate individual responses to the energy choices that depart from the perfect rationality expected of homo economicus; social studies emphasize the role of socio-cultural factors, habits and structural aspects; and traditional economics elaborate on how, under rational decision-making, regulations like carbon pricing and other fiscal instruments can trigger a change in energy demand. Thus, ways of capturing these drivers, their influence and feedback processes are urgently required. This allows for the emergence of tipping points that bring demand-side mitigation strategies at the required speed and scale [48].

3.1.1. *Empirical and granular data (Figure2-B)*

Are the backbone of bottom-up micro models, e.g. ABMs. Empirical studies are fundamental in a) understanding the system; b) capturing heterogeneity; c) learning interactions and feedback, particularly in behavioral and social aspects. Many studies relied on surveys, e.g. household energy consumption and new technology/service adaptation [3]. Others employ geo-informatics techniques such as remote sensing and combine them with machine learning and AI techniques, which could provide an opportunity to extract, track, and analysis structural and climate changes over time and space.

3.1.2. *Agent-based models (Figure2-D)*

Agent-based computational modelling is considered the most promising approach to address the complexity of diversity of change in climate-energy-economy models [106,132,133]. This method is a frontrunner as it is designed to account for *heterogeneous agents* (individuals, firms, etc.), different lifestyles, bounded rationality, and social influences. Synthesis of social science and energy research – combining contributions from economics, psychology, sociology, governance and policy, technological innovation, statistics, and energy modelling – can provide a broad perspective to improve the assessment tools. Unlike other approaches, ABM is not limited to studies of perfectly rational agents or abstract micro details in aggregate system-level equations; instead, ABM can represent the behaviors – such as individual energy decisions and behavioral change – using a range of behavioral theories. In addition, ABM provides functionality to examine how interactions of heterogeneous agents at the micro level give rise to the emergence of macro outcomes, including those relevant for climate mitigation, such as the adoption of low-carbon behavioral strategies and technologies over space and time [19,95,133]. The ABM approach simulates complex and nonlinear behavior that is intractable in equilibrium models.

3.1.3. *Bottom-up models of infrastructures and their use (Figure2-D)*

System dynamics, engineering, mathematical, and econometric

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[1] Complementary modelling refers to the practice of using multiple modelling techniques or approaches to gain a more comprehensive understanding of a complex system or problem.

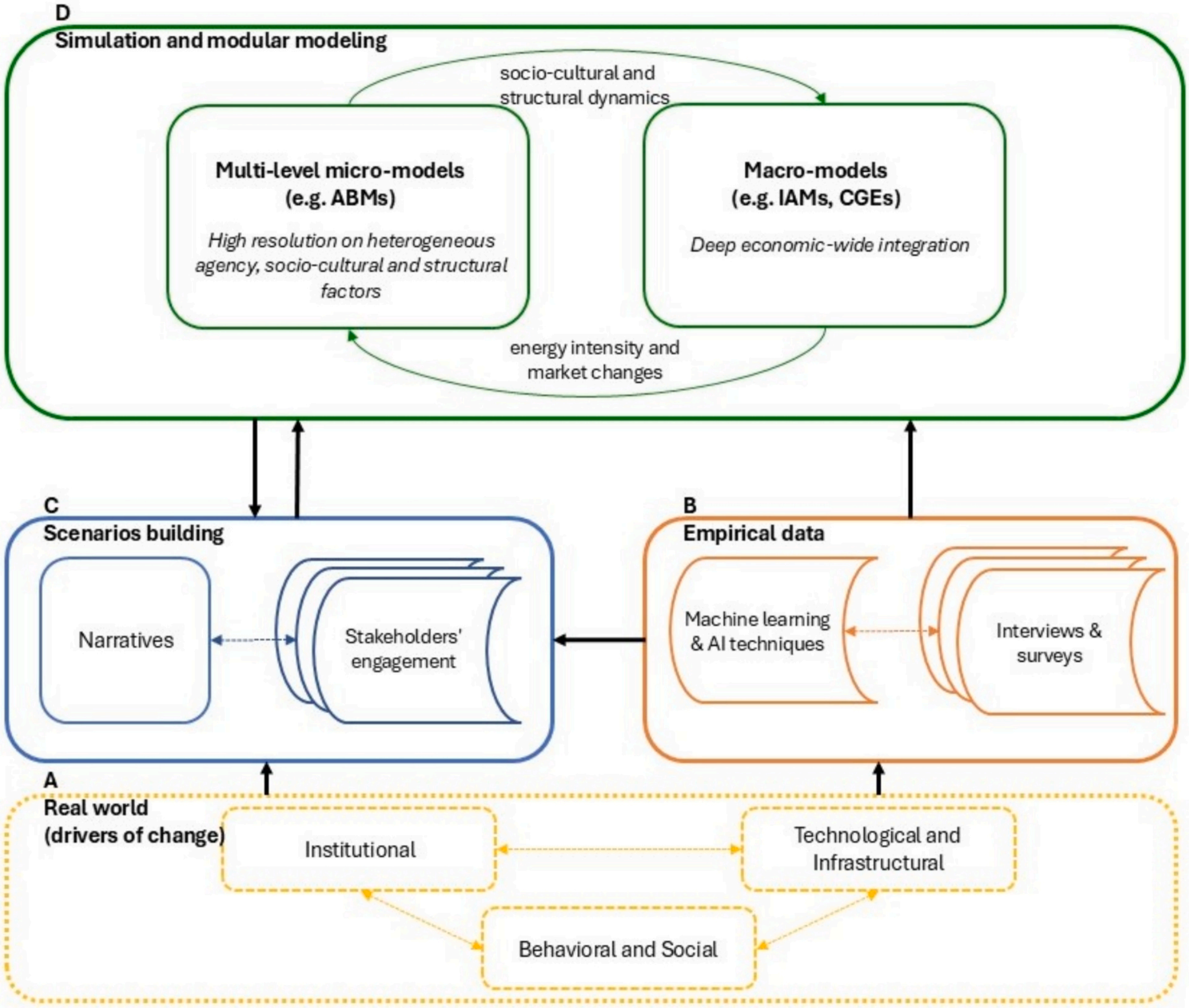

Fig. 2. Modular and complementary modelling framework. This framework comprises four main components: **A) Real world**—represents drivers of change in the transition to low energy demand; **B) Empirical data**—used to understand the real world, including drivers and barriers, through various methods, either standalone or combined; **C) Scenario building**—involves multi-level stakeholder engagement to shape technology, social innovation, and narratives; **D) Modular modelling**—includes multi-level, empirically and theoretically grounded micro-models, and economy-wide macro-models. To explore and identify drivers that could accelerate the transformation, barriers that could delay it, and key actors of change, empirical data is essential. This data can be collected through various methods, such as surveys (across multiple levels and spatial/temporal scales), machine learning and AI techniques for handling big data, and stakeholder workshops. For instance, interviews and surveys are effective for understanding human cognitive decisions and social dynamics, while machine learning and AI help capture spatial structures and institutional settings. Empirical studies are crucial for understanding the system, capturing heterogeneity, and learning about interactions and feedback, particularly in behavioral and social aspects. Based on these empirical studies, modular models are developed to quantitatively assess the impacts of low energy demand options. This provides an interactive platform for stakeholders and decision-makers to explore various behavioral, socio-cultural, infrastructural, and institutional scenarios over time and space, to foresee diverse low energy demand pathways and their tipping points in different contexts, and to identify plausible and feasible end-use strategies for future planning. Additionally, this framework allows decision-makers to adjust their focus, both temporally and spatially.

models focus on a specific sector and/or end-use service(s), e.g. nutrition, buildings, mobility, and materials, technology and innovation. While these models are scattered in different levels of heterogeneity and geographical scale, they are naïve in capturing behavioral and social aspects, particularly (spatial) interactions and learnings. Modelling this level of heterogeneity and granularity, individual behavior, socio-cultural dynamics, and services under various institutional and political contexts requires a high amount and high quality of data. Generic economic models that only look at price sensitivity neglect crucial interactions. Specifically, a change in marginal prices of a specific mode has effects that strongly depend on the availability of alternative modes and associated costs of time [134]. For example, easy accessibility via public transport, a highly spatialized issue, can improve the steering effect of congestion charges or CO_2 prices in transportation by a factor of 2 to 3 [135]. Hence the granular and spatial data on individual energy-related decisions, infrastructure availability, and socio-cultural and institutional context is crucial also when setting economic instruments.

A new class of models can now make use of the *big data* on infrastructure and mobility patterns now available and apply *artificial intelligence*-based approaches [136]. This was demonstrated for the city of Porto, where neural network-based identification of urban form attributes related to energy demand was used for assessing scenarios of settlement expansion [137]. This approach opens up new opportunities to model building and street scale attributes and their changes as relevant for climate change mitigation [138] (Fig. 2-C).

3.2. Macro-models: Deep economic-wide integration

Macroeconomic Computable General Equilibrium (CGE) and Integrated Assessment Models (IAMs) are popular among governments and academia for ex-ante policy analysis. They rely on advancements in micro-based macro-economic theory that represent the aggregate behavior of rational and fully-informed economic individuals and their trade interactions via supply chains [106]. Macro-economic models and integrated assessment tools address a broad range of policy issues by simulating the connections across all sectors of the economy [139–141] (Figure2-D. These quantitative tools range from macro-economic assessments and cross-sectoral impacts to detailed microsimulation models for a specific technology. Comprehensive empirical IAMs and CGEs (e.g. MESSAGE, IMAGE, GAINS, and GCAM), which support quantitative climate change mitigation policy assessments, are strong in tracing cross-sectoral impacts and feedback in the economy as a whole and in linking to readily available datasets. However, their econometrically estimated equations reflect past behavior, making it difficult to integrate behavioral and social changes. For example, IAMs involve a combination of data-driven equations and expert-based inputs. However, capturing the full range of behavioral and social shifts in response to climate policies and technological advancements can still be challenging. IAMs often lean on historical data and trends to inform their underlying assumptions and projections, which might not fully capture the potential for transformative shifts in human behavior and societal dynamics.

3.3. Scenarios building

3.3.1. Innovation(Figure2-C)

Transition to low energy demand varies across sectors, countries, and innovations. Studies show that the innovation process and challenges are fourfold: emergence, (early) adaptation, diffusion, and stabilization (replacement and reconfiguration) [1,142,143]. These four phases do not have linear progress in technological, social, and business innovations. Some of them may occur due to the learning process, conflict, or changing coalitions [142]. By actively involving stakeholders, modelers can understand and incorporate technological, social, and business innovations. Simultaneously, they can enhance the flexibility of their models to effectively incorporate unexpected breakthroughs and rapid progress that may emerge along the way. Engaging stakeholders in the modelling process involves incorporating their input during the design phase to ensure scenarios and outputs reflect their priorities and perspectives [144,145]. Hosting workshops, fostering collaborative decision-making, and transparently communicating model assumptions and results build trust and promote meaningful participation [146,147]. Rapid innovation cycles drive continual improvements in performance and responsiveness to consumer behavior. For example, digitalization adds a new data infrastructure that shapes behavior, social interaction, and lifestyles in cities [148], as exemplified by multimodal routing information provided by apps. While digitalization itself adds energy use and GHG emissions at the scale of 1–2 % at global levels [149,150] (but rising quickly and responsible for >10 % of energy use in 5 US states, and for >20 % in Ireland [151]), its most significant impact is via the changes and modifications it causes to everyday behavior, habits, and patterns. This granularity and particularly abrupt emergence and diffusion could easily be captured by micro-models, such as agent-based models. By adopting a flexible and adaptive approach to modelling, we can ensure that our predictions remain accurate and relevant, even as new advancements emerge.

3.3.2. Stakeholders' engagement and multi-level governance (Figure2-C)

In the transition to a low energy demand, contributions from all spheres of society will be required. Only cooperative action across individuals, cultures, geographies, and governments will effectively control and curtail the impact of the global climate crisis. There are several benefits to see stakeholder engagement as an integral part of the modelling framework. First, individuals -learning from interacting with models- will need to contribute in their different roles as citizens, investors, professionals, role models, and consumers [2]. Second, building and maintaining public trust is part of what scientists do when they communicate their research, and this trust can ultimately support transformative change. Similarly, public understanding and engagement with science and citizen participation, including through the popularization of science, are essential to equip citizens to make informed personal and professional choices. Third, stakeholders' engagement can help solve real-world human-environment interaction problems at various levels and scales and thus accelerate the transition to low-carbon energy demand [147]. Finally, the transition to low energy demand is a social process dependent on the actions of key actors [152]. Therefore, model developers should actively engage with stakeholder communities - from civil society to high-level policy-makers - and offer an integrative participatory framework at different stages. The aim of stakeholder engagement can differ, and there are various methods and tools to use [146]. One key motivation is that stakeholders are rarely passive recipients of scientific information but rather agents who learn by actively engaging with models and scientific findings. It is worth nothing that, although the importance and effectiveness of stockholders' engagement in energy systems modelling is well recognized in the literature, knowledge gaps remain regarding the principles of collaborative and co-production approaches, as well as the democratization of energy systems modelling and planning process [147].

3.4. Development and implementation

We envision a large community effort to co-create and co-develop a modular and complementary modelling platform. The framework's primary characteristic lies in its modular organization of models and techniques operating at various resolutions. These encompass behavioral economics and bounded rationality at a micro level, sector-specific modelling, and macro-economic equilibrium dynamics, forming a comprehensive and versatile platform for analysis and decision-making. Integrating stochastic processes (e.g. Monte Carlo Simulation) is highly advantageous, particularly when dealing with uncertain processes like innovation or other intrinsically uncertain phenomena. Nevertheless, through multi-level stakeholder engagement, we can explore and predict advancements in technological, social, and business innovations, along with the challenges they may encounter, and utilize these insights as narratives to drive informed decision-making.

A key concern is that the high complexity of the framework leads to modelling risk, such as error propagation across model components and bias propagation. Even a single model focused on behavior can lead to different qualitative and quantitative results depending on modelers' interpretation of model specification [153]. Our framework, hence, is no truth-finding machine but rather an approach to answer if-when questions, allowing for the consideration of diverse perspectives and levels of granularity.

Specifically, to achieve the balance between complexity and simplicity, our approach emphasizes a modular design that allows flexibility in model selection and integration. By offering a platform that consists of multiple models, users can choose the level of complexity appropriate to their research question and domain, ensuring that more intricate models are employed only when necessary. This adaptive structure minimizes the risk of false certainties by enabling users to customize their models according to context-specific factors, such as time scales, spatial boundaries, and decision-making processes. By encouraging iterative refinement and collaboration among a broad community of experts, we aim to foster a dynamic process that continuously updates and improves the models, reducing the likelihood of exacerbating uncertainties and promoting more reliable, context-aware outcomes.

By adopting an open-source approach, the platform benefits from the collective expertise of a global community of academics, stakeholders and policymakers. This allows for continuous improvement, feature enrichment, and rapid identification and resolution of issues, ultimately leading to a more robust and adaptable tool. One key aspect of the platform is its emphasis on documentation. We stress the importance of transparent model assumptions, parameter choices, and sensitivity analyses, which help identify and communicate uncertainties rather than reinforcing unwarranted precision. The developers document every step of the implementation process, encompassing the underlying methodologies, data sources, and algorithms used. This comprehensive documentation not only aids users in understanding the framework but also paves the way for its seamless integration into existing workflows and research endeavors. Moreover, the user-friendly interface empowers users to effortlessly navigate and harness the platform's functionalities, regardless of their technical expertise. By providing an accessible platform, the framework fosters inclusivity and encourages diverse participation, thus enriching the co-creation process with a broader array of insights and perspectives. Additionally, the platform's ingenious zoom-in and out functionality ensures optimal flexibility according to user requirements, allowing them to (dis)activate specific modules and analysis as needed. This feature enables users to seamlessly navigate between different levels of granularity, tailoring the framework's capabilities to suit their precise needs. Whether users desire a subject-oriented, in-depth analysis or a broader, high-level overview, the framework empowers them to customize the experience, making it an indispensable tool for a wide range of applications.

Our approach seeks to strike a balance between complexity and accessibility. The flexibility inherent in our framework is key to maintaining the participatory nature of the process while integrating more intricate modelling when suitable. By providing a modular and adaptable structure, users can engage with simplified models that focus on core dynamics, making the process accessible to stakeholders with varying levels of expertise. As the participatory process evolves, more complexity can be introduced in a controlled and gradual manner, allowing stakeholders to build a deeper understanding of the system. This approach fosters collaboration, as participants can actively contribute to model design and refinement, ensuring that the integration of more detailed models remains relevant and context-specific. Through this flexibility, we aim to empower stakeholders to shape the modelling process, ensuring that their input is valued and that the final models align with both their needs and the complexities of the real-world systems being studied.

A salient way to bring the community together around the platform is to provide recognition and prestige to those providing open-source input to the platform, where use cases and cross-linkages to other model components serve as equivalent to citations. Sessions as part of established conferences and, eventually, a new dedicated conference series can serve as a forum for researchers and stakeholders to interact and elaborate on the platform. Moreover, the framework presents opportunities for thorough policy evaluation tailored to specific requirements and research inquiries. While one model adopts an external approach by inputting policies like carbon taxes into the system, facilitating the computation of their effectiveness concerning costs and emission reductions [154,155]. Conversely, other models can embrace an internal perspective, whereby policies are predicted as an integral facet of its dynamics, as already done by IAMs for coarse and long-term policies [156], and by ABMs in particular urban settings [157].

Our framework provides a powerful tool for researchers, practitioners, and non-modelers alike. As such, it holds the potential to revolutionize collaborative problem-solving across diverse disciplines and drive innovation to new heights. We present a first attempt of this framework implementation as a proof of concept in the supplementary materials.

4. The way forward

Economists and modelers recognize that achieving low energy demand pathways necessitates a substantial shift in incentives. This perspective underscores the primary drivers of change and delves into their critical integration into the modelling of low energy demand pathways. Climate-energy solution models must be firmly rooted in empirical data, reflecting the diverse contextual options and implementation pathways. Multi-level empirical-based micro-models can assist researchers in comprehending and quantitatively capturing the aggregated impact of heterogeneous individual behavior within various social dynamics, infrastructural designs, institutional settings, and emergent innovations. They help assess energy demand by reflecting the granularity of human behavior and the myriad social, infrastructural, and institutional factors influencing decisions beyond mere economic considerations.

Our proposal revolves around a modular and complementary modelling framework that underscores the significance of inter-and trans-disciplinary collaboration, particularly in climate-energy modelling. This approach aims to enhance the accuracy, validity, and reliability of assessing low energy demand pathways. Moreover, we emphasize the importance of multi-level governance, science communication, and stakeholder engagement in accelerating the transition to low energy demand. By adopting a modular framework, models gain the capability to zoom in and out, both temporally and spatially, providing policy-relevant insights across various sectoral, spatial, and temporal scales, contingent upon the research questions, scope, or pertinent challenges.

Our framework not only contributes technically to modelling advancement but also underscores the necessity to transcend standard assumptions and evaluation criteria. Energy and climate mitigation policies should extend beyond economic cost-benefit incentives. Instead, policies must be empirically scrutinized, particularly in terms of their institutional embedding and meta-enabling factors of policymaking, such as social trust. Policymakers and stakeholders should not merely be perceived as passive recipients of scientific information; rather, they should actively engage in information exploration and scenario analysis, fostering mutual learning. This places engagement and communication at the forefront of the policymaking process. Stakeholders, including citizens, businesses, financial sectors, and policymakers, should actively participate in designing, exploring, and implementing scientific scenarios.

CRediT authorship contribution statement

Leila Niamir: Conceptualization, Investigation, Writing – original draft, Writing - Review & Editing, Visualization. **Felix Creutzig:** Investigation, Writing - Review & Editing, Visualization

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2025.103988.

Data availability

No data was used for the research described in the article.

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