ENCLUDE

Energy Citizens for Inclusive Decarbonization

Model adjustments and modifications to match emerging energy citizenship trends and patterns

WP5 - The impact of energy citizenship in decarbonization pathways

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Preface

The overall vision of ENCLUDE is to help the EU to fulfil its promise of a just and inclusive decarbonization pathway through sharing and co-creating new knowledge and practices that maximize the number and diversity of citizens that are willing and are able to contribute to the energy transition. Motivated by achieving an equitable and sustainable future and the fulfilment of individual potential, ENCLUDE will contribute to the upcoming transformation of energy use by: **(1).** Assembling, aligning, and adapting disparate energy citizenship concepts for diverse communities of citizens and for different scales of policymaking, lowering the barrier for action, **(2).** Operationalizing the energy citizenship concept at all scales of policymaking for decarbonization, and **(3).** Catalyzing a chain reaction of decarbonization actions across the EU.

1. Changes with respect to the DoA

None.

2. Dissemination and uptake

This report is the first out of five deliverables under Work Package 5 of the ENCLUDE project and sets out to match an ensemble of three well-established models, namely: an agent-based model (ATOM), a demand-side management model (DREEM), and an integrated assessment model (IMAGE), to emerging trends/ patterns of energy citizenship. In particular, it aims at: **(i.)** identifying key trends/ patterns of energy citizenship relevant to the field of energy system modeling, **(ii.)** providing an overview of the ENCLUDE modeling ensemble and the process through which the ENCLUDE models are already able to address the identified trends/ patterns of energy citizenship, and **(iii.)** analyzing gaps and synthesizing further model developments, modifications, and adjustments in order for the ENCLUDE modeling ensemble to be able to understand the multi-scale relationship between energy citizenship and decarbonization pathways in different contexts as a basis for providing appropriate decision-support. As such, this report may easily be used both within and outside of the project, by researchers interested in the fields of energy system modeling and energy citizenship.

3. Short summary of results

Citizens have played, and will be playing an increasingly important role in the energy transition. This increasingly active participation of citizens in the energy system has given rise to a new concept, that of "energy citizenship." Around this term there are various trends/ patterns that have also gained significance in recent years, such as:

- Prosumerism
- Formation of energy communities
- Establishment of eco-villages
- Lifestyle changes
- Energy efficiency measures, such as adjusting the thermostat lower.
- Citizens' behavior, e.g., willingness to participate in collective energy initiatives.
- Preferences towards RES.
- Participation in energy transition movements.
- Participation in energy sector planning and decision-making, including through policy co-design initiatives, public consultation, and participatory energy landscape design.

In the context of ENCLUDE it is envisaged to explore the decarbonization potential of energy citizenship via modeling the micro- and macroscale of emerging energy citizenship trends/ patterns. To this end, the models that are employed in ENCLUDE, namely ATOM, DREEM, and IMAGE, are documented and presented in their current state, along with their capabilities and the ways that they are already able to address a subset of the emerging energy citizenship trends/ patterns. Additionally, a protocol is developed for the soft-linking of the models in order to explore the decarbonization potential of the different aspects of energy citizenship. Finally, the areas for future development of the models are discussed in regard to how to organically incorporate the rest of the trends/ patterns into the models.

4. Evidence of accomplishment

This report serves as evidence of accomplishment.

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Executive Summary

In the transition to a state of net-zero emissions of greenhouse gases, citizens are supposed to play a much larger role, including as self-consumers and participants in energy communities. As a result of this increasingly participatory role of citizens in the energy system the new concept of *energy citizenship* has emerged in the recent years. Around this term, we can also find emerging trends/ patterns that can relate to: **(i.)** the active participation in the energy market, such as the concept of prosumerism, smart technologies, etc., **(ii.)** behavioral attributes of citizens, **(iii.)** individual lifestyle changes, **(iv.)** collective initiatives and expressions of energy citizenship, and **(v.)** political activities, The trends/ patterns that are identified are listed below:

- Prosumerism.
- Formation of energy communities.
- Establishment of eco-villages.
- Lifestyle changes.
- Energy efficiency measures, such as adjusting the thermostat lower.
- Citizens' behavior, e.g., willingness to participate in collective energy initiatives.
- Preferences towards RES.
- Participation in energy transition movements.
- Participation in energy sector planning and decision-making, including through policy co-design initiatives, public consultation, and participatory energy landscape design.

Moreover, energy system modeling has been playing an increasingly important role over the past 30 years in providing useful and measurable insights about energy policies. In spite of the increasing importance and use of energy system models, social aspects, such as the ones listed above, are currently underrepresented in these models. In particular, most models take a techno-economic approach, which limits their ability for including social aspects and dynamics, such as policy preferences and social acceptance.

Apart from the identification of the trends/ patterns around energy citizenship, a parallel process of documenting the energy models that are employed in ENCLUDE, namely *ATOM*, *DREEM,* and *IMAGE*, entailed the detailed documentation of the current state of the three models, i.e., their capabilities and limitations, their input and output variables and their technical characteristics, such as geographical and temporal coverage and resolution, sectors covered, etc. But more importantly, this process enabled the specification of how the models already address some of the aforementioned trends/ patterns, such as prosumerism and behavioral aspects of citizens, and what areas of further development are necessary to address the rest of them. Finally, the various interface protocols for the soft-linking of the models are developed and presented, concerning the data transfer and "communication" between the models.

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List of Abbreviations/ Acronyms

ABM	Agent-based model/ modeling
BES	Building Energy System
CDD	Cooling Degree Days
CEI	Collective energy initiative
CO_2	Carbon dioxide
DSM	Demand-side management
EC	European Commission
ECCP	European Climate Change Programme
EED	Energy Efficiency Directive
ETS	Emissions Trading System
EU	European Union
GDP	Gross domestic product
GHG	Greenhouse gas
HDD	Heating Degree Days
HDI	Human development index
IAM	Integrated assessment model/ modeling
PV	Photovoltaics
RED	Renewable Energy Directive
RES	Renewable energy sources
UNFCCC	United Nations Framework Convention on Climate Change
WP	Work Package

1. Introduction

During the last two decades, the European Union (EU) has been a global leader in fighting climate change through its ambitious policies (Oberthür, 2011; Wurzel et al., 2016), since 1991, when the first Community strategy was launched with the goal of reducing carbon dioxide (CO_2) emissions and increasing energy efficiency. Efforts to mitigate the climate change have thus been ongoing for several years, driven not only by EU priorities, but also by the need to fulfill the EU's international commitments under the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, and, more recently, the Paris Agreement (Stavrakas et al., 2018).

The European Climate Change Programme (ECCP) was implemented as a direct strategic initiative, resulting in a combination of diverse climate change mitigation strategies. As a result, EU law was introduced, which had to be transcribed and executed at the Member State level. Climate and energy policies were combined in a single package of objectives for decreasing greenhouse gas (GHG) emissions, as well as measures for the further deployment of renewable energy sources (RES) and energy efficiency improvements, in the 2020 climate and energy package, enacted in 2009. This framework is mostly preserved in the EU's 2030 package. It is also commonly known that the energy sector accounts for a significant amount of overall GHG emissions, and that the EU is working on decarbonizing it, including the promotion of renewable energy sources and energy efficiency improvements. The European Commission (EC) presented the "Winter Package" in November 2016, which covered all aspects of the energy system and shaped the policy framework for the post-2020 era (Michas et al., 2019; Rosenow et al., 2017).

EU's progressive climate initiatives have advanced in recent years, and the EC released the European "Green Deal" at the end of 2019, which is a comprehensive strategy for the EU to become the world's first climate-neutral continent by 2050 (European Commission, 2019). The 2030 Climate Target Plan, for example, is part of the European "Green Deal" and seeks to reduce net GHG emissions by at least 55% by 2030 (compared to the 1990 levels). This is a significant improvement above the previous objective of at least 40% set in the EU's "2030 Climate and Energy framework[1]". Apart from the outmoded aim of at least a 40% reduction in GHG emissions compared to 1990 levels, the EU's 2030 climate and energy framework has two additional significant targets for 2030: (i.) at least a 32% share of renewable energy (Renewable Energy Directive- RED II) (European Commission, 2018)), and **(ii.)** at least 32.5% improvement in energy efficiency (Energy Efficiency Directive- EED) (European Commission., 2006)). These two targets are still in effect.

The "Green Deal" presented an initial roadmap of the key policies and measures needed to transform the EU's economy for a sustainable future. Key elements and policy areas are:

- Increasing the EU's Climate ambition for 2030 and 2050.
- Supplying clean, affordable, and secure energy.
- Mobilizing industry for a clean and circular economy.
- Building and renovating in an energy and resource-efficient way.
- Accelerating the shift to sustainable and smart mobility.
- Zero-pollution ambition for a toxic-free environment.
- Preserving and restoring ecosystems and biodiversity.

[1] https://ec.europa.eu/clima/policies/strategies/2030_en

- Fair, healthy, and environmentally-friendly food system.
- Financing the transition.
- "Leave no one behind" (just transition).

For achieving climate neutrality, key legislation and policies have been outlined in the EU climate action and the "Green Deal[2]:"

- Reducing the GHG emissions of the electricity generation, industry, and aviation sectors via the EU Emissions Trading System (EU ETS); Contribution of forestry and land use to the GHG emissions' reduction; GHG emission reduction from transport using, for instance, CO_2 emission standards for vehicles.
- Setting national GHG emission targets for non-EU-ETS sectors, such as transport, buildings, and agriculture.
- Boosting energy efficiency, RES, and governance of the EU member states' energy and climate policies as well as promoting innovative low-carbon technologies.
- Phasing down climate-warming fluorinated GHGs, protecting the ozone layer, and adapting to the impacts of climate change.
- Funding climate action.

In addition, in 2020, a Recovery plan was also set by the EC, the European Parliament, and EU leaders, to enable the EU countries to repair the economic and social damage caused by the COVID-19 crisis (European Commission, 2020). A total of €1.8 trillion has been allocated for this purpose, making it the biggest stimulus package ever financed by EU finances. In addition, financial and technical aid will be provided to those who will be most impacted by the energy transition, known as the "Just Transition Mechanism". Over the years 2021-2027, at least €100 billion will be mobilized for the most affected regions[3]. As a consequence, mobilizing more public and private funds and boosting investments in research and innovation, in combination with other instruments included in the EU's recovery plan, will provide the planned transformation of the EU's energy system with an extra boost.

Finally, following Russia's invasion of Ukraine, the EC presented in March of 2022 the "REPowerEU" plan[4], a joint European action to accelerate the clean energy transition and increase Europe's energy independence from unreliable suppliers and volatile fossil fuels.

1.1. The role of citizens in the European energy transition

The actions proposed by the "Green Deal" and the "REPowerEU" plan, aimed at raising the EU's climate ambition and energy independence, are projected to result in a full transformation of the present energy system by investing in practical and creative technological choices, as well as empowering citizens and involving them in the energy transition. Furthermore, the EU's Energy Union policy emphasizes the significance of putting "people at the center" of the energy transition and envisions a Union where "*citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, actively participate in the market, and where vulnerable consumers are protected*" (European Commission, 2021).

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[2] https://ec.europa.eu/clima/policies/eu-climate-action_en

[3] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[4] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511

In this context, citizens are expected to play a much larger role as self-consumers and participants in energy communities (EU, 2018), and they will drive changes in the energy system, influencing both energy demand and supply. As a result, we require transitions that are not just technologically or economically possible, but also socially and politically acceptable, taking into consideration individuals' preferences, acceptance, and behavioral changes (Cherp et al., 2018). As a result of this increasingly participatory role of citizens in the energy system the new concept of "*Energy citizenship*" has emerged during recent years.

Energy citizenship is a term that describes how citizens are increasingly engaging with the energy transition, from economic, political, and social perspectives (Campos & Marín-González, 2020). According to Campos & Marín-González (2020), energy citizenship can be broadly defined as "*a view of the public that emphasizes awareness of responsibility for climate change, equity and justice (…), and the potential for (collective) energy actions*." This broad definition lends itself to be linked to various other emerging trends/ patterns that can relate to: **(i.)** the active participation in the energy market, such as the concept of prosumerism, smart technologies, etc., **(ii.)** behavioral aspects of citizens, **(iii.)** lifestyle changes in the daily lives of citizens, **(iv.)** collective initiatives and expressions of energy citizenship, such as the formation of energy communities, co-operatives, eco-villages, or collective energy decision-making, such as housing association boards, etc., and **(v.)** political activities, such as participation in social movements and civil society initiatives advancing democratic visions of energy transition and/ or energy policymaking taking the form of participation in energy sector planning and decision-making, including through policy co-design initiatives, public consultation, and participatory energy landscape design.

In this context, facilitating the energy transition towards climate neutrality in Europe by 2050 requires us to develop a new set of energy modeling tools, which will be able to simulate and analyze the drivers and barriers to complete decarbonization, including decentralization, a large-scale deployment of variable renewable energy, resulting in a greatly increased demand for system-side flexibility, sector-coupling, including electrification of transportation and heating, and the effects of alternative market designs on the behavior of different energy sector players.

1.2. Energy system modeling and energy citizenship

Energy system modeling has been playing an increasingly important role over the past 50 years in providing useful and measurable insights about energy policies (Süsser, Ceglarz, et al., 2021). According to Pfenninger et al. (2014) "*energy system models are not only a tool for the definition of scenarios and long-term planning strategies, but also for the expression of the semantics used to formalize the "scattered knowledge about the complex interactions of the energy sector*." The field of energy system modeling is prolific, and many models have been and are currently being developed using different methodologies and working approaches.

The necessity to balance energy supply and demand is present in all energy system models. However, current science literature accepts that energy demand is usually an exogenous input assumption, either as a static demand or with some flexibility, rather than a modeling outcome. This necessitates that modelers reflect energy demand for a wide range of sectors at the appropriate temporal and geographical resolution for their modeling tools (Chang et al., 2021). Several projects have attempted to simulate thermal demand using both bottom-up and top-down methodologies (Oconnell et al., 2014), but their integration into energy modeling tools is still minimal.

In this context, relying on demand-side modeling methods that take into account citizens' behavioral characteristics is critical to determining future profile patterns of the future transformation, but it has been misused thus far. However, scientific support for climate action entails not just judging feasibility and desirability in terms of "what," as in policy and outcome, but also "when," "where," and, most importantly, "whom." Without the essential behavioral and cultural changes, the world's response to the climate issue will be insufficient. This might be due to a lack of adoption of low-carbon technology, the continuation of high-carbon lifestyles, or broader economic rebound effects (Nikas, Lieu, et al., 2020).

For example, in Europe's shift to a more decentralized vision of a low-carbon energy system, where citizens take ownership of the transition, benefit from new technologies to lower their bills, and actively participate in the market, part of the required infrastructure will only be developed if citizens are willing to invest in/ pursue the technological capabilities required. However, given that it is unlikely that they will invest in new technological options with the primary goal of supporting the energy system (e.g., flexibility), it is reasonable to assume that they will only invest according to a value derived from a higher proportion of self-produced energy consumed.

While technological infrastructure is already in place, new and innovative business models and legal frameworks are required to maximize the value of technological capabilities and to commercialize them in order to recompense citizens (Li et al., 2019; Tzani et al., 2022). However, due to conflicts between citizens' and market actors' interests, the existing European legislative framework leads to situations where business models do not fully use demand-side capabilities, even when they exist (Wolisz et al., 2016). Given that in modern energy systems technological innovation will continuously pose new challenges to existing regulatory frameworks, innovations in regulation should be as important as regulating innovations (Rubino, 2018). As a result, efficient policymaking around Europe should explore "*game changer*" business models that incentivize both citizens and other market actors to incorporate demand flexibility into the markets that can valorize it.

However, in spite of the increasing importance and use of energy system models, the above aspects are currently underrepresented in these models. In particular, most models take a technoeconomic approach, which limits their ability for including social aspects and dynamics, such as policy preferences, or social acceptance (Chatterjee et al., 2022). What is noteworthy is that social aspects can also play a significant role in accelerating or impeding processes within the energy transition, while there is a growing awareness of the importance of these dynamics. These factors are important for the development of energy models because societies can have a significant impact on driving or limiting the energy transition: citizens, for example, can develop and participate in community energy projects while also opposing local energy infrastructure development. Current models tend to treat the social dimension of the energy transition as an added layer of analysis, i.e., they consider society as a larger social context and, as a result, they overlook interactions between societal factors and other factors such as technology, economy, and even the environment (Süsser, Pickering, et al., 2021).

Linking social science and the concept of energy citizenship to computer-based modeling is an important topic because it can broaden the perspective on and understanding of the complex subject of the energy transition. To this end, the ENCLUDE modeling ensemble will play an influential role in understanding the diffusion of technological and social innovations, and the interactions between key characteristics of citizens' behavior affecting investment decisions.

1.3. Objectives and scope of this deliverable

This report is the first out of five deliverables under Work Package (WP) 5 of the ENCLUDE project and sets out to match an ensemble of three well-established models, namely: an agent-based model (ABM), a demand-side management (DSM) model, and an integrated assessment model (IAM), to emerging trends/ patterns of energy citizenship. More specifically, Deliverable 5.1 aims at: **(i.)** identifying key trends/ patterns of energy citizenship relevant to the field of energy system modeling, **(ii.)** providing an overview of the ENCLUDE modeling ensemble and the process through which the ENCLUDE models are already able to address the identified trends/ patterns of energy citizenship, and **(iii.)** analyzing gaps and synthesizing further model developments, modifications, and adjustments in order for the ENCLUDE modeling ensemble to be able to understand the multi-scale relationship between energy citizenship and decarbonization pathways in different contexts as a basis for providing appropriate decision-support. The main research questions of our work are: "*What are the trends/ patterns of energy citizenship that the ENCLUDE modeling ensemble is already capable of addressing*?"

and "*How can we further improve the ENCLUDE modeling ensemble in order to provide a more comprehensive modeling of the "energy citizenship" concept, also exploring the multi-scale relationship between its various forms and the decarbonization of the energy system*?"

1.4. Structure of this report

The remainder of this Deliverable is structured as follows:

- **Section 2** provides a short overview of the three-step analytical approach followed to identify key trends/ patterns of energy citizenship relevant to the field of energy system modeling and match the ENCLUDE modeling ensemble to the key trends/ patterns of energy citizenship identified.
- **Section 3** provides a short overview of the key energy citizenship trends/ patterns identified with relevance to the field of energy system modeling.
- **Section 4** introduces the reader to the ENCLUDE modeling ensemble, presenting the key characteristics and capabilities of each model.
- **Section 5** analyzes how the ENCLUDE modeling ensemble is already capable of addressing the identified energy citizenship trends/ patterns, also highlighting gaps and the need for further model developments, modifications, and adjustments.
- **Section 6**, finally, provides conclusions, summarizes limitations, and indicates next steps and fields of future research.

2. Analytical approach

To identify key trends/ patterns of energy citizenship relevant to the field of energy system modeling and to match the ENCLUDE modeling ensemble to the trends/ patterns identified, we followed the analytical approach presented in **Figure 1**.

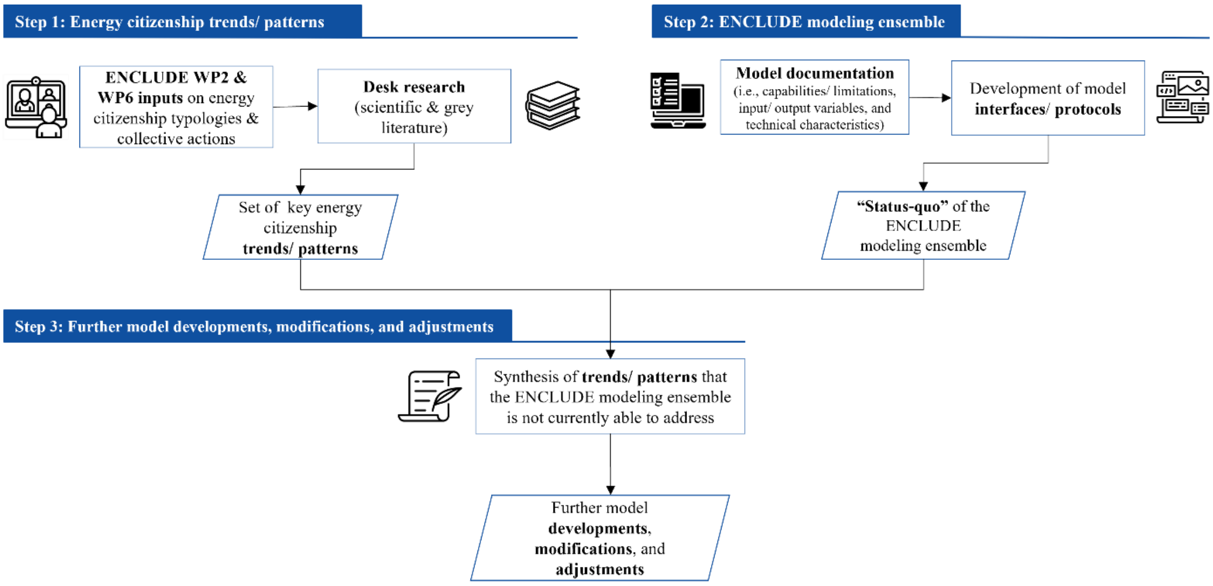

Figure 1. Analytical approach followed in the context of this report.

2.1. Step 1: Energy citizenship trends/ patterns

As a first step, we set out to identify key trends/ patterns that emerge around the central concept of energy citizenship and could be relevant to the field of energy system modeling. To do so, we built on preliminary findings on the different energy citizenship typologies and the work carried out under the ENCLUDE WP2 (still work in progress), and on the findings on collective actions and the work performed under WP6 (Djinlev & Pearce, 2022). This allowed us to develop an initial understanding of the different trends/ patterns surrounding the concept of energy citizenship and come up with a set of relevant search keywords, e.g., {"prosumers," "collectivist," "smart consumer," "(energy)citizen," "lifestyle," "behavior," "social aspects"} AND {"modeling," "energy modeling," "energy system modeling," "agent-based modeling," "demand-side management modeling," "integrated assessment modeling"}. These keywords guided our desk research in the scientific and the grey literature.

More specifically, in the case of scientific literature, we conducted a search of energy-related peer-reviewed journal articles in the "Science Direct" and "Google Scholar" databases, using the above keywords. Search results were constrained to the period 2010-2022. In the case of grey literature, the search process was centered around relevant technical reports and position papers to supplement existing knowledge and experience. For this case, search results were constrained to the period 2017-2022. Finally, we also made use of previous research knowledge found in deliverables from EC-funded projects with similar scope, like the "sister projects" to ENCLUDE, i.e., "dialogues[5]," "EC^2 [6]," "EnergyPROSPECTS[7]," and "GRETA[8]," or other projects with a focus on energy system modeling, like "SENTINEL[9]" and "openENTRANCE[10]."

2.2. Step 2: ENCLUDE modeling ensemble

The second step of our approach comprises all the work that is related to the documentation of the energy models that will be employed in ENCLUDE. This work entails the detailed documentation of the current state of the three models, i.e., their capabilities and limitations, their input and output variables, and their technical characteristics, e.g., geographical, and temporal coverage and resolution, sectors covered, etc. To this end, a template matrix was developed to collect all the model-relevant information (see **Appendix A: Documenting the ENCLUDE models**). This data collection process then enabled us to develop a matching matrix, optimizing the connections between the ENCLUDE models and their ability to address the identified trends/ patterns. Moreover, the various interface protocols for the soft-linkage of the models were developed, concerning the data transfer and the "communication" between the models. Based on this work, we summarized the "status-quo" of the ENCLUDE modeling ensemble.

2.3. Step 3: Further model developments, modifications, and adjustments

Finally, based on the identified energy citizenship trends/ patterns and the "status-quo" of the ENCLUDE models, a gap analysis was enabled to synthesize the trends/ patterns of energy citizenship that are not currently addressed by the ENCLUDE models. This allowed us to identify further model developments, modifications, and adjustments required so that the ENCLUDE modeling ensemble is able to understand and simulate the multi-scale relationship between energy citizenship and decarbonization pathways in different contexts as a basis for providing appropriate decision-support.

[5] https://www.dialoguesproject.eu/
[6] https://ec2project.eu/
[7] https://www.energyprospects.eu/
[8] https://projectgreta.eu/
[9] https://sentinel.energy/
[10] https://openentrance.eu/

3. Energy citizenship trends/ patterns

The concept of energy citizenship, as an emergent concept itself, still remains under-theorized and the boundaries surrounding it are not strictly defined. Varying forms of energy citizenship have emerged (and continue to emerge) within the energy domain, influenced and shaped by the socio-political, economic, and cultural specificities found in particular cases. Based on our desk research, a key set of energy citizenship trends/ patterns, which could also be relevant to energy system modeling, are presented in **Table 1**, and are further analyzed in the sub-sections below, in order to establish a common ground of understanding, also in the context of how they are relevant to the field of energy system modeling.

By combining insights from the scientific literature (Dellavalle & Czako, 2022; Krumm et al., 2022; Süsser et al., 2022; Wahlund & Palm, 2022), we selected the following five thematic groups, namely: **(i.)** active participation in the energy market, **(ii.)** actions towards energy efficiency, **(iii.)** behavioral aspects, **(iv.)** collective expressions of energy citizenship, and **(v.)** political activities, in order to categorize the identified energy citizenship trends/ patterns.

Table 1. Identified energy citizenship trends/ patterns based on our desk research categorized across the level of analysis (individual/ collective) and in five thematic groups.

Level	Group	Trend/ Pattern	Literature source
Individual	Active participation in the energy market	• Prosumerism	(Krumm et al., 2022; Kühnbach et al., 2022; Trutnevyte et al., 2019)
Individual	Actions towards energy efficiency	• Lifestyle changes • Energy efficiency measures	(Creutzig et al., 2018; Spyridaki et al., 2020; Stephenson et al., 2010)
Individual	Behavioral aspects	• Citizens' behavior • Preferences towards RES	(Borch, 2018; Devine-Wright & Batel, 2017; European Commission, 2021; Göllinger, 2012; Kati et al., 2021; Knopper et al., 2014; Månsson, 2015; Morrissey et al., 2016; Quentin, 2019; Samadi et al., 2017; Tzani et al., 2020; Vasilakis et al., 2016; Voigt et al., 2019)
Collective	Collective expressions of energy citizenship	• Formation of energy communities • Establishment of eco-villages	(Calvo & Valero, 2022; Campos & Marín-González, 2020; Łapniewska, 2019; Moreau et al., 2019; Moret & Pinson, 2019; Nikas, Lieu, et al., 2020; Sovacool et al., 2022; Wahlund & Palm, 2022)
Collective	Political activities	• Participation in energy transition movements • Participatory processes in energy sector planning & decision-making	(Hielscher et al., 2022; Wahlund & Palm, 2022)

3.1. Active participation in the energy market

From the energy transition a new generation of citizens has emerged, who take on a more active role as producers, distributors, consumers, and sellers of energy, often from RES; the so-called "*prosumers*." Citizens are increasingly becoming individual owners, thus, consuming their own electricity (Krumm et al., 2022), and playing a facilitating and supportive role in driving the energy transition (Trutnevyte et al., 2019). "*Prosumerism*" is the concept that refers to the act of energy consumers to be also producers of energy, e.g., through small-scale RES technologies installed in their residence, etc., or to consumers being able to provide flexibility to the grid by adjusting their consumption patterns (Kühnbach et al., 2022). This trend can have a quantifiable effect on the GHG emissions, while keeping intact the electricity grid (Stavrakas et al., 2020).

3.2. Actions towards energy efficiency

Various individual *lifestyle changes* that we as citizens can make, and can lead to more sustainable ways of living, are an important aspect of energy citizenship. The way our own norms, practices, and culture directly correlate to our energy behavior (Stephenson et al., 2010), the way we behave as consumers, and how our lifestyle affects climate change mitigation (Creutzig et al., 2018), have been areas of interest for many researchers. Various daily activities, such as home appliances' use, heating and washing, etc., influence a household's levels of energy consumption and form a core part of being an energy citizen. Individual energy conservation measures that result from the raised awareness around one's own energy consumption can be beneficial to the reduction of energy usage (Spyridaki et al., 2020). For example, the action of lowering the thermostat of a residence can have a substantial impact on the energy use of the residence.

3.3. Behavioral aspects

Apart from lifestyle changes, more esoteric *behavioral aspects* of citizens can also play an important role in studying energy citizenship. In academia, behavioral change is often seen, not as a welfare loss, but as a gain in wellbeing and satisfaction (Samadi et al., 2017), as a beneficial lifestyle innovation (Göllinger, 2012), and the "holy grail" of sustainability (Morrissey et al., 2016). These aspects concern the internal beliefs and views on which citizens base their decision-making process. For example, the preferences towards renewable energy technologies, which are also linked to the phenomenon of "NIMBY-ism," can inform citizens' decision to invest in a collective renewable energy project. Thus, these behavioral aspects can be considered in the process of policy design and implementation of new measures and incentives (Tzani et al., 2020).

Public preferences and *opinions* are frequently highlighted in the context of renewable energy infrastructure development and, overall, the transition to a RES-dominated energy system achieves high public approval levels within the EU (The European Comission, 2021). Issues typically relate to the increasing number of renewable energy plants and associated transmission infrastructure, where conflicts arise from place attachment (Devine-Wright & Batel, 2017), planning and siting (Quentin, 2019), visual and aesthetic impacts (Borch, 2018), land-use conflicts (Månsson, 2015), biodiversity loss (Kati et al., 2021; Vasilakis et al., 2016; Voigt et al., 2019), noise, and general human health issues (Knopper et al., 2014). Finally, citizens' *willingness to participate in energy communities* can also be linked to the system of core beliefs they possess.

3.4. Collective expressions of energy citizenship

Moreover, *energy communities* and other various *collective energy initiatives* (CEIs), such as energy collectives and co-operatives, are legal entities that relate to the communal and localized production of energy, in order to optimize the usage of their resources (Moret & Pinson, 2019). CEIs can bring numerous benefits at the local level, including new opportunities for local employment, improvements in social infrastructure developments, and environmental mitigation and enhancement (Nikas, Lieu, et al., 2020). For instance, in the context of wind farm projects, such initiatives can prevent project-related conflicts, increase local acceptance, and enhance opportunities for regional development (Calvo & Valero, 2022; Moreau et al., 2019; Sovacool et al., 2022).

The establishment of *eco-villages* also expresses a collective form of energy citizenship, but they can present differences when compared to typical energy community structures. Eco-villages is a broad term that can encompass small, self-sufficient communities that focus on reducing their environmental impact and developing more sustainable lifestyles. Hence, eco-villages are often linked to more sustainable ways of living that can be found within the community, such as sustainable waste management systems, water treatment systems, irrigation, architecture, etc.

Overall, both the concepts of *prosumerism* and *community energy* have been linked to terms such as energy justice, energy democracy, solidarity-based economy (Campos & Marín-González, 2020; Wahlund & Palm, 2022), and gender equality (Łapniewska, 2019), which carry a positive connotation.

3.5. Political activities

Additionally, the *participation in energy transition movements*, such as social movements and civil society initiatives advancing democratic visions of energy transition, is another trend around energy citizenship (Wahlund & Palm, 2022), where citizens can have an active role in the dialogue around energy. Social movements, for example, against fossil fuels can have considerable impact by holding accountable the responsible players in court cases. Moreover, by linking together various social movements to wider networks, creates more widespread collective actions that can potentially influence the general public opinion (Hielscher et al., 2022).

One final aspect of energy citizenship that is identified is the *participatory processes* that take place in *energy sector planning* and *decision-making*, such as policy co-design initiatives, public consultation, and participatory energy landscape design (Wahlund & Palm, 2022). These processes enhance the active role of citizens by considering citizens' perspectives and giving them the opportunity to voice their opinions in matters that ultimate affect their own lives; this is the reason why such processes should be emphasized.

3.6. Energy system modeling and energy citizenship

Based on our desk research, we see that each one of the identified trends/ patterns reveals, and is linked to, a different facet of energy citizenship. Some of these aspects highlight the *collective* expressions of energy citizenship, such as the formation of energy communities, or the participation in energy transition social movements, where citizens are empowered through their collective actions. On the other hand, there are trends/ patterns that are linked to *individual* actions and behaviors, such as for example, prosumerism, lifestyle changes, or the personal preferences towards RES technologies, bringing forth the important role each individual can play in the energy transition.

Of course, the individual and collective scales are intertwined through the upscaling of individual action to collective action. Moreover, a distinction between *actions* and *abstractions* can be made. On one hand, we have the formation of energy communities and prosumerism, where citizens act in a clear-cut way by actively participating in the production side of the energy system, while on the other hand, we identify aspects such as individual behaviors and core beliefs that play an internal role in the citizens' decision-making process.

However, existing energy system models have limitations in representing such aspects of energy citizenship. A recent study by (Krumm et al., 2022) provides a good overview and shows that different types of models have different capabilities to address aspects such as social barriers for solar PV adoption (Nikas, Stavrakas, et al., 2020), peer-to-peer energy trading in local communities (Perger et al., 2021), and drivers and patterns of household energy consumption (Stavrakas & Flamos, 2020). But there are also significant gaps, especially in dealing with transition dynamics, e.g., speed of transformations and path dependencies (Trutnevyte et al., 2019), etc., and socio-technical systems that captures stakeholder heterogeneity, e.g., zero energy communities (Mittal et al., 2019), etc. To this end, researchers (Krumm et al., 2022; Süsser et al., 2022) have suggested that existing energy system models need to be further developed and their limitations need to be compensated by exploring more nuanced bottom-up modeling approaches, like ABMs.

Energy system models have the capacity to address various of these trends/ patterns in multiple ways, and of course are continually upgraded to incorporate more. For example, the concept of prosumerism can be addressed by energy system models by incorporating the aspect of self-production in the models, in the process of defining the energy system under study, and thus compute the allocation of energy loads in the grid.

Moreover, the collective expressions of energy citizenship, such as the formation and participation in collective energy production initiatives, energy communities, or eco-villages, can have a twofold link to energy system modeling. First, as with prosumers, they can be studied inside the energy system and derive the benefits that they can produce, such as the reduction in energy costs, or the benefits to the grid that such a decentralized energy system can provide, or the energy savings achieved by the more sustainable ways of living introduced by eco-villages. Second, they can be studied as expressions of

social innovations and how such concepts could be adopted by, or diffused within, a population.
Additionally, all the individual behavioral aspects can be incorporated in energy system modeling, for example in ABM, by building citizen profiles that reflect those aspects and are weighted against other factors during the agents' decision-making process. Simultaneously, themes of lifestyle changes can be incorporated in energy system modeling in the derivation of energy demand profiles of citizens, while also taking into consideration the citizen's thermal comfort.
Finally, the political activities' aspect mentioned earlier, such as the participation in social movements related to the energy transition can indirectly play a role in energy system modeling. This can be achieved by studying the core beliefs they represent and how their members form their opinions and views, and, thus, enabling a more realistic characterization of citizen profiles, while also exploring how social innovations diffuse within a society.

4. The ENCLUDE modeling ensemble

One of ENCLUDE's fundamental goals is to contribute to a more comprehensive modeling of the "*energy citizenship*" concept, by using the combined strengths of ABM, DSM modeling, and IAM, exploring, thus, the multi-scale relationship between the various forms of energy citizenship and the decarbonization of the energy system at the local level; and by scaling-up to the regional, the national, or even the supranational level. To this end, ENCLUDE brings onboard the **A**gent-based **T**echnology ad**O**ption **M**odel (ATOM), the **D**ynamic high-**R**esolution d**E**mand-sid**E** **M**anagement (DREEM) model, and the **I**ntegrated **M**odel to **A**ssess the **G**lobal **E**nvironment (IMAGE).

ATOM and DREEM are a part of the Technoeconomics of Energy Systems laboratory (TEESlab[11]) Modeling (TEEM) suite[12], while the IMAGE[13] model has been developed by the PBL Netherlands Environmental Assessment Agency[14].

4.1. Agent-based modeling: ATOM

Since there is a multitude of factors affecting an individual's, or a household's, decisions to invest in, and adopt, an innovative energy technology, such as small-scale photovoltaic (PV) system, or even a social innovation, ABM techniques provide an appropriate framework to simulate the adoption/ decision-making process of the members of a heterogeneous social system. ABM comprehends a system as a collection of independent decision-making entities called "*agents*" and it is a very flexible modeling method as it describes the micro-level behavior/ behavioral tendencies and the individual preferences of agents, and their interaction within a social network (MacAl & North, 2010; Ringler et al., 2016), and allows the inclusion of considerable detail and nuance about their decision-making process and (inter-)actions (Bonabeau, 2002).

ABMs also provide an intuitive framework for considering the explicit attributes of both technology and human behavior, and are considered part of a new generation of models that describe sustainability problems in a richer and more nuanced way, and address policy issues (Taylor et al., 2016), as simulating agents' decisions and interactions represents a more "real-world" process (Nikolic & Ghorbani, 2011).

ATOM (Michas et al., 2020; Stavrakas et al., 2019) simulates the dynamics of technology and social innovation diffusion among consumers and other types of agency, e.g., communities of citizens, eco-village structures, etc. The novelty of the model lies in obtaining realistic uncertainty bounds and decomposing the output uncertainty in its major contributing sources. The model comprises three separate modules (**Figure 2**).

- A *calibration* module that defines the parameters influencing the agents' behavior in a tailored way, each time according to the application at hand (see an indicative example in **Figure 3**), while also defining suitable ranges of values for these agent-related parameters according to historical data and observations.
- A *sensitivity-analysis* module that quantifies uncertainties related to potential adopters' attributes and decision-making criteria.

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[11] https://teeslab.unipi.gr/
[12] https://teeslab.unipi.gr/models/
[13] https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.2_Documentation
[14] https://www.pbl.nl/en

- A *scenario-analysis* module, which based on the calibrated values of the agent-related parameters, simulates the plausible adoption behavior of agents (or diffusion of the technology/ social innovation under study), within the geographical and socioeconomic context of interest, under different support policy schemes (i.e., forward-looking simulations).

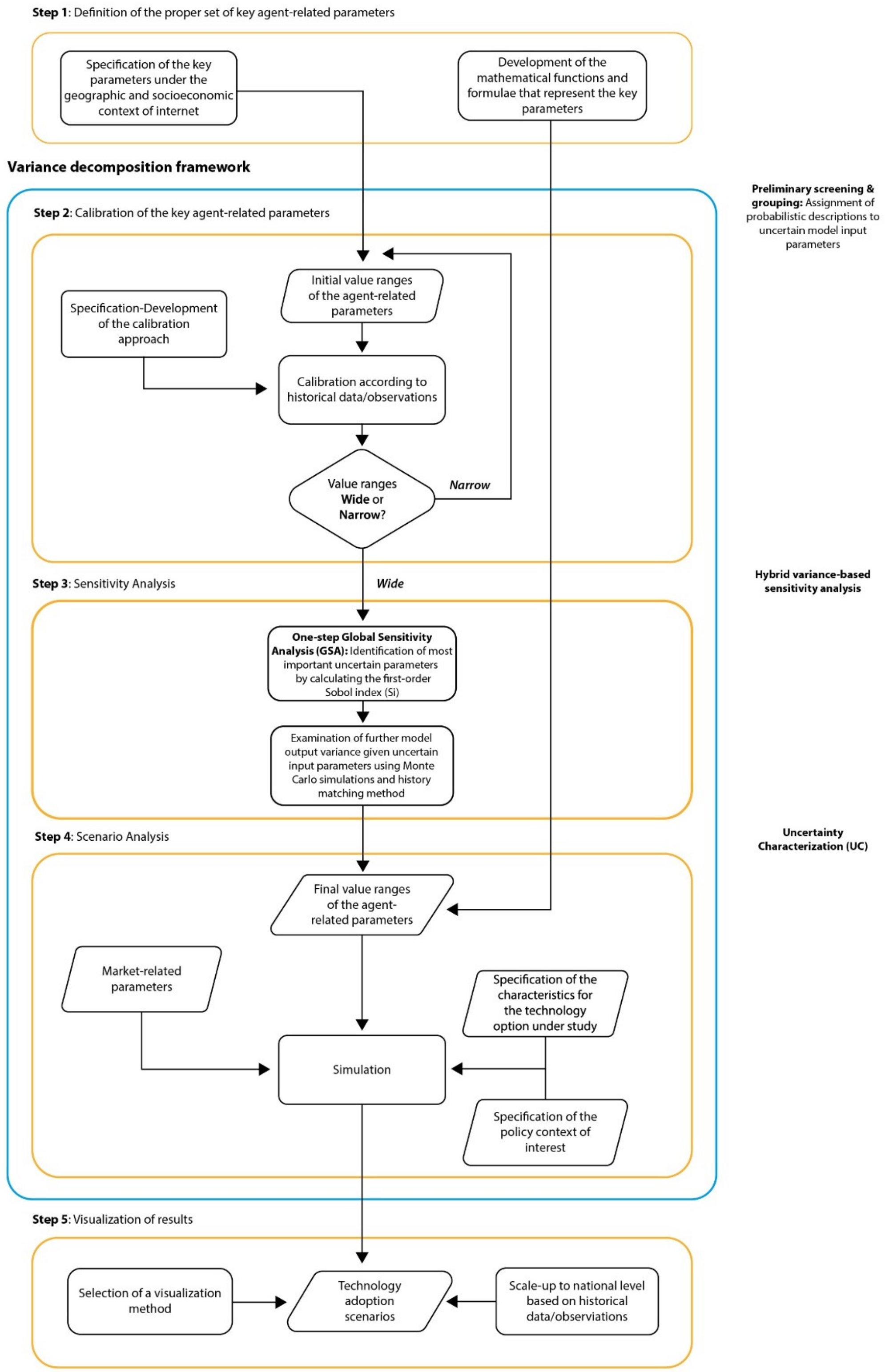

Figure 2. Current modeling architecture of ATOM. *Source*: (Stavrakas et al., 2019).

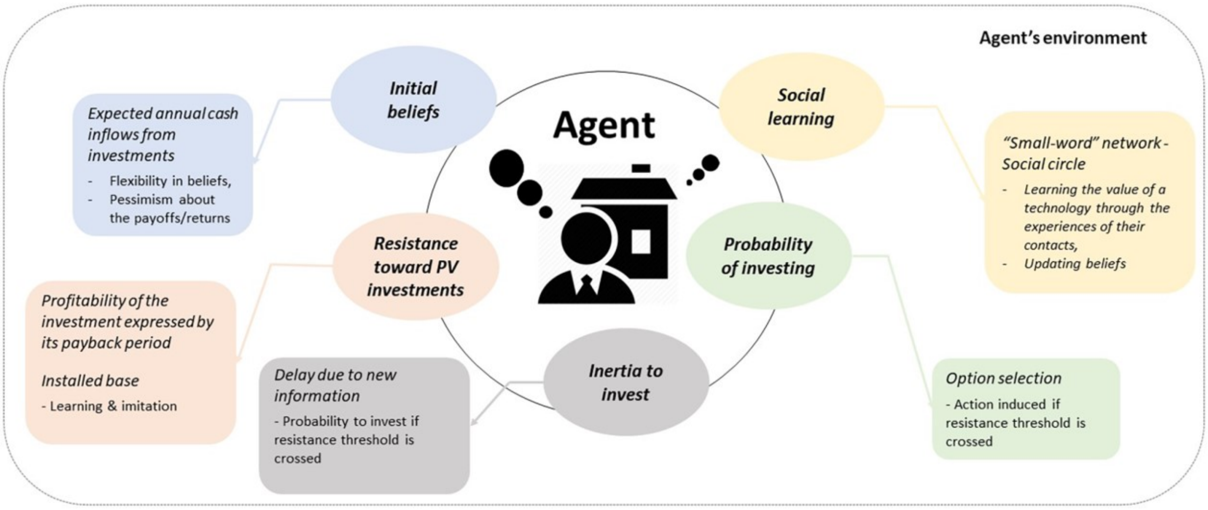

Figure 3. Set of agent-related parameters used for the ATOM model, when studying the concept of "*prosumerism*" and the adoption of small-scale PV systems in the residential sector. Source: (Stavrakas et al., 2019).

As an example, ATOM can be used to investigate the expected effectiveness of various policy support schemes (e.g., feed-in tariffs, net-metering, different typologies of self-consumption schemes that subsidize part of the initial investment costs of storage systems, etc.) in driving investments in small-scale PV systems, with the achievement of small-scale PV capacity targets in mind, for the geographical and socioeconomic context of interest.

Each agent has a personal initial belief about the predicted annual cash inflows from investing in a small-scale PV system in this scenario. A Gaussian distribution is used to represent this belief. Furthermore, each agent receives information from the agents in its social circle who have previously invested in a PV system to capture the impacts of social learning. This data is utilized to update the agent's perceptions about the real profitability of their investments thus far. Given a fresh observation, this is comparable to updating a Gaussian prior. Accordingly, each agent has a social circle. A "small-world" network, which is a type of mathematical graph, is used to represent this phenomenon (**Figure 4**).

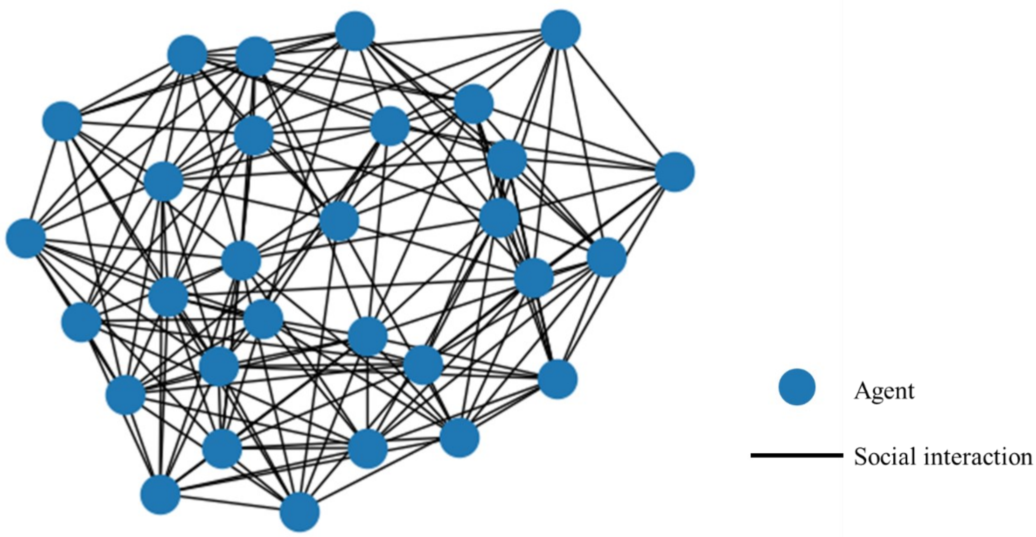

Figure 4. Example of a "small-world" network of agents.

4.2. Demand-side management modeling: DREEM

One of the main challenges of a transition based on a high RES penetration is integrating these variable energy sources without jeopardizing security, reliability, and resilience of the electricity system (Schlachtberger et al., 2016). DSM, which encompasses the whole spectrum of management functions associated with guiding demand-side operations, including program planning, assessment, implementation, and monitoring, is a key approach to this aim. Its major goal is to enhance the energy system from

the end-user's perspective in terms of consumption and cost efficiency (Lampropoulos et al., 2013).
DSM covers a wide variety of topics, from increasing energy efficiency to sophisticated real-time control of distributed energy resources via smart devices with incentives to encourage specific consumption/ production patterns (Palensky & Dietrich, 2011). DSM delivers considerable economic benefit to all players participating and interacting in the current energy network as a result of this, while also reducing the carbon footprint of traditional generators (Albadi & El-Saadany, 2007).
According to the scientific literature the main aspects of DSM are: **(i.)** Energy Efficiency, **(ii.)** Strategic Load Growth, **(iii.)** Demand-Response, **(iv.)** Time-of-Use, and **(v.)** Spinning Reserve (Palensky & Dietrich, 2011). The notion of energy management, on the other hand, shifts from utility-driven control to one that involves end-use customers (citizens and other market participants) in setting prices and clearing the market (Yu et al., 2017). Consequently, terms like Strategic Load Growth or Spinning Reserve appear to be out of date for the time being, with energy conservation and Demand-Response being the most dependable, cost-effective, and efficient ways to influence the demand curve. Both strategies essentially compensate end-users for changing their consumption habits and routines (Borsche & Andersson, 2015). Demand-Response, in particular, may shift consumption from periods when energy is scarce to times when it is plentiful, such as when renewable energy output is high. Demand-Response schemes enable local power consumption to be managed in response to supply conditions like high market pricing, peak demand, or regulatory signals. Lower grid running costs, higher system dependability, and improved energy efficiency can all be accomplished as a result of this (Shariatzadeh et al., 2015).
Furthermore, also considering the concept of "*prosumerism*" in the context of the upcoming energy transition (Parag & Sovacool, 2016), fostering the role and evaluating the impact of end-use product-service offerings into the future energy regime is imperative (Geelen et al., 2013). To this end, user interaction and resource management should be taken into account initially through the lens of DSM modeling. DSM modeling can help electricity distribution network operators model network peak demand, demand aggregators estimate potential demand-side flexibility, government agencies evaluate incentive scheme costs, and electricity retailers understand the impact of different technology adoption on their demand portfolio, to name a few examples. As a result, accurate DSM modeling might be useful for evaluating Demand-Response systems aimed largely at residential consumers, as well as providing guidance for the development of products and services connected to smart-grid or smart city paradigms. DSM modeling may be used to investigate power usage patterns, energy efficiency problems, and consumer behavior, particularly in the residential sector. DSM modeling typically includes inputs such as building envelope characteristics, climate properties, occupancy and behavior patterns, indoor temperature, end-use equipment characteristics and flexibility, load, or generation profiles in the case of RES, and aggregation for a time period, as well as validation. However, energy demand and management modeling are important components of DSM models, and their structure is generally defined by the technique employed for the energy demand portion of end-use. In order to achieve this, bottom-up and top-down methodologies alike have been developed. Bottom-up approaches aggregate load profiles, whereas top-down methods represent household power demand as a whole in terms of its general characteristics. Bottom-up models are seen to be more concise in general since they allow for the aggregation of diverse home kinds with varying characteristics and information (Swan & Ugursal, 2009).
However, most models in the scientific literature only address DSM in a limited or simplified way, and it is frequently employed for prediction purposes. The fundamental concern with DSM models is that they must be flexible while still include all critical features of end-use. The major features and guiding principles of a DSM model for determining what should be integrated and excluded, or simplified in the interests of computing efficiency and acknowledgment of data availability constraints can be condensed as follows (Stavrakas & Flamos, 2020):

- Bottom-up structure.

- Capability to be integrated with other models and be easily reused.
- Capability to produce outputs at a high resolution (i.e., one minute).
- Data requirements that are achievable such that the model can be self-contained.
- Seasonal variability to reflect the changing level of demand between winter and summer.
- Computational efficiency to simulate large numbers of buildings with the appropriate diversity of demand.
- Modular structure to reduce simulation complexity owing to the multidisciplinary nature and input data requirements.
- Considering occupant behaviour along with determination of end-use qualities to bridge the gap between statistical and engineering models.
- Inclusion of practical load control strategies that will allow price-based Demand-Response signals to enable the smooth operation of the smart grid/ city paradigm.
- Capability to link the energy system to economic development and technological breakthroughs (i.e., inclusion of alternative energy technologies, or other energy carriers at a later date).

Considering all the above, **DREEM** (Koasidis et al., 2022; Stavrakas & Flamos, 2020) is a bottom-up hybrid model that incorporates elements of both statistics and engineering models. By extending the computational capabilities of existing Building Energy System (BES) models to assess the benefits and limitations of demand-flexibility, the model provides an entry-level understanding of DSM modeling in the building sector, primarily for consumers and other actors involved in the energy system.

The novelty of the DREEM model mainly lies in its modularity, as its structure is decomposed into individual modules characterized by the main principles of component- and modular-based system modeling approach, namely "*the interdependence of decisions within modules; the independence of decisions between modules; and the hierarchical dependence of modules on components embodying standards and design rules*" (Pereverza et al., 2019).

This modular approach allows for more flexibility in terms of possible system configurations and computational efficiency towards a wide range of scenarios studying different aspects of end-use (as for example the scenarios/ transition pathways that will be simulated to explore the decarbonization potential of energy citizenship in ENCLUDE). It also allows for the thorough inclusion of future technical advancements, such as heat pumps or electric cars, in light of energy transitions that foresee complete electrification of the heating and transportation sectors. Because scientific literature indicates that there are limits to how much technological complexity can be integrated without running into computational and other challenges, the DREEM model stands out among other models in the area (Nikas et al., 2018). The model also offers the capacity to provide output for a collection of buildings and might be used to estimate residential energy consumption as part of a larger study of urban, regional, or national energy systems.

The DREEM model consists of multiple components, each of which is composed of additional modules. The overall architecture of the model, as visualized in **Figure 5**, makes it flexible to be adapted, modified, and extended in the future. The "Buildings" library (Michael Wetter, 2011) was used to create all of the model modules. It is an open-source, publicly accessible Modelica library for building energy and control systems. Modelica is an equation-based, object-oriented modeling language for dynamic systems simulation (M. Wetter, 2009), , and it has been utilized in a number of research and applications for the design and simulation of different BES and control systems (Bünning et al., 2017; Lauster et al., 2014; Michael Wetter et al., 2016; Zuo et al., 2016). Python scripts have been produced to represent sections of the Demand-Response and control components, as well as to enable the interface with the Dymola simulation environment, in addition to the Modelica models. **Table 2** provides a short description of each component, along with its individual modules.

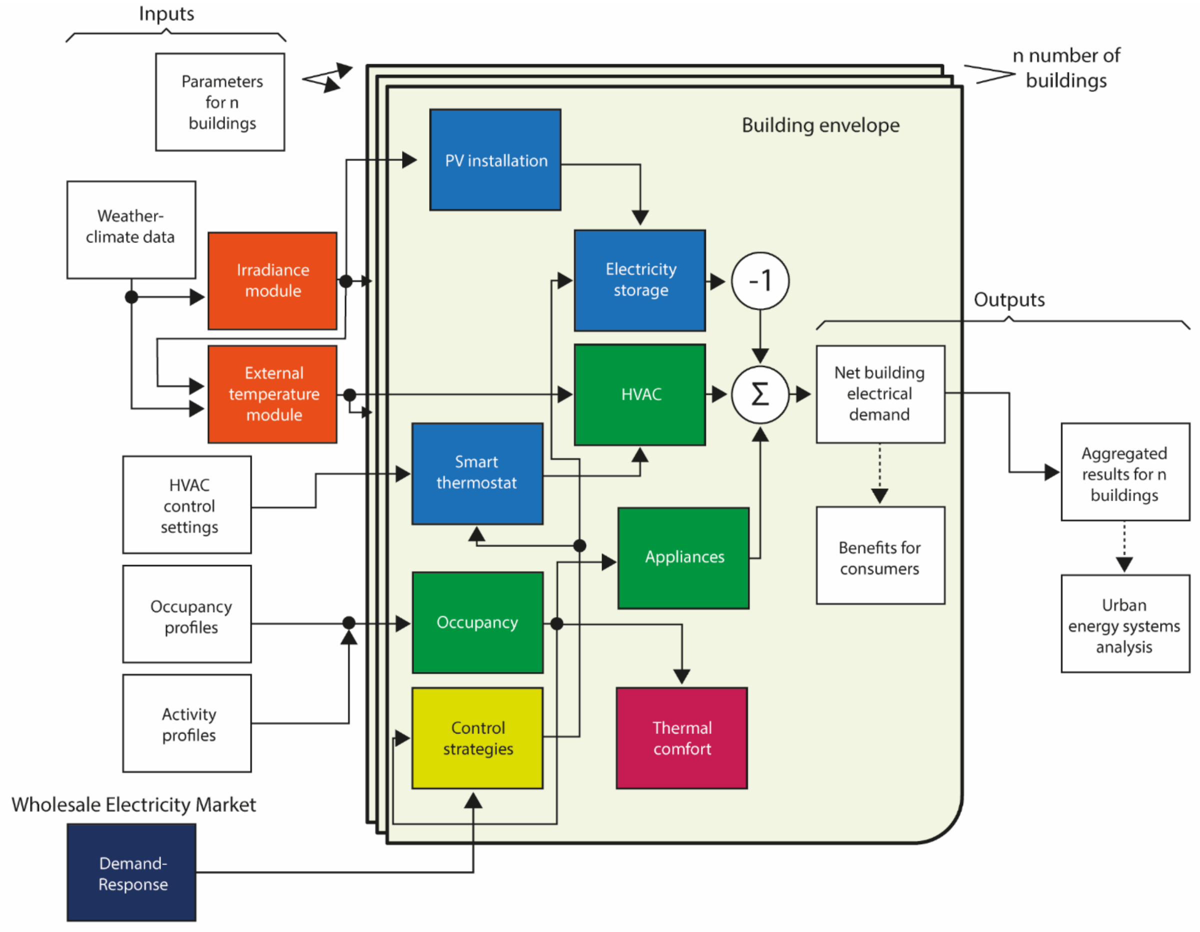

Figure 5. Current modeling architecture of DREEM. *Source*: (Stavrakas & Flamos, 2020).

Table 2. Hierarchical structure of the DREEM model: Short description of the main components and modules. *Source*: (Stavrakas & Flamos, 2020). Color coding in accordance with **Figure 5.**

Components	Modules	Description
C1: Weather/ Climate	-	This single-module component is responsible for generating climatic boundary conditions. It reads weather data from the respective files and then provides them to the other components, where and when necessary.
C2: Building envelope	-	This single-module component models different building typologies with the corresponding characteristics, properties, and heat-conduction elements.
C3: Energy demand	C3M1: Occupancy	This module defines and sets the parameters for the behavior and the activities of the occupants by generating and storing default patterns, such as for the case of a residential building: wake-up times and arrival times from work, washing and cooking hours, etc. To make the individual more stochastic, there is an uncertainty variable that may be employed. To account for the effect of "sharing of appliances," active occupancy modeling is also provided.
	C3M2: Appliances	This module is responsible for generating energy demand profiles from appliances, using statistics, and describing their total mean daily energy demand and related power-use properties, such as steady-state consumption or typical use cycles, as appropriate. The "Occupancy" module focuses on how likely it is that certain appliances will be used.
	C3M3: Heating, Ventilation, and Air-Conditioning	This module is responsible for heating, ventilation, and air-conditioning inside the building, according to the "Smart thermostat" module's input data and signals.
C4: Thermal comfort	-	This single-module component is responsible for determining, based on international standards, appropriate thermal conditions and temperature ranges that result in thermal satisfaction of occupants.

C_5: Flexibility management	C_5M_1: Photovoltaic system	This module contains information about the orientation of the roof to determine the PV generation based on the position of the sun and recorded irradiation data for the location of interest.
	C_5M_2: Electricity storage	This module contains models that represent different energy storages. It takes as an input the power that should be stored in/ extracted from the storage. The "Control strategies" component is in charge of ensuring that only a fair quantity of power is transferred and that the state of charge remains within acceptable limits.
	C_5M_3: Smart thermostat	The heating, ventilation, and air-conditioning control system is controlled by this module. It provides signals to the "HVAC" module to produce the heat and ventilation flows within the building by receiving the interior temperature as a measured signal and depending on the difference between the set and measured temperatures.
C_6: Demand-Response	-	This single-module component simulates Demand-Response mechanisms that motivate the consumers to respond to real-time price-based signals.
C_7: Control strategies	-	This single module component is responsible for the energy management supervision strategy that, given the time-shifting events of demand and the occupancy signals, aims at achieving energy savings and cost-effectiveness.

4.3. Integrated assessment modeling: IMAGE

IAMs cover a variety of key processes, ranging from human activities that act as a primary driving force, to the behavior of the natural system, and impacts on the natural environment and on human development (Parson & Fisher-Vanden, 1997). Climate change, land-use change, biodiversity loss, altered nutrient cycles, and water shortages are the most prevalent. These very complex challenges are characterized by long-term interconnected dynamics and are either global issues, such as climate change, or appear in a comparable form in numerous areas, giving them a universal aspect (Wang et al., 2017). These worldwide environmental concerns typically arise as human cultures utilize natural resources to sustain their growth, such as providing energy, food, water, and shelter.

While most IAMs have traditionally concentrated on climate change and air pollution, these models have recently been expanded to assess a growing number of impacts, including air and water quality, water scarcity, non-RES (e.g., fossil fuels, phosphorus, etc.) depletion, and overexploitation of renewable resources (e.g., fish stocks, forests, etc.) (Bosetti, 2021). In general, IAMs are designed to offer insights into how driving forces cause a variety of effects, taking into consideration some of the most important feedback and feed-forward mechanisms (Intergovernmental Panel on Climate Change, 2019).

In this context, the **IMAGE** model (Stehfest et al., 2014; van Vuuren et al., 2015) is an IAM framework that models the global environmental effects of human activities. It depicts how civilization, the biosphere, and the climate system interact to analyze sustainability issues including climate change, biodiversity, and human well-being. The model may be used to look at long-term scenarios for future environmental and sustainable development issues, as well as possible solutions.

The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes that result from interacting socioeconomic and environmental factors. IAMs, such as the IMAGE framework (**Figure 6**), are powerful tools for assessing complex, large-scale environmental, and sustainable development issues. For a more detailed view of the IMAGE modeling framework see **Appendix B: Detailed architecture of the IMAGE model**. Because many of these issues are intertwined, IAMs are required to examine the ramifications of these connections. Long-term scenarios can be used to best portray the significant inertia in the human-environment system.

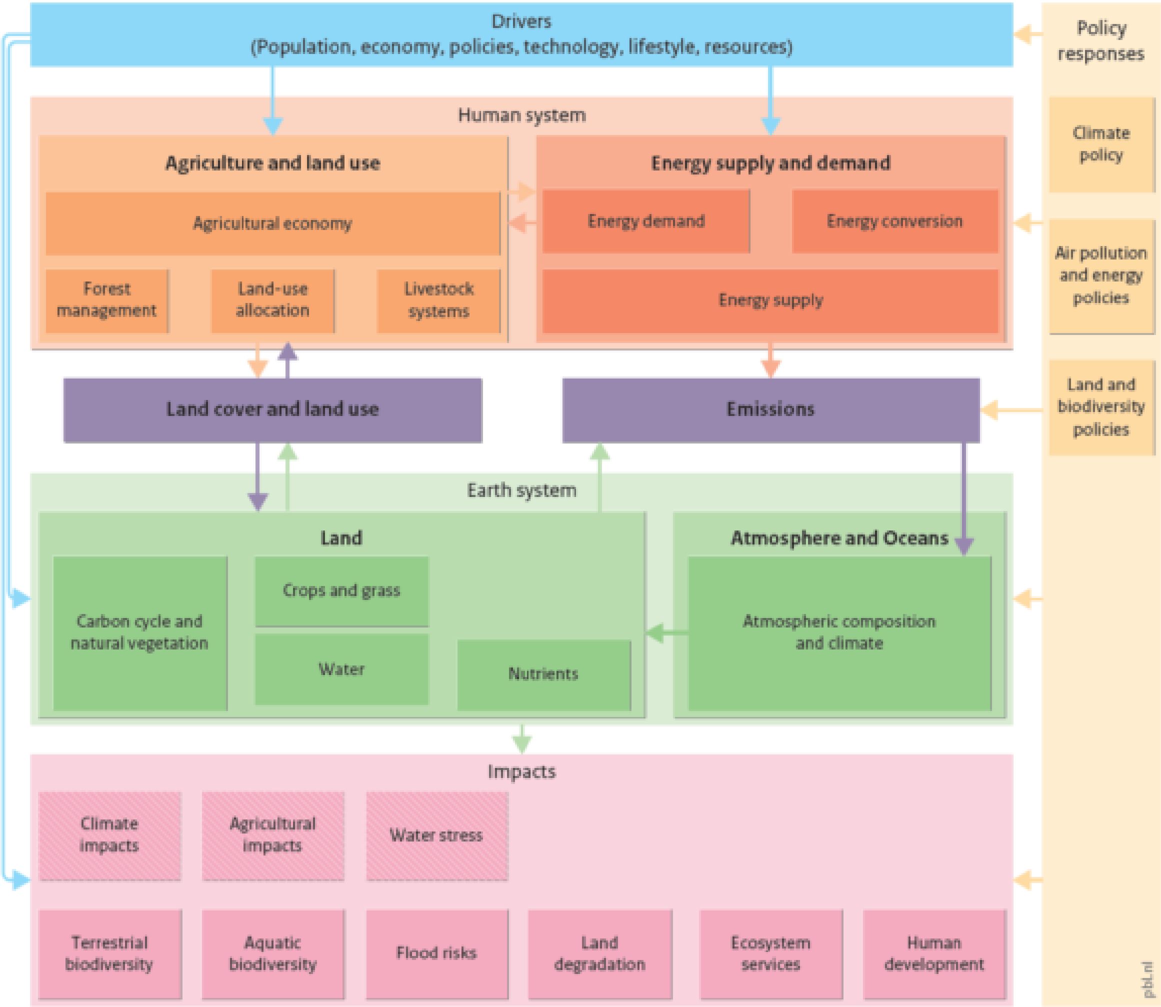

Figure 6. IMAGE model architecture. *Source*: (*IMAGE Framework Schematic*, 2014).

5. ENCLUDE modeling ensemble and energy citizenship trends/ patterns

Following the identification of the key energy citizenship trends/ patterns that could also be relevant to the field of energy system modeling, in this section, we provide an overview of the process through which the ENCLUDE modeling ensemble is already able to address the identified trends/ patterns. We also analyze modeling gaps and synthesize further model developments, modifications, and adjustments in order for the ENCLUDE modeling ensemble to be able to understand the multi-scale relationship between energy citizenship and decarbonization pathways in different contexts as a basis for providing appropriate decision-support.

5.1. "Status quo" of the ENCLUDE modeling ensemble

The data collection process in terms of documenting the full capabilities of each one of the ENCLUDE models in detail in order to optimize the connections between the modeling ensemble and their ability to address the identified trends/ patterns of energy citizenship allowed us to summarize the "status-quo" of the ENCLUDE modeling ensemble. **Figure 7** visualizes a mapping of the critical issues that each one of the ENCLUDE models has been designed to address.

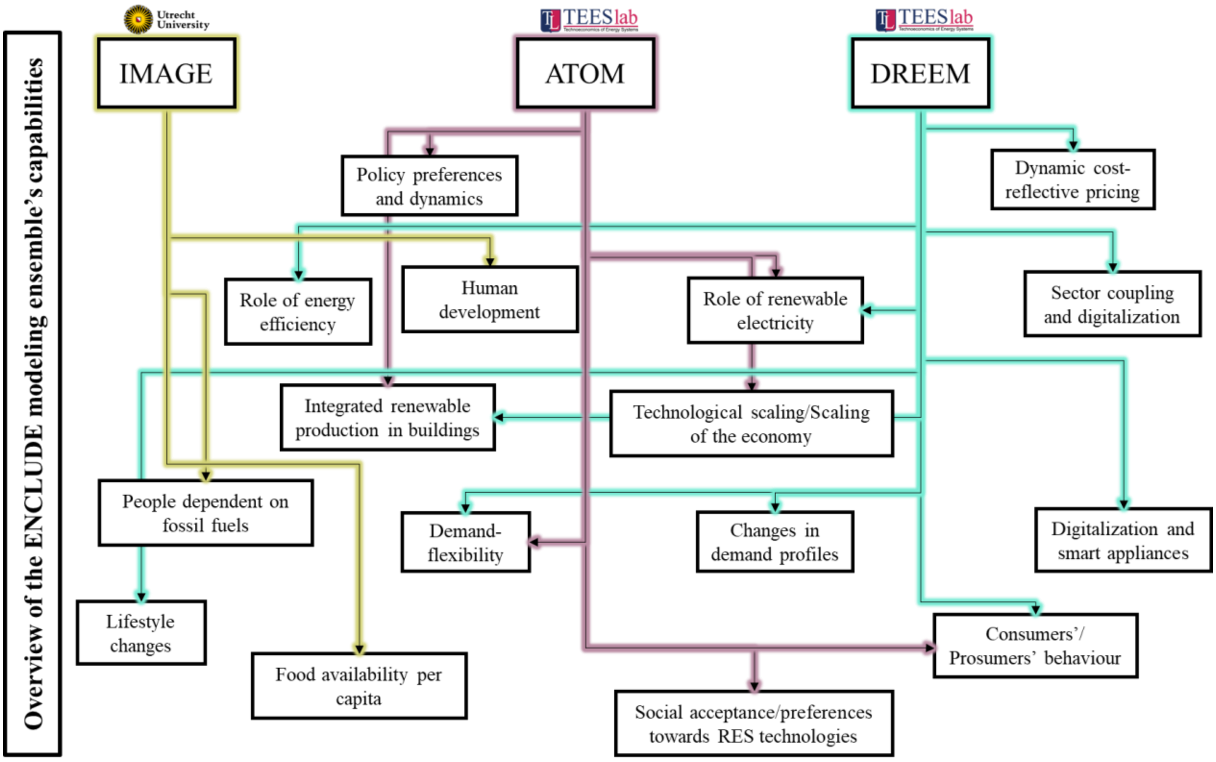

Figure 7. Overview of the ENCLUDE modeling ensemble's capabilities: Mapping of the critical issues that each model has been designed to address.

5.2. Addressing the identified energy citizenship trends/ patterns

Based on our desk research, we see that concepts such as prosumerism, energy communities and collectives, are found prominently in the relevant literature (Kühnbach et al., 2022; Moret & Pinson, 2019). Additionally, according to (Süsser et al., 2022), the users of models and their results express that social acceptance, or rejection of new energy infrastructure, individual and collective participation in the energy system, consumer behavior and lifestyle changes, and policy preferences and dynamics in energy system models are also important. For example, social resistance can have an impact on real-world implementation of electricity grids and onshore wind developments by delaying the projected timeline of the implementation.

When it comes to the ENCLUDE modeling ensemble, our matching of the models' capabilities to the identified energy citizenship trends/ patterns has shown us that the ENCLUDE models are already capable of adequately addressing various aspects of energy citizenship (**Figure 8**). For example, the behavioral aspects of energy citizenship are considered endogenously within the ATOM model, while lifestyle changes can already be modeled with the DREEM model. Furthermore, the aspect of prosumerism is explicitly modeled withing the ENCLUDE modeling architectures. In general, the trends/ patterns that are associated with the individual level are more clearly represented within the modeling ensemble, while the collective level is the area of focus for further developments, modifications, and adjustments.

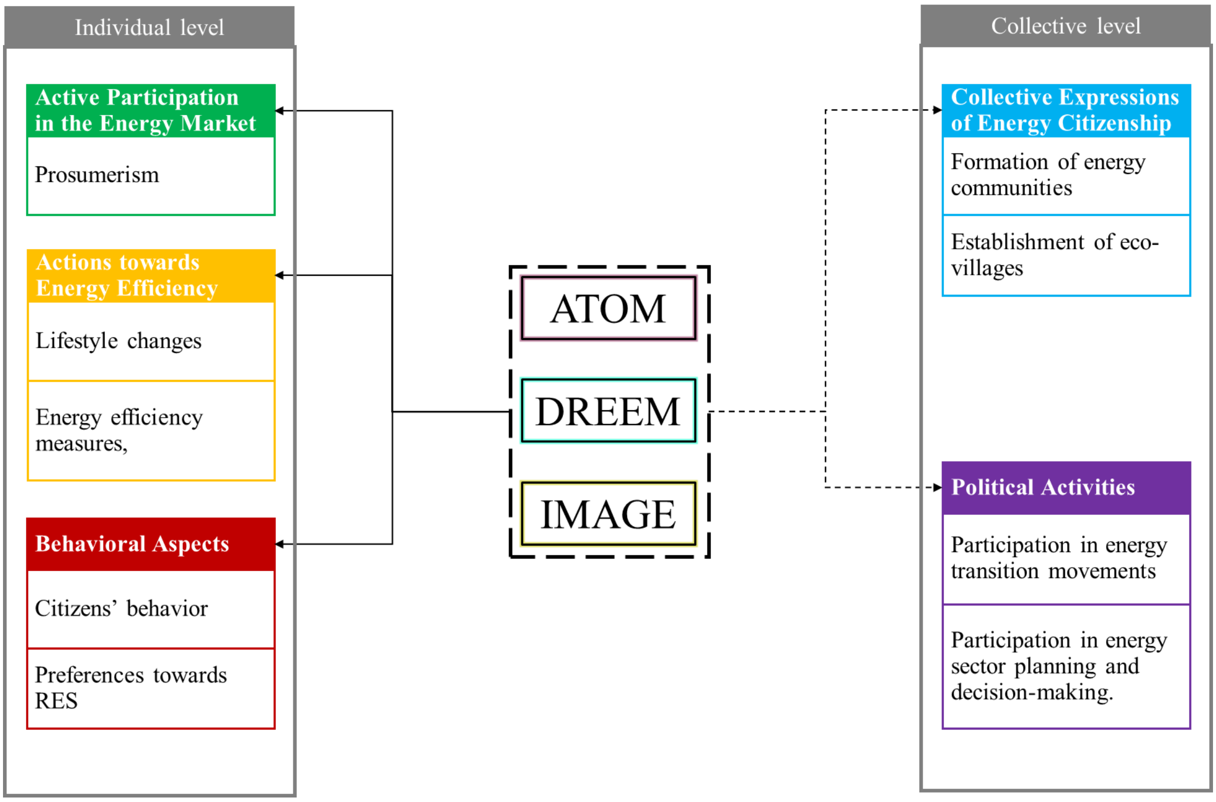

Figure 8. Summary of the energy citizenship trends/ patterns that the ENCLUDE modeling ensemble is already capable to address (continuous-line arrows) and that will be further developed, modified, and adjusted so that it is able to address (dash-line arrows).

5.2.1. Different scales of analysis

Starting from the micro scale, ENCLUDE acknowledges the necessity to improve understanding on the individual and the collective factors relevant to the decision-making process of the emergence of the energy citizenship, and on the specific social innovations and technological capacity for engaging citizens and incentivizing household- and community-level changes.

In this respect, ATOM will explore the ways in which envisaged social innovations and technological infrastructure can be adopted by, and diffused into, households/ communities of different profiles. In addition, the DREEM model will be used to explore the benefits of social innovations, and of the technological capability required towards energy autonomy at a micro-scale (i.e., household and citizen communities).

The micro-level perspective of the two energy system models will be coupled with the IMAGE model in order to assess the scaled-up decarbonization potential and climate implications of different energy citizenship trends/ patterns, in terms of key climate impacts, aggregated emissions, and adaptation requirements that follow from social innovations at the local level. This will enable to expand the ENCLUDE's modeling focus of analysis to the macro level and will allow a detailed study of the relationship between the concept of energy citizenship and the remaining emission gap that needs to be narrowed and eventually closed, also considering all recent policy developments at the EU level and the commitment for Europe to become the first climate-neutral continent by 2050.

5.2.1.1. Addressing the micro scale of energy citizenship

Many technological advancements and government programs fail because they do not take into account what is important to the public (i.e., the motivating factors shaping their adoption preferences). People and their social connections have a significant impact on the diffusion of technological/ social innovations, as well as the general dynamics of technological/ social transformation. Transitions, on the other hand, are difficult to scientifically comprehend due to the effect of a wide variety of contextual factors on policy processes, society, and agency.

Taking into account the variety of interests, motives, and other elements that influence people's decisions can assist lessen the ambiguity that can lead to policy failure. Upgrading **ATOM** and adapting it to knowledge gaps/ user needs/ research priorities/ social trends/ patterns, identified through scientific literature and prior experience is critical in this regard, as modeling agents' decisions and interactions represents a more "real-world" process that addresses the limitations and constraints of centralized, optimization models (Stavrakas et al., 2021), by introducing a layer of control and decision-making, thereby allowing greater understanding of macrophenomena. ATOM, as it currently stands, is able to simulate the adoption of technological innovations, such as small-scale PV systems, residential storage systems, electric vehicles, etc., and to explore the various behavioral aspects and internal thought processes and preferences of citizens (**Figure 9**).

In this context, ATOM's initial modeling framework has been enhanced, and will continue to be enhanced, to investigate the impact of more agent-related characteristics on technology adoption and social innovation diffusion. The attitude of Greek consumers toward installing small-scale PV systems, for example, differs according to their income and education levels, and appears to be connected with their consumption patterns and demographic factors, according to scientific research (Tsantopoulos et al., 2014). To perform socially-informed modeling activities, the model will be used to investigate various behavioral and socioeconomic characteristics. Furthermore, in accordance with the United Nations' goal to ensure that "no one is left behind," involving "hard to reach" citizens and understanding how their objectives and views might be translated into the needs, or opportunities, of a low-carbon transition, is essential.

As a result, we have strengthened the ATOM modeling framework by reflecting on the decision-making process of distinct consumer/ citizen profiles in order to effectively develop and conduct socio-technically informed modeling exercises. User profiles that go beyond capturing the mainstream dominant groups, focusing on communities and groups that face social/ economic alienation, including women and other genders, and/ or demographics that are typically excluded due to racialization, face other forms of discrimination, or face challenges, such as forced migration as a result of conflicts, have received special attention (e.g., refugees, etc.). These aspects will be further enhanced by the data that the case study survey in the scope of the ENCLUDE WP3[15] will yield.

The factors/ parameters that are anticipated to control human behavior will be utilized as inputs into the model to investigate the effects of human-centered interventions in various geographic and socioeconomic contexts and levels. This exercise will show how the model can evolve from a technology adoption stand-alone model to a model that simulates the diffusion of social innovations, scaling them up from individuals to large social structures like energy communities, ecovillages, and so on, based on user needs and stakeholder/ citizen feedback. In this approach, the ATOM modeling framework might

[15] https://encludeproject.eu/about/work-structure

be used to investigate how envisioned social improvements and technical infrastructure are embraced by and distributed throughout households/ communities with various socioeconomic, behavioral, and lifestyle profiles.

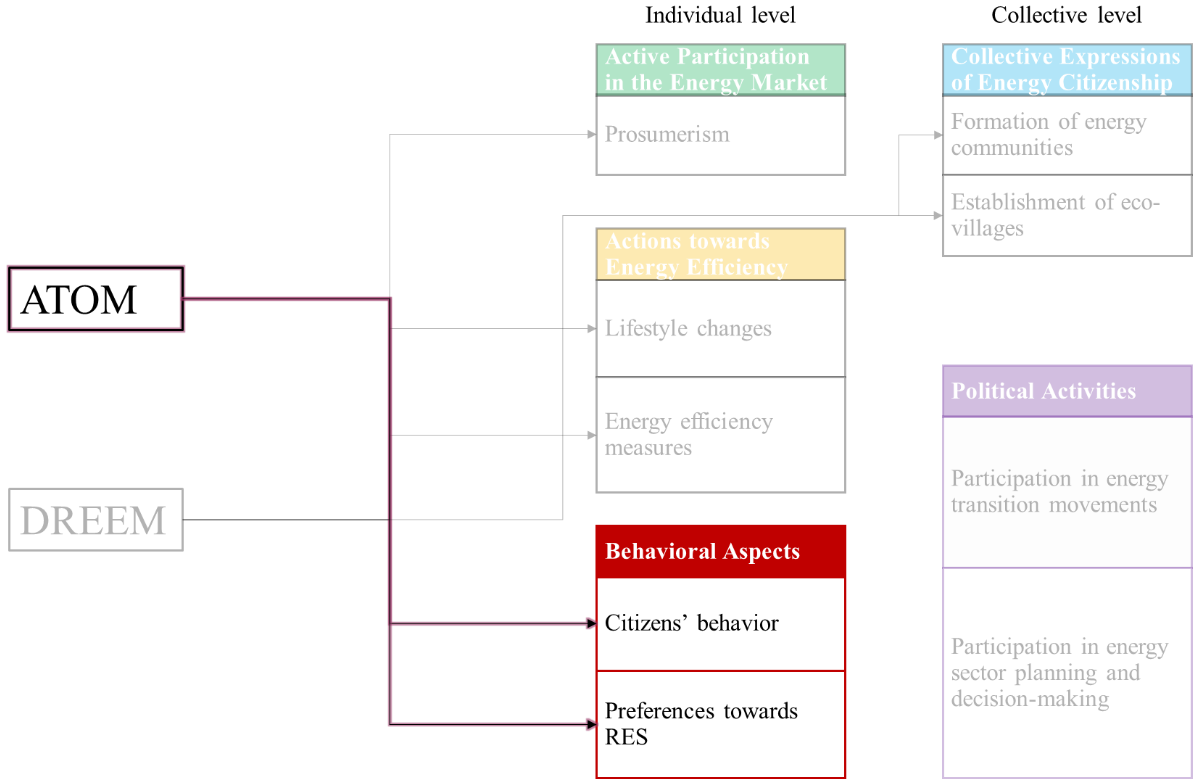

Figure 9. Energy citizenship trends/ patterns that the ATOM model is already able to address.

On the other hand, it is difficult to address lifestyle changes as a whole since they can describe a quite broad spectrum of activities when it comes to modeling. **DREEM** requires specific input data to model any parameter, and lifestyle changes need to be defined more narrowly in terms of a "*particular change in lifestyle*," which mostly can be related to specific citizen activities and behaviors. For example, adjusting the thermostat to a lower setting can achieve considerable energy savings to those achieved through renovation measures. But, also, it is important that occupants do not sacrifice their thermal comfort and energy needs.

DREEM tackles the issue of thermal comfort by including a modeling component dedicated to finding optimal interior thermal conditions (**Figure 10**) and temperature ranges that result in the occupants' thermal satisfaction based on the "DIN EN ISO 7730" (DIN EN ISO 7730, 2005), "ASHRAE 55" (Taleghani et al., 2013), and "EN 15251" (CEN, 2007) international standards. The DREEM model will be utilized to predict the potential for energy savings through the setback analysis of thermostat setpoints in this setting, as well as behavioral factors of people. This study proposes that energy savings may be realized if consumers are prepared to lower their thermostat setpoints without sacrificing thermal comfort. This activity will also allow behavioral elements of heating and cooling to be explored.

Furthermore, by bringing together all of the fundamental features of end-use with a demand-response modeling framework that relies on the notion of time-based demand-response techniques, the DREEM model will be utilized to investigate further applications related to behavioral components. Time-based demand response methods are the most successful demand-side management solutions because their intrinsic features are better suited to real-world uncertain and variable energy consumptions. This exercise will explore the decision-making framework and solve the dynamic pricing problem in a hierarchical electricity market that takes into account service providers' profits, but more significantly, customers' costs/benefits, capturing the energy citizen's perspective. Different probabilistic approaches will

be used to simulate citizens' decision-making behavior in order to investigate different degrees of benefits based on consumers' likelihood to comply with these demand-response signals (i.e., their intention to shift loads to the next hours without compromising thermal comfort and energy needs).
In addition, the DREEM model will be employed to tackle various aspects of prosumerism in the residential sector, assessing in parallel potential costs and benefits, and explore business models that could incentivize citizens to invest in technological infrastructure towards energy sufficiency, such as small-scale PV and battery storage systems. These are prime examples of prosumerism and can be expanded from the individual level of energy citizenship to the collective level by simulating a collection of households investing and participating in such activities.
Finally, using representative data from the literature, the DREEM model can address selected rebound effects due to behavioral consumption trends/ patterns, such as the quantification of direct rebound effects associated with the shift from incandescent or halogen bulbs to more energy efficient compact fluorescent lamps or light emitting diodes. These shifts in types of lighting technologies are the external result of internal behavioral aspects that characterize energy citizens.

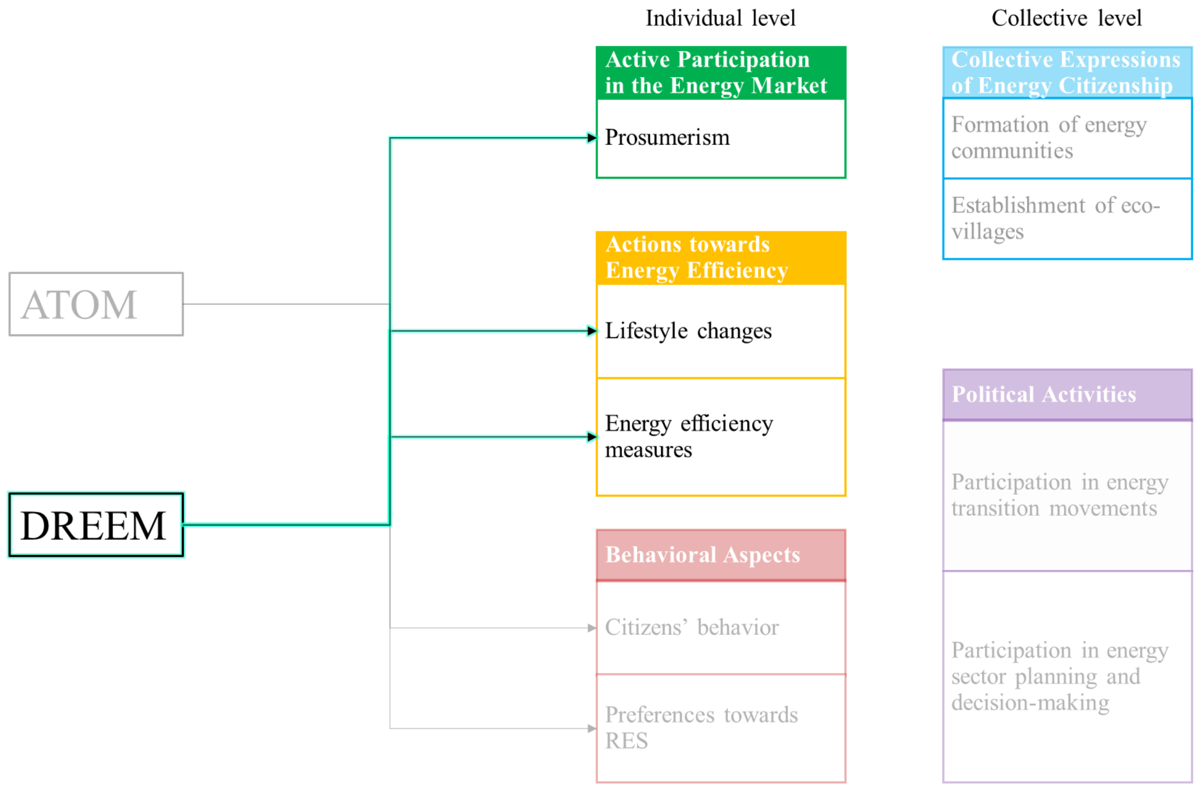

Figure 10. Energy citizenship trends/ patterns that the DREEM model is already able to address.

5.2.1.2. Upscaling the decarbonization potential of energy citizenship

With the overall aim to assess the scaled-up decarbonization potential and climate implications of the different aspects of energy citizenship, in terms of aggregated emissions among other indicators, the micro-level perspective of the ATOM and DREEM models will be coupled with the IMAGE model, enabling, thus, the upscale of the findings from the local/ regional level to the national/ supranational level (**Figure 11**). This will allow a detailed study of the relationship between the concept of energy citizenship and the remaining emissions' gap that needs to be narrowed and eventually closed.

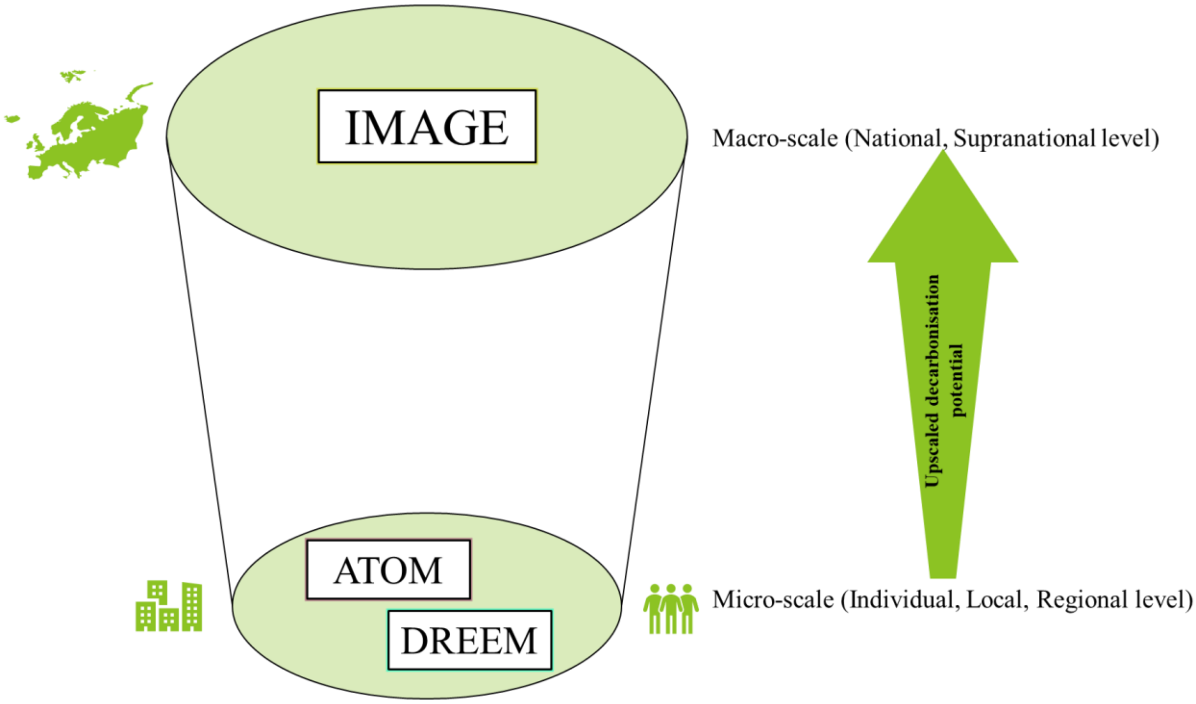

Figure 11. Upscaling the decarbonization potential of energy citizenship with the ENCLUDE modeling ensemble.

The IMAGE model consists of various modules and sub-models; here we focus on three modules, which in the context of the ENCLUDE project, will be used to explore and assess the upscaled decarbonization potential of different aspects of energy citizenship, namely: **(i.)** the "*Building stock*," module, **(ii.)** the "*Insulation*," module, and **(iii.)** the "*Appliances*" module.

The "*Buildings stock*" module has a dynamic and explicit description of the building stock enabling a detailed estimation of key indicators, e.g., residential energy demand, emissions, etc. The main inputs to the module are exogenously developed floorspace projections that assume a causal relationship with household expenditures, calibrated based on census data. The floor space simulates the yearly inflows and outflows of the global building stock from 1971 to 2100, distinguishing per region, income class, and age. The floor space affects the energy demand for space heating of the buildings. The module also includes a decomposition of the stock into new buildings, decommissioned buildings (buildings that are near the end of their lifetime and are demolished and reconstructed), and abandoned buildings (those are similar to decommissioned buildings but are not reconstructed). By tracking the building stock, a bottom-up and consistent calculation of buildings' envelope efficiency across building vintages can be done. This in turn allows for determining the energy demand for heating and cooling for different vintages.

Climate effects on energy demand for space heating and cooling in the "*Buildings stock*" module are accounted for through Heating Degree Days (HDD) and Cooling Degree Days (CDD), measures of how warm, or cold a period of days is. These values differ per region and per year, and affect how much energy demand is needed based on the temperature. However, these values also reflect the temperature set indoors and, therefore, represent consumer behavior. For example, if households would adjust the thermostat to a lower temperature in the winter months, a lower HDD would be needed. These values contribute to the total energy demand for the space heating and cooling energy services within the residential sector.

On the other hand, the "*Insulation*" module uses the different groups of the buildings stock under study to simulate the investment decisions of the residents based on the relative cost of improving the energy efficiency of building envelopes through insulation. These investments in insulation are possible during the construction of new buildings and during the renovation of older buildings. Specifically, there is a decision between six possible insulation levels, ranging from "very low" to "zero energy building" equivalent. In the case of older buildings there is a second decision to determine if the buildings will undergo renovation. Each insulation level has its own investment costs and thermal properties. The decision to invest in insulation is based on economic factors, such as the investment cost of insulation installations, different discount rates of the economic quintiles, and the benefits of increasing insulation through reduction of fuel consumption. Furthermore, preferences and behavioral aspects are incorporated in these economic decisions in the form of a premium cost. The outcome of this module is different insulation levels applied to the building stock's sub-groups allowing for estimation and future projection of the average stock's useful energy intensity. This intensity is later used by other residential modules for the projection of the sector's energy demand and CO_2 emissions.

Finally, the "*Appliances*" module provides a detailed representation of the electric appliances used in the residential building stock. Devices represented include fans, air coolers, air conditioners, refrigerators, microwaves, washing machines, clothes dryers, dish washers, TVs, VCR/ DVD, and PCs. Decisive factors are accounted for, such as the diffusion of the appliances in different regions and income classes, the outage of power, devices' efficiency, and potential subsidies enabling the estimation of the total electricity required by appliance type, region, and income class; thus, contributing to projections of the total energy demand and emissions in residential buildings.

5.2.2. Interlinkage of the ENCLUDE models

By starting with a bottom-up approach, from the micro-scale of individuals and of local/ regional collective energy initiatives, and then upscaling to the national and/ or supranational level (macro-scale), ENCLUDE ensures a more comprehensive assessment of the decarbonization potential of the different aspects of energy citizenship. To do that, we need to bring together the models that represent these different scales of analysis, i.e., soft-linking the ENCLUDE models to create a unified modeling ensemble (**Figure 12**).

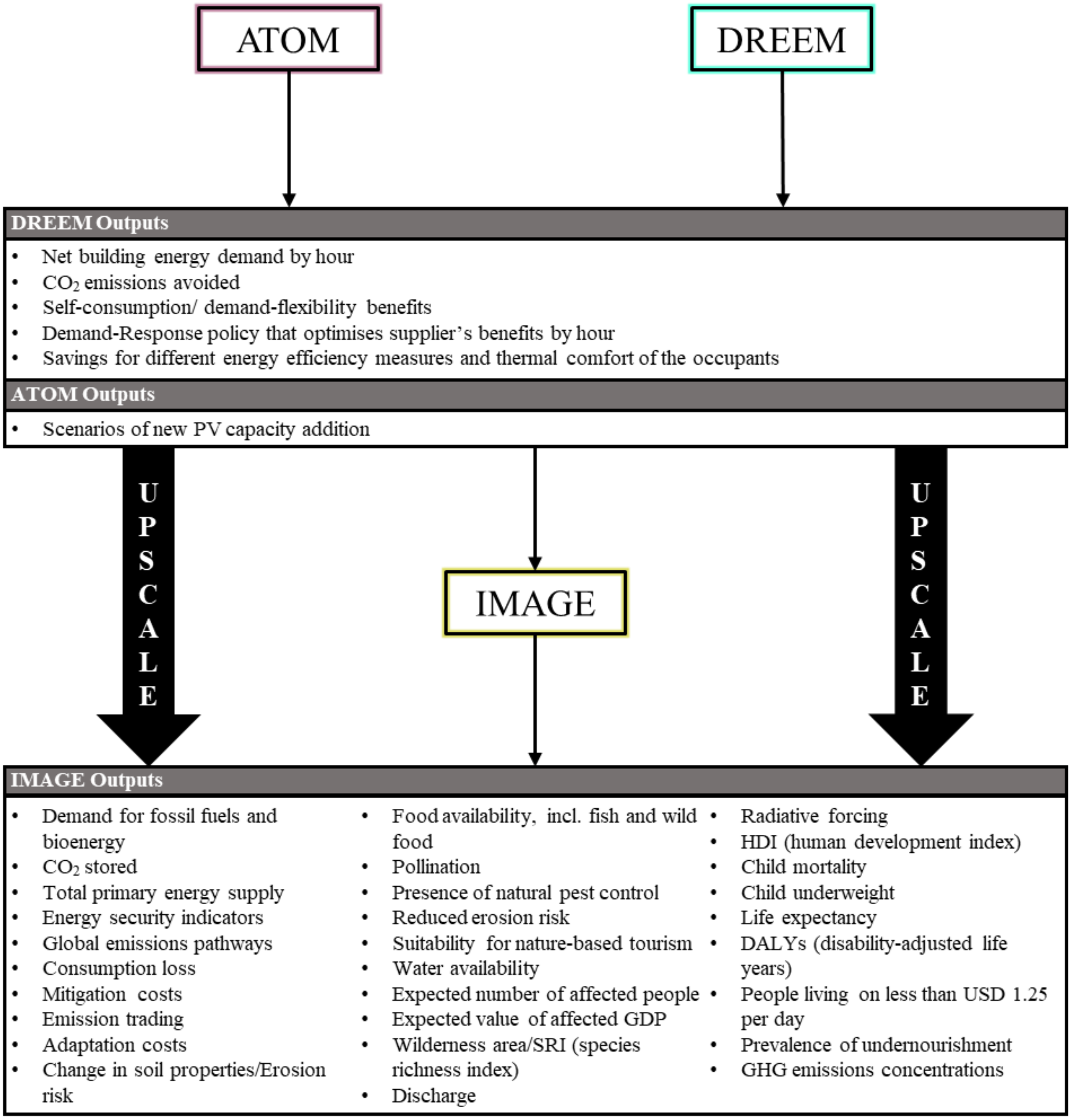

Figure 12. Developing a unified modeling ensemble by soft-linking the ENCLUDE models.

As described in **Section 2**, the second step towards this interlinkage was to thoroughly document the current status of the models in order to identify the areas where necessary further developments, modifications, and adjustments need to be made. To this end, a template was created to gather all the necessary information of the models, e.g., geographical, and temporal resolution, sectorial coverage, socioeconomic factors included, etc. For a more detailed description of the information gathered, see **Appendix A: Documenting the ENCLUDE models**, while in **Figure 13** a short presentation of the different model information that describe the current status of the ENCLUDE modeling ensemble is provided.

Model	Sectors: Energy sources	Energy transformation	Energy storage	Industry	Transportation	Buildings	Agriculture, Forestry, Land Use (AFOLU)
ATOM	Yes					Yes	
DREEM			Yes			Yes	
IMAGE	Yes	Yes		Yes	Yes	Yes	Yes

Model	Mitigation Adaptation: Adaptation	Behavioural Changes	Buildings	Industry	Agriculture	LULUCF	Synthetic fuel production	Hydrogen production	Electricity generation	Heat generation
ATOM										
DREEM			Yes							
IMAGE	No	Yes (partly)	Yes	Yes	Yes (Not land practices)	Yes	No (Only biomass)	Yes	Yes	Yes
Model	**Road**	**Rail**	**Aviation**	**Shipping**	**Modal shifts**					
ATOM										
DREEM										
IMAGE	Yes	No (only electric rail)	Yes	Yes	Yes					

Model	Socioeconomic: Demography	GDP	Employment	Investment	Public finances	Economic activity	Incomes
ATOM	Exogenous	Exogenous	Endogenous	Exogenous		Exogenous/Endogenous	Endogenous
DREEM	Exogenous	Endogenous	Exogenous	Endogenous	Endogenous	Exogenous/Endogenous	Exogenous
IMAGE	Exogenous	Exogenous					

Model	Emission: CO2	CH4	N2O	F-gases	Land-use CO2	PMs (BC, OC, PM2.5)	SOx	NOx	NH3	CO / VOC
ATOM										
DREEM	Exogenous									
IMAGE	Endogenous	Endogenous	Endogenous	Endogenous	Endogenous	Endogenous	Endogenous	Endogenous	Endogenous	Endogenous

Model	Policies: Emissions mitigation	Energy	Land	Trade
ATOM		Feasible w/ modifications		
DREEM	Feasible w/ modifications	Feasible		
IMAGE	Feasible	Feasible	Feasible w/ modifications	Feasible w/ modifications (only regulations policies)

Model	SDGs: §1. No Poverty (e.g., intra-country distributional impact by income level)	§2. Zero hunger (e.g., food prices, shortages)	§3. Health (e.g., air-pollution related mortality)	§4. Quality education	§5. Gender equality	§6. Clean water and sanitation (e.g., groundwater depletion)	§7. Affordable and clean energy (e.g., traditional biomass use, %renewable energy)	§8. Decent work & economic growth (e.g., impact on GDPpc, jobs)
ATOM							Projections on new solar PV capacity additions in the building sector	
DREEM			Yes				Decentralized RES generation, Self-consumption cost-benefit ratios	
IMAGE	Exogenous scenarios	Partly	Yes			Partly	Yes	
Model	**§9. Industry, innovation & infrastructure (e.g., R&D investments)**	**§10: Reduced inequalities (e.g., intra-country distributional impact, gini coefficient)**	**§11: Sustainable Cities & Communities (e.g., PMs from city transport + buildings)**	**§12: Responsible production & consumption (e.g., % recycled waste, embedded emissions)**	**§13: Climate action**	**§15: Life on land (e.g., land use for forests, rate of land use change)**	**§16: Peace, Justice and institutions**	
ATOM								
DREEM			Levelized Cost of Saved Energy (LCSE) of different Energy Efficiency Measures (EEMs) in the building sector, Demand-Flexibility cost-benefit ratios		Footprint impact of private consumption in the building sector			
IMAGE			Partly	Partly	Yes	Yes		

Figure 13. Current status of the ENCLUDE modeling ensemble.

In many cases, there are redundancies in terms of models that produce the same or similar results. Consequently, it's critical to comprehend how these modeling output overlaps might be used to influence the model linking process. Typically, the result of one model is utilized as an input in another model to link multiple energy system models. The DREEM model, for example, may results on service energy consumption on an annual and/ or hourly basis. However, its bottom-up structure enables it to analyze the many components of end-use in the residential sector in greater depth, as well as to incorporate behavioral characteristics of end-use to improve modeling outputs' resolution and accuracy. On the other hand, IMAGE can provide global constraints for European and national energy models, by simulating their global system, and provide regional resource demands. This could include the quantity of available biomass and/ or synthetic fuels for import into Europe from elsewhere in the world.

Model interface protocols are also necessary for coupling energy system models together and allowing them to be operated on a "mix-and-match" basis. These are the methods that convert a model's output into a format that can be used as an input to another model, resulting in reliable soft-links. Such interface protocols must be open source and transparent, allowing anybody to utilize them to link more models to existing models, resulting in specialized modeling ensembles capable of answering specific research questions of interest.

They must also be mindful of uncertainty, developing a set of algorithms that will allow the tracking of cascading uncertainties across various models. One model (X) may, for example, delve down to the level of individual heating and cooling systems needed by certain building standards. An energy supply system model (Y) might then utilize the resultant temporal patterns of aggregate building energy demand to determine the best mix of energy supply, taking into account other energy demand sectors such as transportation and industry.

Many recent models, in particular IAMs, such as the IMAGE model (van Vuuren et al., 2015), have many modules that may operate independently. The modules were designed to be coupled in all of these scenarios, with the structure and function of one core module defining the structure and function of the others. Instead, we need to create a platform that allows model users to link together models that were never intended to be run together. New models can be brought in and added to offer more detail about features of the system or problems that previous modelers may not have considered (Süsser et al., 2022). ENCLUDE will benefit from such an existing platform and interlinkage protocols, and the work already performed under the EC-funded H2020 "SENTINEL[16]" project, in which all the three ENCLUDE models are part of.

5.2.2.1. Data sharing and model interface protocols

The core purpose of the ENCLUDE modeling interface is to allow data exchange between the three different modeling tools in a way that can be automated. This is challenging because not only do different models use different data formats, but also, metadata may. or may not exist, and conventions on units, or variable naming differ between different models and research communities. To address this, we developed a flexible data standardization that can form the "glue" between the models, allowing them to be used together, and a user interface that makes it easier for the modeling teams to actually make use of this data format.

The protocol aims to find a balance between information needed to derive consistent results and the detailed data description and assumptions that will be developed within WPs 2, 3 and 6, which deal with various energy citizen typologies and collective expressions of energy citizenship, such as data gathered from the case study analysis. In this way, it helps to avoid duplicating inputs and outputs, or making contradictive assumptions.

The application of the models in the ENCLUDE modeling ensemble to a variety of case studies, taking into account stakeholder and model user insights and requirements, is a critical step in ensuring that they will operate not just in theory, but also in practice. To this end, under WP3, ENCLUDE includes a set of case studies at the regional geographical level, while this localized potential is envisaged to be upscaled to the national and/ or the supranational level. Every modeling exercise requires an extensive amount of input data. Since different and diverse models will be applied in ENCLUDE, they will require input data from diverse sources. These sources include, of course, the survey data that will be gathered from the case studies of ENCLUDE, qualitative data from stakeholders' and citizens' insights from the ENCLUDE Academy[17], and, finally, existing databases, like the "ECHOES" database[18].

In this context, a Data Gathering Protocol is an important step to organise the workflow of the data collection process in the implementation of the case studies, ensuring that data providers have a single point of communication within the project. Furthermore, as it is important for the ENCLUDE project to improve quality and transparency of energy system modeling, it is essential to document the sources and the path of data from the providers to each model. Data collected from public sources will be made available on the project website. Depending on the models applied in each case study, publicly available data will include, among others, transmission capacities between, or within countries (including both statistics for the current situation and planned projects, which can be used in the scenarios formulation), installed generation capacity by country, or region, historical and projected energy demand profiles, weather data, agents on the electricity wholesale markets, fuel costs, etc.

In regard to collecting and storing data, we will closely follow the principles described in the ENCLUDE

[16] https://sentinel.energy/

[17] https://encludeproject.eu/enclude-academy-energy-citizen-leadership

[18] https://db.echoes-project.eu/echoes/home

"Data Management Plan," which suggests storing model input data in, either ".csv" files to allow for an easy and low-threshold access, or in a more complex data management platform.
Finally, energy system models require typically a lot of (historical/ census) data for calibration purposes, estimating parameters, and performing projections. Although a large amount of data already exists in the public domain, some of it might need to be collected from specific public and/ or private organizations operating in the energy sector. More specifically, regarding data security, data gathered within ENCLUDE will be distributed to the modeling teams and will be initially stored by the coordinator of the case studies (WP3). All data stored will be regularly backed-up to ensure the possibility of data recovery. Data in use for modeling from different ENCLUDE partners will be subject to each institute's policies for data security and backup. For any data included in the central ENCLUDE repository we will follow the procedures described in the ENCLUDE "Data Management Plan."
Along with model input data, contact information of identified key persons within data providers will be gathered. This stakeholder data will be under restricted access, available only to selected projected partners, ensuring that all the binding legislative agreements between partners (as dictated by the ENCLUDE "Consortium Agreement" and the ENCLUDE "Ethics Requirements") are respected. No identifiable data will be stored longer than required. After the completion of the project, all collected data will be destroyed.

Making the case study data FAIR (Findable, Accessible, Inter-operable, and Re-usable)
Making data available, findable, inter-operable, and open are core aspects of the ENCLUDE project. These principles will be applied to data that will be used for the case studies following the approaches described below.
Making data Findable
The raw data, as collected from data providers, will be described through meta-data. The overall approach used for the data management in ENCLUDE will be considered for the case studies data as well, in coordination with WP3.
Making data Accessible
The raw data, as collected from data providers, will be stored in a repository so that they can be accessible by all the ENCLUDE modeling teams, following the guidelines of the ENCLUDE data management plan.
Making data Inter-operable
The data collected for the case studies will be inter-operable; that means data exchange and re-use between researchers, institutions, organizations, and countries will be possible. We will adhere to format standards compliant with available (open) software applications as much as possible.
Making data Re-usable
ENCLUDE partners have already signed a memorandum of understanding that all new data developed during the project will be made openly available (ENCLUDE data management plan), to the extent that this is, of course, feasible. However, we envision the use of open licenses for input data, insofar as this is possible based on what licensing restrictions applied to data from third parties. These principles will be applied to all data collected within ENCLUDE.

5.3. Further model developments, modifications, and adjustments

Although the ENCLUDE modeling ensemble is already able to address a lot of the identified energy citizenship trends/ patterns, our matching and mapping has shown that the main area for further modeling developments is geared towards the collective level of energy citizenship (**Figure 8**). In particular, the collective expressions of energy citizenship (e.g., energy communities, eco-villages, etc.) will be an area of focus for further development, especially for ATOM and DREEM, as these models currently do not simulate such grassroot innovations to the desirable extent.
Modeling developments, modifications, and adjustments will be informed by the much-needed context

from the case study analysis of WP3 and the insights provided by stakeholders and citizens, such as the participants of the ENCLUDE Academy[19] (WP6). This insightful feedback from a diverse group of people and sources, and in accordance with the future work of WP5, i.e., the development and the simulation of decarbonization pathways to examine a variety of different combinations of future trends/ patterns based on the characteristics of the case studies, will enhance future developments, modifications, and adjustments of the ENCLUDE modeling ensemble and ensure that modeling outcomes are useful for, and relevant to, citizens' needs.

In this context, thus, and since it is important to not just only study the required social innovations, but also the way that these innovations diffuse into, and are adopted by, the larger society, the initial modeling framework of ATOM will be modified and adjusted to provide diffusion projections of socio-technical changes (e.g., diffusion of energy communities, low-carbon lifestyle, etc.). Typically, the three main ways that grassroot innovations, as energy communities, ecovillages, etc., tend to influence larger society are through: **(1).** Replication, **(2).** Growth in scale, and **(3).** Translation (Hossain, 2018). In this context, ATOM will explore all the three ways by addressing replication as the growth of the number of the grassroot innovations under study, growth in scale as either the growth of specific grassroot innovations, or the growth of their influence through partnerships and programs, and translation as the adoption of relevant policies and practices by mainstream society and institutions.

On the other hand, DREEM will be applied to develop business models that explore the benefits of different technological configurations towards energy autonomy and lifestyle changes in different types of grassroot innovations. In this context, the model will be modified to explore different structures of energy communities, ecovillages, etc., in different geographical and socioeconomic contexts, as these will be specified by the case study analysis under WP3.

An indicative example of such an adjustment of the DREEM model could be modeling an ecovillage structure consisting of a number of households in the different climatic zones in Greece- as weather profiles have a great impact on consumption patterns, and thus different technological configurations, or lifestyle changes, may be appropriate for each climatic zone. The communities under study could rely on central on-site RES generation and storage infrastructures to cover their daily energy needs, providing, when possible, ancillary services to the grid. As the DREEM model includes a detailed modeling component focusing on thermal comfort, different heating/ cooling options could be also tested to explore cost-effectiveness without compromising the thermal comfort of people. In addition, considering green building techniques, different building envelope and material configurations could be tested to explore impacts associated with building construction. Ride sharing strategies could be also explored through the use of electric vehicles, supporting this way relevant trends/ patterns towards the decarbonization of the transport sector. Finally, different energy supervision control strategies could be tested to optimize the energy management of the ecovillage structure under study.

Finally, our desk research has shown that, when it comes to more abstract trends/ patterns of energy citizenship that manifest themselves, as, for example, participating in energy transition social movements, or in energy sector planning and decision-making processes, e.g., policy co-design initiatives, public consultation, participatory energy landscape design, etc., providing quantified estimations through modeling approaches is challenging. Such trends/ patterns represent social innovations that cannot be directly quantified, but certainly have an impact on the energy transition as a whole, since they highlight the societal transition that takes place in parallel. Thus, it is important to make a conscious

[19] https://encludeproject.eu/enclude-academy-energy-citizen-leadership

effort, first, about understanding how these abstract social innovations diffuse and spread through a community of citizens and, second, about the results of such a diffusion and how they can affect the core beliefs and behavior of citizens; thus, they could be modeled indirectly, mainly via input data, e.g., citizen insights, preferences, etc., and/ or modeling assumptions.

6. Conclusions

Moving forward, citizens are expected to increasingly play a much larger and, most importantly, more active role, in the energy transition, as self-consumers, or through their participation in energy communities, and other social innovations, movements, etc. Thus, they now have the chance to ignite changes in the energy system, impacting both sides of the energy system, i.e., both demand and supply. This increasingly participatory role of citizens in the energy system has laid the groundwork for the emergence of the new concept of energy citizenship over the past few years. Energy citizenship manifests itself in various forms, which are often informed and shaped by the socio-political, economic, and cultural specificities found in particular cases, while different trends/ patterns could encircle the core concept of it.

On the other hand, energy system modeling has been also playing an important role in supporting policymaking around Europe, and has done so for at least 30 years now. However, most of the existing energy models continue to focus on mainly assessing the technoeconomic aspects of the energy transition, while neglecting the inherent social, cultural, and political aspects. Such aspects include the integration and the better representation of social impacts on energy politics and policies, the social acceptance of energy technologies and infrastructure, and citizens' behavior and lifestyle choices by energy system models. Despite the fact that modelers are increasingly acknowledging social changes as major drivers or impediments, they continue to exclude them from their models since such features are typically difficult to measure in a robust manner (Köhler et al., 2018; Trutnevyte et al., 2019). In this context, thus, increasing the involvement of social scientists in the modeling development process is imperative, and linking social science and the concept of energy citizenship to computer-based modeling is an important topic because it can broaden the perspective on, and the understanding of, the complex subject of the energy transition.

To this end, ENCLUDE's fundamental goals is to contribute to a more comprehensive modeling of energy citizenship, by using the combined strengths of agent-based modeling, demand-side management modeling, and integrated assessment modeling, exploring, thus, the multi-scale relationship between the various forms of energy citizenship and the decarbonization of the energy system at the local level; and by scaling-up to the regional, the national, or even the supranational level.

In this context, this deliverable set out to match an ensemble of three well-established models, namely: an agent-based model (ATOM), a demand-side management model (DREEM), and an integrated assessment model (IMAGE), to emerging trends/ patterns of energy citizenship. More specifically, it aimed at: **(i.)** identifying key trends/ patterns of energy citizenship relevant to the field of energy system modeling, **(ii.)** providing an overview of the ENCLUDE modeling ensemble and the process through which the ENCLUDE models are already capable of addressing the identified trends/ patterns of energy citizenship, and **(iii.)** analyzing gaps and synthesizing further model developments, modifications, and adjustments in order for the ENCLUDE modeling ensemble to be able to understand the multi-scale relationship between energy citizenship and decarbonization pathways in different contexts as a basis for providing appropriate decision-support.

We showed how all the three models will be further developed, modified, and adjusted and how the models' features and capabilities will be enhanced towards a better representation of the social aspects and implications of the energy transition, also advancing the understanding of the social impacts of the transition, and supporting decision-makers and citizens alike.

Such an indicative example is the identification of the necessary agent-related parameters for ATOM, or DREEM, to reflect on different citizen profiles and types of behavior/ lifestyles. By calibrating to historical data and then simulating, the models could assess the decarbonization potential of strategic groups of citizens to demonstrate which citizen clusters are more inclined towards the adoption of a specific technological option, or a social innovation, across different geographical contexts and scales, and different socioeconomic environments. The decarbonization potential of the different citizen clusters could be then upscaled to larger levels, allowing the assessment of the contribution that energy citizenship has in bridging the remaining emissions' gap.

Finally, by soft-linking the three models, we will be able to identify socially preferred and environmentally responsible pathways that are consistent with current and future decarbonization goals, moving away from monolithic modelling techniques that have historically monopolized the field of energy systems modeling by focusing primarily on least-cost pathways.

6.1. Limitations

Moving forward, the focus with the ENCLUDE modeling ensemble lies on the application of the models to the ENCLUDE case studies to test their usefulness. A critical stage for the successful application of the models is data collection. As in any computational model, the ENCLUDE models are only as good as the data they receive as input. Although the models have been restructured and readjusted to incorporate new aspects, thus, data availability is always a major shortcoming. For example, so far, we have been dealing with difficulties to find historical data on the adoption of storage systems in the residential sector, or the adoption of electric vehicles. In this context, thus, stakeholder insights during the model application process will be instrumental.

Furthermore, the trends/ patterns, that have been identified through this initial desk research are not "set in stone." This means that the trends/ patterns mentioned within this Deliverable are meant to provide a guiding direction to the different aspects of energy citizenship that are mainly underrepresented in energy system models. Therefore, as ENCLUDE progresses and grows it is almost certain that more specific trends/ patterns will present themselves, e.g., by the insights provided from the work performed under the ENCLUDE WP2 ("ENCLUDE energy citizenship typologies"), WP3 ("ENCLUDE case studies" and the contextualization of energy citizenship), and WP6 (Citizen insights and participation in the "ENCLUDE Academy").

Moreover, we note that the model developments, modifications, and adjustments that have taken place so far, mainly serve the role of setting up the necessary technical framework, such as the data sharing and model interface protocols. Further model developments, modifications, and adjustments to the core modeling methodologies in order to best capture the nuances of the energy citizenship trends/ patterns that have been already identified, and the ones that will be further identified, will take place. This process is dynamic and will continue as the ENCLUDE project progresses and as new ideas and concepts present themselves and are further developed.

This is to be expected, as this initial conceptualization of how the models stand right now and how they could collaborate to provide insightful results for the decarbonization potential of energy citizenship goes hand-in-hand with the field work that is to be implemented; mainly with the case study analysis performed under WP3, which is envisaged to provide the necessary contextualization that in turn will inform the model simulations performed. This exchange of information and data will certainly enrich the modeling exercises and will provide the groundwork for the future, more detailed and targeted model developments, modifications, and adjustments that will be required.

On the other hand, each one of the three models has their own limitations, which derive from their modeling structure, methodological approach followed, design, objective, etc. Such a limitation, for example, is the models' geographical coverage; although some of the identified trends/ patterns, such as consumer behavior, are addressed by the micro-scale models, i.e., ATOM and DREEM, the geographical coverage of these models is only limited to specific countries and/ or regions. This limitation is mainly due to their bottom-up structure, which requires a lot of resources so that it is expanded to more countries and/ or regions. Thus, some of the identified trends/ patterns will be addressed at a specific coverage. However, considering that the objective of the ENCLUDE modeling ensemble is to mainly understand the magnitude of the impact of the identified trends/ patterns, limited geographical coverage is not expected to be a significant barrier to simulations; simulations will definitely allow to quantify the magnitude and the importance of the identified energy citizenship trends/ patterns in the energy transition, and of course they would provide the starting point for the process of upscaling to a wider geographical context.

Apart from the limitations regarding the models' geographical coverage, the ENCLUDE models also have certain methodological limitations mostly due to data unavailability. For instance, scientific data about societal and behavioral factors are scarcely available, and often only for a specific country, or a specific region, while they are rarely available as timeseries data to account for changes over time. A better availability of survey data on the social, cultural, and political aspects of the energy transition could substantially improve modeling efforts, as could the availability of data on regulations, which is currently very difficult to obtain for more than single countries and multiple years.

6.2. Outlook: Development of participatory decarbonization pathways

Finally, the future activities of WP5, apart from the further development of the models, include formulation of the decarbonization pathways/ scenarios to which the ENCLUDE modeling ensemble will be applied. A significant portion of information and insights are expected to be gathered from stakeholder (and especially citizen) engagement processes in order to incorporate real-world perspectives inside the models.

The decarbonization pathways developed will be based on the case study specifications that will take place under WP3. These pathways will also integrate insights from recent low-carbon transition pathways in literature and databases (e.g., IPCC SR1.5 Scenario Explorer[20], etc.) to produce the most up-to-date and policy-relevant evidence on the contribution of energy citizenship to reaching climate neutrality. The decarbonization pathways will examine different states of uncertain parameters to study the decarbonization impact of the different forms of energy citizenship, while for each uncertain parameter, decarbonization pathways will be developed based on empirical work with local stakeholders.

As a result, feasible and robust decarbonization pathways, which will be agreed by, and co-produced with citizens and communities, and could realistically be implemented by policymakers and other relevant stakeholders, will be produced. This will enable us to identify not just least-cost pathways, which have traditionally dominated such modeling exercises, but rather institutionally and socially preferred, politically realistic, least-risk, and environmentally responsible pathways, in line with current and increased decarbonization ambitions and clear road-mapping across various time horizons.

[20] https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/login?redirect=%2Fworkspaces

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Appendix A: Documenting the ENCLUDE models

The **template** that was developed and used for the documentation of the current state and capabilities of the ENCLUDE models is presented in further detail below. In the template information about the models are collected. This information includes for example the spatial and temporal coverage that each model has, the sector coverage of each model, policies that can be addressed, etc.

Category	Subcategory	Sector name	Model Coverage (Yes/No)
Energy sources		Coal	
Energy sources		Lignite	
Energy sources		Oil	
Energy sources		Natural Gas	
Energy sources		Nuclear	
Energy sources		Biomass	
Energy sources		Hydro	
Energy sources		Solar	
Energy sources		Wind	
Energy sources		Geothermal	
Energy sources		Tidal/ Wave	
Energy sources		Other	
Energy sources		Aggregated	
Energy transformation		Electricity	
Energy transformation		Hydrogen	
Energy transformation		Oil refining	
Energy transformation		Gas-to-liquids	
Energy transformation		Coal-to-liquids	
Energy transformation		Coal-to-gas	
Energy transformation		Bio-to-liquids	
Energy transformation		Bio-to-gas	
Energy transformation		Other	
Energy transformation		Aggregated	
Energy storage		Pumped-hydro	
Energy storage		Batteries	
Energy storage		Hydrogen	
Energy storage		Power-to-gas	
Energy storage		Other	
Energy storage		Aggregated	
Energy storage		Power-to-liquid	
Industry		Aggregated	
Industry		Agriculture	
Industry		Cement	
Industry		Chemicals	
Industry		Food processing	
Industry		Iron and steel	
Industry		Non-ferrous metals	
Industry		Other	
Industry		Pulp and Paper	
Industry		Textiles and leather	

Sectors | MitigationAdaptation | SocioEcon | Emissions | Policies | SDGs | Model_Info | Regions | Comments

Category	Subcategory	Names	Model Coverage (Yes/No)
Adaptation		Additional cooling of buildings	
Adaptation		Building material choices	
Adaptation		Coastal protection	
Adaptation		Early warning systems	
Adaptation		Flood management	
Adaptation		Forest Fire management	
Adaptation		Green spaces in cities	
Adaptation		Land use adaptation/planning	
Adaptation		Retreat / Elevated infrastructure	
Adaptation		River restoration/rehabilatation	
Adaptation		Water use restrictions	
Behavioural Changes		Travelling less	
Behavioural Changes		Less energy service demand	
Behavioural Changes		Lower material consumption	
Behavioural Changes		Less product demand	
Buildings	Heating	Gas replacing oil / coal	
Buildings	Heating	Biofuels	
Buildings	Heating	Electricity	
Buildings	Heating	Hydrogen	
Buildings	Heating	Solar thermal	
Buildings	Heating	Building shell efficiency	
Buildings	Heating	Other	
Buildings	Lighting	Efficient lighting	
Buildings	Appliances	Efficient appliances	
Buildings	Cooling	Electricity	
Buildings	Cooling	Building shell efficiency	
Industry	Process heat	Gas replacing oil / coal	
Industry	Process heat	Biomass	
Industry	Process heat	Hydrogen	
Industry	Process heat	Electricity	
Industry	Machine drives	Gas replacing oil / coal	
Industry	Machine drives	Electricity	
Industry	Steam	Gas replacing oil / coal	
Industry	Steam	Electricity	
Industry	CHP	Gas replacing oil / coal	
Industry	CHP	Biomass	
Industry	Overall industry	CCS	
Industry	Overall industry	CDR/NETs	
Agriculture	Energy use	Gas replacing oil / coal	
Agriculture	Energy use	Biomass	

Sectors | **MitigationAdaptation** | SocioEcon | Emissions | Policies | SDGs | Model_Info | Regions | Comments

Category	Socioecon	Model Coverage (Exogenous/Endogenous/Not Represented)
Demography	Population	
Demography	Urbanisation	
GDP	GDP	
GDP	Private consumption	
GDP	Public consumption	
GDP	Gross fixed capital formation	
GDP	Exports	
GDP	Imports	
GDP	Trade balance	
GDP	Aggregated	
Employment	Total	
Employment	by eductional attainment level	
Employment	by age	
Employment	by sex	
Employment	by econcomic activity	
Employment	Aggregated	
Investment	Macroeconomic	
Investment	Private Investments	
Investment	Public investments	
Investment	Aggregated	
Public finances	Expenditures	
Public finances	Receipts	
Public finances	Social benefits	
Public finances	Balances	
Public finances	Aggregated	
Economic activity	Production	
Economic activity	Value added	
Economic activity	Imports	
Economic activity	Exports	
Economic activity	Employment	
Economic activity	Energy expenditure	
Economic activity	Investments	
Economic activity	Raw material consumption	
Economic activity	Other materials consumption	
Economic activity	Aggregated	
Incomes	Total gross/real disposable income	

Sectors | MitigationAdaptation | **SocioEcon** | Emissions | Policies | SDGs | Model_Info | Regions | Comments

Emission	Model Coverage (Exogenous/Endogenous/Not Represented)
CO2	
CH4	
N2O	
F-gases	
Land-use CO2	
PMs (BC, OC, PM2.5)	
SOx	
NOx	
NH3	
CO / VOC	

Sectors | MitigationAdaptation | SocioEcon | Emissions | Policies | SDGs | Model_Info | Regions | Comments

Category	Policy	Model coverage (Feasible/Feasible with Modifications/Not Feasible)
Emissions mitigation	Tax	
Emissions mitigation	Emissions target / quota (annual)	
Emissions mitigation	Emissions target / quota (cumulative)	
Emissions mitigation	Regulations (emissions standards, etc...)	
Emissions mitigation	Global Temperature / Radiative Forcing target	
Emissions mitigation	Financial supports (negative emissions, CDMs, Green Climate Fund)	
Energy	Tax	
Energy	Subsidy	
Energy	Energy mix target	
Energy	Efficiency target	
Energy	Regulations (thermal regulation in buildings, banning of diesel cars in urban areas, etc...)	
Land	Protected lands	
Land	Production quotas	
Land	Carbon sink pricing / Land use change emissions tax	
Land	Afforestation targets	
Trade	Carbon border tax on imports	
Trade	Carbon border supports on exports	
Trade	Regulations policies (certifications, Best-available technologies, standards, etc...)	

Sectors | MitigationAdaptation | SocioEcon | Emissions | Policies | SDGs | Model_Info | Regions | Comments

SDGs	What metrices does the model produce in respect to this SDG (separate with semi-colons)?
§1. No Poverty (e.g., intra-country distributional impact by income level)	
§2. Zero hunger (e.g., food prices, shortages)	
§3. Health (e.g., air-pollution related mortality)	
§4. Quality education	
§5. Gender equality	
§6. Clean water and sanitation (e.g., groundwater depletion)	
§7. Affordable and clean energy (e.g., traditional biomass use, %renewable energy)	
§8. Decent work & economic growth (e.g., impact on GDPpc, jobs)	
§9. Industry, innovation & infrastructure (e.g., R&D investments)	
§10: Reduced inequalities (e.g., intra-country distributional impact, gini coefficient)	
§11: Sustainable Cities & Communities (e.g., PMs from city transport + buildings)	
§12: Responsible production & consumption (e.g., % recycled waste, embedded emissions)	
§13: Climate action	
§15: Life on land (e.g., land use for forests, rate of land use change)	
§16: Peace, Justice and institutions	

Sectors | MitigationAdaptation | SocioEcon | Emissions | Policies | **SDGs** | Model_Info | Regions | Comments

Model acronym	
Full name	
Short description	
Institute	
Type of model	
Short overview (extended description)	
Key features	

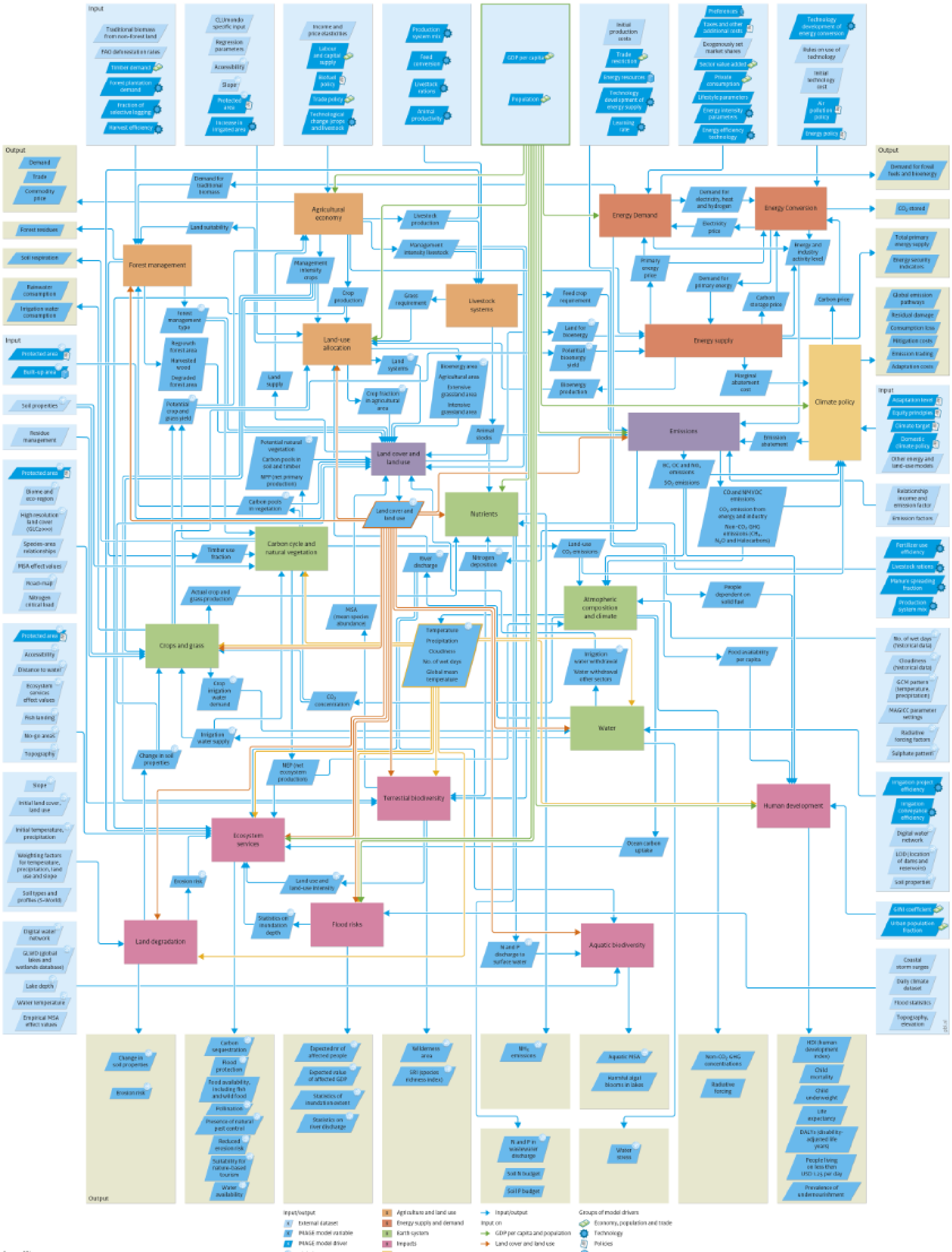
Sectors | MitigationAdaptation | SocioEcon | Emissions | Policies | SDGs | **Model_Info** | Regions | Comments

Region	Country	Code	Countries	Code
		#N/A	Afghanista	AF
		#N/A	Aland Islar	AX
		#N/A	Albania	AL
		#N/A	Algeria	DZ
		#N/A	American S	AS
		#N/A	Andorra	AD
		#N/A	Angola	AO
		#N/A	Anguilla	AI
		#N/A	Antarctica	AQ
		#N/A	Antigua an	AG
		#N/A	Argentina	AR
		#N/A	Armenia	AM
		#N/A	Aruba	AW
		#N/A	Australia	AU
		#N/A	Austria	AT
		#N/A	Azerbaijan	AZ
		#N/A	Bahamas	BS
		#N/A	Bahrain	BH
		#N/A	Banglades	BD
		#N/A	Barbados	BB
		#N/A	Belarus	BY
		#N/A	Belgium	BE
		#N/A	Belize	BZ
		#N/A	Benin	BJ
		#N/A	Bermuda	BM
		#N/A	Bhutan	BT
		#N/A	Bolivia	BO
			Bonaire,	

Sectors | MitigationAdaptation | SocioEcon | Emissions | Policies | SDGs | Model_Info | **Regions** | Comments

Appendix B: Detailed architecture of the IMAGE model

The detailed architecture of the IMAGE model is presented in the figure below, including all the various components that comprise it, the way that they interact, and the way that they are interconnected.



Source: PBL 2014

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- Eko-свест
- MISSIONS PUBLIQUES Bringing citizens into policy
- HOLISTIC
- University of Victoria

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