ENCLUDE
Energy Citizens for Inclusive
Decarbonization

Decarbonization potential of energy citizenship at the national and the EU levels

WP5 – The impact of energy citizenship in decarbonization pathways

08/07/2024

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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 who are willing and 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 policy making, lowering the barrier for action. (2) Operationalizing the energy citizenship concept at all scales of policy making for decarbonization. (3) Catalyzing a chain reaction of decarbonization actions across the EU.

1. Changes with respect to the DoA

The only deviation from the amended Grant Agreement is the extension of Deliverable 5.4 by 1 month. This is mainly attributed to the extra time needed to incorporate insights and feedback from discussions that took place during the General Assembly meeting in Athens and the ENCLUDE workshop organized with energy community representatives and policymakers and other stakeholders from the Municipality of Athens (those meetings took place on the 23rd and the 24th of May 2024), into modeling results.

In view of the ENCLUDE final events and dissemination activities, this was a great opportunity for the ENCLUDE modeling team to polish their results based on a user-oriented evaluation process and adjust findings and recommendations in Deliverable 5.4.

Given the interdisciplinary nature of Deliverable 5.4, this short extension also allowed for additional reviews from ENCLUDE partners with a background in social science and humanities with a view to further improving its quality and the implications derived.

This deviation impacts neither the objectives nor the successful implementation of other Tasks and WPs.

2. Dissemination and uptake

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. Hence, this report will be disseminated through the project's social media channels in order to communicate the key results and insights in an easily digestible manner. Also, it will be uploaded to open research platforms (e.g., Zenodo), in order to reach a broader research audience.

3. Short Overview

This report is the fourth (4th) out of five (5) deliverables under Work Package 5 of the ENCLUDE project and builds on the work done previously in Deliverable 5.1 and Deliverable 5.2, namely the "*people-centered*" storylines and the "*future-world*" narratives, as well as in Deliverable 5.3 and the modeling applications on the decarbonization impact of energy citizenship at the micro scale (local level, i.e., household, community, municipality).

In this deliverable, we upscaled modeling outcomes from Deliverable 5.3, and by enhancing the ENCLUDE modeling ensemble accordingly, we employed it to extract insights regarding the decarbonization potential of different manifestations of energy citizenship at the macro scale (i.e., national and supranational (European Union) level).

To simulate the different transition pathways that were derived from the ENCLUDE transformative scenario design framework, as applied to different real-life case studies, three (3) models were employed, namely: *ATOM* (**A**gent-based **T**echnology ad**O**ption **M**odel), *IMAGE* (**I**ntegrated **M**odel to **A**ssess the **G**lobal **E**nvironment), and *OSeMOSYS-GR* (**O**pen-**S**ource **e**nergy **MO**deling **SYS**tem for **GR**eece).

Modeling applications presented in this report include:

(**i**). Exploring transition pathways of empowering prosumerism and citizen adoption of small-scale photovoltaic systems in Denmark, France, and Greece by 2030, under the "*Power to the People*" storyline and different "future-world" narratives, also extracting insights on citizens' decision-making behavior (using the *ATOM* model). Case study selection was based on geographical diversity to account for different radiation profiles between the northern, the central, and the southern Member States, and thus, difference in expected photovoltaic adoption projections.

(ii). Exploring the impact of citizen participation in power sector planning in Greece, in terms of citizens' preferences, acceptance (or opposition) levels, and decision-making behavior, towards the evolution of capacity requirements, the resulting electricity mix, and the achievement of national targets by 2050, under different potential future developments (using the *OSeMOSYS-GR* model).

(iii). Exploring different transition pathways in the transport and the residential sectors in Western Europe towards the achievement of the European Union's targets by 2050 (using the *IMAGE* model).

4. Evidence of accomplishment

This report serves as evidence of accomplishment.

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Executive Summary

The European Union's "*Green Deal*" along with the "*Clean Energy for all Europeans Package*" outline policy pathways towards a net-zero greenhouse gas emission target by 2050, which place increasing emphasis on putting people at the center of the energy system and envision a future in which citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, and actively participate in the energy market. In this direction, future energy policies and decarbonization strategies need to be socially just and inclusive, taking into consideration citizens' preferences and acceptance.

In this context, since the early 2000s scholars have been increasingly recognizing the limitations of the traditional top-down approach to climate and energy policy, which fails to account for the social and cultural dimensions of energy use and production. Addressing this, the concept of "*energy citizenship*" has emerged and gained in recent years considerable attention due to its potential to bridge the gap between energy transition policies and social participation, by emphasizing the significance of participatory and democratic processes in decision-making and underlining the need for a more inclusive and equitable energy system.

Nevertheless, discourse surrounding energy matters has predominantly centered on technical and economic considerations, often overlooking discussions on inclusive and democratic governance. This is also reflected in contemporary energy modeling practices and scenario-based research approaches, where focus is primarily placed on the technological optimization and economic implications of the energy transition, often disregarding social and environmental aspects, and treating them as external narratives, only to be considered "*on-top*" of modelling results, serving merely as a perspective for discussing scenarios and narratives.

Underrepresentation of such elements combined with disproportionate emphasis on technoeconomic factors can lead to oversimplified models and scenarios that fail to inform policymakers about the multiple dimensions crucial for a sustainable and inclusive energy transition. A transition that is well-aligned with the European Union's climate policy objectives and the Paris Agreement is inherently a societal process that may not adhere strictly to cost optimization principles, and, in this respect, there has been a growing body of research, especially over the past few years, seeking to integrate social sciences into scenario-based exploration and modeling analysis.

The ENCLUDE project contributes to the latter by using the strengths of energy system and integrated assessment models, aiming at a more holistic modeling of the different manifestations of energy citizenship, exploring the multi-scale relationship between its various forms and decarbonization. In this context, in this report, we expand our work under Deliverable 5.3, and we employ the enhanced ENCLUDE modeling ensemble to extract useful and policy-relevant insights about the decarbonization potential of different manifestations of energy citizenship at the national and the supranational levels.

Starting point of our work is the application of the ENCLUDE framework for transformative scenario design based on storylines of energy citizenship and potential evolutions of the future, which encompasses a broad spectrum of uncertainties and embraces the depth of complexity of the energy landscape, at the local, the national, and the supranational levels, to real-life case studies to derive a set of different transition pathways that will be simulated using the ENCLUDE modeling tools.

This framework, as developed and presented under Deliverable 5.1 and Deliverable 5.2, does not only consider regulatory influences and technological advancements, but also delves into the social, cultural, and behavioral manifestations of citizens, envisioning energy futures that go beyond the comfort zone of current scenario-based research and examine out-of-ordinary extremes.

Set to explore the decarbonization potential of different expressions of energy citizenship as manifested at the *national* and the *supranational* levels, in this deliverable, we focus on all four (4) "*people-*

centered” storylines, namely: (**i**). “*Power to the People*”, (**ii**). “*Habitual Creatures*”, (**iii**). “*Band Together*”, and (**iv**). “*People to the Streets*”, which, combined with the “*future-world*” narratives, i.e., **a.** “*Familiar World*”, **b.** “*Unified World*”, and **c.** “*Fragmented World*”, allowed us to create a scenario space to study the case-specific decarbonization pathways of interest, acknowledging and considering through our case study selection, the depth of complexity and diversity across the European energy and policy landscape.

In this endeavor, we harnessed the power of existing models comprising the ENCLUDE modeling ensemble, as well as expanded it by developing a new modeling framework (i.e., OSeMOSYS-GR) to study different energy planning alternatives in Greece by 2050, based on different citizens’ preferences and different levels of acceptance (or opposition).

Specifically, to simulate the different scenarios, three (3) of the five (5) models that comprise the ENCLUDE modeling ensemble were employed, namely:

- ATOM (**A**gent-based **T**echnology ad**O**ption **M**odel),
- IMAGE (**I**ntegrated **M**odel to **A**ssess the **G**lobal **E**nvironment),
- OSeMOSYS-GR (**O**pen-**S**ource **e**nergy **MO**deling **SYS**tem for **GR**eece).

Below we present a short overview of the modeling work conducted in this deliverable along with overarching key messages:

“*Power to the People*” by empowering prosumerism and citizen adoption of small-scale photovoltaic systems at the Member State level by 2030

Building on the modeling work we conducted under the “*Power to the People*” storyline in Deliverable 5.3, focusing on assessing the profitability and the decarbonization potential of citizen investments in small-scale photovoltaic systems at the household level, in different European Union’s cities, by 2050, we soft-linked the **D**ynamic high-**R**esolution d**E**mand-sid**E** **M**anagement (DREEM) model with ATOM.

By feeding simulation results at the local level in ATOM our goal was to explore the decarbonization potential and the potential for further diffusion of small-scale photovoltaic systems (in terms of projected capacity additions) by 2030 at the national level of three (3) Member States, i.e., Denmark, France, and Greece, also quantifying the (aleatoric or epistemic) uncertainty that characterizes citizens’ decision-making behavior, under the three (3) different evolutions of the future and for different policy schemes of interest, based on the existing regulatory landscape in each Member State.

Our findings highlight country-specific recommendations for the further support of the small-scale photovoltaic sector by 2030, also considering national characteristics of each case study and targets by 2030, while they also acknowledge the importance of policymakers continuing to support the growth of prosumerism and empowering citizen investments in small-scale photovoltaic and residential storage systems through favorable policies and incentives, ensuring that citizens can reap the financial benefits and contribute to a more resilient and sustainable energy system.

Combining “*Power to the People*” with “*People to the Streets*” storylines towards citizen preference-led energy planning alternatives and 100% renewable-based national energy systems

Considering the increasingly participatory role of citizens and other societal actors in the combat against the climate crisis, driving changes in the energy system, and particularly in the supply side, in this modeling application our goal was to analyze preference-led energy system planning alternatives under various future-world evolutions. To do so, we integrated citizen preferences into an open-source, highly resolved, bottom-up capacity expansion model, OSeMOSYS-GR, to enable the assessment of social preferences alongside other aspects like technical feasibility and costs, in Greece, by 2050.

More specifically, in the context of the "*Power to the People*" (focusing on the individual level of expressions of energy citizenship) and the "*People to the Streets*" (focusing on the collective level of expressions of energy citizenship) storylines, we sought to explore: (**1**)**.** how citizen participation in power sector planning and decision-making affects the capacity requirements and the resulting electricity mix of future transition pathways, (**2**)**.** how the costs and the carbon footprint of centralized and decentralized systems compare between different future-world evolutions, as well as (**3**)**.** the potential socioeconomic benefits derived from citizen-led investments and how they compare among different policy mixes and potential future evolutions of the surrounding environment.

Modeling findings show that citizens' preferences and acceptance levels with regards to power sector planning can have a significant impact on the future capacity growth of different energy technologies (e.g., small-scale solar power projects, large-scale utility wind power projects). Overall, the combination of energy planning and mix findings with the different storylines including various citizens' preferences and acceptance (or opposition) levels provides tangible trends and patterns to be considered for future power sector planning strategies.

Decarbonizing the transport and the residential sectors in Western Europe under different "*people-centered*" storylines and manifestations of energy citizenship

Finally, by employing an integrated assessment model, the IMAGE model, we aimed at a broader and more aggregated approach in modeling different patterns and trends of energy citizenship at the upscaled (supranational) level, across all the ENCLUDE "*people-centered*" storylines and under the different "*future world*" narratives.

On the individual level (in terms of expressions of energy citizenship), the "*Habitual Creatures*" storyline includes less technological-related behavioral changes, mostly driven by cost-savings and intrinsic motivation for sufficiency and health, which are enabled mostly by design, social norms, and marketing, while the "*Power to the People*" storyline, conversely, includes more technological-related behavioral changes, mostly driven by autonomy and energy security concerns, and enabled by subsidies, funding, regulation, and improved research and development.

On the other hand, on the collective level (in terms of expressions of energy citizenship), the "*Band Together*" storyline encompasses collective behavioral changes with a mix of technological and non-technological characteristics. These are mostly motivationally driven by cost-savings, social cohesion, and optimized use of time and space, while they are also enabled by infrastructure, flexibility for initiatives, cooperation for improved communication, necessary knowledge, and social norm shifts. In addition, the "*People to the Streets*" storyline includes behavioral changes with less direct effect on energy demand. With a more systemic focus, these changes are driven mostly by an emphasis on technological solutions, seeking responsibility from companies and government, but also through social cohesion to start social movements, while they are also enabled by campaign funding, lobbying organizations, shareholder activist groups, functional government, and policymakers.

Modeling outcomes show that the decarbonization potential is the highest in the transport sector for the "*Power to the People*" storyline and in the residential sector for the "*Band Together*" storyline, compared to the other "*people-centered*" storylines under study.

On the other hand, modeling outcomes also show that behavioral actions are more significant (in terms of their decarbonization potential) in the residential sector than in the transport sector, as "*People to the Streets*", "*Habitual Creatures*", "*Power to the People*", and "*Band Together*" (in increasing order of magnitude) all deviate substantially from the "*Shared Socioeconomic Pathway #2* no climate policy" reference scenarios. However, these changes are still far away from a 2^oC reference scenario, while in the transport sector, the "*Power to the People*" storyline would go beyond the 2^oC reference scenario.

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List of Abbreviations/ Acronyms

ABM	Agent-based model/ modeling
ANIMO	grAssroot iNnovation dIffusion MOdel
ATOM	Agent-based Technology adOption Model
BAPV	Building-attached photovoltaic
BAU	Business as usual
BESS	Battery energy storage system
BIPV	Building-integrated photovoltaic
CCS	Carbon capture and storage
CDD	Cooling degree days
CEI	Collective energy initiative
CEM	Capacity expansion model
CO_2	Carbon dioxide
CTA	Central technical authority
DREEM	Dynamic high-Resolution dEmand-sidE Management model
EC	European Commission
EU	European Union
EV	Electric vehicle
FiT	Feed-in tariff
GHG	Greenhouse gas
GP	Gaussian process
HDD	Heating degree days
IAM	Integrated assessment model/ modeling
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
NECP	National Energy and Climate Plan
OSeMOSYS-GR	Open-Source energy Modeling SYStem for GReece
PV	Photovoltaic
R&D	Research and Development
RED	Renewable Energy Directive
RES	Renewable energy sources
RQ	Research question
SDGs	Sustainable Development Goals

SSP	Shared Socioeconomic Pathway
TEESlab	Technoeconomics of Energy Systems laboratory
TMB	Travel money budget
TTB	Travel time budget
VRE	Variable renewable energy
WP	Work package

1. Introduction

Climate change has unquestionably emerged as a prominent and critical crisis of significant concern and relevance over the past two (2) decades. Its repercussions are attributed to human activities, particularly those resulting from the Industrial Revolution and subsequent periods (Vlasis et al., 2021). The increase in global temperatures has led to the occurrence of the warmest years experienced by humanity in the past two (2) decades (Verhaeghe & Mauerhofer, 2023). In this context, to effectively address climate change, it is imperative that the National Energy and Climate Plans (NECPs) of the European Union’s (EU) member states are harmonized with the specific requirements for addressing the impacts of climate change at the national level. This in turn can lead to the attainment of the supranational climate targets set by the EU.

The most recent EU’s climate targets have been established under the framework of the European Green Deal, which was introduced by the EU in the latter part of 2019 (European Commission, 2019b). The strategy encompasses a holistic approach aimed at attaining climate neutrality by 2050, which serves as the primary objective. However, in addition to this objective, the European Green Deal encompasses a more ambitious goal of achieving a minimum 55% reduction in greenhouse gas (GHG) emissions by 2030, in comparison to the emission levels recorded in 1990 (European Commission, 2019c). Moreover, the EU presented the "Clean energy for all Europeans" package in 2019 with the aim of reducing carbon emissions in the EU’s energy system (European Commission, 2019a). The package comprises eight (8) new laws and legislations that are designed to produce significant benefits for the environment, consumers, and the overall economy and society. This endeavor significantly contributes to the EU's overarching objective of attaining climate neutrality by 2050.

However, the invasion of Ukraine by Russia in 2022, and the resulting energy crisis in Europe have raised concerns about the energy security of the shared European energy system. Recalling the energy crises of the 1970s and late 2000s, where efforts to increase the availability of fossil fuels were seen as the solution, the current exceptional circumstance requires a different response. The concept of security of supply, particularly in terms of its geopolitical implications, is increasingly closely linked to the affordability of energy. As a result, a more comprehensive decarbonization strategy is seen as the most feasible long-term option (Osička & Černoch, 2022).

To address the resulting challenges, in March of 2022, the European Commission (EC) introduced the "REPowerEU" plan, a collaborative effort by the EU to expedite the shift to clean energy and enhance the continent's energy autonomy by reducing dependence on unpredictable suppliers and fluctuating fossil fuels (European Commission, 2022). To accomplish these objectives, specific actions of importance have been identified across the following pillars (Kleanthis, Koutsandreas, et al., 2022):

- Maximizing energy efficiency;
- Exploring a diversified range of energy imports;
- Advocating for the replacement of fossil fuels and expediting Europe's shift toward clean energy;
- Intelligent financial choices and investments.

In order to progress in this direction, despite the uncertainty of the future, it is crucial to take swift action to steer society towards energy systems that are primarily powered by renewable energy sources (RES) by 2050. This could manifest in different ways, such as formulating strategies for the implementation of new generation assets, harmonizing policies across different sectors, and considering the perspectives of multiple stakeholders. Thus, there is a planned and gradually underway transition from fossil fuels to renewables.

Up until now, the focus in climate change mitigation has primarily been on the technical and infrastructural elements of the energy transition. However, although technological innovations are undoubtedly necessary and our knowledge of them is extensive, it is important to recognize that technology alone cannot single-handedly solve the climate crisis. The root causes of the problem lie within the intricate societal systems (Matschoss et al., 2022); how society and citizens change is less certain, as behaviors and lifestyles are constantly changing and are expected to change substantially in the future. Yet, anticipating or imagining how these will change is a challenge and generally unexplored in the field of climate change mitigation.

To help realize the vision of a green, inclusive, and fair transition by 2050, the role of citizens and other societal actors as well as their empowerment and involvement is of utmost importance and has been acknowledged within the EU's recent strategic and legislative frameworks. A better understanding of social change, thus, is required to investigate potential future evolutions of the energy transition.

1.1. The role of citizens in the European energy transition

With the implementation of the European Green Deal and the "REPowerEU" plan, the EU is set to achieve its climate goals and enhance energy independence. These initiatives will bring about a complete overhaul of the current energy system by prioritizing innovative technological solutions and actively engaging citizens and other relevant stakeholders in the transition.

In addition, the Energy Union policy of the EU highlights the importance of prioritizing individuals in the energy transition. It envisions a Union where citizens play a central role, benefiting from new technologies to lower their energy bills, actively engaging in the market, and ensuring protection for vulnerable consumers (European Commission, 2021).

Given the current situation, it is anticipated that individuals will have a greater responsibility as self-consumers and active members of collective initiatives, like energy communities, and that their actions will have a significant impact on the energy system, affecting both the demand and the supply sides. In this context, thus, transitions that are not only technologically feasible and economically possible, but also socially and politically acceptable, are necessary, also considering individual preferences, acceptance, and behavioral and lifestyle changes (Cherp et al., 2018). Due to the anticipated increase in the involvement of citizens and other societal actors in future energy systems, the concept of "*energy citizenship*" has emerged in recent years.

"*Energy citizenship*" is a term that describes how citizens are constantly engaging with the energy transition, from an economic, political, and social perspective, and conceives citizens and societies as active rather than passive stakeholders in the evolution of the energy system (Laakso et al., 2023). In particular, 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*" (Campos & Marín-González, 2020).

This broad definition can be connected to various emerging trends and patterns that can relate to (Fotopoulos et al., 2024): (**i**)**.** the active participation of citizens in the energy market, such as through the concept of "*prosumerism*", the increasing adoption of energy efficiency and smart technologies, and other related solutions, (**ii**)**.** behavioral aspects of citizens and the impact of lifestyle changes in their daily lives, (**iii**)**.** collective initiatives and expressions of energy citizenship, such as the formation of energy communities, co-operatives, eco-villages, or collective decision-making through housing association boards, etc., (**iv**)**.** political activities such as participation in social movements and civil society initiatives advancing democratic visions of energy transition and/ or policymaking taking the form of participation in energy sector planning and decision-making, including through co-design initiatives, public consultation, and participatory design of potential future energy landscapes.

By participating in various energy-related activities and by taking an active role in the shift toward cleaner and more sustainable energy systems, citizens can collectively and individually contribute meaningfully to the fight against the climate change crisis.

1.2. Transition pathways and energy citizenship

Making decisions on climate and energy policies to achieve the desired future energy paradigms is a difficult and complicated process due to a number of internal and external variables (such as technical advancements, societal changes, behavioral aspects, economic developments, etc.) that impact the dynamics of the energy system (Haasnoot et al., 2013). Decision-makers may have trouble taking all these factors into account, while attempting to develop robust policies, frequently as a result of a lack of information regarding the uncertainties they must take into account (Forni et al., 2016).

Policymaking under deep uncertainty, especially under long-term projections, implies that policymakers will encounter difficulties when asked to design and implement a new policy, and/ or how a particular policy instrument affects various sectors. Predicting the future and deciding on the most probable evolution before applying a policy has proven to be a difficult undertaking.

Various challenges and the way they are addressed are crucial in shaping future transition pathways in meeting the Paris Agreement "*well-below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees Celsius*" target. Five (5) key energy sector challenges, to support basic human needs, development, and well-being are: **(i).** the energy demand growth and its coupling with demographic and economic drivers, **(ii).** phasing out of traditional forms of energy use and improving energy access and modernization of energy use in the context of structural economic changes, **(iii).** the expansion of primary energy supplies, **(iv).** the future of existing, and the build-up of, new energy infrastructure and innovative technological solutions, and **(v).** the reduction of GHG emissions and other pollutants. These challenges are related to key scientific debates on global and long-term developments in the energy sector.

In addition, the complex decisions concerning mitigation portfolios for limiting warming to 1.5°C can have both a positive and negative impact on the achievement of other societal objectives, such as sustainable development. For example, demand-side and energy efficiency measures, and lifestyle choices that limit energy, resource, and GHG-intensive food demand support sustainable development. The coupling between socioeconomic development patterns and energy demand has been identified as a fundamental issue for understanding the scale and structure of energy demand (Csereklyei & Stern, 2015; Grubler et al., 2012; Jakob et al., 2012; Schäfer, 2005).

Moreover, according to the International Panel on Climate Change (IPCC), on a global scale, demand-side measures are key to 1.5°C pathways. Scenarios focused on demand-side measures demonstrate the potential to reduce global GHG emissions in end-use sectors by 40-70% by 2050 compared to baseline scenarios (IPCC, 2023a).

Demand-side mitigation involves making changes to infrastructure use, adopting new end-use technologies, and promoting sociocultural and behavioral changes. Such changes can include the implementation of smart grids, the integration of technological and social innovations like information and communication technologies, the establishment of energy communities, and the adoption of sustainable habits such as reducing food waste and embracing sustainable and healthy diets.

In addition, limiting global warming to 1.5°C must also be accomplished in tandem with poverty reduction and better energy security, and it can deliver significant public health benefits through improved air quality, averting millions of premature deaths. On the other hand, some transition pathways, such as expanding bioenergy, may result in trade-offs that must be considered, such as significant land-use changes and reduction of available land for food production.

As a response to the uncertainty surrounding the different potential evolutions of the future energy system and the different pathways that could be followed to attain a green, inclusive, and fair socioeconomic system, researchers utilize the concept of "*scenario-based analysis*" to present various future development trajectories and climate-/ energy-related trends, which describe different transition pathways to a decarbonized energy system, without implying probabilities on the actual implementation of each scenario (Levesque et al., 2018a).

Such scenario-based analyses often aim to explore conditions leading to long-term objectives (e.g., 1.5°C global warming) (B. C. O'Neill et al., 2017), while providing an outline of qualitative trends and quantitative projections regarding emissions, societal futures, economic implications, and climate impacts including the evaluation of the implicit uncertainty introduced. Especially long-term global scenarios have become of particular importance to climate research and climate policy planning, since the "*Special Report on Emission Scenarios*" (Nakicenovic & Swart, 2000).

For more than two (2) decades, long-term global scenarios have been critical in climate change analysis (Nakicenovic & Swart, 2000; Raskin et al., 2005; D. P. van Vuuren et al., 2012). While there are other methods for characterizing the future (Lempert et al., 2004; Webster et al., 2003), alternative scenarios are an important tool for exploring uncertainty in future conditions of the society and climate (Jones et al., 2014). Societal development scenarios frequently include both qualitative and quantitative components (Ash et al., 2010; Raskin et al., 2005; Rothman et al., 2007; D. P. van Vuuren et al., 2012).

Qualitative narratives (or *storylines*) describe the evolution of societal aspects that are difficult to quantify (such as the quality of institutions, political stability, environmental awareness, etc.), and provide a basis for further elaboration of the scenarios by users. *Quantitative components* define common assumptions for elements like population and economic growth, or rates of technological shifts that can be meaningfully quantified and used as inputs to models for modeling energy and land use, emissions, and other outcomes.

In this context, the concept of "*Shared Socioeconomic Pathways (SSPs)*" has been proposed as a new set of scenarios to be used as a basis of future climate research and present alternative futures of societal development till the end of the 21st century (B. O'Neill et al., 2014; D. van Vuuren & Carter, 2014).

The SSPs form a set of five (5) possible future development pathways that result in fundamentally different states of human society; each SSP builds on a unique narrative and articulates the challenges on mitigation efforts and adaptation to climate change that come along with each narrative.

Despite their global scale in their original form, SSPs have been interpreted in quantitative scenarios in multiple studies, serving as the basis for long-term projections concerning different contexts, sectors, and scales to facilitate effective mitigation and adaptation planning in areas of interest.

The SSPs can also be used in combination with additional climate-specific assumptions to explore the effects, both positive and negative, of climate policies in different contexts, or to assess the overall implications of climate change. Indicatively, SSPs have been utilized to study uncertainties related to socioeconomic factors such as population changes, economic growth, technological advancements, urbanization, and education from 2020 to 2100. They have also been used recently to predict long-term useful energy and final energy demands in buildings (Chakraborty et al., 2021; Levesque et al., 2018a).

By examining prospective energy futures, the need for a fair and inclusive energy transition and the advancing role of citizens in the future energy regime, are core aspects of alternative sociotechnical pathways that could lead to the vision of decarbonization, especially in the EU, which has been a frontrunner in policies that foster the transition to a carbon-neutral socioeconomic environment. In this context, case-specific decarbonization pathways are typically created to accomplish a single predetermined climate target.

Reduced mitigation expenditures, rather than climate-related harm or long-term development impacts, are commonly used as the base for these paths to the desired climate target. Interactions between mitigation and other Sustainable Development Goals (SDGs), on the other hand, present both barriers and opportunities for climate policy (UN DESA., 2023). Consequently, substantial efforts are being undertaken to assess the effects of various mitigation pathways on long-term development.

Efforts are being made to incorporate climate change mitigation into a range of objectives that align more closely with societal concerns and may offer cost savings compared to individual policies (e.g., Clarke, Jiang, Fisher-Vanden, et al (2014)). For instance, well-crafted policies have the potential to ensure widespread energy access, reduce air pollution, and address the challenges of climate change (Awewomom et al., 2024; IEA, 2017).

Considering all the above, it becomes apparent, thus, that the concept of "*energy citizenship*" could play a crucial role if incorporated in scenario-based analyses that aim to develop transition pathways towards desired energy futures and the target of decarbonization.

However, the development of such scenarios and pathways, solely, is not enough, as policymakers need decision and support tools, which are able to explore the interplay of economic decision-making and behavioral heterogeneity in, for example, households' energy choices when testing common climate mitigation policies (e.g., carbon pricing), socioeconomic alternatives in a world with changing climate, etc.

1.3. Energy system modeling and energy citizenship

Energy system models have been a valuable tool towards well-informed decision- and policymaking processes in Europe over the past few decades: they have simulated multiple energy transition scenarios and pathways and have reflected on different possible evolutions of the energy systems (Süsser, Ceglarz, et al., 2021).

Energy system models are purposeful mathematical simplifications of reality- "*smaller, less detailed, less complex, or all together*", but they are also shaped by, and potentially shaping, the social world, in which they are embedded (Van Egmond & Zeiss, 2010). The same holds true for the modelers themselves, who define the model's nature-based theories, empirics, and also their ideas and mental models, respectively (Ellenbeck & Lilliestam, 2019). Thus, computer and mental models are mutually dependent.

In this regard, models can serve as spaces for "*discourse*" and "*negotiation*", allowing scientists and policymakers to come together and foster a shared understanding, collaborate, and shape knowledge and policy (Den Butter & Morgan, 1998). Hence, energy system models can provide valuable support for governmental decision-making processes (Lopion et al., 2018); however, they cannot be a "*final decision for the policy process to [be] simply implement[ed]*" (Gilbert et al., 2018).

As stated by 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*". In this context, the field of energy system modeling has been prolific, and many models have been and are currently being developed using different methodologies and working approaches.

Linking social science and the concept of "*energy citizenship*" to modeling tools is an important topic because it can broaden the perspective on, and understanding of, the complex subject of the energy transition, the diffusion of the technological and social innovations required, and the interactions between key characteristics of citizens' behavior affecting investment decisions.

Considering the wide spectrum of activities that the concept of "*energy citizenship*" encompasses and its multi-dimensional approach to tackling climate change, it has become increasingly evident that the transition of the energy system, i.e., the established ways of producing, distributing and consuming energy in the present societies towards carbon neutrality, involves more than substituting fossil fuels with renewable energy. Instead, it implies a transformation in collective, shared practices of governing and managing the energy system and the emergence of new social roles (e.g., Bjerkan et al., 2021), and this requires the consolidation of the "*energy citizenship*" concept.

For example, when it comes to the EU and the 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 and pursue the technological capabilities required.

However, given that it is unlikely that citizens 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 the value derived from a higher proportion of self-produced/ self-consumed energy.

In that regard, 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 (K. Li et al., 2019; Tzani et al., 2022). Nevertheless, 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. In this context, relying on demand-side modeling tools that consider citizens' behavioral characteristics is critical to determining profile patterns of future transformations.

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 crisis 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 (Nikas, Lieu, et al., 2020; Papantonis et al., 2022).

However, despite the increasing importance and use of energy system models, important aspects such as the ones mentioned above are often underrepresented. In particular, most models take a technoeconomic and/ or cost-optimization approach, which limits their ability for including social aspects and dynamics, such as policy preferences, or social acceptance (Chatterjee et al., 2022; Süsser, Martin, 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 system 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).

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, or further adjust the existing ones and match them with existing needs, to simulate and analyze the drivers and barriers to complete decarbonization, including decentralization, a large-scale deployment of variable renewable energy (VRE) sources, resulting in a greatly increased demand for system-side flexibility, sector-coupling, including electrification of transport and heating, and the effects of alternative market designs on the behavior of different energy sector players (Kleanthis, Stavrakas, et al., 2022; Süsser, Gaschnig, et al., 2022).

1.4. Energy citizenship at the national and the supranational levels

According to recent literature "*there is a risk of diluting the ambition at the national level, a persistent lack of coordination of national energy policies*" and a serious *"need to strengthen common financing, policy coordination, and governance tools*" (Defard, 2023). This calls for a variety of actions by a wide range of actors at different levels of influence and for improved governance structures and collaboration across different policymaking levels, e.g., administrative levels within countries (Intergovernmental Panel on Climate Change (IPCC), 2022; Wang et al., 2024).

When it comes to energy citizenship and its various expressions, we have to properly acknowledge their potential to influence the decarbonization process at various scales of analysis, starting at the local level and going all the way up to the supranational (EU, or even global) level. This allows for evaluating in a bottom-up way the potential of the different forms of energy citizenship, either individual or collective, in contributing to the achievement of climate and energy targets at the Member State, or even the EU level, and the vision of climate neutrality by 2050.

For example, citizens could actively contribute to the energy transition by investing in technologies that enable them to partake in self-production and self-consumption practices. While doing so, it is expected that they will reap the various benefits associated with this decentralized transformation, e.g., reduction in energy bills (Weinand et al., 2023), income generation (Gautier et al., 2017), driven by acts like directives, and other legislation, as mandated by national governments and the EU (Petrovics et al., 2022).

This means that while it is important to evaluate such aspects at the local level to come up with well-targeted policy recommendations, eventually policymakers and practitioners also need to evaluate the decarbonization potential, e.g., emission reduction, required investments, of different configurations and actions at an upscaled level so that they find the optimal combination of policy measures.

In addition, when citizens come together to form collective expressions of energy citizenship, as collective prosumerism, etc., they are able, through the consolidation of resources, knowledge, and skills, to collectively execute larger-scale projects, which may be difficult to accomplish independently, also enhancing their influence and optimizing the advantages they receive (Inês et al., 2020; Pillan et al., 2023). Such communal initiatives enable the participation of several individuals in decision-making and collaborative efforts, promoting a sense of community involvement and responsibility for energy generation (Gui & MacGill, 2018).

An evaluation at an upscaled level is important in this case too, though. For example, regulatory frameworks at the national level, or even the supranational level, need to be designed to govern the interactions between such collective expressions and grid operators. Such regulations could have a significant impact on the collective actions and can be quite intricate because to the increasing diversity of schemes, business models, types of prosumers, and grid-related challenges (Heffron & Talus, 2016).

On the other hand, the transposition of relevant EU directives, which provide standardized definitions of collective prosumerism, could potentially create challenges at the national level too, due to the implementation of new legal frameworks that complicate the process of dealing with the existing diversity of collective prosumers (Inês et al., 2020).

On another expression of energy citizenship, ensuring that citizens adopt low-carbon behaviors is essential for making significant progress in the transition to a society with reduced carbon emissions. Modifying one's lifestyle can have a substantial influence on energy consumption, carbon emissions, and the overall sustainability of the environment at the national level. For example, promoting the utilization of public transport, cycling, walking, and electric vehicles (EVs) can effectively diminish carbon emissions in transport of a Member State, a high emitting sector overall. Advocating for sustainable forms of transport at the micro scale, thus, can significantly contribute to the decarbonization of the transport sector in the EU (Spandagos et al., 2022; Watabe & Yamabe-Ledoux, 2023).

Moreover, other lifestyle changes at the micro scale, like waste reduction and recycling methods, such as minimizing waste, reusing resources, and decomposing organic waste, can effectively reduce carbon emissions linked to the disposal of trash in landfills and incinerators (Budihardjo et al., 2023), which results to a higher decarbonization potential of Member States. Through the implementation of sustainable waste management strategies, citizens have the ability to make a valuable contribution to the circular economy and reduce the negative effects of trash disposal on the environment at both the national and the EU levels.

In addition, sustainable consumption involves making deliberate decisions regarding European citizens' purchases, consumption, and disposal practices, which can greatly influence carbon emissions (Dong et al., 2023). By selecting items with little packaging, opting for locally sourced and organic foods, and decreasing the intake of meat and dairy products, individuals can effectively decrease carbon emissions linked to the manufacture, distribution, and disposal of these items at a national, or even a supranational level (Koide et al., 2021).

Finally, recent scientific literature argues that the transition to fair, sustainable, and inclusive future societies is essentially a political battle, and thus endeavors to move away from fossil fuels and achieve decarbonization in societies will lack effectiveness unless they address and disrupt the prevailing energy power systems (Burke & Stephens, 2018). In line with this, during the past decade, there has been a notable increase in social movements opposing the use of fossil fuels.

In this context, a recent scientific article by Hielscher et al., (2022) highlighted the contentious politics surrounding sustainability transitions and the influence of social movements. Specifically, through case studies focusing on onshore oil and gas and coal projects in the Netherlands, Poland, and the United Kingdom over the past decade, they analyzed the interplay between social mobilizations, policy developments, and industry activities. The findings of the study showed that social movements discouraging the use of fossil fuels have been able to strengthen efforts to address and influence fossil fuel policies. They have pursued legal action and engaged in planning processes aligned with national climate change targets, holding actors involved in fossil fuel activities accountable. Additionally, these movements have established connections with broader climate change movements worldwide, shaping collective action frames that sway public opinion and compel national governments to transition away from fossil fuels, contributing to a sustainable development at a supranational level.

Overall, it becomes apparent that energy citizenship encompasses both campaigning for structural transformation and making sustainable decisions in citizens' everyday lives to diminish their carbon emissions and foster a more sustainable future, which can have a significant impact at both the micro (local and regional) and the macro scales (national and supranational). This is a complex nexus that needs to be studied from different angles and perspectives, in order to provide decision-makers and other relevant stakeholders with as well-informed advising as possible.

1.5. Objectives and scope of this deliverable

Since the concept of "*energy citizenship*" has such a large variety of expressions, it is obvious that it can greatly influence decarbonization processes on multiple fronts and scales. Especially at the national and the EU scales, though, it is crucial to better understand how the impacts of the different manifestations of energy citizenship have been studied so far. A recurring challenge noticed in recent literature is the lack of using quantitative methods, such as energy system models; most research is based on either field studies or surveys and interviews. Such methods, while they do offer benefits and can pave the way for further research on the subject, can only derive general trends and implications that may not be adequate for policymaking.

The ENCLUDE Work Package 5 (WP5) addresses this gap by using the strengths of energy system and integrated assessment models, aiming at a more holistic modeling of the different aspects of energy citizenship, exploring the multi-scale relationship between its various forms and the decarbonization of the energy system. As part of this deliverable ("*D5.4: Report on the decarbonization impact of energy citizenship at the national and the EU levels*"), the ENCLUDE modeling suite, including two (2) agent-based models (ABMs), a demand-side management model, an energy planning optimization and capacity expansion model (CEM), and an integrated assessment model (IAM), adds a quantitative dimension to the research around the concept of energy citizenship and its expressions at the upscaled level.

In this deliverable, we build again on previous ENCLUDE work under "*WP5: The impact of energy citizenship in decarbonization pathways*", namely: Deliverable 5.1 ("*D5.1: Report on models' adjustments and modifications to match emerging energy citizenship trends and patterns*"), Deliverable 5.2 ("*D5.2: Report on the development of decarbonization pathways based on social innovations of energy citizenship*"), and Deliverable 5.3 ("*D5.3: Report on the impact of energy citizenship at the local level*"), as follows:

"*D5.1: Report on models' adjustments and modifications to match emerging energy citizenship trends and patterns*" in a nutshell (Tsopelas et al., 2022):

In this deliverable, different aspects of energy citizenship were identified and articulated through desk research, which were then categorized in distinct patterns and trends, each one describing a key aspect of energy citizenship, as follows:

- Active participation in the energy market;
- Actions towards energy efficiency;
- Behavioral aspects and lifestyle changes;
- Collective expressions of energy citizenship;
- Political activities.

The ENCLUDE modeling ensemble and its capabilities were also presented.

"*D5.2: Report on the development of decarbonization pathways based on social innovations of energy citizenship*" in a nutshell (Tsopelas et al., 2023):

As part of this deliverable, the identified patterns and trends of energy citizenship served as guidelines for the development of four (4) "***people-centered***" storylines, a short description of which is provided below:

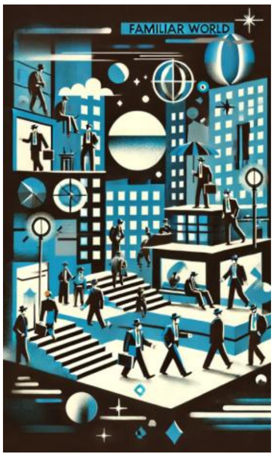
“***Power to the People***”**:** This storyline explores a decentralized energy system where citizens become more actively participating in the energy transition, investing in relevant green infrastructure as small-scale photovoltaic (PV) systems (prosumerism) and energy efficiency and smart technologies.

“***Band Together***”**:** This storyline focuses on citizens' collective actions in the energy system, such as the formation of energy communities, where optimized and localized energy production and resource utilization can take place.

“***Habitual Creatures***”**:** This storyline revolves around daily habits of citizens and how small changes in everyday life and their lifestyle can impact the energy transition and contribute to the decarbonization of the energy system.

“***People to the Streets***”**:** This storyline emphasizes political activism surrounding climate change and citizen participation in social movements and civil society initiatives advancing democratic visions of energy transition.

In addition, and by expanding the concept of SSPs, as presented above, a set of three (3) “***future-world***” narratives referring to different potential evolutions of the future in terms of external systemic factors that are related to institutions and organizations were also formulated; a short description is presented below (*Note that the images presented were created with the assistance of AI and DALL·E 2*[1]):



“***A Familiar World***”**:** This narrative simulates the future-world evolution in its present state, with the current rates of decarbonization and the baseline scenario specifications as foreseen by current policy documents, relevant announcements, and political decisions made at the EU level.

“***A Unified World***”**:** This narrative simulates a future-world evolution in which society, governments, and nations around the EU, but also at the global level, come together and unite against climate change, as the biggest crisis of our age. Policymaking processes all around the world promote acceleration of decarbonization through transnational collaboration and investments in green solutions as soon as possible.

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[1] https://openai.com/index/dall-e-2/

"***A Fragmented World***"**:** This narrative simulates potential future-world evolutions of undesired societies, which tend more and more to "dystopia" in the sense of extreme or even exaggerated worst-case scenarios, e.g., more totalitarian regimes arise, more social inequalities, more control over people through the usage of propaganda, censoring of information or denial of free thought, the gradual loss of individuality, enforcement of conformity, rise of individualism and anti-collectivism, more (war) conflicts at the regional and transnational level. This narrative assumes that policymaking processes emphasize more regional and national security rather than combating the climate crisis.

"*D5.3: Report on the impact of energy citizenship at the local level*" in a nutshell (Fotopoulos et al., 2024):

By combining the work conducted under the previous two (2) WP5 deliverables, and by following the overarching design of WP5, in Deliverable 5.3 we proceeded with the next step, which was to design transition scenarios and decarbonization pathways in different real-world case studies, as selected from the extensive and well-detailed case study pool developed as part of the work conducted under the ENCLUDE WP3 (Brenner-Fliesser et al., 2023).

For example, recognizing the importance of the "Power to the People" storyline, we appraised the potential impacts of prosumerism at the local level, towards greener futures, while we also assessed the decarbonization potential of investing in energy efficiency solutions and adopting energy-related lifestyle changes at the local level of municipalities and the value of collective citizen activities in contributing to meaningful changes over time.

To do so, the ENCLUDE modeling ensemble (**Table 1**) was employed to provide quantified results on the decarbonization potential of these different variations of energy citizenship at the local level. To adjust our work and match it to the case-specific characteristics of the analyzed case studies and to the needs of the patterns and trends of energy citizenship identified, the previously modeling ensemble, as presented in the context of Deliverable 5.1, is further expanded with two (2) new modeling additions.

In Deliverable 5.3, we introduced one of these new entries, the ANIMO modeling framework, a new modeling framework further enhancing the ENCLUDE modeling ensemble's capabilities towards a broader and, at the same time, deeper (more holistic) exploration of the different energy citizenship expressions.

Complementing the modeling work performed under Deliverable 5.3, in this report, our main goal is to develop a comprehensive understanding of the decarbonization potential of the different variations of energy citizenship at an upscaled level. By employing the enhanced ENCLUDE modeling ensemble we try to shed light on how different aspects of energy citizenship could support the shift to a decarbonized energy paradigm at both the national and the supranational levels across the EU.

More specifically, building on findings of Deliverable 5.3 about the decarbonization potential of the concept of "prosumerism" and the "*Power to the People*" storyline, in this work we upscale our modeling work and explore different diffusion scenarios of small-scale PV installations in the residential sector of three (3) Member States, evaluating the efficacy of different existing policy schemes in achieving national targets by 2030 and reducing carbon dioxide (CO_2) emissions at the national level.

In addition, we strive to comprehend the influence of different transition pathways under a combined "*Power to the People*" and "*People to the Streets*" storyline towards different configurations of a future energy system and decision-making at the national level, also considering citizens' acceptance and individual preferences.

To do so, in this report, we introduce the second new entry of the ENCLUDE modeling ensemble, the OSeMOSYS-GR, a country-specific implementation of the OSeMOSYS modeling framework, which has been developed and adjusted to accurately model the unique characteristics of the Greek power system for the period 2021-2050.

Last but not least, we utilize an IAM to explore the scaled-up decarbonization impact of all the four (4) "*people-centered*" storylines in both the transport and the residential sectors at the supranational (EU) level.

Overall, case studies across different geographical contexts, socioeconomic environments, and scales of analysis are modeled, with our aim being, eventually, and by combining the work under both Deliverable 5.3 and this report (Deliverable 5.4), a sound and robust understanding of the multi-scale relationship between the different energy citizenship expressions and decarbonization pathways, not only theoretically, but also through real-life practical implementations.

Furthermore, in both deliverables, more information on the workings and capabilities of the ENCLUDE modeling ensemble is provided. As such, both reports may easily be used both within and outside of the project, by policymakers and other relevant end-users from the field of policy and practice using our findings to derive interesting and policy-relevant implications and recommendations, and by researchers and other end-users from the field of academia that are interested in the ways that different patterns and trends of energy citizenship at the local, the regional, the national, or even the supranational and the EU levels can be integrated into the design of decarbonization pathways and simulated through the use of energy system models.

Based on the specifications of the case studies and the capabilities of each modeling tool (i.e., national or EU spatial resolution), in this deliverable we present results from the application of the ATOM, the IMAGE, and the OSeMOSYS-GR models.

Table 1. The enhanced ENCLUDE modeling ensemble.

Modeling framework	***Description***
gr**A**ssroot i**N**novation d**I**ffusion **MO**del (**ANIMO**)	**ANIMO** is an agent-based model capable of simulating the diffusion of social innovations, such as the creation of, and participation in, energy community projects, and investigating how envisioned social improvements are embraced by, and distributed throughout, households and individuals with various socio-economic, behavioral, and lifestyle profiles.
Agent-based **T**echnology ad**O**ption **M**odel (**ATOM**)	**ATOM** is an agent-based model, which based on the plausibility of its results compared to historical data and observations, simulates the expected effectiveness of various policy schemes on technology adoption (e.g., small-scale solar PV, battery energy storage systems, heat pumps, EVs, etc.) in the residential sector, for the geographical and socio-economic context under study. Apart from exploring the expected effectiveness of technology adoption under policy schemes of interest, the model allows us to consider and explicitly quantify the uncertainties that are related to agents' preferences and decision-making criteria (i.e., behavioral uncertainty). As agents in the model, we refer to citizens and households.
Dynamic high-**R**esolution d**E**mand-sid**E** **M**anagement	**DREEM** is a fully-integrated energy demand and demand-side management simulation model, focusing on the building sector, which expands the computational capabilities of existing Building

(**DREEM**)	Energy System and demand-side models, by not only calculating energy demand, but by also assessing the benefits and limitations of demand flexibility, primarily for the main end-users (consumers/ citizens), and, then for other energy system actors involved (e.g., suppliers, retailers).
Integrated **M**odel to **A**ssess the **G**lobal **E**nvironment (**IMAGE**)	**IMAGE** is an IAM suited to large scale and long-term assessments of interactions between human development and the natural environment, and integrates a range of sectors, ecosystems, and indicators. The model identifies socio-economic pathways and projects the implications for energy, land, water, and other natural resources, subject to resource availability and quality.
Open-**S**ource **e**nergy **MO**deling **SYS**tem for **GR**eece (**OSeMOSYS-GR**)	**OSeMOSYS** is an energy system optimization and capacity expansion model generator that follows a dynamic, deterministic, technology-rich, bottom-up, linear-programming approach for medium-to-long-term energy planning. It is utilized to determine the most economically efficient pathway by minimizing the discounted cost of the system and by optimizing the capacity and electricity generation of each technology to meet the predefined final energy demand. **OSeMOSYS-GR** is a country-specific implementation of OSeMOSYS that has been developed as part of the ENCLUDE modeling ensemble and adjusted to accurately model the unique characteristics of the Greek power system for the period 2021-2050.

1.6. Structure of this deliverable

The remainder of this deliverable is structured as follows:

- **Section 2** includes an overview of the methodology followed.
- **Section 3** matches the identified patterns and trends of energy citizenship to the individual modeling tools of the ENCLUDE ensemble, based on their capabilities.
- **Section 4** provides a description of the modeling tools' limitations and capabilities as well as the further modifications and adjustments that took place for model application.
- **Section 5** presents an overview of the final scenario space designed and to be simulated by the ENCLUDE modeling ensemble, based on the "*people-centered*" storylines and the "*future-world*" narratives developed.
- **Section 6** presents the specification of the analyzed case studies, along with respective parameters that were used, the data collection and treatment process followed, etc.
- **Section 7** presents simulation results of the model application to the case studies.
- **Section 8** provides conclusions and recommendations of our work, summarizes limitations, and highlights next steps and areas of further research.

2. Methodology

To assess and evaluate the decarbonization potential of energy citizenship at the national and supranational level, we follow a multi-method approach similar to the one that was followed in **Deliverable 5.3**[2]. Our working approach, as depicted in **Figure 1**, comprises five (5) distinct methodological steps, culminating in the derivation of valuable insights and policy recommendations from the results obtained through the various modeling frameworks utilized in this study.

We start with matching the different patterns and trends of energy citizenship (as derived in **Deliverable 5.1**[3]) to the enhanced ENCLUDE modeling ensemble, while we continue with designing the ENCLUDE scenario space for the real-life applications under study, considering the different "*people-centered*" storylines and "*future-world*" narratives (as derived in **Deliverable 5.2**[4]) and the specifications of the case studies, and the parameterization of the different modeling frameworks that are used. Finally, we conclude our analysis by presenting policy recommendations and valuable insights as derived from modeling outcomes.

2.1. Step 1: Matching patterns and trends of energy citizenship to the ENCLUDE modeling ensemble

As part of the ENCLUDE Deliverable 5.1 (Tsopelas et al., 2022), desk research on patterns and trends of energy citizenship was conducted, also based on insights and preliminary findings on typologies of energy citizenship that were developed as part of the work conducted in the context of the ENCLUDE WP2 (Dunphy et al., 2023).

In parallel, a detailed documentation of the ENCLUDE modeling ensemble took place, entailing the current state of the models, their capabilities and limitations, their input and output variables, and their technical characteristics, e.g., spatial, temporal, and sectoral coverage and resolution.

A data collection process enabled us to also develop a matching matrix, optimizing the connections between the models and their ability to address the identified patterns and trends of energy citizenship, both at the individual and the collective levels.

In addition, several interface protocols to facilitate the soft linkage of the models, where necessary, and upscale results at the local level to the national level, were designed, concerning data transfer and model communication and interoperability. Based on this work, we summarized the "*status-quo*" of the ENCLUDE modeling ensemble.

The above allowed us to cluster the identified patterns and trends of energy citizenship in a matching matrix. More specifically, during the period March-June 2023, the identified patterns and trends were mapped again onto the ENCLUDE models to redefine the model capacities for addressing various aspects of energy citizenship both at the individual and collective level and potential model developments, modifications, and adjustments required.

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[2] https://zenodo.org/records/11190946

[3] https://zenodo.org/records/7094195

[4] https://zenodo.org/records/7638853

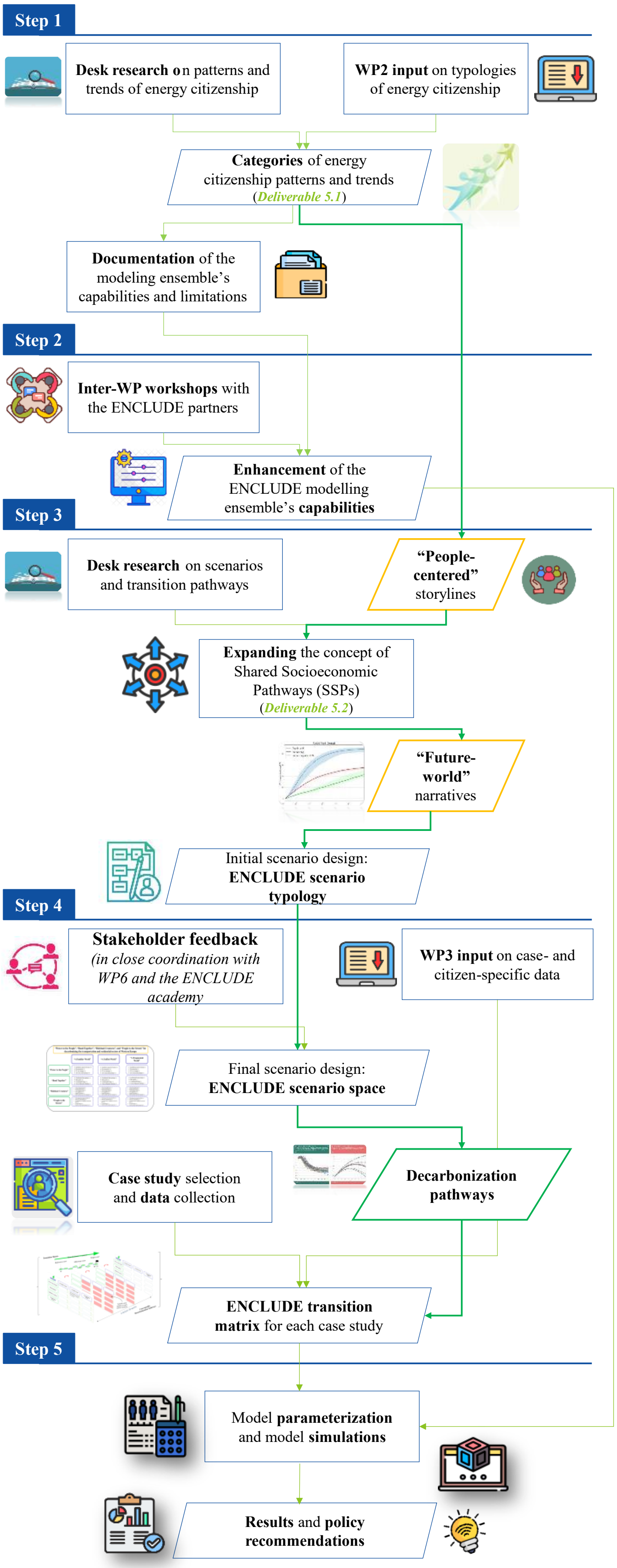


Figure 1. Multi-method approach as followed in the context of the ENCLUDE WP5 to assess and evaluate the decarbonization impact of energy citizenship at the upscaled level.

2.2. Step 2: Further model developments, modifications, and adjustments

After matching the identified patterns and trends of energy citizenship to the ENCLUDE modeling ensemble, two (2) inter-WP online workshops were conducted between September and October 2023, to discuss model capacities in terms of addressing the different aspects of energy citizenship.

During these workshops, partners engaged in discussions regarding model inputs, anticipated outcomes, and the process of selecting prospective case studies. Partners also provided feedback on the potential integration of important variables and assumptions, as well as the collection of data required for the calibration and parameterization of the modeling ensemble.

This gap analysis highlighted specific patterns and trends of energy citizenship that were not adequately addressed by the ENCLUDE modeling ensemble. It also allowed further model developments, modifications, and adjustments required so that the modeling ensemble is able to simulate the decarbonization pathways developed as part of the work under this deliverable.

In this context, a new modeling framework, OSeMOSYS-GR, building upon the foundation of the existing energy system optimization model generator OSeMOSYS (Howells et al., 2011), was developed, while the original modeling frameworks of ATOM and IMAGE were modified.

Finally, in addition to these modifications, models' documentations outlining their technical details, encompassing their functionalities, constraints, input and output variables, as well as technical specifications related to specific geographical contexts, the sectors they encompass, and their temporal resolutions and modeling horizons, have been revisited and updated.

2.3. Step 3: Scenario design, storylines, and narratives

The following step focuses on designing the initial scenario space, within which case-specific decarbonization pathways are defined. Starting point for the initial design of the scenario space was the work implemented in the context of the ENCLUDE Deliverable 5.2 (Tsopelas et al., 2023) and the desk research on scenario-based analysis related to the concept of energy citizenship, with a specific focus on the IPCC's SR1.5 and its accompanying database (IPCC SR1.5 Scenario Explorer) (Huppmann et al., 2019; Masson-Delmotte et al., 2018).

To ensure that the final set of the decarbonization pathways developed for the ENCLUDE applications are based on the most up-to-date and policy-relevant evidence on the contribution of energy citizenship in contributing to the visions of decarbonization and climate neutrality, we also used as a basis of our desk research the IPCC Assessment Report 6 (IPCC, 2023b).

In parallel, we enhanced our work under Step 1 by further elaborating on the categories of the energy citizenship patterns and trends identified under Deliverable 5.1 (Tsopelas et al., 2022). This resulted in the development of a set of "*people-centered*" storylines that depict different aspects of energy citizenship in terms of the different ways that citizens can actively participate in the energy transition. This work has also been showcased in Deliverable 5.2.

By combining the insights of our desk research on scenario-based analysis around the concept of energy citizenship with the final set of the *ENCLUDE "people-centered" storylines*, our next goal was to further expand our scenario space with alternative scenarios that explore uncertainty in future conditions of the society and climate and describe the evolution of societal aspects that are difficult to quantify (such as the quality of institutions, political stability, environmental awareness, etc.), and provide a basis for further elaboration of the scenarios by users.

This enabled us to also encompass the impact of various "environments" that could potentially encompass citizens and citizen-specific expressions of energy citizenship, such as external systemic shifts that may arise in future developments concerning governmental institutions, organizations, and nationwide societal changes, among others.

To do so, we expanded upon the concept of SSPs, which consist of five (5) qualitative descriptions of anticipated shifts in demographics, human development, economics and lifestyle, laws and institutions, technology, and environment and natural resources (Liu et al., 2024). The conceptual framework for the design and utilization of SSPs often involves the development of global pathways that depict the future progression of important societal elements.

As part of Deliverable 5.2, we enhanced and modified this collection of qualitative descriptions to create a set of three (3) qualitative descriptions, the ENCLUDE *"future-world"* narratives, which can complement the "*people-centered*" storylines in the development of the ENCLUDE scenario typology.

In this report, our main objective was to create the scenario space by building upon previous work in WP5. The purpose of this scenario space is to be applicable to various case studies, to which the ENCLUDE modeling ensemble will be applied. The scenario space is initially designed by combining the "people-centered" storylines with the "future-world" narratives into the ENCLUDE scenario typology (**Figure 2**).

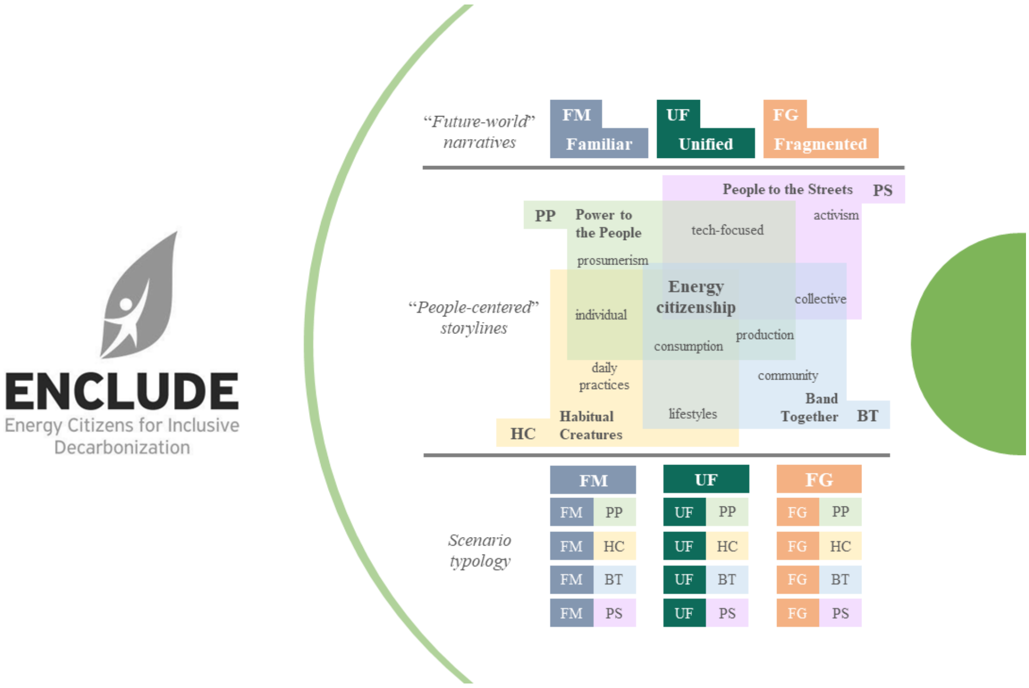


Figure 2. The ENCLUDE scenario typology showcasing all the potential combinations of the ENCLUDE "people-centered" storylines and "future-world" narratives towards the development of the ENCLUDE scenario space.

2.4. Step 4: Case study specification and decarbonization pathways

As Carlsen et al. (2016) point out, a broad and balanced scenario space is typically needed in order to implement scenario-based research correctly and effectively. Researchers can gain a deeper understanding of the intricacies of societal changes and predict possible difficulties and opportunities by examining several storylines and narratives that span a wide range of possibilities.

An expansive range of possible scenarios enables a detailed examination of future transition pathways, taking into account variables such as activities connected to climate and energy, improvements in technology, changes in society, and the rate at which behaviors are adopted. This method allows policymakers and stakeholders to anticipate different possibilities and create strong strategies for sustainable and resilient solutions.

On the contrary, creating a limited and ill-defined scenario space may lead to failing to anticipate certain developments or underestimating the complexities of societal transitions which in turn can result in the implementation of insufficient or misguided policies and biased decision-making.

For instance, an overly optimistic scenario that neglects the challenges of transitioning to RES and assumes rapid global cooperation without accounting for geopolitical challenges could result in ineffective policy responses.

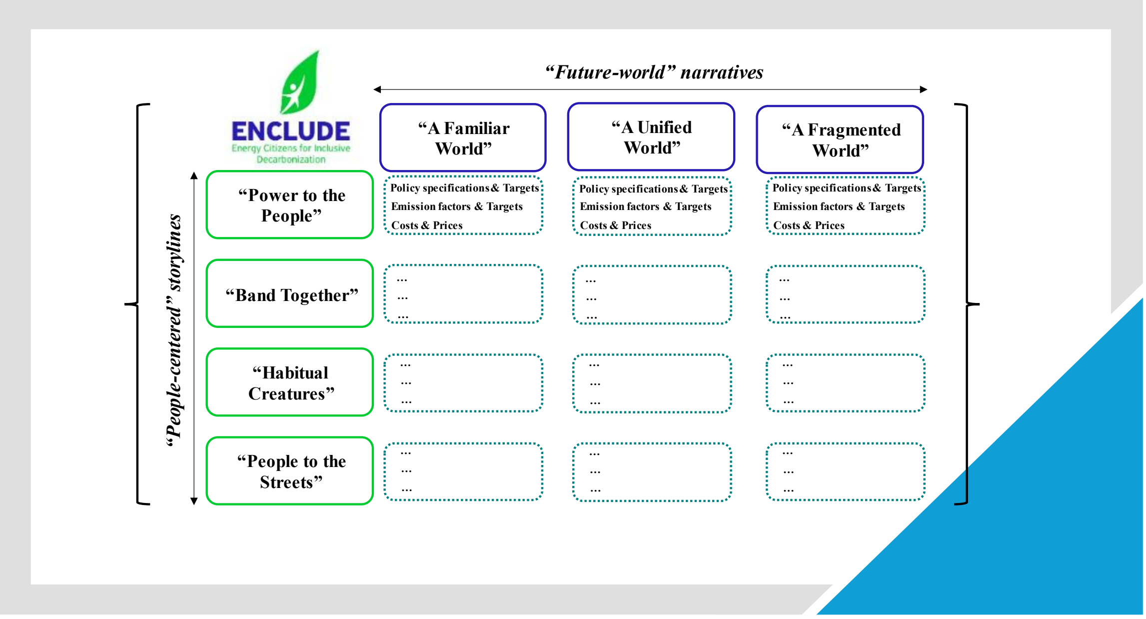
By anchoring decisions solely in best-case scenarios, a misleading perception of security and a failure to adequately prepare for contingencies can be created. Similarly, an excessively conservative scenario space- one that underestimates the pace of technological advancements, policy changes, or societal shifts- can stifle innovation and hinder progress.

If policymakers are on the side of caution, overly conservative scenario space may perpetuate reliance on outdated technologies and impede the transition to more sustainable practices. For example, envisioning a future where the status quo prevails without accounting for breakthroughs in renewable energy or shifts in citizens' behavior might discourage investments in cutting-edge technologies.

This can lead to missed opportunities for transformative change and result in inadequate preparations for a rapidly evolving climate landscape. All things considered, in both cases, the potential ripple effects of oversights and misjudges extend to economic repercussions, social disruptions, and exacerbation of climate-related vulnerabilities.

It is imperative, thus, to design a scenario space which encompasses a broad spectrum of possible futures, acknowledging uncertainties and embracing the depth of complexity of the European landscape, at the local, the national, and the transnational level.

Based on these insights, the ENCLUDE scenario typology serves as the initial framework for developing the ENCLUDE scenario space (**Figure 3**), which, applied to specific case studies, will lead to the final ENCLUDE transition matrix and real-life decarbonization pathways of energy citizenship.



	"A Familiar World"	"A Unified World"	"A Fragmented World"
"Power to the People"	Policy specifications & Targets Emission factors & Targets Costs & Prices	Policy specifications & Targets Emission factors & Targets Costs & Prices	Policy specifications & Targets Emission factors & Targets Costs & Prices
"Band Together"	… … …	… … …	… … …
"Habitual Creatures"	… … …	… … …	… … …
"People to the Streets"	… … …	… … …	… … …

Figure 3. The ENCLUDE scenario space to be applied to specific case studies for the development of real-life decarbonization pathways.

As a next step, we selected a set of case studies to which we apply the enhanced ENCLUDE modeling ensemble. To do so, we explored diverse cases across Europe to illuminate the full range of differences and demonstrate cross-cutting themes. The geographical dimension adds an important value to quantifying the impact of energy citizenship, in terms of the decarbonization potential of its various expressions, at the local level and to better understanding the several important implications of geographies in the EU's policymaking landscape.

Our selection focused on the spatial variation across contexts and the emphasis on cross-case differences of political, social, cultural, economic, demographic, and technological particularities of energy systems.

The main source of information and data for the selection and specification of the case studies was the case study pool developed and maintained in WP3 (Brenner-Fliesser et al., 2023). This way, we were able to collect data provided in the questionnaire developed by WP3 and filter the case studies to select those that we would delve deeper into based on their policy relevance and according to enhanced capabilities of the ENCLUDE modeling ensemble.

By applying the ENCLUDE scenario space to each case study, and by considering case-specific characteristics and citizen-specific data, the ENCLUDE three-dimension transition matrix is produced for each one of the case studies, comprising a final case-specific set of decarbonization pathways (**Figure 4**).

To supplement our work and ensure that the ENCLUDE transition matrix is designed in a way that is policy relevant, we incorporated insights and specifications from the latest policy documents, in accordance with the emission caps of the updated mitigation targets for 2030 and 2050, as outlined in the "Fit for 55" package and the European Green Deal strategy.

Based on the latter, an indicative modeling time horizon, i.e., reference year (simulation start year), interim milestone years (where and if necessary), and the target year (simulation end year), were specified, to be adjusted, though, each time, based on the case-specific characteristics of the application under study.

Finally, to also make sure that the ENCLUDE transition matrix is not only policy relevant, but also helpful and supportive of the different potential end-users' needs, relevant stakeholders' and practitioners' feedback (in close coordination with the work conducted as part of WP6 and the ENCLUDE Academy) was also considered to diversify and expand the decarbonization pathways developed, and eventually account for possible uncertainties and different potential evolutions of the future energy system (Djinlev & Pearce, 2022).

After receiving input from stakeholders, we expanded our scenario space and transition matrix by incorporating various exogenous variables such as emission factors, changes in electricity prices and costs, fuel costs, technological costs, updated configurations, and benefits for citizens and other power actors involved. These additions were made in line with the specifications of the "*people-centered*" storylines and "*future-world*" narratives.

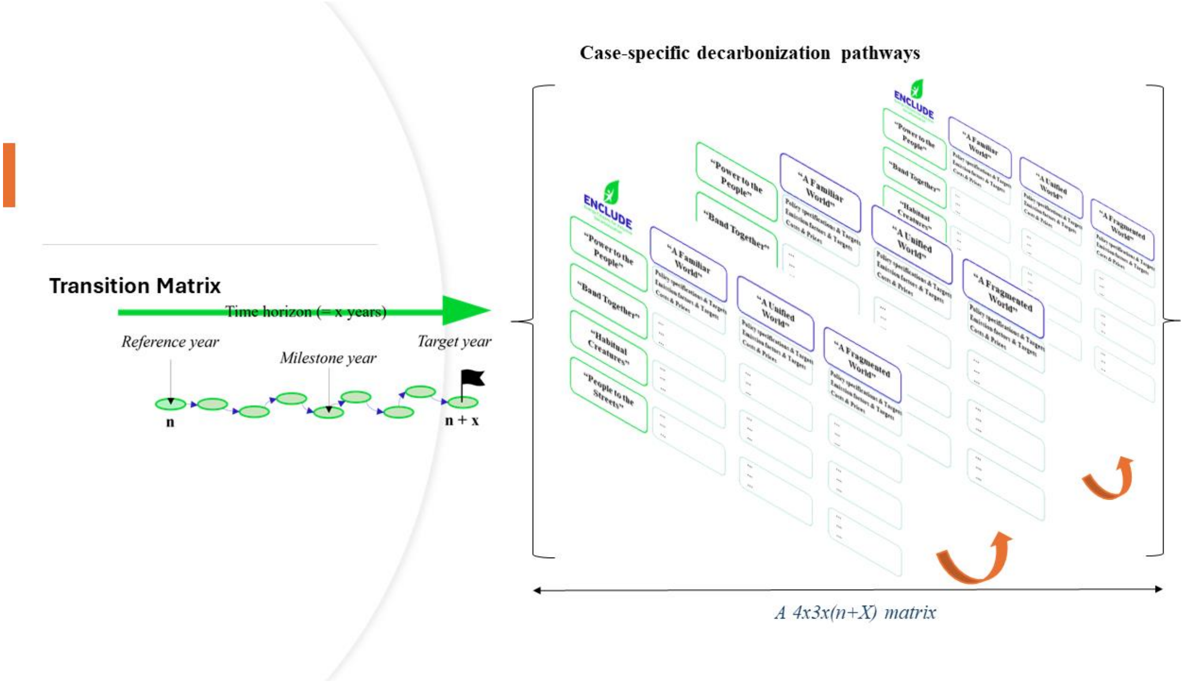


Figure 4. The ENCLUDE three-dimension transition matrix to develop case-specific decarbonization pathways in each application under study.

2.5. Step 5: Model application and policy recommendations

As a fifth and final step, we used the enhanced ENCLUDE modeling ensemble to simulate the matrix of the case-specific decarbonization pathways derived, for the time horizon (e.g., 2030 reflecting on the short-term EU targets, 2040 reflecting on the mid-term EU targets, 2050 reflecting on the long-term EU targets) and the time interval (e.g., one hour, one year, five years) of interest in each application at hand.

Simulations were designed to yield insights that augment our understanding about the decarbonization potential inherent in different energy citizenship expressions at both the national and the supranational (EU) levels.

By projecting decarbonization pathways and examining the implications of citizen engagement, simulations offer complementary insights into the transformative potential of energy citizenship, which has also been highlighted in the qualitative assessments undertaken by other ENCLUDE WPs.

Furthermore, considering the interdisciplinary nature of this deliverable, modeling outcomes have also been shared among other WP leaders, especially the WPs with a background in social science and humanities, fostering collaborative efforts to develop robust policy recommendations aimed at empowering citizens to enact meaningful change, whether as citizens of individual Member States, or as EU citizens collectively.

In this context, to further strengthen our work and make it as useful to potential end-users as possible, a two-fold user-oriented evaluation approach was followed during the 6th ENCLUDE General Assembly meeting in Athens, which took place on the 23rd and the 24th of May 2024:

- During the first day (23rd of May 2024), a focused session on WP5 modeling outcomes took place so that all the ENCLUDE colleagues work collectively on polishing modeling results at both the local (Deliverable 5.3) and the upscaled (Deliverable 5.4) levels and deriving robust policy recommendations and dissemination and communication material to further promote findings, also in view of the ENCLUDE final event in Brussels (25th of September 2024).

- During the second day (24th of May 2024), a workshop with representatives from the C40[5] network, the REScoop.eu[6] federation of citizen energy cooperatives in Europe, and the Municipality of Athens, also in presence of the mayor and the vice-mayor of climate governance and social economy, took place to jointly discuss on issues of effective citizen engagement and how modeling outcomes could further support this cause.

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[5] https://www.c40.org/

[6] https://www.rescoop.eu/

3. Matching “people-centered” storylines to the ENCLUDE modeling ensemble

A preliminary matching of the identified patterns and trends of energy citizenship to the ENCLUDE modeling ensemble, based on the detailed documentation of its “status-quo”, capabilities, limitations, input and output variables, and technical characteristics, e.g., spatial, temporal, and sectoral coverage and resolution, took place as part of Deliverable 5.1 (Tsopelas et al., 2022).

A matching matrix was created by collecting data to enhance the integration of the models and their effectiveness in addressing the identified patterns and trends. In addition, several interface protocols were designed to facilitate the connection between models, with a specific focus on data transfer and ensuring interoperability and communication between the models.

Expanding the work presented as part of Deliverable 5.3 (Fotopoulos et al., 2024), which emphasized developing decarbonization pathways at the local level, in this deliverable, we updated our gap analysis with a focus on developing case-specific decarbonization pathways at both the national and the EU levels.

The objective of this analysis was to find any novel patterns and trends of energy citizenship that have not been previously examined by the ENCLUDE modeling ensemble, also considering the new directions derived from the development of the “*people-centered*” storylines and the “*future-world*” narratives, the insights from the work conducted under WP3 and WP6 (and the ENCLUDE Academy), and relevant end-users’ and other stakeholders’ feedback.

This approach not only allowed us to identify the required enhancements, adjustments, and modifications to the models, but also offered us an in-depth understanding of the interconnectedness between energy citizenship patterns and trends, transition pathways, and the ENCLUDE modeling ensemble. Based on this work, we revised and further updated the “*status-quo*” of the ENCLUDE modeling ensemble (**Figure 5** and **Figure 6**).

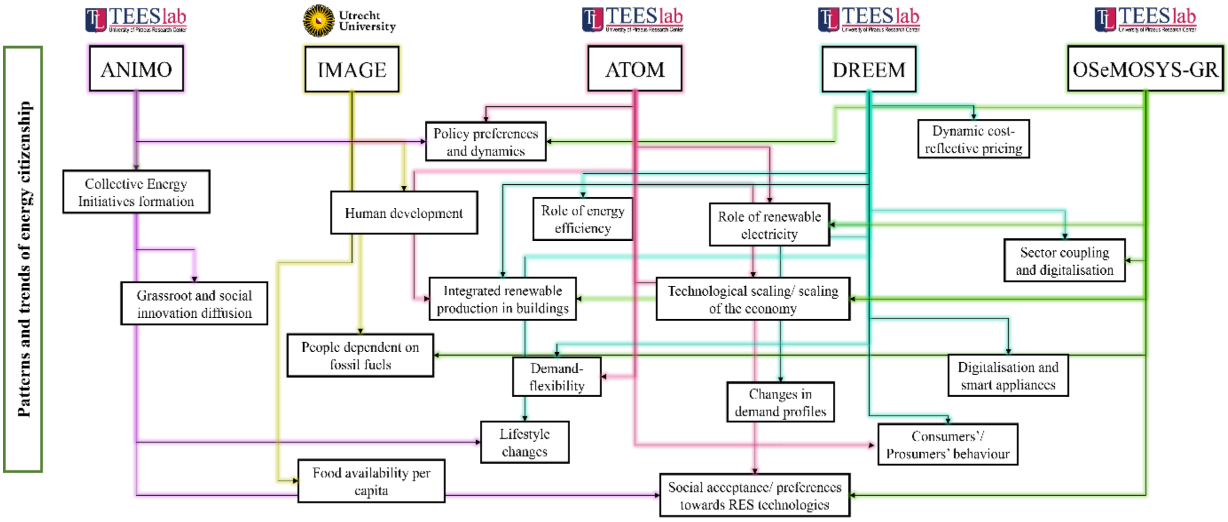

Figure 5. Updated “status-quo” of the ENCLUDE modeling ensemble: Mapping of the patterns and trends of energy citizenship that each model has been designed and further developed and modified to address.

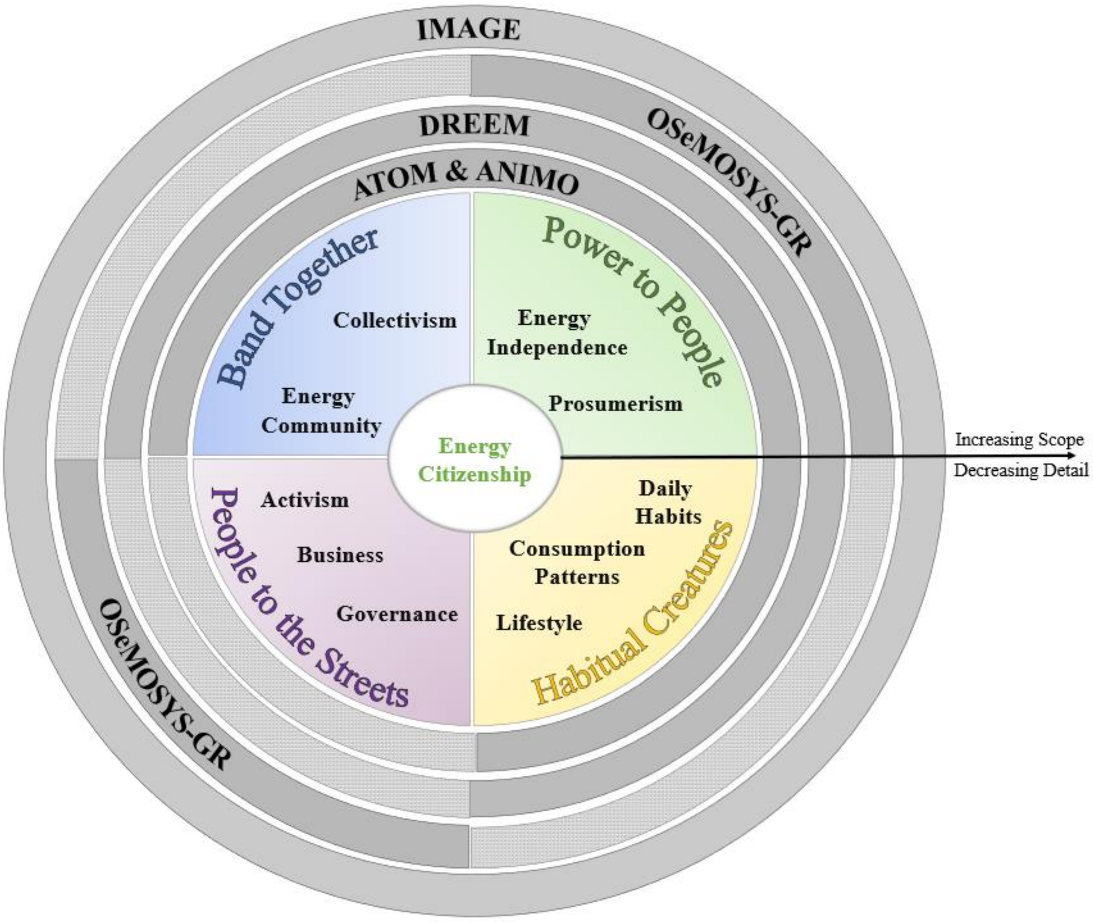

Figure 6. Summary of the "people-centered" storylines that the enhanced ENCLUDE modeling ensemble is capable to address post further developments, modifications, and adjustments.

3.1. Model matching to "people-centered" storylines at the meso and the macro scales

Since an important issue to address in the context of this work is "*scale*" there was a need to capture nuances of energy citizenship at both the national and the EU levels. Building upon the previous work of Deliverable 5.3, which focused on the micro-scale (local level), our research acknowledges the importance of understanding both individual and collective factors that influence the decision-making processes involved in the development of energy citizenship at the *meso* (national level) and *macro* (supranational level) scales.

This entails an exploration of the particular social innovations and technological capabilities that engage citizens and encourage changes at both the household (individual) and the community (collective) level. **Figure 7** illustrates the multi-scale relationship of the ENCLUDE modeling ensemble and indicates the specific scale of analysis in which the various models will be used in this deliverable.

To that end, we proceeded to the development of a new modeling framework for energy system optimization taking into account the specific characteristics of the Greek power sector, namely **OSeMOSYS-GR**. OSeMOSYS-GR is based on the already existing OSeMOSYS modeling framework, which follows a dynamic, deterministic, technology-rich, bottom-up, linear-programming approach for medium and long-term energy planning (Howells et al., 2011).

Overall, in the context of this deliverable, since we emphasize in the decarbonization potential of energy citizenship at the meso and the macro scales, the ATOM, OSeMOSYS-GR, and IMAGE modeling frameworks are employed to provide us with valuable insights and policy implications.

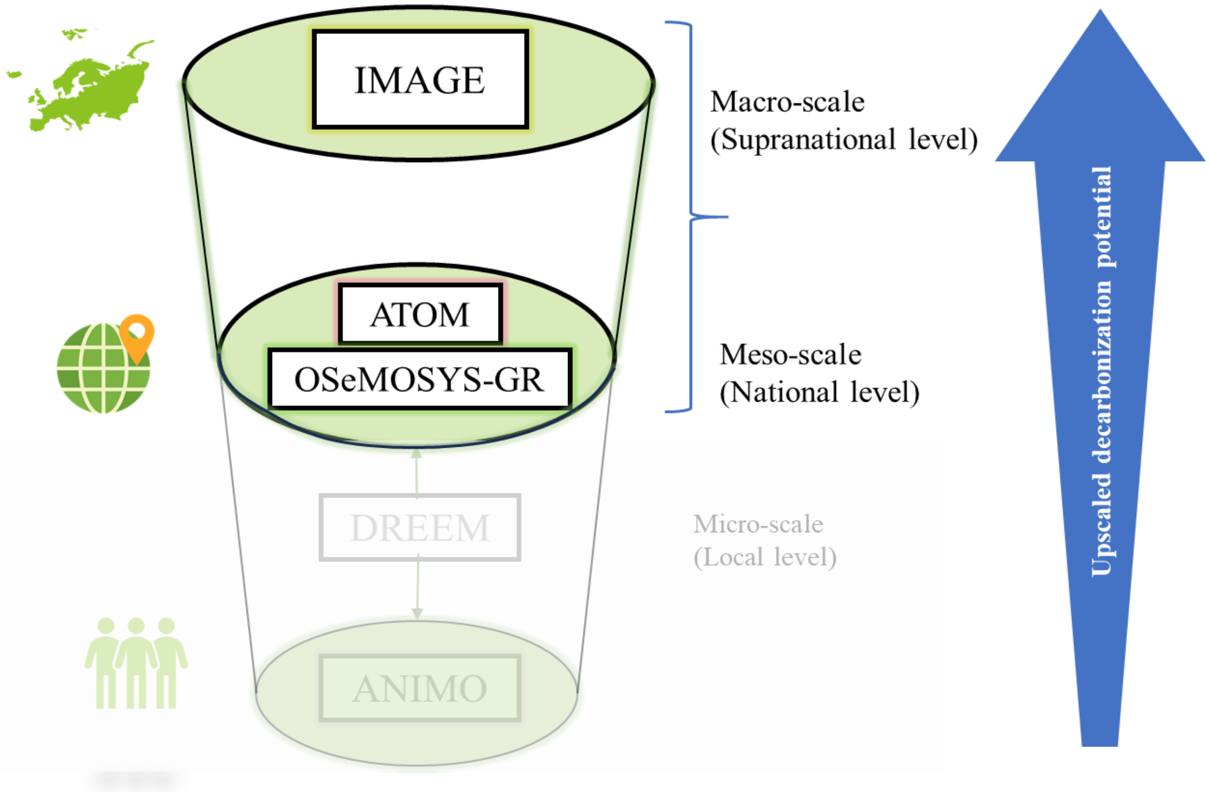

Figure 7. Different scales of analysis of the decarbonization potential of the identified patterns and trends of energy citizenship based on the current “status-quo” of the ENCLUDE modeling ensemble.

3.1.1. The agent-based technology adoption model (ATOM)

ABM techniques provide an appropriate framework for replicating the decision-making behavior of individuals, referred to as "agents," in a varied social environment (Bonabeau, 2002). In this context, the **A**gent-based **T**echnology ad**O**ption **M**odel (**ATOM**) is an ABM, which based on the plausibility of its results compared to historical data and observations, simulates the expected effectiveness of various policy schemes on technology adoption (small-scale solar PV, battery energy storage systems (BESS), heat pumps, EVs, etc.) in the residential sector, for the geographical and socioeconomic contexts of interest (Michas et al., 2020).

Apart from exploring the expected effectiveness of technology adoption under policy schemes of interest, the model also allows to consider and explicitly quantify uncertainties that are related to agents' (i.e., citizens' and households') preferences and decision-making criteria (i.e., behavioral uncertainty).

In the context of this deliverable, ATOM was further developed and utilized to address the "*Power to the People*" storyline (**Figure 8**) and the potential of prosumerism within different geographical and socioeconomic contexts across the EU, evaluating the adoption potential of small-scale solar PV installations by 2030 and considering different citizen behavioral profiles.

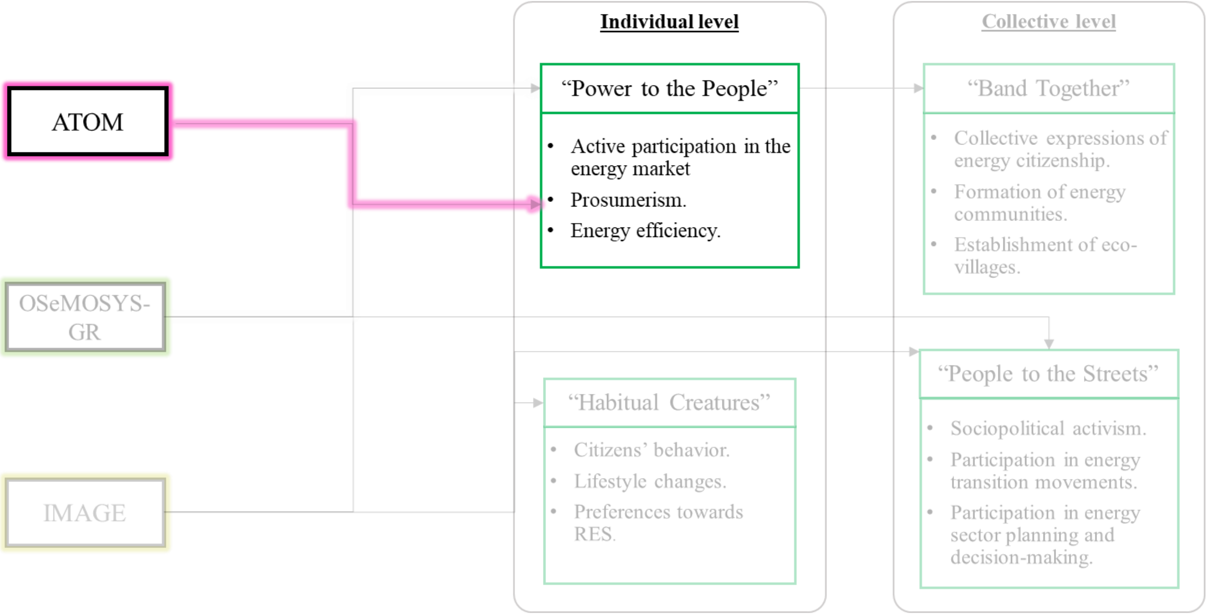

Figure 8. "People-centered" storylines that ATOM was further developed, modified, and adjusted to address in the context of the real-life applications under study at the upscaled level.

With the aim of performing socially well-informed modeling activities, an extensive database is required, therefore, ATOM is supplemented with a complete framework for parameter estimation as well as quantification of the uncertainty that governs its ability to replicate real-life processes and make future projections, to facilitate the design and implementation of policies and initiatives that align with public sentiment.

Forward-looking simulations performed with ATOM encompass various agent-related factors, including inertia toward PV investments, resistance to adopt solar PV installations, and propensity to engage in prosumer activities. Additionally, market-related parameters such as capital costs associated with solar PV systems, household electricity prices, feed-in tariffs (FiT), and other market dynamics are taken into account.

By integrating these multifaceted parameters, ATOM offers insights into the intricate interplay between socioeconomic factors and the adoption of small-scale solar PV systems. This approach allows for a nuanced understanding of the drivers and barriers influencing prosumers' behavior and the uptake of RES systems in different contexts.

3.1.2. The open-source energy modeling system for Greece (OSeMOSYS-GR)

The Open-**S**ource energy MOdeling SYStem (OSeMOSYS) is an open-source model generator used for developing energy planning and integrated assessment models from the scale of continents down to the scale of countries, regions, and villages (Howells et al., 2011).

In this context, the **O**pen-**S**ource **e**nergy **MO**deling **SYS**tem for **GR**eece (**OSeMOSYS-GR**) is a new modeling tool designed and developed in the context of the ENCLUDE project, as an adjusted country-specific implementation of the OSeMOSYS framework to accurately model the unique characteristics of the Greek power system for the period 2021-2050.

In the context of this deliverable, OSeMOSYS-GR is employed to quantify the impacts of the "*Power to the People*" and the "*People to the Streets*" storylines by simulating case-specific transition pathways that envision patterns and trends of energy citizenship as citizens' active participation in the energy market and participation in sectoral planning and decision-making (**Figure 9**).

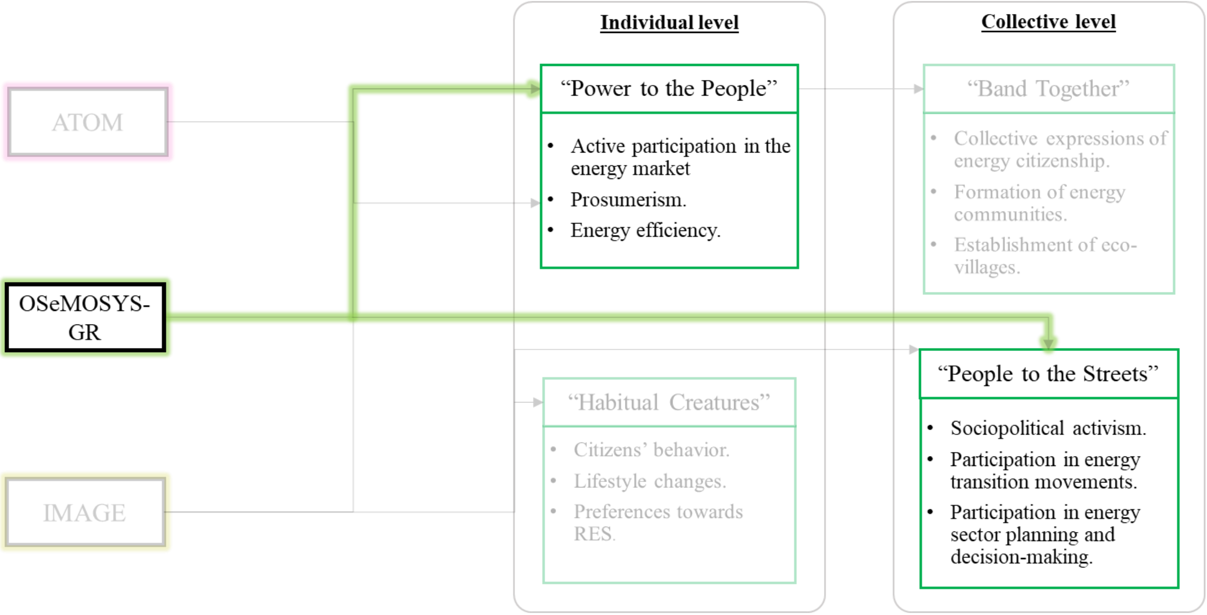

Figure 9. "People-centered" storylines that the OSeMOSYS-GR model was originally designed, developed, and adjusted to address in the context of the real-life applications under study at the upscaled level.

More specifically, under the "*Power to the People*" storyline, OSeMOSYS-GR is matched with the active participation in the energy market trend to simulate the potential environmental and socio-economic benefits of prosumerism through the integration of small-scale solar PV installations in the residential sector, considering different technology adoption trends (feeding on results from ATOM from its application in the case of Greece), as part of the overarching energy planning for the decarbonization of the Greek electricity system. This allows us to examine alternative power sector configurations that emphasize citizen-led decentralized power generation.

Additionally, OSeMOSYS-GR is matched with sociopolitical activities under the "*People to the Streets*" storyline to assess how social mobilization contributes to shaping energy sectoral planning and decision-making processes through the optimization of the energy system at the national level.

To do so, OSeMOSYS-GR integrates through specific technology saturation assumptions (i.e., reducing the technology potential, setting upper and lower production limits, or even technology exclusion) the influence of energy transition movements advocating for sustainable energy practices and environmental objectives under the prism of "*A Unified World*", while opposing such practices and objectives under the prism of "*A Fragmented World*", e.g., people believe that climate change is the biggest crisis of our generation and thus they stand united against the further use of fossil fuels; thus, decarbonization and phase out of fossil fuels take place faster, versus people standing indifferent in front of the climate crisis, opposing to RES projects (not-in-my-backyard) and prioritizing low energy bills and security.

So far, there is lack of scientific literature that indicates the impact of citizen-led decision-making on energy sector planning. A recent study by Vågerö & Zeyringer (2023) has already acknowledged that this could be a topic of interest for energy system modelers in the upcoming years, while Pfenninger et al. (2014) have noted for over a decade now that a big challenge for energy system modelers in the twenty-first century will be the integration of the human behavior and social risks in the energy system optimization modeling frameworks.

In this context, Fell et al. (2020) have tried to capture the risks of a socially inequitable carbon neutral transition using the energy system optimization model “Energy System Modeling Environment” (ESME) and identify the relevant mechanisms that could impact the different population sub-groups. They concluded that energy system optimization modeling should also account for the need for socially equitable energy transitions at both the national and the supranational (i.e., EU) level.

Finally, a relevant study on optimizing energy systems under different sociopolitical storylines of potential future-world developments has been conducted by Mayer et al. (2024) in the context of the EC-funded Horizon 2020 “SENTINEL” project[7] (see Michas et al. (2022) for further information). Through the soft-linkage of QTDIAN, a toolbox of qualitative and quantitative descriptions that examine the sociopolitical factors of the energy transition by deriving storylines that builds on governance logics (Süsser, Lilliestam, et al., 2021), and Euro-Calliope, an optimization energy system modeling framework, based on the already-existed Calliope modeling framework (Pfenninger & Pickering, 2018), the optimal energy system configurations under given storyline-specific boundary conditions were calculated.

Overall, by integrating such insights, OSeMOSYS-GR sets to provide a more comprehensive understanding of the sociopolitical dimensions of the energy transition, hopefully empowering decision-makers to adopt inclusive and participatory approaches toward achieving sustainable energy goals.

3.1.3. The integrated model to assess the global environment (IMAGE)

We use the **I**ntegrated **M**odel to **A**ssess the **G**lobal **E**nvironment (**IMAGE**) to model all the four (4) storylines and different patterns and trends of energy citizenship as identified during previous work under the ENCLUDE WP5 through themes and behavioral actions (**Figure 10**), but in contrast to the other models, at an aggregate level with less detailed and general assumptions.

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[7] https://sentinel.energy/

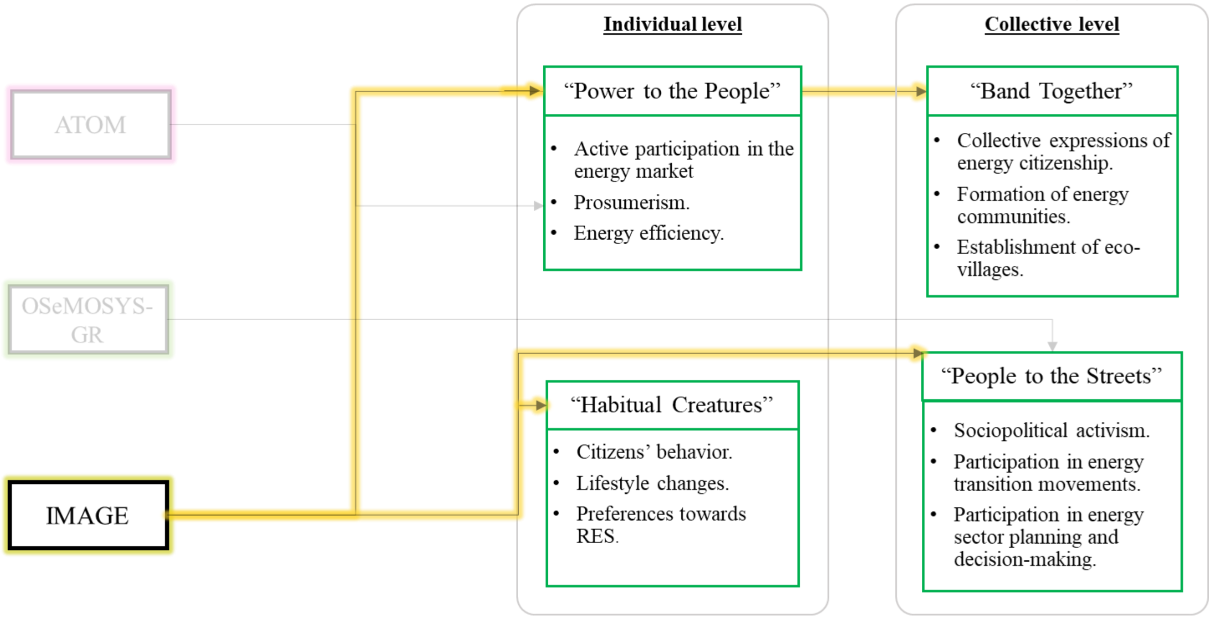

Figure 10. "People-centered" storylines that the IMAGE integrated assessment model was further developed, modified, and adjusted to address in the context of the real-life applications under study at the upscaled level.

- On the <u>individual</u> level:

For the "***Power to the People***" storyline, two (2) themes are matching: renovation and building and individual technologies, which all relate to the prosumer actions:

- Under the renovation and building, passive homes and insulation actions complement the individual technologies, rooftop PV installations, residential BESS, electric cooking, EVs as storage, and air-source heat pumps.
- These actions are both energy consumption and production related (i.e., making the energy citizen a prosumer) and are generally motivated by cost savings, energy or gas independence, and wanting to be eco-friendly and comfortable.
- Factors enabling these actions include subsidies, gas and energy prices, regulation, improved research and development (R&D), and affordability in installation.

For the "***Habitual Creatures***" storyline, we identify five (5) matching themes, namely, incremental adjustments, housing choices, travel, diets, and leisure, which relate mostly to energy use directly and indirectly:

- Under "*incremental adjustments*", thermostat adjustments, housing efficiencies, and taking shorter showers are mostly motivated by cost savings, being eco-friendly, and comfort. These actions are enabled by smart system design, default setting, a shift in social norms, and marketing about their benefits.
- Having fewer appliances and opting for smaller living spaces falls under "*housing choices*", motivated by simpler living and sufficiency in addition to cost savings. Factors such as appliance and home design enable these actions.
- Under "*travel*", a shift towards public and active transport, is motivated by health and the ability to multitask (e.g., working in a train as opposed to driving a car). These actions are enabled by improved infrastructure, convenience, and the availability of options.
- Under the "*diets*" theme, a more sustainable diet with a mix of vegetarian, vegan, and flexitarian locally sourced foods is motivated by health but also cost savings and being eco-friendly.
- Under the "*leisure*" theme, eco-tourism closer to home is motivated mostly by eco-friendly values but enabled by the availability of options and marketing thereof.

- On the collective level:

For the "***Band Together***" storyline, communal technologies, communal living, communal daily travel, and communal holidays, are key themes:

- In communal technologies, geothermal heat pumps for multiple households and mini grids are motivated by cost savings, shared experiences, and optimizing of supply and demand while enabled by incentives and infrastructural opportunities by city planners and local government.
- In communal living, choosing communal spaces such as gyms, laundry, and dining areas is motivated by shared experiences and social cohesion, but also optimizing space and cost savings. These actions would be facilitated by neighborhood initiatives, cooperation, shifts in social norms, but also housing infrastructures.
- For communal daily travel, options such as carpooling, and bike and car sharing would be frequently used, motivated by social interaction, cost savings, but also optimizing of space (from fewer parking spots).
- For communal holidays, shared staycations, or longer stays focus on social cohesion and shared experience, while cost savings with either one holiday home or closer-to-home locations. These are mostly enabled by social norm shifts.

For the “***People to the Streets***” storyline, key themes are public awareness campaigns, advocacy and lobbying, shareholder activism, community lawsuits, and protests and demonstrations. In this storyline, we highlight behaviors that can be adopted:

- For public awareness campaigns, creating awareness to choose and create demand for green energy providers is largely motivated by the emphasis for technology change and the overall lack of awareness of the environmental benefits of green energy providers. This would be enabled through funding for campaigns, social movements and activism.
- In advocacy and lobbying, citizen lobbyists could educate decision-makers about RES benefits and strategies. This is largely motivated by the need to seek responsibility from companies and government for decarbonization. Organizations to help citizen lobbyists are key to enabling these actions.
- For shareholder activism, citizens can leverage big companies for investing in RES, for example. These actions are mostly motivated by seeking responsibility from high-polluting companies. To enable them, shareholder activist groups make it possible.
- For community litigation, citizens can sue companies for sustainable action, motivated by social cohesion, and facilitated by lawyers, social media, grassroots initiatives, and government support.
- For protests and demonstrations, citizens can push for a RES-based energy mix, which is largely motivated by social cohesion, shared experiences, the emphasis on systems’ change, and responsibility from companies and government. Factors that enable this change include social media, marketing, and social media influencers.

Table 2 synthesizes all the different themes and behavioral actions under the four (4) ENCLUDE “*people-centered*” storylines, as categorized by the motivations that drive them, and the enabling factors facilitating them.

Table 2. Themes, behavioral actions, motivations, and enabling factors of the ENCLUDE “people-centered” storylines assumed for modeling with the IMAGE integrated assessment model.

“People-centered” storylines	***Themes***	***Behavioral actions***	***Motivations***	***Enabling factors***	***Factors influencing emergence of Collective Energy Initiatives (CEIs)*** Matowska et al. (2024) Deliverable: 3.2 (WP3)
“*Power to the People*”	Renovation and building	Passive homes	Innovative; eco-friendly; comfort	Infrastructure; architecture; regulations; marketing.	**Autonomy and energy security** (Energy communities): desire of members for independence in energy production & energy crisis as catalyst – uncertainty in the energy market encourages participation. **Funding and subsidies** (ECs): Crucial role of private funding especially in the initial stages; Central Technical Authorities (CTAs): use public funding, especially from sources such as EU funding. **Regulation and administrative aspects** (ECs): administrative changes and bureaucratic procedures & unclear regulatory frameworks and legislative uncertainty impacting formation and functioning.
		Insulation	Cost-savings; eco-friendly; comfort	Subsidies; regulations; marketing.	
	Individual technologies	Rooftop PV	Energy poverty from isolated living areas; less reliance on gas	Subsidies; gas & energy price; regulation; marketing.	
		Battery storage systems	Energy independence	Improved R&D for battery technologies; affordable system provisions; prepaid or leasing systems.	
		Electric cooking	Less reliance on gas	Incentives for shift from gas to induction.	
		EVs as storage	Optimize RE generation; eco-friendly	Subsidies on vehicles and storage; gas and energy price; marketing.	
		Air-source heat pumps for heating and cooling	Energy poverty; less reliance on gas; comfort; eco-friendly	Subsidies; gas and energy price; regulation; marketing.	
	Communal technologies	Geothermal heat pumps for heating and cooling	Cost-savings (through collective	Incentives and infrastructural opportunities provided by city	**Communication** (ECs): facilitating discussions is crucial, as it fosters engagement and

"*Band Together*"			effort); shared experiences	planners and local government.	prevents detachment. **Technologies and knowledge requirements** (ECs): importance of grid stability and connection possibilities; influence of easily accessible technologies and geographical location; some technologies ruled out due to higher costs affecting financing; (CTAs): technology selection driven by compatibility with geographical settings; focus on low-maintenance technologies, often centered around specific options like PV installations.
		Mini grids	Cost-savings (through collective effort); optimized supply and demand		
	Communal living	Communal gym	Social cohesion; shared experiences; cost-savings; optimized use of shared spaces	Neighborhood initiatives; housing cooperation; social norms shift; housing infrastructure.	
		Communal laundry			
		Communal dining and cooking			
	Communal daily travel	Carpooling	Social interaction; prefer not to drive; cost-savings	Peer-to-peer applications; social norms shift; neighborhood networks.	
		Bikes & e-bikes sharing	Optimizing of space; cost-savings; convenience	Peer-to-peer applications and companies.	
		Car sharing	Optimizing of space; cost-savings	Infrastructure; peer-to-peer application; availability; neighborhood facilitated.	
	Communal holidays	Shared staycations or longer-stays	Social cohesion; shared experiences; cost-savings	Social norms shift.	
	Incremental adjustments	Thermostat adjustment	Cost-savings; eco-friendly; comfort	Smart system design; default-setting; social norms; marketing.	**Energy cost reduction** (CTAs)**:** members motivated by reducing energy expenses and achieving self-sufficiency

“Habitual Creatures”		Housing efficiencies: LED lamps, smart metering, standby mode appliances, heat recovery	Cost-savings; eco-friendly	Smart system design; default-setting; social norms; marketing.	**Intrinsic motivation** (ECs): motivated by sustainability; (CTAs): motivated by reducing energy expenses.
		Shorter showers	Cost-savings; eco-friendly	Shower design; social norms; marketing.	
	Housing choices	Fewer appliances	Simpler; cost-savings; eco-friendly	Design of appliances; social norms; marketing.	
		Smaller floorspace	Sufficiency; cost-savings; eco-friendly	Efficient home design; regulation; social norms; marketing.	
	Travel	Shift to public and active transport	Cost-savings; health; eco-friendly; multi-tasking	Infrastructure; availability and convenience; social norms; marketing.	
	Diets	Mix of vegetarian, vegan and flexitarians and locally sourced	Health; eco-friendly; cost-savings	Availability in supermarkets & restaurants; social norms; R&D into meat replacements.	
	Leisure	Eco-tourism, volunteering, eco-locations, closer to home	Eco-friendly	Availability of options; default-setting; marketing.	
“People to the Streets”	Public awareness campaigns	Create awareness to choosing green energy providers	Emphasis on technology change; lack of awareness among consumers	Funding for campaigns; social movements; activism.	
	Advocacy and lobbying	Educate decisionmakers about renewables’ benefits and strategies	Seek responsibility from companies and government	Established lobbying organizations.	
	Shareholder	Leverage big companies to invest	Seek responsibility	Established shareholder activist	

	activism	in renewables	from high-polluting companies	groups.	
	Community lawsuits	Sue companies for sustainable action	Social cohesion	Law; social media; grassroots initiatives; government.	
	Protests and demonstrations	Push for renewable energy mix	Social cohesion; shared experiences; emphasis on systems change; seek responsibility from companies and government	Social media; marketing; influencers.	

3.2. Model matching to “people-centered” storylines at the micro scale

The incorporation of well-established models in the ENCLUDE modeling ensemble, in addition to the development of a new modeling framework, has facilitated a thorough investigation of the dynamics surrounding the concept of energy citizenship and its different forms and expressions, along with decarbonization implications for the energy transition at the micro scale (local level) of analysis.

These modeling applications have been presented in the previous ENCLUDE WP5 deliverable (“*D5.3: Report on the decarbonization potential of energy citizenship at the local level*”) (Fotopoulos et al., 2024)[8]. By simulating several and different transition pathways, extracted from the ENCLUDE “*people-centered*” storylines, important key messages have surfaced, providing insight into various facets of public involvement in the shift toward sustainable energy systems.

3.2.1. “Power to the People” through empowering prosumerism in EU cities

More specifically, recognizing the importance of the “*Power to the People*” storyline, we used the ENCLUDE scenario space and the DREEM model (Stavrakas & Flamos, 2020) to appraise the potential impacts of prosumerism by 2050- through empowerment of citizen investments in small-scale PV and residential BESS- at the local level, in 11 EU cities and five (5) different Member States of diverse geographical, climate, and socioeconomic conditions, namely Denmark, France, Greece, Portugal, and Spain.

Modeling outcomes showed that the profitability of empowering prosumerism through citizen investments in small-scale/ rooftop PV systems at the local level and the EU cities under study depends on the policy schemes of use and capacity of the PV system:

- Current net metering schemes appear more financially attractive when citizens invest in capacities of around 3kWp, which provide the lowest payback period (roughly an average of 3.5 years across all case studies under the “*Familiar World*” narrative) compared to the other policy schemes under study, i.e., FiT and net billing.
- Current FiT schemes tend to yield higher profitability when citizens invest in larger capacities (> 4kWp), especially when featuring a high fixed price for remuneration, as citizens are incentivized to generate greater electricity volumes to channel to the grid. The latter is mainly suitable in cases in which electrification of end-uses in the residential sector is advanced and, thus, higher electricity demand is observed.
- Current net billing schemes, i.e., in the cases of Portugal and Spain, fall short when it comes to empower citizen investments and people-powered transitions based on prosumerism, as excess electricity is currently sold back to the grid at its wholesale price rather than at its retail price, resulting in longer payback periods.

3.2.2. “Band Together” and further diffusion and growth of Collective Energy Initiatives

Furthermore, in the context of the EU’s transition to a future greener energy system and achieving the vision of climate neutrality by 2050, CEIs like energy community and ecovillage structures, are expected to play a vital role as an important collective expression of the concept of “energy citizenship”. To this end, we developed a new ABM framework, ANIMO, to simulate the diffusion of (such as the creation of, and participation in) energy community projects, and investigate how envisioned social improvements are embraced by, and distributed throughout, households and individuals with various socioeconomic, behavioral, and lifestyle profiles.

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[8] https://zenodo.org/records/11190946

The main premise behind the model's development is that the main ways that grassroot innovations as energy communities and/ or ecovillages tend to typically influence larger society are through ***(1). replication***, *(2)*. ***growth in scale***, and *(3)*. ***translation*** (Boyer, 2018).

Our ambition is that ANIMO is further developed to the point that it can address all these three (3) ways; addressing "*replication*" as the growth of the number of energy communities, "*growth in scale*" as, either the growth of specific communities, or the growth of their influence through partnerships and funding programs, and "*translation*" as the adoption of community-relevant policies and practices by mainstream society and institutions.

The three (3) case studies in which the ANIMO framework was applied are: (**i**). the "*Cloughjordan Ecovillage*" in Ireland, (**ii**). the "*EnergieC Midden-Delfland*" in the Netherlands, and (**iii**). the "*Belica Energy Community*" in North Macedonia.

We identified a set of *"character attributes*", i.e., "*financial concern*", "*environmental awareness*", "*energy independence*", *and* "*sense of community*", that are deemed important in influencing citizens' decision-making process when it comes to participation in CEIs. Based on specific combinations of these *"character attributes"*, we created a set of "*Personas*", i.e., "***Eco-Conscious Savers***", "***Tech Trailblazers***", "***Self-Reliant Savers***", "***Security-Minded Sceptics***", "***Eco-Collaborators***", and "***Green Guardians***", representing possible real-life citizens' perspectives for participating in CEIs.

These "*Personas*" were parameterized based on real-world data for the selected case studies and fed into the ANIMO framework. Overall, our analysis allowed us to identify:

- The most influential "*Personas*" in driving further growth and diffusion of the CEIs under study, along with targeted communication strategies and tailored initiatives that resonate with the specific motivations of these "*Personas*", as well as significantly increase their interest and likelihood for participation (**Table 3**).

Table 3. Most influential citizen personas further driving growth and diffusion of the Collective Energy Initiatives under study, as identified using the ANIMO modeling framework. *Kindly note that the images presented were created with the assistance of AI (DALL·E 2*[9]*).*

Personas	Characteristics, traits, and recommendations
"***The Tech Trailblazers***"	"*Excited about technologically innovative aspects of energy communities, they value smart home integration, increased energy independence, and enjoy the sense of community and collaboration towards shared goals*".
	• Emphasis on innovation, smart technologies, and showcase the community's use of cutting-edge technologies for energy management, smart home integration, and data analysis. • Organize tech workshops and demonstrations to provide opportunities for residents to experience technology firsthand and learn about its benefits. • Partner with technology companies to offer exclusive discounts or early access to new products for community members.
"***The Eco-Collaborators***"	"*Community-oriented people that value collective action to combat the climate crisis. They are motivated by contributing to a larger environmental movement with like-minded neighbors and appreciate the focus on renewable*

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[9] https://openai.com/index/dall-e-2/

	energy to reduce their environmental impact”.
	• Highlight of the collective environmental impact and how mass participation can make a real difference. • Showcasing community projects, by organizing workshops, educational sessions, or tree-planting events that foster a sense of collaboration and shared purpose. • Leverage of social media and digital tools such as online platforms for residents to connect, share ideas, and celebrate collective achievements towards environmental goals.
“***The Green Guardians***”	“*Environmentalists prioritizing sustainability and energy independence. Concerned about “grey” energy's impact, they seek to reduce their carbon footprint through on-site renewable energy and reduced grid reliance, aligning with their desire for energy autonomy*”.
	• Clear communication of the community's commitment to RES, reduced carbon footprint, and overall environmental benefits. • Collaboration with local or national environmental groups to endorse the community and its environmental impact. • Offer educational opportunities, by hosting workshops or seminars on climate change, RES technologies, and benefits of sustainable living.

- *Population density* and *social connectivity* as key drivers of further diffusion and growth of the CEIs under study. Findings clearly demonstrated the cascade effect of mass participation, highlighting a "*ripple effect*" that can significantly accelerate energy transition. Especially when delving into case studies situated in densely populated areas, we concluded that the “*Unified World*” narrative can lead to approximately 75% greater community growth by 2030, when compared to baseline projections, i.e., the “*Familiar World*” narrative.

- The decarbonization potential correlated with increased citizen participation in, and further growth of the CEIs under study, also highlighting the positive impact of collective expressions of energy citizenship on reducing CO_2 emissions by 2030 at the local level.

3.2.3. *A tale of “Power to the People” and “Habitual Creatures”: A “green” rebranding of a Coal and Carbon Intensive Region into a city of the people, by the people, for the people*

Finally, acknowledging the relevance and coherence between the “*Power to the People*” and the “*Habitual Creatures*” storylines, in terms of empowering people to be more active in the energy transition by not only investing in the necessary technological infrastructure, but by also adopting lifestyles and behavioral changes that could lead to a lower CO_2 footprint, we combined both storylines and we used the DREEM model to investigate if a citizen-led transition based on citizen investments in energy efficiency and citizen adoption of low-carbon lifestyles and behaviors can lead to a just and inclusive transition in the municipality of Megalopolis, which is considered as a Carbon and Coal Intensive Region in Greece.

Modeling results on transition pathways under the "*Unified World*" narrative- in which citizens in the municipality of Megalopolis unite against climate crisis and prioritize investments in energy efficiency solutions and electrification and adopt low-carbon lifestyles and behaviors- demonstrate significantly lower costs by 2050 at both the household and the municipality level compared to transition pathways under the "*Fragmented World*" narrative. More specifically:

- Although citizens remain sceptic about climate change and reliant to the use of fossil fuels under the "*Fragmented World*" narrative, considering coal and natural gas as the most reliable solutions towards energy security and lower energy bills, it is the "*Unified World*" narrative that leads to lower energy bills by 2050.
- Total costs per household by 2050, under the "*Unified World*" narrative, mark savings of approximately 63.1% compared to the "*Fragmented World*" narrative.
- Annual costs per household under the "*Familiar World*" narrative are projected to dip below €1,000 by around 2030 and stay below €1,000 with a decreasing trend by 2050.
- A cumulative amount of around €300 million could be saved by 2050 at the municipality level. Scaling down from the municipality to the household level, this is translated to total savings of around 60,000 € per household (i.e., ~3 times the current gross domestic product per capita in Greece). Considering that local economy, which is currently mainly dependent on the energy and the mining sector, will undergo an abrupt pathway towards the phase out of lignite, and that by 2025 (when lignite-fired units are expected to close) employment and income levels could be significantly reduced, a citizen-led transition like the one studied, could decrease households' energy costs, limiting the effect of wage decreases, and thus providing a significant helping hand to the most vulnerable citizen groups.
- The CO_2 emission reduction levels achieved by 2030 under the "*Unified World*" narrative are attained more than a decade later under the "*Familiar World*" narrative, i.e., which refers to the existing transition trajectory for Megalopolis based on the latest specifications of the NECP in Greece.

4. Further model developments, modifications, and adjustments of the ENCLUDE modeling ensemble

After matching the ENCLUDE “people-centered” storylines to the ENCLUDE modeling ensemble, further model developments, modifications, and adjustments took place so that the ATOM, the IMAGE, and the OSeMOSYS-GR modeling frameworks are able to simulate the case-specific decarbonization pathways developed as part of the work under this deliverable.

In this section we present these model modifications and adjustments, which will also be used to update earlier versions of the models’ documentation in the ENCLUDE Policy Interactive Policy Platform[10] (as part of the word conducted in the context of the ENCLUDE **WP7**).

4.1. The ATOM modeling framework

The **A**gent-based **T**echnology ad**O**ption **M**odel (**ATOM**) is an ABM, which based on the plausibility of its results compared to historical data and observations, simulates the expected effectiveness of various policy schemes on technology adoption (small-scale solar PV systems, BESS, heat pumps, EVs, etc.) in the residential sector, for the geographical and socioeconomic contexts of interest (Michas et al., 2020).

Apart from exploring the expected effectiveness of technology adoption under policy schemes of interest, the model also allows to consider and explicitly quantify uncertainties that are related to agents’ (i.e., citizens’ and households’) preferences and decision-making criteria (i.e., behavioral uncertainty).

The original architecture of ATOM consists of three (3) main modeling modules (**Figure 11**):

- (**i**)**.** a “*calibration*” module that establishes the key parameters governing agents' behavior and their appropriate value ranges, based on historical data and observations,
- (**ii**)**.** a “*sensitivity analysis*” module that quantifies uncertainties related to the agents' characteristics and decision-making criteria rather than the more obvious uncertainties based on calibration results,
- (**iii**)**.** a “*scenario analysis*” module that examines the potential behavior of technology adopters in different geographic and socioeconomic contexts through forward-looking simulations, considering different policy schemes of interest.

The novelty of ATOM compared to existing models lies in obtaining realistic uncertainty bounds and splitting the total model’s output uncertainty in its major contributing sources, based on a variance decomposition framework and an uncertainty characterization method, while accounting for structural uncertainty. Thus, ATOM supports the definition of uncertainty ranges, considering the type (i.e., input, parametric, and structural) and the nature of uncertainty (i.e., epistemic, or aleatory), and how uncertainty propagates to the model’s outcomes over the planning time horizon.

Variance decomposition takes place in all three modules; by allowing the user to select preliminary values for the agent-related parameters according to the plausibility of its results based on historical data and observations (goodness-of-fit statistics), the model captures input uncertainty (i.e., calibration module).

By deriving forward-looking simulations for different behavioral profiles (i.e., different set of agent-related parameters), from willing to invest to risk-averse consumers, ATOM captures parametric uncertainty (i.e., scenario analysis module).

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[10] https://energycitizenship.eu/

Both types of uncertainty are then propagated through the model, and their contribution to the total model's output variance is quantified. The rest of the uncertainty is assumed to be explained by the model's structure.

Note that the uncertainty propagation for the agent-related parameters is done for each one of them, allowing calculation of the sensitivity of each parameter to the model's output, in the context of a variance-based sensitivity analysis (Sobol method), and calculation of the relative contribution of the variance for each parameter to the total model output's variance (i.e., sensitivity analysis module).

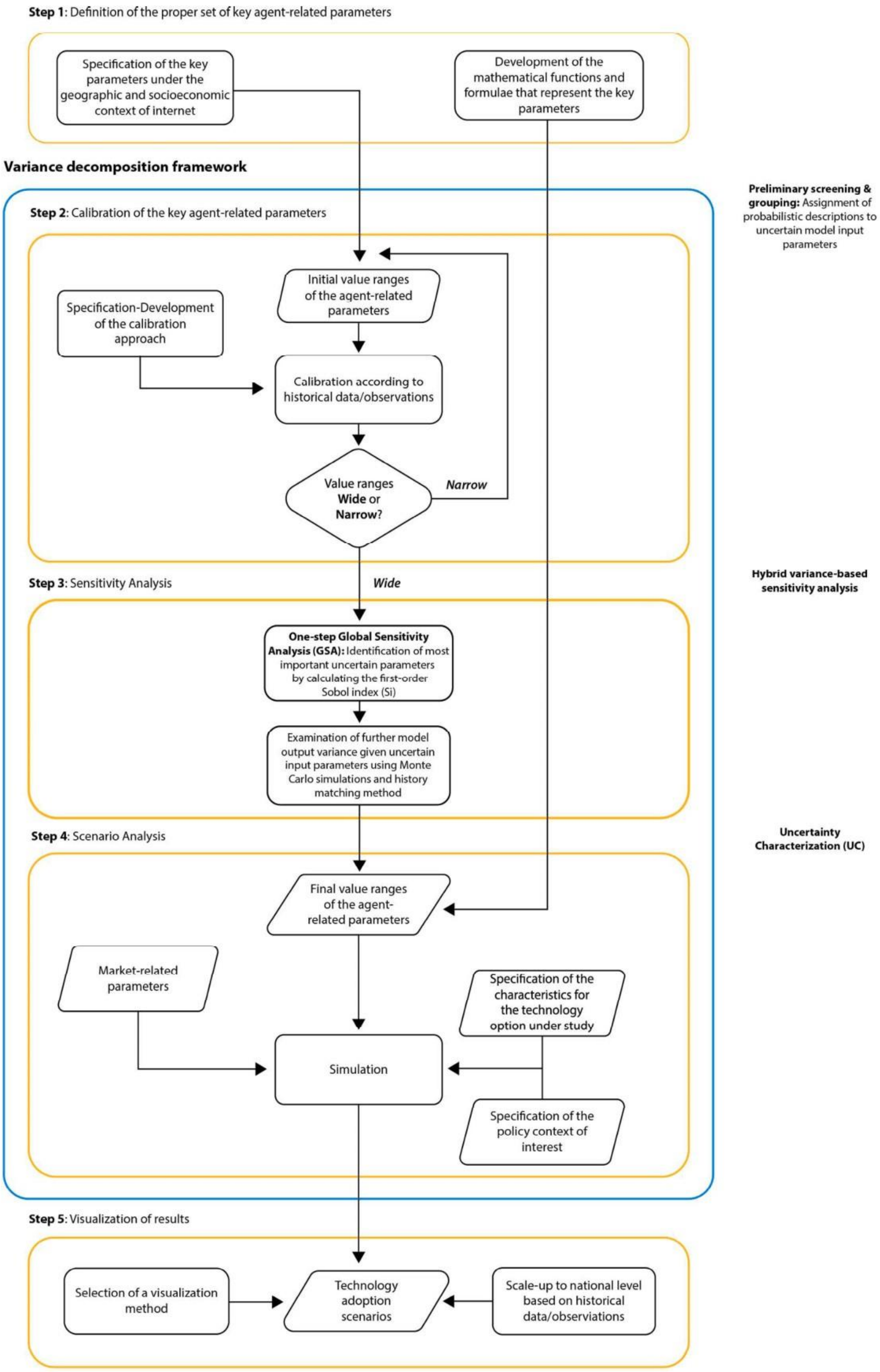

Figure 11. The original modeling architecture of ATOM, as modified and further adjusted in the context of this study. Source: Stavrakas et al. (2019).

ATOM is part of the Technoeconomics of Energy Systems laboratory (TEESlab[11]) Modeling suite (TEEM). All of the model's modules have been developed in Python source code. Supporting efforts around Europe towards open model development, ATOM is open access[12] under the "GNU Affero General Public License".

The updated ENCLUDE version of the model, including associate source code, datasets, and detailed documentations to enable the models' use, modification, and republication, will be distributed through the TEESlab UPRC's GitHub page, while case study results will be made available in the ENCLUDE Interactive Policy Platform (as developed in the context of the ENCLUDE WP7).

To address the modeling needs of the work presented in this report and in order for the model to become capable of quantifying the decarbonization potential of the "*Power to the People*" storyline and simulating case-specific transition pathways that envision patterns and trends of energy citizenship as citizens' active participation to the energy market and actions towards increasing energy autonomy and achieving energy savings, the model's original architecture and capacities mathematical background, as presented by Stavrakas et al., 2019, have been expanded.

Below, we provide a description of how the main model's modules have been modified and further adjusted for the needs of the application at hand. For this study, agents represent households that contemplate the adoption of small-scale solar PV systems, under different policy schemes and "*future-world*" narratives.

4.1.1. Selection and definition of the key agent-related parameters for solar PV adoption

ATOM can investigate specific behavioral preferences exhibited by citizens; these behavioral preferences encapsulate many different factors that affect the decision-making process of prospective investors and are expressed through the model's agent-related parameters.

Based on prior knowledge and insights from the scientific literature, we established an appropriate set of agent-related parameters, specific selected for the case of small-scale PV adoption (**Figure 12**):

- **Beliefs:** Beliefs start with each agent's private initial belief about the expected annual cash inflows from investing in a PV system of 300Wp.

  The belief is represented by a *Gaussian distribution* with a mean value of μ^{CF} and precision of ρ^{CF}. Small values of ρ^{CF} indicate a high degree of adaptability in beliefs, meaning that even a small amount of evidence can cause the agent's beliefs to change and low values of μ^{CF} indicate a pessimistic outlook on the potential benefits from the investment.

  Consequently, agents with high μ^{CF} values and low ρ^{CF} values indicate a willingness to invest, whereas agents with low μ^{CF} values and high ρ^{CF} values indicate a preference for avoiding risk. The initial beliefs of each agent are stochastically sampled from two global probability distributions. One distribution represents the mean value μ^{CF}, while the other represents the precision ρ^{CF}.

  Furthermore, on the one hand, the value ranges of the beliefs' parameter are highly dependent on the various market variables and each scheme's explicit features. On the other hand, the intrinsic beliefs encompassing the knowledge regarding the examined technology and the social environment (Ehnert et al., 2018).

  The "Beliefs" parameter is updated at each iteration, based on inputs received the "Social learning" and the "Resistance towards PV investments" agent-related parameters, while it feeds into the "Probability of investing" agent-related parameter at each iteration.

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[11] https://teeslab.unipi.gr/

[12] https://github.com/TEESlab-UPRC/ATOM

- **Social learning:** According to Young (2009), the following definition of social learning is given: “*People adopt [the innovation] once they see enough empirical evidence to convince them that [the innovation] is worth adopting, where the evidence is generated by the outcomes among prior adopters. Individuals may adopt at different times, due to differences in their prior beliefs, amount of information gathered, and idiosyncratic costs*”.

  In order to account for the impact of social learning, every agent is provided with information from the agents within its social network who have already made investments in solar PV installations. This knowledge pertains to the present profitability of their investments up to this point and is utilized to revise the agent's beliefs. This is equivalent to revising a Gaussian prior based on a fresh observation.

  Consequently, every agent possesses a social network. This condition is represented as a “small world” network, which is a type of mathematical graph. The number of connections per node is intentionally limited. This is because, although people may have numerous connections (such as through social media), investment decisions are mostly impacted by a smaller, more intimate group.

  According to Stephenson & Carswell (2012), households may make the decision to change based on their unique circumstances. However, a common factor that influences this decision is having knowledge about the experience of another household that went through a similar change. This provides a point of comparison and may also be encouraged by family or friends.

  The social circle of each agent remains constant during the simulation (i.e., the neighboring agents are the same till the end of the simulation). The updated belief value comes as a result of a weighted summary of the previous value and the calculated annual revenue of the "neighboring" agents that have already invested.

- **Resistance towards PV investments:** Agents have a notable resistance to investing in PV systems. Resistance is determined by calculating the total amount of two (2) parameters, which are assigned different weights. These parameters are:

  - The investment's profitability, which is measured by its payback period. Therefore, the higher the profitability, the shorter the payback period, and the lower the resistance. It is presumed that agents can utilize their beliefs about the anticipated cash inflows to assess the profitability of investing. Considering that the agents' beliefs are given in terms of probabilities, we can calculate the following z_i values, where $i = 1,2,\dots,n$ denotes the years after the simulation as follows:

    $$z_i = \frac{\mu^{CF} \cdot \sum_i^t \left(\frac{1}{(1+d)^t}\right) - capex}{\frac{i}{\rho^{CF}}} \cdot N(0,1)$$

    where $capex$ refers to capital expenditures, which represent the funds used for acquiring, upgrading, or maintaining fixed assets, d represents the discount rate, which is the rate used to determine the present value of future cash flows, z_i represents the probability that the investment's discounted payback period is exactly equal to i.

    Under the assumption that all agents assess an investment's value based on the time it takes to recover its costs with a 90% probability, this formula provides the corresponding payback period, denoted as i.

  - The difference between the overall count of agents in the simulation and the subset of agents who have already made investments. As the difference decreases, the installed base increases; and as the installed base increases, the resistance decreases.

Baranzini et al. (2017) presented evidence supporting the notion that both learning and imitation play crucial roles in the social transmission necessary for the widespread adoption of solar PV. In order to capture the concept of imitation (social influence), we intend to make the attitude toward PV dependent on the installed base. The weights of this sum are determined based on a global probability distribution.

- **Probability of investing:** Agents possess a specific threshold value for their resistance parameter. When the latter falls below the threshold value, action may be triggered, but it is not guaranteed. During the calibration phase, we made the assumption that agents determine the size of their PV system based on an empirical probability distribution generated from historical data and observations. It is important to acknowledge that the model utilized for the predictive simulations varies from the one employed for calibration in the following manners:
    - *Available options*: When the agents opt to invest in solar PV, they have the opportunity to select from a restricted range of options, all of which are accessible to all the agents. The available options pertain to the installed size of the PV system, specifically 2.4 kWp, 4.8 kWp, and 9.6 kWp.
    - *The option selection rule*: It states that when an agent evaluates many options favorably, the *SoftMax rule* (i.e., normalized exponential function) is used to make a selection. The probability of investing in option j is determined by the agent's resistance to it, denoted as r_j. This probability is calculated using the normalized exponential function, where $P(j) = \frac{e^{-r_j}}{\sum_k e^{-r_k}}$.
- **Inertia to invest:** This is the simplest reason why innovations take time to diffuse, as people delay acting based on new information (F. G. N. Li & Strachan, 2017). In ATOM, even if the resistance towards PV investments is lower than the set threshold (probability of investment), and thus the investment is positively evaluated by the agent, only a certain percentage of these agents proceeds with the actual implementation of the investment.

  For example, even if the investment environment seems favorable for adopting a new technology, many agents do not take the final decision, especially when it comes to a new policy scheme.

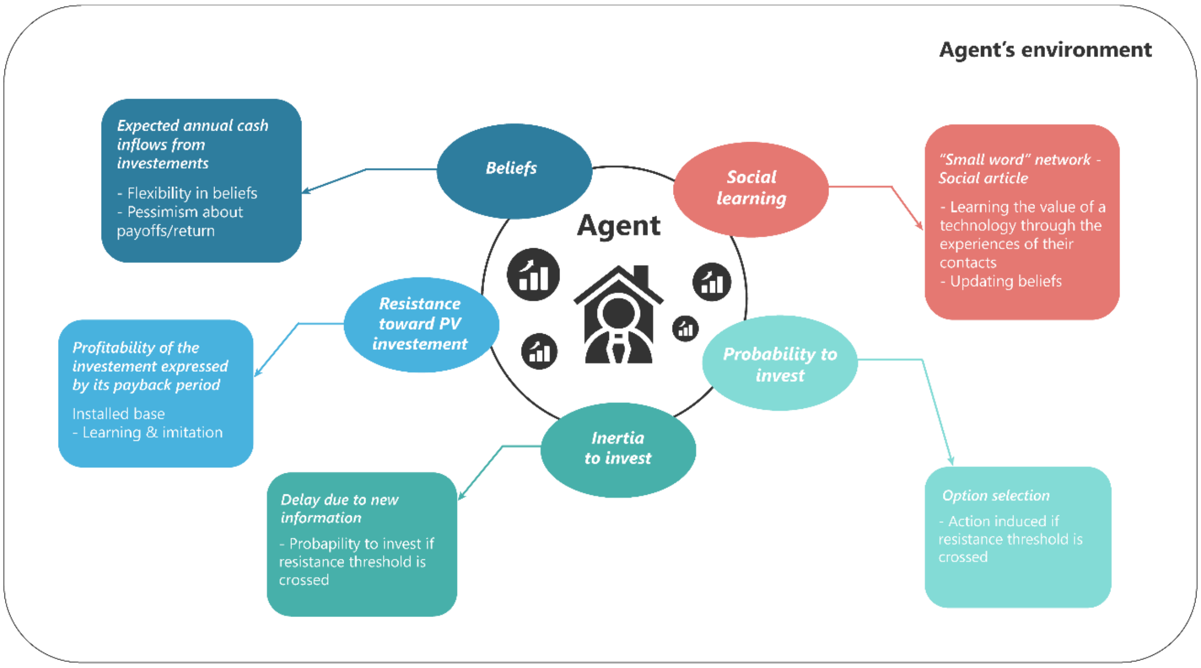


Figure 12. Set of agent-related parameters used in ATOM for the adoption of small-scale photovoltaic systems, as adapted by Stavrakas et al. (2019).

Finally, the value ranges of all the agent-related parameters and the distributions assumed must be determined by calibration- fitting against historical data. An indicative example of the initial set of agent-related parameters, as selected and mathematically defined to be used in ATOM, in the context of this study, is presented **Table 4**.

Table 4. An indicative set of agent-related parameters along with their initial value ranges, which are chosen arbitrarily, to be used in the ATOM framework.

Agent-related parameter	Description	Min	Max
Initial beliefs	Global distribution's shape parameter that designates the agents' mean value.	100	250
	Global distribution's shape parameter that designates the agents' standard deviation.	10	50
Social learning	Global distribution's scale parameter that designates the agents' mean value.	10	50
	Global distribution's scale parameter that designates the agents' standard deviation.	5	20
Resistance towards PV investments	Global distribution's shape parameter that designates profitability's weight to the agents' resistance.	0.5	5
	Global distribution's scale parameter that designates profitability's weight to the agents' resistance.	0.1	1
	Global distribution's shape parameter that designates installed base's weight to the agents' resistance.	0.5	5
	Global distribution's scale parameter that designates installed base's weight to the agents' resistance.	0.1	1
Probability of investing	Global distribution's shape parameter that designates the agents' upper limit of resistance.	10	30
	Global distribution's scale parameter that designates the agents' upper limit of resistance.	5	10
Inertia to invest	No change in this parameter during calibration due to the	0.01	

	impact that it will have in the model’s outcomes (kept constant).

4.1.2. Module #1: “Calibration of the key agent-related parameters”

The agent-related parameters in the model are assigned values using a calibration approach that determines the suitable ranges, based on historical data and observations. This calibration process enables the measurement and evaluation of uncertainties associated with agents’ behavior and decision-making criteria. Calibration within the ATOM modeling framework is based on the use of emulators, notably Gaussian Process (GP) emulators (Stavrakas et al., 2019).

GP emulators are well-suited for evaluating the uncertainty of their estimations because to their probabilistic nature (Papadelis & Flamos, 2019; Reiker et al., 2021). They accurately demonstrate the influence of parametric uncertainty in the model on the outcomes. The calibration process entails utilizing historical data and past observations that are pertinent to the technology being examined, within the specific geographical and socioeconomic context of interest.

This technique assumes that past fluctuations in parameter values serve as an indication of future uncertainties. It also guarantees that the parameter ranges of the model are neither excessively narrow nor needlessly wide, resulting in simulation results that are more precise and dependable.

Calibration process in ATOM comprises multiple steps to guarantee precise configuration of the agent-related parameters and correct quantification of uncertainties:

- **Selecting the initial parameters’ value ranges:** The initial value ranges for each parameter connected to the agent are selected arbitrarily. The objective at this stage is to verify that the GP emulator can be adapted to a sufficiently extensive input space, encompassing a wide range of potential parameter values (**Table 4**).
- **Fitting the GP emulator:** The GP emulator is trained using the outcomes derived from multiple parameter combinations simulated within ATOM. Within this particular situation, the parameter combinations function as the input data, while the model's outcomes serve as the output data for the GP emulator.
- **Creating input data:** To generate the input data, initial ranges are determined for each parameter value. ATOM is thereafter executed for 150 distinct combinations of parameters. The first parameter combinations are chosen using a maximin “Latin Hypercube Design” (J.-S. Park, 1994). The “Latin Hypercube Design” approach was selected because of its ability to completely fill the input space by maximizing the shortest distance between the generated points, thus successfully covering a wide range of parameter combinations.
- **Assessing and modifying the parameters’ value ranges:** Upon completion of the calibration process, the parameters' value ranges are assessed. If it is determined that the ranges are excessively limited, they must be reevaluated and maybe broadened. On the other hand, if the ranges are broader than required, sensitivity analysis is performed to identify which parameters should be modified.

4.1.3. Module #2: “Sensitivity analysis”

Sensitivity analysis is a method used to determine the parameters that have a substantial impact on the outputs of a model. It ensures that the ranges of these parameters are modified correctly by measuring the significance of uncertain parameters and identifying which of the n characteristics of an input dataset $X = \{x_j\}_{j=1}^{n}$ are mostly responsible for the uncertainty in the model's outcomes (y).

In this context, X symbolizes the set of agent-related parameters associated with the agents, x_j represents the particular agent-related parameters, and n indicates the overall count of parameters.

The methodology we employ relies on variance-based sensitivity analysis utilizing the *Sobol method*, which is a type of "*Global Sensitivity Analysis*" (Glen & Isaacs, 2012; Nossent et al., 2011). The Sobol method enables us to decompose the variance of the model's output y and assign it to the different input parameters x_j. This procedure encompasses the subsequent steps:

- We limit the value ranges of the parameters that have minimal influence on the uncertainty of the model's outputs. Therefore, the original dataset X is transformed into $X' = \{x'_j\}_{j=1}^{n'}$.
- For each characteristic, written as $\{x'_j\}_{j=1}^{n'}$, in the remaining set of parameters X', we divide X' into two sets: the first set includes the selected characteristic, while the second set, denoted as $EX' = (x'_j, X_{-j})$, includes the other characteristics.
- Then, we evaluate the impact of the uncertainty surrounding x'_j on the sensitivity of y by measuring the expected decrease in the variance of y when the true value of x'_j is known. In order to determine the anticipated decrease in variance, we employ the following mathematical equation (Saltelli et al., 2010):

$$V_{x'_j}(E(y \mid x'_j)) = \frac{1}{N}\sum_{i=1}^{N}\{f(B)_i(f\left(A_B^{(j)}\right)_i - f(A)_i)\}$$

where A and B are independent matrices of size $N \times n'$, each containing samples of the inputs of the model.

- In order to generate these matrices, we utilize a Sobol sequence (Saltelli et al., 2010). Sobol sequences are specifically designed to cover the unit hypercube with a lower discrepancy compared to purely random sampling. The index j ranges from 1 to n', while the index j ranges from 1 to N, where N represents the total number of input samples. The term $f(A)_i$ denotes the i$^{\text{th}}$ component of the vector that represents the output of the Gaussian process emulator when evaluated at $X'_* = A$.

Furthermore, the term $A_B^{(j)}$ denotes a matrix in which column j is derived from matrix B, while all other columns are derived from matrix A. The matrices A and B can be derived from a Sobol sequence of size $N \times 2 \cdot n'$, with A representing the left half of the sequence and B representing the right half.

- To determine the major effect of x_j on y, we calculate the first order sensitivity coefficient S_j using the expression $V_{x'_j}(E(y \mid x'_j))$ as follows:

$$S_j = \frac{V_{x'_j}(E(y \mid x'_j))}{V(y)} \in [0, 1]$$

- Then, in order to mitigate additional uncertainty in the model, we employ the history matching method, a proven technique that has been effectively utilized in various scientific disciplines, including the calibration of ABMs (Andrianakis et al., 2015).

The method revolves around quantifying the primary uncertainties that affect the calibration procedure. In order to achieve this, we employ the methodology introduced by Kennedy & O'hagan (2001).

This methodology involves eliminating subsets of the parameters' space that are improbable to yield an acceptable match between the model's predictions and the past observations. As the feasible space diminishes, emulators improve in their smoothness and accuracy, enabling us to focus on specific regions of the parameter space that we are exploring.

Consequently, throughout the iterative process called "waves" unrealistic parameter values are eliminated, and new GP emulators are built after each "wave".

To conclude, although the Sobol method can be immediately applied to the entire parameter set, it may become computationally expensive if there are a high number of uncertain parameters. The uniqueness of our technique resides in utilizing emulators, which are considerably faster approximations of the original model. This enables us to apply *Monte Carlo* sampling methods that would otherwise be excessively costly in terms of computational resources.

4.1.4. Module #3: "Scenario analysis"

Predictive "*what-if*" scenario analysis is employed as a following phase inside an ABM framework to offer insights into more precise inquiries directed at the model and to facilitate comparisons between two or more possibilities in order to quantify their disparities.

The market-related *parameters* of the model are determined based on historical or current situations that are relevant to the specific geographical and socioeconomic context of interest. Therefore, the specific attributes of the technology being examined, and the policy framework are defined.

For example, the evolution of the retail electricity price, the evolution of the solar PV capital costs, and the evolution of total residential electricity demand, are market-related parameters that need to be determined in the framework of ATOM. This process culminates with forward-looking simulations that study the evolution of the system through interactions between the agents. These simulations analyze a sequence of events and reactions to determine whether policy measures produce desirable outcomes.

The values of the agent-related parameters are adjusted in different runs, using calibration findings, to create realistic scenarios (based on past observations) of agents' profiles and to examine how uncertainty affects the model's results. This stage also allows for uncertainty characterization (i.e., epistemic or aleatory).

Based on ATOM's results, we develop "best-case" and "worst-case" scenarios about the policy schemes that could have a greater impact on the agents' decision-making behavior in terms of investments and make concrete policy recommendations.

4.1.5. Visualization of forward-looking simulations

Lastly, the adoption trajectories are upscaled to the national level using historical data and past observations. This approach guarantees that the simulation results are based on realistic and context-specific parameters.

The outcomes of these simulations are subsequently visualized using error bars to graphically represent the "*cone of uncertainty*". This visual representation is essential because it demonstrates how uncertainty propagates through the model's results as the projection period extends into the future.

This allows for a more detailed comprehension of the potential fluctuations in the adoption of small-scale solar PV systems under various policy frameworks. This comprehensive visualization aids stakeholders and policymakers in effectively evaluating the risks and uncertainties related to long-term planning and decision-making in the context of adopting renewable energy technologies and efforts to reduce carbon emissions.

4.2. The OSeMOSYS-GR modeling framework

The Open-Source energy MOdeling SYStem (OSeMOSYS) is an open-source model generator used for developing energy planning and integrated assessment models from the scale of continents down to the scale of countries, regions, and villages (Howells et al., 2011).

OSeMOSYS calculates the energy supply mix (in terms of capacity and generation) that satisfies the demand for energy services each year and at each time interval in the analyzed scenario, aiming to minimize the total discounted costs. It has the capability to encompass all or specific energy sectors, such as heat, electricity, and transport. It allows users to determine the spatial and temporal scope and scale of analysis.

Energy demand can be fulfilled by utilizing various technologies that possess specific technoeconomic attributes and rely on a specific set of resources, determined by their potential and costs. In addition, policy scenarios can impose specific technical limitations, economic conditions, and energy or environmental targets. Similar to other long-term optimization modeling tools, OSeMOSYS assumes a single decision-maker, perfect foresight, and competitive markets.

Mathematically speaking, it is a framework that combines deterministic, linear optimization, and long-term modeling. Mixed-integer linear programming can be used to optimize discrete power plant capacity expansions and other similar functions. One of its primary features is the wide and flexible concept of technology and energy vectors.

Technology encompasses all assets involved in the conversion of energy, including resource extraction, processing to electricity supply, transmission and distribution, and end-use appliances. It could thus pertain to various things, such as an oil refinery, a hydropower plant, or a heating system.

Each technology is distinguished by a transfer function determined by several economic, technical, and environmental factors, including investment and operating costs, availability, efficiency, capacity factors, emission factors, minimum load, etc.

The OSeMOSYS code is structured into sets of equations, consisting of an objective function and several constraints. The blocks of code enable a modular structure where various capabilities can be added or removed according to the user's requirements. The adaptable and customizable framework of OSeMOSYS enables its utilization in diverse applications with varying scales, complexities, and purposes. More details regarding the equations can be found in its documentation (KTH - Division of Energy Systems, 2023).

In this deliverable, the **O**pen-**S**ource **e**nergy **MO**deling **SYS**tem for **GR**eece (**OSeMOSYS-GR**) is a new modeling tool designed and developed in the context of the ENCLUDE project, as an adjusted country-specific implementation of the OSeMOSYS framework to accurately model the unique characteristics of the Greek power system for the period 2021-2050.

OSeMOSYS-GR operates on a temporal framework where each year is divided into 48 time slices, representing four distinct day-types (night, morning, noon, afternoon) each spanning six hours daily across twelve days, one for each month of the year.

The electricity supply system within OSeMOSYS-GR includes importing and extraction technologies, alongside fossil-fired power plants utilizing lignite, natural gas, and oil. Additionally, it incorporates RES such as hydro, onshore and offshore wind, utility, commercial, and rooftop solar PV, biomass, and geothermal.

Moreover, the model integrates energy storage technologies like pumped hydro and large-scale and small-scale batteries as well as hydrogen production and consumption through electrolyzers and fuel cells. Furthermore, it considers transmission and distribution losses, along with interconnections with neighboring countries.

A comprehensive illustration of the OSeMOSYS-GR framework, as it has been developed and currently stands, is depicted in **Figure 13**.

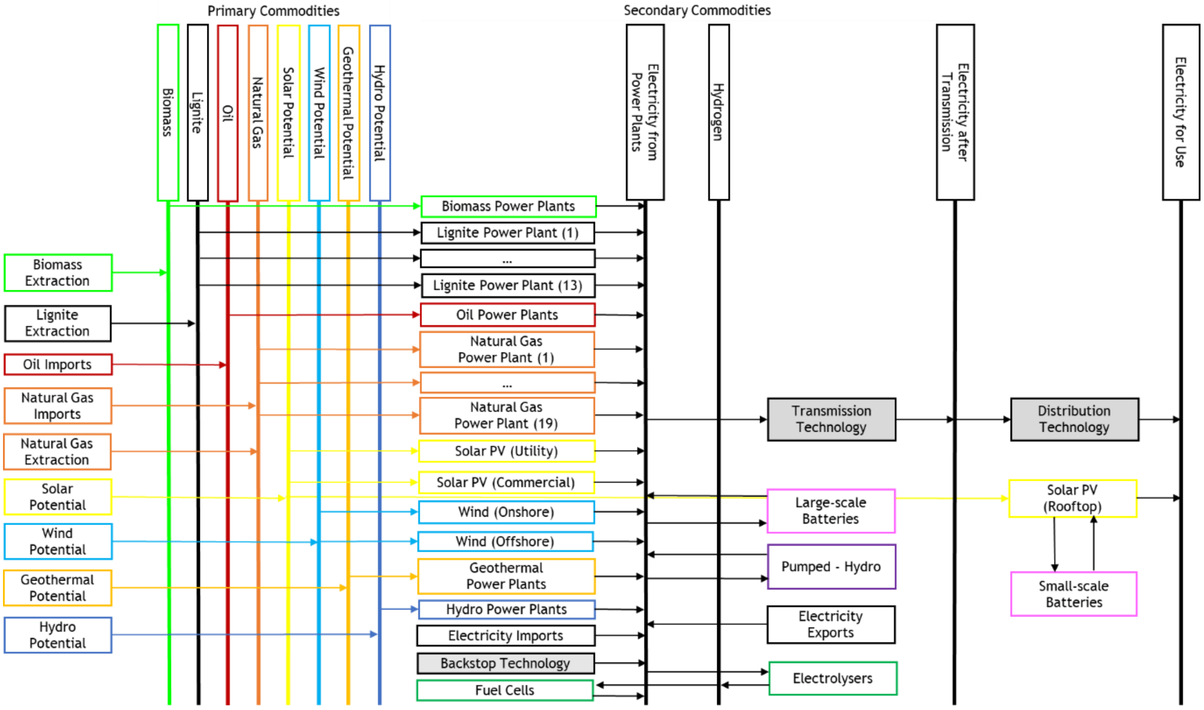


Figure 13. The modeling architecture of OSeMOSYS-GR, as it has been developed in the context of the work conducted under the ENCLUDE Work Package 5 and the modeling needs of this study.

In this report, OSeMOSYS-GR will compute the potential impact wielded by citizen-led energy sector planning and decision-making processes, underscoring citizens as catalysts for decarbonizing the Greek power sector.

Specifically, the application of OSeMOSYS-GR will provide insights into key energy, environmental, and economic impacts of prosumerism and energy transition movements within the future Greek electricity system.

This analysis does not only describe the technical prerequisites but also sheds light on the nuanced socio-economic and behavioral factors influencing the transition toward a sustainable energy paradigm.

By synthesizing intricate datasets, modeling scenarios, and sociopolitical dynamics, OSeMOSYS-GR attempts to provide stakeholders with policy recommendations to navigate the complexities inherent in achieving a carbon-neutral power sector while stimulating inclusive participation and equitable distribution of benefits across society.

4.3. The IMAGE modeling framework

the **I**ntegrated **M**odel to **A**ssess the **G**lobal **E**nvironment (**IMAGE**) deals with a spectrum of global environmental issues and sustainability challenges, among which climate change, land-use change, biodiversity loss, modified nutrient cycles, and water scarcity stand out as the most prominent (PBL Netherlands Environmental Assessment Agency, 2021).

These issues are profoundly intricate, characterized by long-term dynamics, and exhibit either global manifestations, such as climate change, or occur in similar forms across various regions, rendering them inherently global in nature.

Typically, these global environmental issues have arisen as human societies have utilized natural resources to propel their development, encompassing the provision of energy, food, water, and shelter.

IMAGE is a detailed integrated modeling framework that represents the interaction between human and natural systems. It is designed for extensive (mostly global) and extended (up to the year 2100) evaluations of the relationships between human development and the natural environment (Admiraal et al., 2016; D. van Vuuren et al., 2021).

It combines several sectors, ecosystems, and indicators. The model identifies socioeconomic routes and forecasts the consequences for energy, land, water, and other natural resources based on resource availability and quality (PBL Netherlands Environmental Assessment Agency, 2021).

Unintended consequences including air, water, and soil pollution, climate change, and the depletion and deterioration of existing resources (fossil fuels, forests) are factored into future forecasts. As a result, the main objective of IMAGE is to shed light in the enduring patterns and consequences of worldwide (supranational) transformations that arise from the interplay between socioeconomic and environmental elements.

IMAGE consists of two (2) primary systems (Stehfest et al., 2014): **(i).** the **Human** (or socioeconomic) system pertains to the enduring progression of human activities that are significant for sustainable development, and **(ii).** the **Earth** system, which refers to alterations in the natural environment.

The two (2) systems are interconnected through the effects of human activities on the “Earth” system and the effects of environmental changes of the “Earth” system on the “Human” system. A depiction of the IMAGE framework and its components is displayed in **Figure 14**.

More information about IMAGE’s functions and structure, can be found in Stehfest et al. (2014) and PBL Netherlands Environmental Assessment Agency (2021).

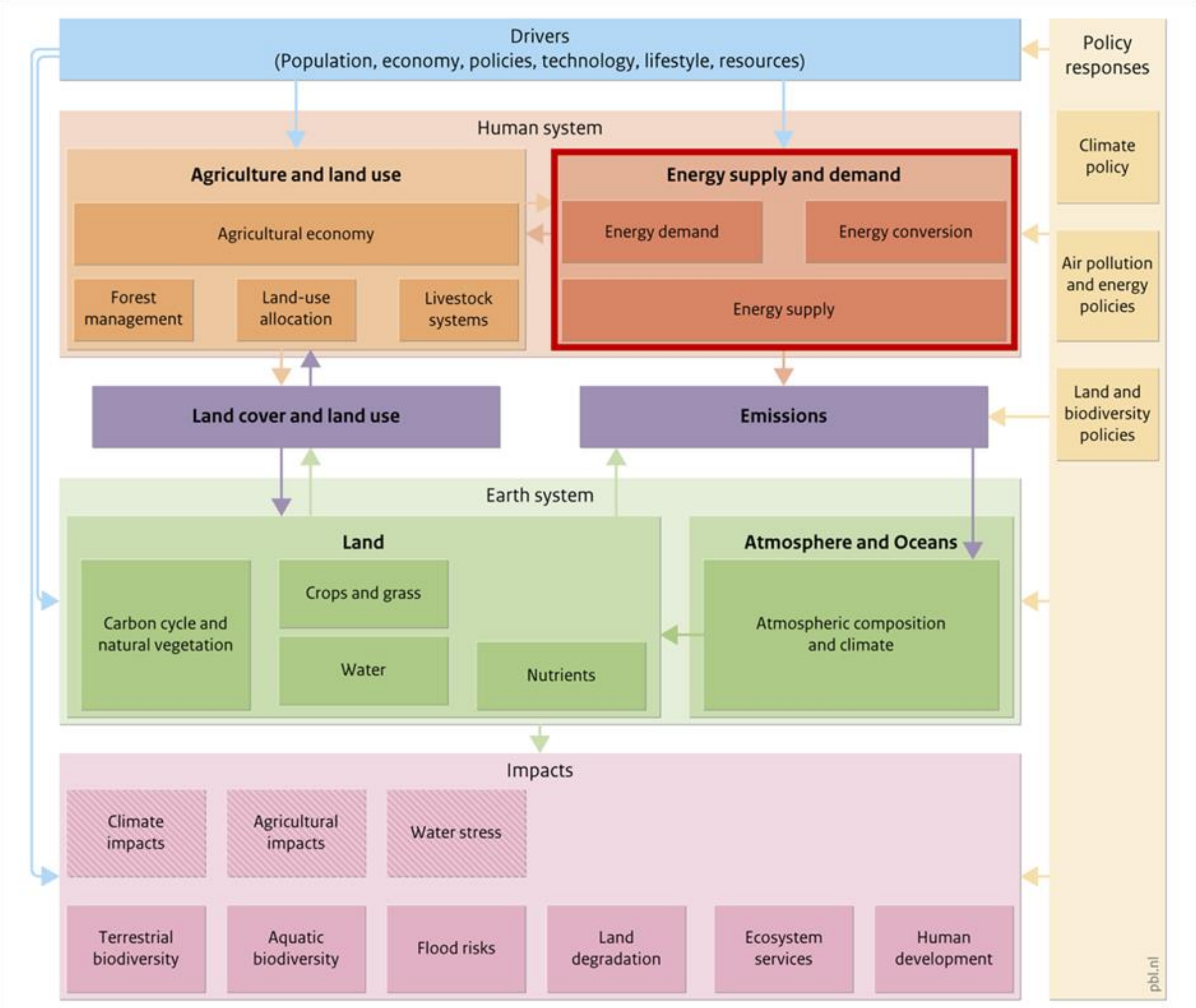


Figure 14. The architecture of IMAGE as it currently stands, with the IMAGE-TIMER energy model shown by a red box. Source: PBL Netherlands Environmental Assessment Agency (2021).

In this deliverable, IMAGE provides insights into the potential long-term decarbonization pathways of energy citizenship. These invaluable insights are set to not only shed light to the intricate interplay among environmental stressors, but also to reveal their profound ramifications for international objectives and human advancement, particularly within the framework of supranational entities such as the EU.

Harnessing the capabilities of IMAGE, the model will aspire to furnish pivotal policy recommendations delineating the complex connections between environmental shifts and broader human development dynamics, with a specific emphasis on the EU (macro scale).

Last but not least, by navigating the inherent uncertainties surrounding environmental transformations, IMAGE will aim to equip policymakers with evidence-based strategies to confront and mitigate the multifaceted challenges posed by environmental degradation, thereby fostering sustainable growth and resilience at an EU-wide (supranational) level.

In this research, due to its complexity, and the advanced development and aggregate regional scope of IAMs, we use the existing structure of the model. Therefore, no significant changes are made to the model, but rather how the variables and input parameters are used.

4.3.1. IMAGE-TIMER energy demand and supply model

Dealing with the concept of "*energy citizenship*", our work focuses specifically on energy demand and supply, and therefore the modeling takes place mostly in the **IMAGE-TIMER** sub-model (shown as by the red box in **Figure 14** and detailed in **Figure 15**).

The sub-model IMAGE-TIMER models annual energy demand and supply across twenty-six (26) global regions, encompassing various sectors such as industry, passenger and freight transport, residential, services, non-energy, and others.

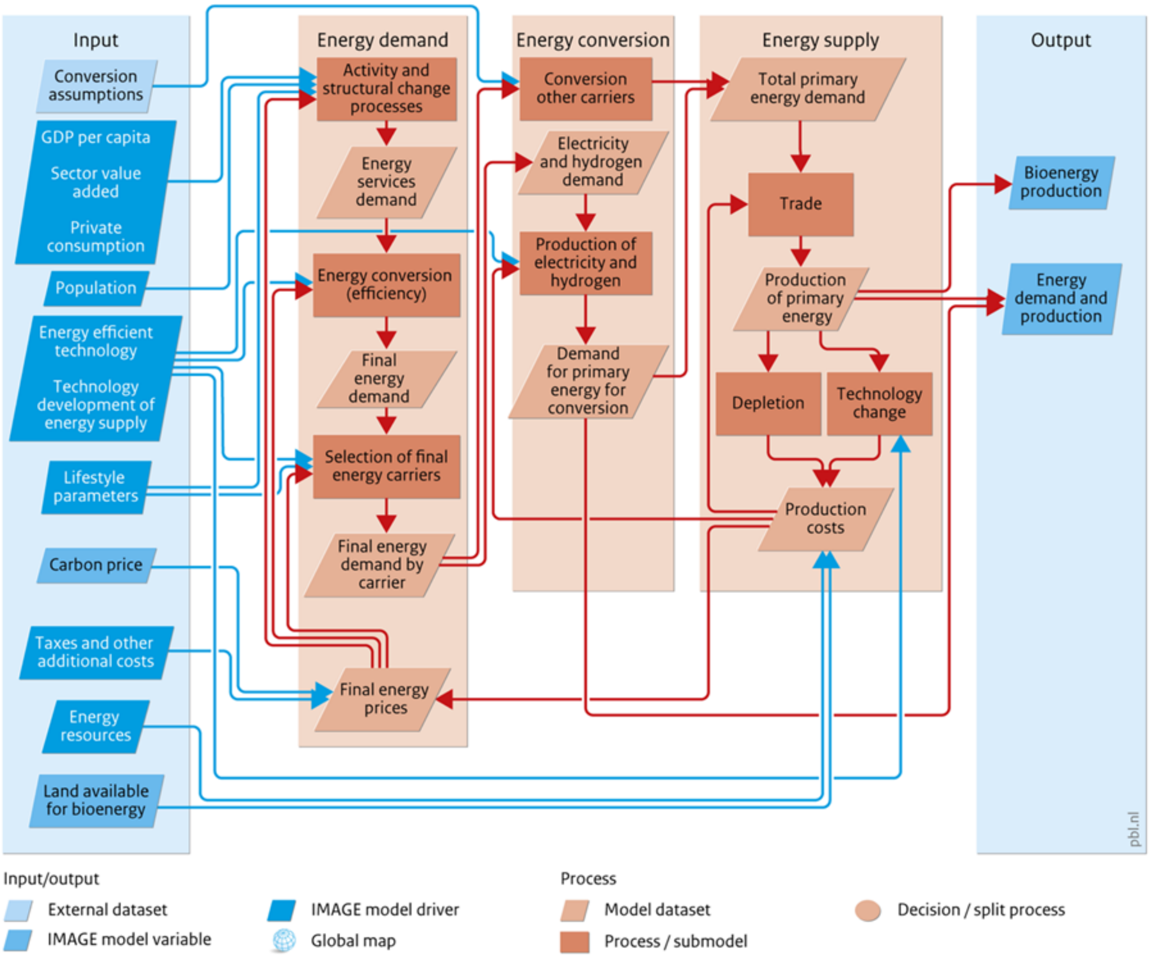
Emissions considered comprise both direct and indirect sources, including those associated with electricity usage. Notably, indirect emissions stemming from shifts in material demand (e.g., the production of EVs) are not factored into the model.

Decision-making processes are not explicitly simulated but approximated through proxies to capture degrees of behavioral diversity (van Sluisveld et al., 2016). Market shares of technologies or energy carriers are determined by a multinomial logit function, which accommodates differences in preferences and costs among options (D. P. van Vuuren et al., 2011).

According to van Sluisveld et al. (2016), these preference factors, aside from costs, reflect governmental policies and consumer inclinations, aiming to represent elusive factors that are challenging to quantify (e.g., decisions to switch transportation modes or opt for smaller residences).

IMAGE-TIMER accommodates regional disparities by calibrating variations in energy demand among regions. For instance, the preference for car travel is stronger in the USA compared to Japan, where public transportation holds a larger share of total passenger transport.

Additionally, Japan has significantly lower floor space per capita compared to the USA, a factor that is taken into consideration (Daioglou et al., 2012). Further elucidation on how behaviors in the transport and the residential sectors are modeled is provided below, given their pivotal roles in this study.



Source: PBL 2014

Figure 15. IMAGE-TIMER, the energy demand and supply model.

TRAVEL model under IMAGE-TIMER

IMAGE-TIMER modifies the behavioral actions associated with travel scenarios by altering inputs and factors within the “TRAVEL” modeling framework (**Figure 16**). For instance, encouraging a sustainable transition in transportation modes involves adjusting the preference factor associated with each mode of travel.

This modification influences the Travel Money Budget (TMB) constraint, which in turn adapts the demand for different modes of travel, as well as the Travel Time Budget (TTB), which dictates the weighting of time and the pricing of each mode.

Various adjustments within the TRAVEL model can be enacted to accommodate behavioral and demand-oriented shifts. To promote greater use of public transportation, adjustments can be made to the preference factor within inputs and to the TTB within “Modes” to influence mode pricing.

Similarly, to encourage higher adoption rates of EVs, alterations can be made to the non-energy costs associated with EV technologies, thereby affecting the perceived costs of vehicles and the composition of vehicle fleets.

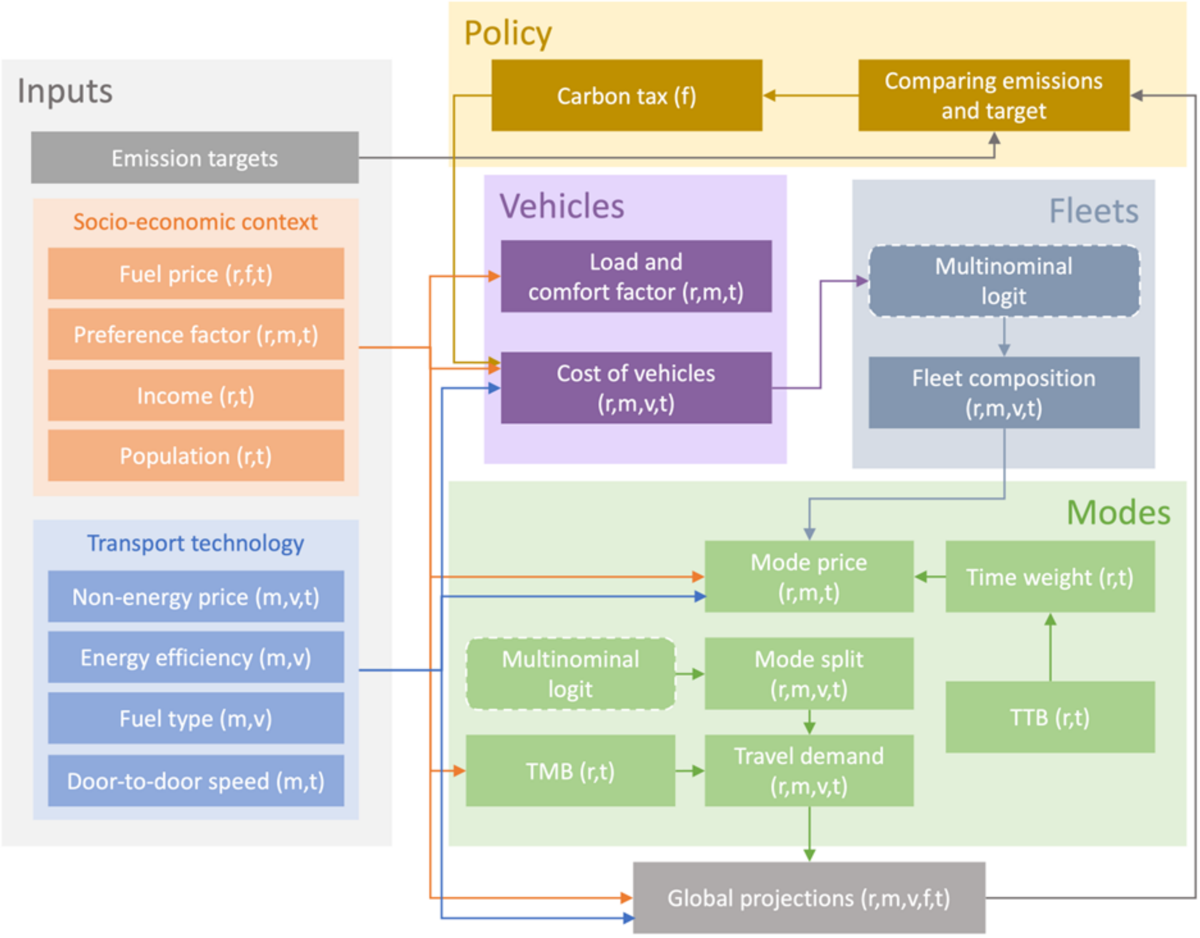


Figure 16. "TRAVEL" model in IMAGE-TIMER with factors dependent on the region (r), travel mode (m), vehicle type (v), fuel type (f), and time (t). Adapted from: Girod et al. (2013).

Residential sector in IMAGE-TIMER

In IMAGE-TIMER, we adjust variables and parameters to simulate the residential behavioral patterns within the residential sector, aligning with assumptions regarding adoption rates and the pace of transition (**Figure 17**).

Most determinants are delineated based on income quintiles and urban/ rural classifications, with exceptions for population density and temperature factors (Daioglou et al., 2012). This approach enables a more diverse and fair portrayal of lifestyle changes, through more heterogeneity.

For instance, it allows for the restriction of the impact of reduced living space to specific groups already accustomed to high per capita floor space (typically rural and affluent groups) by implementing an upper limit (i.e., a maximum m^2 per capita) rather than a proportional decrease.

Notably, Japan has substantially lower floor space per capita compared to the USA, a factor that is duly considered in the model. Consequently, limiting living space would exert a more pronounced effect in the USA than in Japan.

Core determinants- population, household expenditure, population density, household size, and temperature- influence intermediate factors such as floor space and electrification, which in turn shape the demand for energy services encompassing cooking, appliances, space heating and cooling, water heating, and lighting (Daioglou et al., 2012).

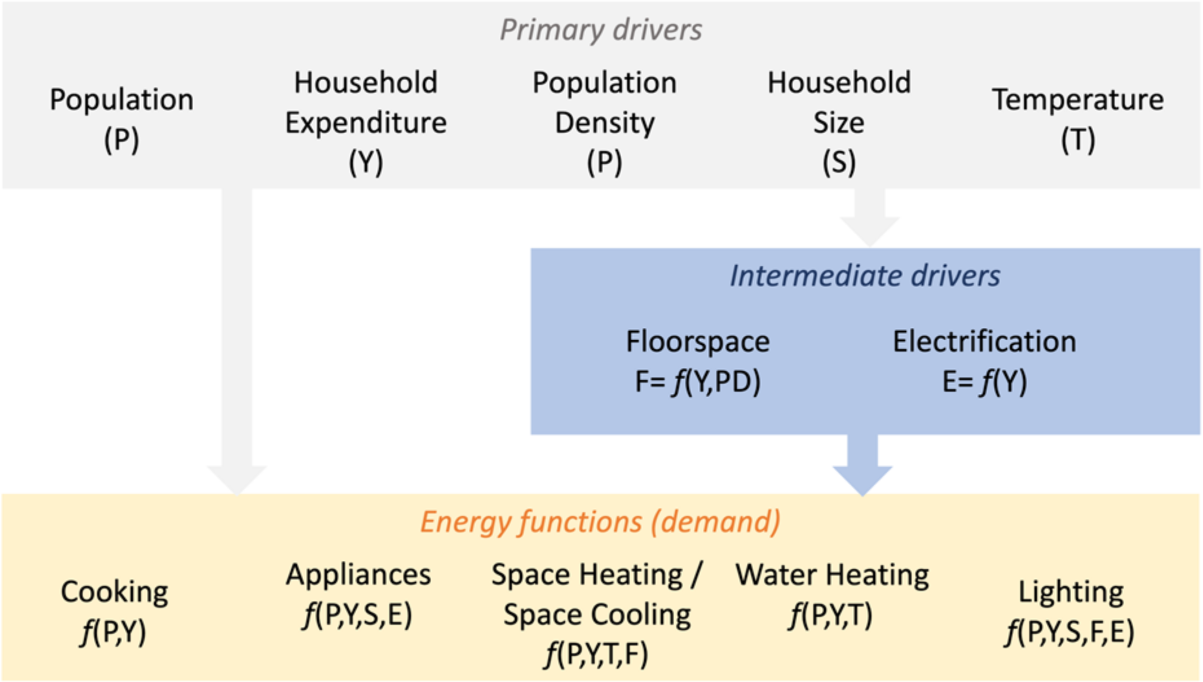


Figure 17. The relationship between residential energy functions and drivers. Adapted from: Daioglou et al. (2012).

5. The ENCLUDE scenario space and transition matrix at the national and the supranational levels

Having outlined the additional model developments, modifications, and adjustments in **Section 3.1**, we now shift our focus toward crafting the scenario space that guides the different model applications. The scenario space is designed to encapsulate the various "*people-centered*" storylines and "*future-world*" narratives, contextualized for both the national and the supranational (EU) levels.

These scenarios will serve as the context in which the different case study applications using the ENCLUDE modeling suite will be conducted, facilitating comprehensive assessments of the potential impacts, trade-offs, and opportunities associated with different "*people-centered*" storylines.

As the urgency of the climate crisis escalates, stakeholders, policymakers, and researchers encounter an array of uncertain and complex future developments (Hallegate et al., 2013). Within the discourse of climate change, the necessity for defining a scenario space holds paramount significance (D. van Vuuren & Carter, 2014). The scenario space design provides a structured approach to explore different pathways toward achieving sustainable and inclusive energy systems (Geels et al., 2017).

Specifications of a scenario space are conducive to exploring diverse potential trajectories, encompassing socioeconomic, technological, and environmental dimensions (B. O'Neill et al., 2014). By exploring scenarios that encompass a range of such dimensions, decision-makers can gain insights into the impacts of various policy measures and formulate resilient strategies for both mitigation and adaptation to climate change (Moss et al., 2010).

This approach allows for the identification of barriers and opportunities for citizen engagement in energy transitions, leading to the development of policies and initiatives that foster greater participation and empowerment (Devine-Wright, 2013).

Furthermore, scenario space specification fosters communication and collaboration among a multitude of stakeholders, nurturing a shared comprehension of the uncertainties inherent in climate change dynamics (D. van Vuuren & Carter, 2014).

In summary, a transformative scenario space design can have a critical role in guiding the development of policies that support energy citizenship at the national and the supranational levels, ensuring that energy transitions are not only sustainable but also fair and inclusive.

On the contrary, failure to establish a well-defined and limited scenario space might lead to the oversight of significant advancements, or the underestimation of the complexities involved in societal transitions. Consequently, this might result in the implementation of insufficient or erroneous policies and prejudiced decision-making.

If scenario spaces are not adequately broad or well-defined, there is a risk of overlooking important aspects or alternative paths. This can leave decision-makers unprepared to properly address emergent difficulties (Clarke, Jiang, Akimoto, et al., 2014).

As a result, policies created within these limited frameworks may not effectively deal with the complex character of societal changes, eventually impeding progress toward sustainable results (Loorbach, 2010).

Furthermore, a scenario space that is unclear or restricted may unintentionally strengthen pre-existing prejudices, resulting in decisions that prioritize some interests or viewpoints over others (D. van Vuuren et al., 2012). Hence, it is crucial to guarantee that scenario spaces are robust and clearly defined to facilitate a comprehensive exploration of future possibilities.

The scenario creating method should consider uncertainty, as there is no guarantee that any trajectory described inside scenarios will occur exactly as expected. In this regard, we have previously made efforts to create well-specified storylines and narratives to capture this aspect in our scenario framework.

Specifically, details and complexities from diverse “*people-centered*” storylines have been combined with “*future-world*” narratives that represent prospective global developments.

Figure 18 illustrates the designed ENCLUDE scenario space of this study, as a result of the combination of the “*people-centered*” storylines that will be explored (i.e., “*Power to the People*”, “*Band Together*”, “*Habitual Creatures*”, and “*People to the Streets*”) along with the three (3) “*future-world*” narratives (i.e. “*A Familiar World*”, “*A Unified World*”, and “*A Fragmented World*”).

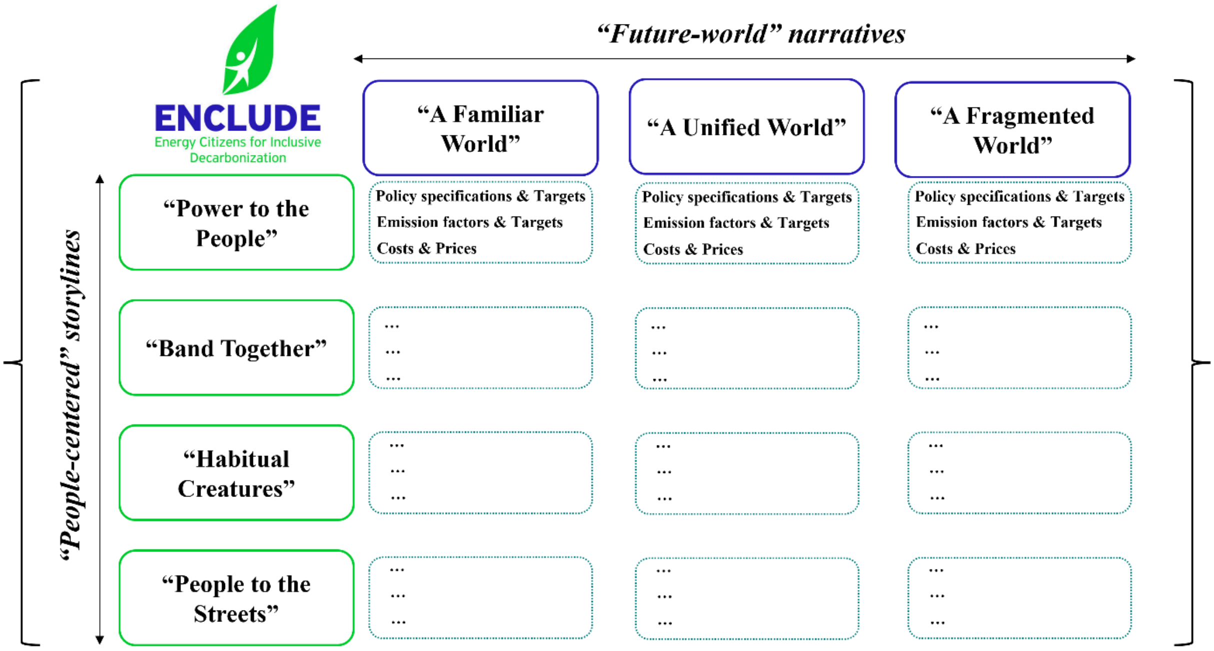


Figure 18. The final ENCLUDE scenario space to be applied to specific case studies for the development of real-life decarbonization pathways at both the national and the supranational levels.

The scenario space definition will drive the specifications of each case study application in **Section 6**. By analyzing the different “*future-world*” narratives that influence the background of the case studies, we further specify and tailor them to develop detailed case-specific decarbonization pathways at the national and the EU levels.

Furthermore, the final ENCLUDE transition matrix (**Figure 19**) is enriched with the changes in various external factors, such as emission factors, changes in energy prices and costs, technological costs, updated configurations, benefits for citizens and other stakeholders in the power sector, etc. These changes are aligned with the specifications of the ENCLUDE "*people-centered*" storylines and "*future-world*" narratives.

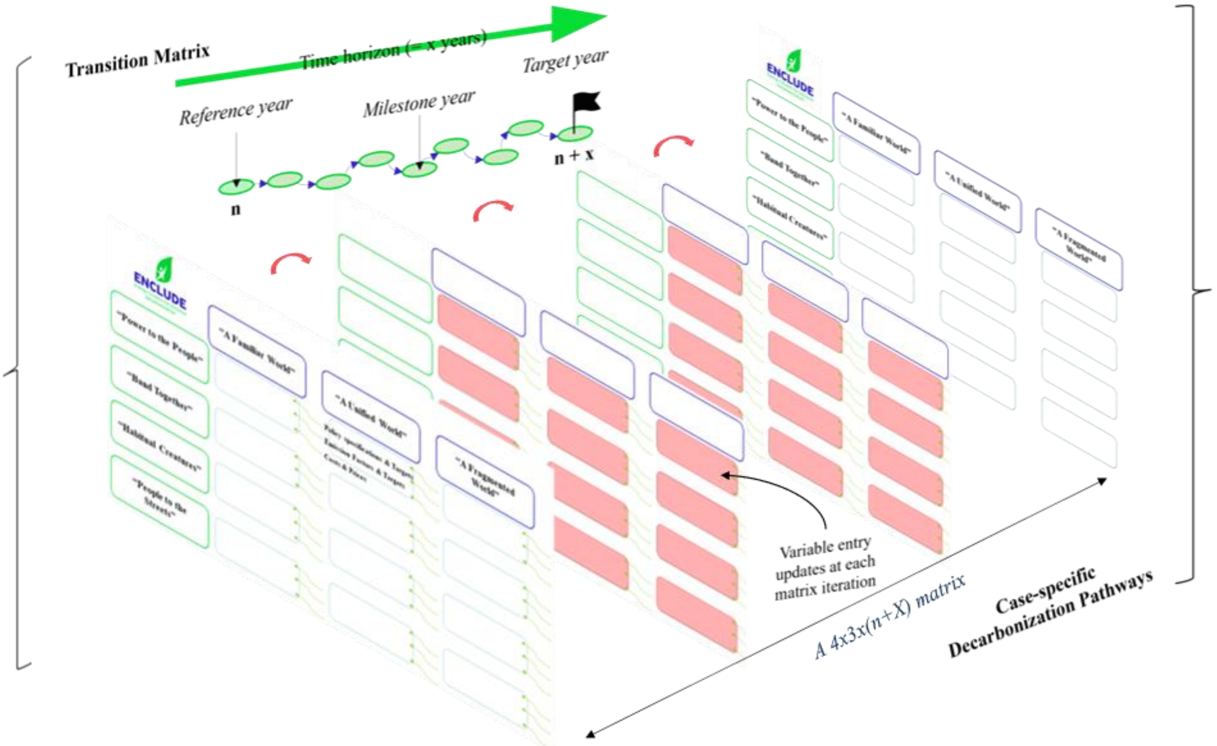


Figure 19. The final ENCLUDE transition matrix for the development of real-life case-specific decarbonization pathways at the national and the supranational levels.

6. Decarbonization pathways in real-life case studies based on “people-centered” storylines

In this section, we present the case studies selected for each one of the ENCLUDE storylines under study to be analyzed by the ENCLUDE modeling ensemble and the rationale behind their selection. In addition, we also present the case-specific scenario space and transition pathways that are integrated into the modeling tools.

Moreover, scenario design is carefully crafted to address the research questions (RQs) outlined in this section. This entails parameterizing the models utilized within the ENCLUDE framework to ensure their alignment with the selected case studies and the overarching research objectives. Through iterative refinement and validation, the models are fine-tuned to accurately capture the complexities of each case study scenario, enabling robust analysis and scenario simulations.

6.1. Case study selection and specification

Geographical dimension adds an important value to quantifying the impact of energy citizenship- in terms of the decarbonization potential of its various expressions- at both the national and the EU levels- and to better understanding the several important implications of geographies in the EU’s policy-making landscape. To this end, we selected and explored a set of diverse case studies across Europe to illuminate the full range of differences and demonstrate cross-cutting themes (**Table 5**).

The main source of information and data for the selection and specification of the case studies was the case study pool developed and maintained in the context of WP3. Our selection focused on the spatial variation across contexts and the emphasis on cross-case differences of political, social, cultural, economic, demographic, and technological particularities of different energy systems across the EU.

Finally, we were able to collect data provided in the questionnaire developed by WP3 and filter the case studies to select those that we would delve into based on their policy relevance and according to enhanced capabilities of the ENCLUDE modeling ensemble.

Table 5. List of the selected case studies to which the ENCLUDE modeling ensemble is applied.

Scale of analysis	“People-centered” storyline	Pattern/ Trend	Model	Sectoral coverage	Time horizon
National (*Denmark*, *France*, *Greece*)	“*Power to the People*”	Prosumerism	ATOM	*Residential*	Until 2030
National (*Greece*)	“*Power to the People*”	Prosumerism	OSeMOSYS-GR	*Power*	Until 2050
	“*People to the Streets*”	Public acceptance/ opposition to green transition through sociopolitical activism/ movements			
Supranational (*Western Europe*)	“*Power to the People*” “*Band Together*” “*Habitual Creatures*” “*People to the Streets*”	Long-term impacts of energy citizenship behavioral actions on emissions.	IMAGE	*Transport* & *Residential*	Until 2050

This section delves into the selection of case studies chosen for analysis using the ENCLUDE modeling ensemble, with a focus on the distinct spatial attributes pertinent to scenario development. We provide a cross-sectional overview of the prevailing conditions ("*status quo*") in Denmark, France, Greece (national level, **Figure 20**), and Western Europe (supranational level, **Figure 21**), highlighting aspects relevant to each employed model.

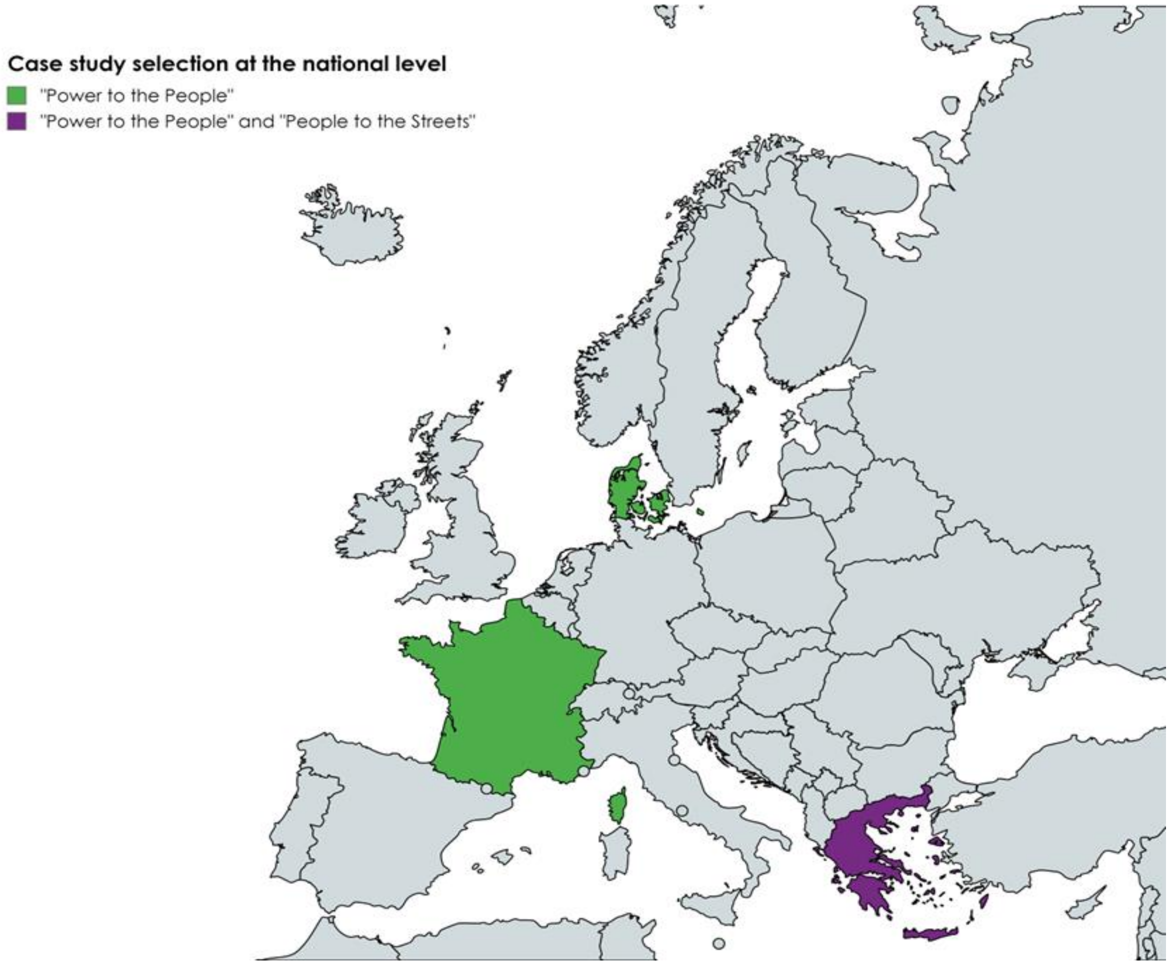


Figure 20. Selected case studies to be modeled using the ENCLUDE modeling ensemble at the national level (visualization developed using the online map-making tool "MapChart[13]").

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[13] https://www.mapchart.net/

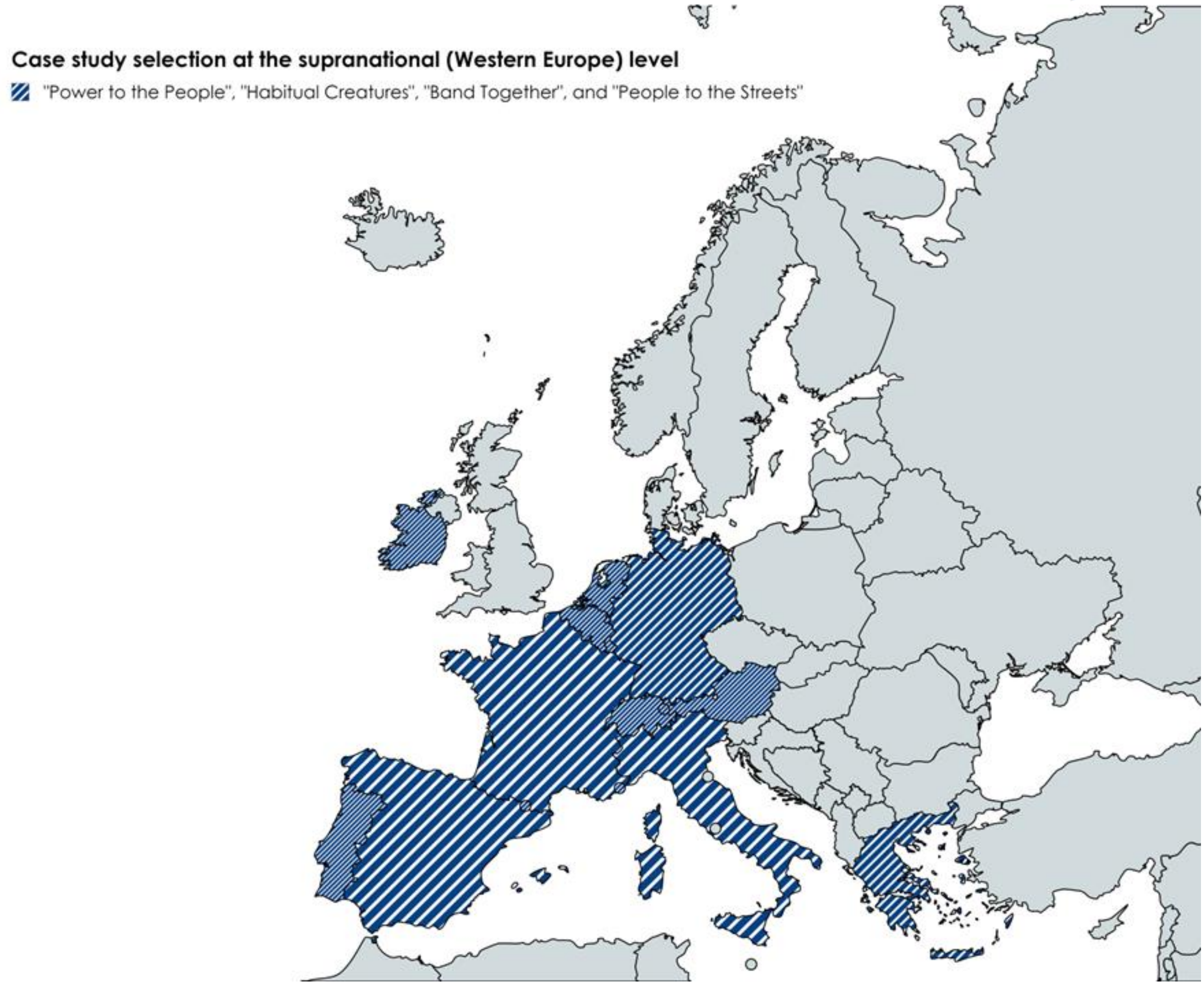

Figure 21. Selected case studies to be modeled using the ENCLUDE modeling ensemble at the supranational level (visualization developed using the online map-making tool “MapChart”).

Our case study selection showcases a great diversity of climate conditions, from “Temperate” (mesothermal climate, Köppen classification represented as “C”) to “Continental” (microthermal climate, Köppen classification represented as “D”), and from “Oceanic” (Köppen classification represented as “Cfb”) to “Mediterranean” (Köppen classification represented as “Cs”) (Arnfield, 2023).

It also showcases a great diversity of socioeconomic conditions between the different Member States under study, like income or employment rates, which should be taken into consideration, as especially when studying the transition to fair and inclusive future societies, vulnerable groups such as low-income households and disadvantaged communities, are of the outmost importance.

In addition, we made sure to select a set of different cases also when it comes to energy transition challenges at both the national and the supranational level, spanning from the decarbonization potential of empowering prosumerism and citizen adoption of PV systems, to citizen acceptance (or opposition) of a greener future through sociopolitical activism and movements, to the decarbonization potential of different behavioral and lifestyle changes, and other manifestations of energy citizenship in the transport and the residential sectors.

Especially at the national level, our selection spans across different policy landscapes, considering different legislative and regulatory frameworks, currently in operation in the selected Member States. For example, prosumerism in France is mainly supported through a FiT policy scheme, while net metering is not yet regulated. Regulatory framework in Denmark, which is a global leader in renewable energy, aims to promote prosumerism mainly through net metering policy schemes where the netting is conducted on an hourly basis.

On the other hand, when it comes to the supranational level, our selection was also based on other important premises. For example, while regionally balanced electricity supply is desirable, it may result in conflicts between local, national, and continental interests. These are indicatively illustrated by examples of environmental implications of small hydro generating units, local wind opposition motivated by the "*not in my back yard*" mindset, concerns about bioenergy exploitation, challenges as the phase out of coal and lignite around Europe, and consequently, concerns about increased unemployment levels of coal workers and the reliance of timely reskilling to reintegrate into economic activities, along with the creation of new green jobs and innovative services.

All these issues are important to consider in order to explore both positive and negative effects for citizens and local and regional economies, and economic and environmental implications at the Member State, or the EU level.

6.1.1. *"Power to the People" transition pathways through empowering prosumerism and citizen adoption of photovoltaic systems*

Under the *"Power to the People"* storyline, the notion of the citizens' active participation in the energy market is further explored. Citizens are increasingly becoming individual owners, thus, consuming their own electricity, and playing a facilitating and supportive role in driving the energy transition (Krumm et al., 2022; Trutnevyte et al., 2019).

"*Prosumerism*" is the concept that refers to the act of citizens investing in energy infrastructure that will transform them from simple consumers of energy to producers and self-consumers of energy (or as the term has been established in the relevant literature the past decade, "*prosumers*") through small-scale RES technologies installed in their residence, being able to provide flexibility to the grid by adjusting their consumption patterns (Kühnbach et al., 2022).

In light of the EU's long-term goal of achieving climate neutrality by 2050, solar PV systems have been recognized as a feasible alternative to traditional energy sources (Koumparou et al., 2017). Within this framework, the concepts of self-consumption and self-production are gaining significant value, particularly in the residential sector.

In both concepts, consumers assume the dual function of prosumers, actively generating and consuming energy, as both concepts encompass the adoption and further diffusion of a wide range of technologies and systems, such as small-scale PV, residential BESS, smart-grid devices, etc., which bring demand flexibility into the market (Jelić et al., 2021).

An increasing number of recent studies in scientific literature has been evaluating PV self-consumption and its economics; these studies mostly focus on PV systems that either solely rely on PV or are combined with residential BESS (Stavrakas et al., 2019). Findings show that if PV self-consumption in the residential sector becomes economically competitive soon, citizens will be willing to self-produce and self-consume electricity instead of buying it from the grid. Such a massive and radical change could impact national power systems around the world, especially if the necessary regulatory framework is not in place and affect the interests of the electricity market stakeholders (Yu, 2018).

In addition, regulatory and financial challenges related to the need for novel market business models and supporting mechanisms are the main obstacles to the sustained exponential growth of PV technology (Michas et al., 2019). Therefore, policymakers should focus on an optimal mix of PV power and other RES technologies; they should also anticipate the risks and uncertainties related to further PV adoption.

Considering all the above, under the ENCLUDE "*Power to the People*" storyline, and in the context of the modeling work presented in this report, we intend to explore transition pathways based on the concept of prosumerism through the further citizen adoption of small-scale PV systems in the residential sector of three (3) different Member States of different geographical and climate conditions and of diverse socioeconomic contexts.

Simulation studies are conducted under different potential future-world evolutions, i.e., the three (3) ENCLUDE "*future-world*" narratives. Below we provide a short policy background of prosumerism in the three (3) selected countries' residential sector.

Denmark

Denmark stands out as a pioneering Member State in the integration of RES within its power sector. A staggering 57.7% of Denmark's electricity generation is derived by wind energy, showcasing the nation's remarkable commitment to harnessing this abundant and clean energy resource (Rövekamp et al., 2021; Statista, 2024a). Additionally, approximately 20.6% of the remaining electricity generation is attributed to bioenergy, further underscoring Denmark's diversified approach to renewable energy utilization (Statista, 2024a).

However, despite impressive developments when it comes to wind energy, adoption of PV systems remains at a nascent stage since solar energy contributes only with 9.3% in power generation (Statista, 2024a). With a per capita solar energy generation of 340 kWh (Our World In Data, 2024b), Denmark currently ranks twelfth (12th) among the 27 EU Member States in this regard.

In the residential sector, the total capacity of small-scale solar PV systems grew significantly from 39 MW to 526 MW with the most recent available relevant data spanning from 2012 to 2018 (IEA, 2018). While Denmark leads the EU in wind energy per capita with 3,218 kWh (Our World In Data, 2024c), there is significant room for growth and development in the solar sector too. This presents an opportunity for the country to further diversify its national RES portfolio and strengthen its position as a global leader in sustainable energy transition.

In this context and considering the potential role that the residential sector could play in the country's decarbonization efforts, it is useful to make a deep dive in the potential for decentralized power generation through the utilization of small-scale solar PV systems (Hansen et al., 2022).

Denmark aims to promote the integration of solar energy in the residential sector mainly through net metering, while prosumers are also able to choose remuneration through a FiT policy scheme but with a significant low fixed price of around 62 €/MWh (compared to the amount that citizens are called to pay for the electricity consumption- around 381 €/MWh including taxes, according to Country Economy (2024a)), applicable for 10 years after the connection with the grid (Wikberg, 2019).

It is noteworthy that Denmark aims to gradually abolish the FiT scheme and keep net metering as the main supporting policy through the application of the legislative framework "BEK no. 999 of 29/06/2016"[14].

All the residential installations (under or equal to 10 kW_p) are exempted from the obligation to pay the so-called Public Service Obligation tariff, while from 2012 and onwards the netting period changed from annual to hourly (Hansen et al., 2022; Wikberg, 2019; Ziras et al., 2021). Finally, according to Ziras et al. (2021), the application of a supportive hourly-based net metering policy scheme in Denmark led from 2010 up to now, to an important tax relief of Danish citizens.

France

In contrast with the other case studies of this deliverable, France is the global leader in the share of nuclear power in the electricity sector with 65.3% (Ritchie & Rosado, 2020) and has the second largest nuclear installed capacity in the world with 61.4 GW after United States (Pata & Samour, 2022). However, France is still in a growing stage when it comes to solar PV installations with only 310

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[14] https://www.retsinformation.dk/eli/lta/2016/999.

kWh/capita of solar energy, which ranks France fourteenth (14th) among all Member States, despite its high potential for the integration of solar energy in the power sector.

More specifically, according to a relevant research conducted by Bódis et al. (2019), France could be able to cover around 28.5% of its final electricity consumption (around 441 TWh) with 125.6 TWh produced by solar PV installations, if rooftop solar PV systems were installed in every rooftop available in the country (estimated around 1,346 km^2), and moreover, in an economically feasible way, since it is estimated that around 88.5 TWh from this potential electricity production could have an LCOE from 0.06 to 0.12 €/ kWh (the rest 37 TWh would have LCOE from 0.12 to 0.15 €/kWh).

It is worthy to mention that numerous studies indicate that despite nuclear power is considered as a “clean” technology, it involves serious environmental and security risks (Ayoub & Sornette, 2023; Lamnatou et al., 2024; Zeraibi et al., 2023). Furthermore, in the context of harmonization with the European Green Deal, France will have to increase RES penetration in the power generation mix since only around 28.5% of the electricity production comes from RES (Statista, 2024c).

In this regard and taking into account the existing solar potential, the residential sector could play a prominent role for the further penetration of solar energy in the national mix, and to that end, citizen adoption of small-scale PV installations could really make the difference in national efforts towards a greener future.

According to the most recent available data, the installed capacity of residential solar PV installations is estimated around 1,800 MW (IEA, 2022b). France aims to further promote the diffusion of small-scale PV systems in the residential sector mainly through the application of a FiT policy scheme according to “Art. 14/Order of May 9 for solar/2017”[15], with a contract duration of 20 years. Currently, the fixed price based on which prosumers are remunerated is equal to 147.4 €/MWh (Bellini, 2024).

It should be noted that net metering is not allowed in France (Fröding & Gasne, 2024; Oriol, 2018); this regulatory landscape underscores the importance of understanding the unique regulatory conditions and market dynamics shaping the adoption of small-scale solar PV systems, offering valuable insights for informing strategic interventions and policy decisions aimed at accelerating the transition to a fair and inclusive future.

Greece

Located in Southern Europe, Greece is a transcontinental country, strategically located at the crossroads of Europe, Asia, and Africa, with a diverse geographical landscape and a large potential in RES (i.e., high solar irradiation levels), which makes it an attractive market choice for both small-scale PV owners and suppliers (Michas et al., 2020).

Furthermore, due to its numerous islands, electricity interconnection of the islands with the mainland in Greece remains a continuous challenge, with the non-interconnected islands depending mainly on conventional generation units. As a result, Greece makes a reasonable selection for a decarbonized vision of a power sector, that relies also on decentralized generation and storage.

More specifically, average Global Horizontal Irradiation in Greece is around 1,639 kWh/m^2 (on an annual basis), which ranks Greece in the third (3rd) position among the Member States (according to data retrieved by Global Solar Atlas[16]). Greece used to traditionally depend on in-house lignite for power generation (Frankowski et al., 2024; Karamaneas et al., 2023; Kontochristopoulos et al., 2021), up to recently, when political decisions set the target of phasing out lignite by 2028 (Stavrakas et al., 2020); the latter made natural gas the predominant fuel with a contribution of 31.73% in the national electricity mix (Statista, 2024b).

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[15] https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000034631446.

[16] https://globalsolaratlas.info/map?c=38.35458,24.488525,7&r=GRC

However, despite its abundant solar potential, Greece has not yet utilized the full potential of solar power integration (Chatzisideris et al., 2017; Nikas, Stavrakas, et al., 2020) since solar energy contributes only with 18.93% in power generation (Statista, 2024b).

It is noteworthy that if small-scale PV installations were to be installed in every available rooftop in the residential sector (estimated around 128 km^2), around 17 TWh could be generated on an annual basis, which means that almost 32% of the final electricity consumption (around 53.5 TWh/year) could have been covered by rooftop solar PV systems (Bódis et al., 2019).

The latter highlights the great potential for Greece to leverage its enormous solar resources and significantly enhance its contribution to renewable energy, thus making progress towards a more sustainable and resilient energy landscape with regards to energy citizenship.

Up to now, according to the most recent official data, the installed rooftop PV capacity (under or equal to 10 kW_p) is around 447 MW (HELAPCO, 2024). The largest rooftop solar PV adoption was achieved from 2009 to 2013 when the first generous FiT policy scheme was in place with a fixed price ranged from 450 €/MWh in 2009 to 294 €/MWh in 2013 (Kërçi et al., 2022; Stavrakas & Flamos, 2022).

Today (2024), prosumers in Greece are able to choose how they will be remunerated; either based on a FiT policy scheme with a fixed price of 87 €/MWh according to "Article 4/L.4414/2016.A'149"[17], or based on a net metering scheme without any remuneration, according to "Law 5037/2023.OFG 78/28.03.2023"[18], and with a four-month netting period.

It is noted that the final settlement takes place after nine (9) four-months and any excess energy that has not been remunerated until then is cleared. These regulatory frameworks in place could play a crucial role in shaping the landscape of rooftop solar PV adoption in Greece, influencing prosumers' behavior and investment decisions.

Based on the case study specifications and the ENCLUDE scenario typology, we ask the following RQs:

RQ$_{1.1}$	*"How could different policy schemes empower prosumerism and further citizen adoption of small-scale PV systems by 2030 in different Member states, under a "Power to the People" storyline and different potential evolutions of the future?"*
RQ$_{1.2}$	*"What is the emission reduction (decarbonization) potential (at the national level) of further empowering prosumerism in these Member States under different potential future-world evolutions?*

6.1.2. Combining "Power to the People" with "People to the Streets" storylines towards people-centered and 100% renewable-based national energy systems

Challenges to transitioning towards a people-centered and 100% renewable-based energy system in the European Union

Confronted with a convergence of crises- escalating climate crisis, geopolitical turmoil, energy insecurity, surging inequalities, and rising cost of living- the urgency for action has never been more evident. Science unequivocally dictates the necessity of a swift transition away from fossil fuels to RES to stay within a safe global warming limit of 1.5°C (IPCC, 2023a).

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[17] https://www.kodiko.gr/nomothesia/document/237723/nomos-4414-2016 (in Greek).

[18] https://deddie.gr/media/31220/νομοσ-5037-2023-φεκ-α-78-28032023.pdf (in Greek).

This means transforming our energy systems by massively increasing sustainable RES deployment towards a 100% renewable-based energy system in the EU by 2040.

With the aim of reducing carbon emissions, the EU has continuously revised its RED; in 2021, the RED was amended under the “Fit-for-55” package to set a new target for RES to account for 40% of the EU's power supply by 2040 (European Commission, 2023). This was further increased to 45% at the end of 2022 through the enactment of the “REPowerEU” plan to improve energy security and reduce reliance on price-volatile fossil fuel imports (European Commission, 2022).

“REPowerEU” consists of a set of emergency measures to accelerate the deployment of RES projects in the EU, including a dedicated Solar Energy Strategy and temporary support for special measures by national governments.

In fact, solar energy is pivotal for a people-centered transition as it can democratize energy production by enabling individuals and local communities to actively participate in and benefit from the energy transition (Climate Action Network, 2024). Rooftop solar PVs with its substantial potential (European Commission, 2024), scalability and accessibility, facilitates households and communities to generate their own power and reduce their energy bills and reliance on volatile, expensive, and polluting fossil fuels, helping to alleviate energy poverty and foster energy independence.

Moreover, PV systems on rooftops do not compete with space use, might have very limited environmental impacts, and their integration into the electricity system is relatively easy due to their proximity to the point of consumption.

The European Green Deal, the Fit-for-55 package, and the “REPowerEU” plan have boosted RES investments in the EU to unprecedented levels, leading to a rapid growth in the installed solar and wind capacity. However, for the EU to meet its 2030 climate targets and international commitments- and to improve energy security- RES deployment must accelerate even faster in the coming years.

According to estimates by the EC, the EU will need to have 592 GW of solar PV and 510 GW of wind capacity installed by 2030 to achieve the target of 69% share of renewable-based electricity in its mix, as set in the “REPowerEU” plan (European Commission, 2022). This would require average annual additions of 48 GW of solar PV and 36 GW of wind (IEA, 2022a).

However, the success of RES initiatives is not solely determined by the number of GW of installed capacity, the efficiency of solar panels, or the height of wind turbines. Rather, it is fundamentally connected to the integration, acceptance, and active involvement of the communities where these projects are planned and implemented, as well as the inclusion of their voices in the decision-making processes.

This is an angle that the EU policy has so far failed to address systemically: decisions related to RES projects often fall under the jurisdiction of individual Member States. Each country- or, in some instances, sub-national region- has its own set of regulations, guidelines, and requirements regarding community engagement, benefit sharing, and other aspects of RES projects. These regulations are influenced by national energy policies, legal frameworks, local contextual factors, and public participation norms.

The varied requirements imposed across jurisdictions enable the customization of community engagement standards to suit local needs. However, the absence of universally shared standards or principles for incorporating community engagement into project design can create a gap between governmental bodies and local communities.

Companies are primarily responsible for developing their own guidelines and strategies, leading to uncertainty about what qualifies as satisfactory engagement in each location. As a result, public participation in the planning of RES projects in Europe often takes place late in the permitting phase and is limited to one-directional information flow in pursuit of instrumental goals, such as convincing the public of a particular project or site, rather than open discussions about project development or design (Stober et al., 2021).

As illustrated in numerous case studies, limited opportunities for meaningful engagement from the civil society have resulted in plans that are not always grounded in practical knowledge and real-world situations, leading to resistance and slowing down further adoption of RES, and particularly of wind power projects (Climate Action Network, 2023).

For example, plans for new onshore wind projects have been subject to local opposition in one-fifth of Dutch municipalities, with dozens of potential onshore wind projects in the Netherlands having been cancelled, delayed, or put on hold amid protests from residents (van Halm, 2022b).

Furthermore, the Norwegian Supreme Court ruled against the construction of two key projects within the Fosen Vind initiative, namely Storheia and Roan (International Work Group for Indigenous Affairs, 2023), in October 2021, while the indigenous Sami community continues to protest against the operation of the existing wind turbines (Reuters, 2023).

As the number of new projects accelerates, these concerns will only intensify. This trend is evident across many European countries, including the UK: while there is overarching support for wind projects, there are valid concerns by local communities regarding their implementation (van Halm, 2022a).

Effective community engagement could help overcome such challenges by either planning projects in an inclusive manner or deciding not to build project on specific lands from the start as well as foster wider community acceptance of RES projects and acceleration more broadly.

Challenges to transitioning towards a people-centered and 100% renewable-based energy system in Greece

Transitioning towards a people-centered and 100% renewable-based energy system in Greece faces several significant challenges:

First, there is a need for substantial investment in RES infrastructure and grid modernization to accommodate decentralized energy production and distribution. In addition, the existing regulatory framework may not adequately support community-led energy initiatives, requiring policy reforms to enable local participation and ownership.

Second, socioeconomic disparities across different regions pose another challenge, as marginalized communities may lack the resources and capacity to engage in RES projects.

Third, public awareness and acceptance of RES projects need to be enhanced, as well as addressing concerns related to job displacement in “grey” energy sectors.

Finally, ensuring energy justice and equitable access to energy for all citizens remains a critical challenge in transitioning towards a sustainable energy system in Greece.

Focusing on decentralized energy production, the average share of rooftop solar PV with a power less than 10 KW is 24% in other European countries, while the respective share in Greece is only 7.2% (energypress.gr, 2024b). According to the Greek RES Operator & Guarantees of Origin, 352 MW of rooftop solar PV systems were installed until May 2022 (DAPEEP SA, 2022).

In 2022, a new FiT scheme for small rooftop solar PV systems up to 6 kW_p was established with a guaranteed price of 87 €/MWh, for a 20-year contract, even though citizens are opting to use the net metering and virtual net schemes instead of this newly introduced program.

Greece is shifting from public support schemes like FiT to the promotion of self-consumption and private power purchase agreements, employing net metering and net billing regimes as a fundamental tool to support decentralized energy generation (especially solar PV). Currently, in Greece, excess energy from an installed PV system can be used to offset consumption through a net metering scheme with a netting period of 3 years (Rokas, 2023).

According to The Green Tank (2024), during 2022-2023 requests for self-consumption through net metering and virtual net metering have increased by 65% (from 15,169 to 35,162 requests). Since 2023, the “Solar on Rooftops” program (238 million) subsidizes the installation of photovoltaic systems with net metering and battery storage which can be installed in parks, on commercial roofs, as well as residential roofs (Hellenic Government, 2023).

Greece has also introduced changes in legislation to accelerate procedures, for instance removing the need for a construction permit for rooftop solar PV installations or providing for a positive silence for small-scale projects (below 50 kW or below 10.8 kW), according to which the absence of a reply by the relevant authorities entails the approval of the permit.

Key barrier to the further development of rooftop solar PV systems is the lack of grid infrastructure to distribute the PV-generated electricity within Greece, causing many rejections to connect and making administrative procedures longer. To avoid problems with security of supply due to lack of infrastructure, grid planning should be reinforced.

In 2023, the total installed capacity of the new self-production PV systems recorded more than 100% increase compared to the year before (energypress.gr, 2024a). According to the Hellenic Association of Photovoltaic Companies (HELAPCO), in the first 11 months of 2023, 209.4 MW of domestic and commercial net-metering and virtual net-metering systems were connected. Specifically, commercial systems amounted to 166.8 MW, while rooftop systems reached 42.6 MW.

It is worth noting that 8.8 MW of the rooftop systems are combined with batteries, which means that they are projects subsidized by the "Solar on Rooftops" program. According to HELAPCO, in 2023, 250 MW of new net-metering systems were installed, with 50 MW being rooftop systems. By January 2024, a total rooftop PV capacity of 14 MW has been installed, while another 60 MW of rooftop systems have been contracted and will be connected within 2024.

HELAPCO estimates that the technical potential of rooftop PV system installations in Greece amounts to a total of 24 GW, of which 12.1 in residential rooftops and 11.2 in industrial-commercial (energypress.gr, 2024b). According to Bódis et al. (2019), the technical potential of Greece for electricity generation from rooftop PV is 17,090 GWh/year. Assuming the average capacity factor for Greece in 2019 (16.25%), the maximum installed capacity for rooftop PV is 12 GW.

The NECP envisages the installation of 100,000 combined PV and storage systems, a total of 1 GW by 2030 (Hellenic Ministry of Environment and Energy, 2023). In this regard, Law 4951/2022 opened up 2 GW of electric space for rooftop systems in the grid (Hellenic Government, 2022).

Currently, there is no roadmap or strategy specific for long-term capacity expansion of rooftop solar PV systems. Policies should be strengthened by setting specific quantitative targets for both individual as well as collective self-consumption beyond 2030.

Furthermore, Greece has made significant strides in promoting the adoption of RES technologies, but ongoing efforts are needed to address challenges related to public acceptance, regulatory stability, and economic viability. Continued engagement with local communities, investment in grid infrastructure, and clarity in policy frameworks will be essential for advancing the transition toward a sustainable energy future.

Table 6 provides examples that illustrate how different approaches to community engagement, such as educational efforts, transparent decision-making, and active involvement of local stakeholders, can lead to successful RES projects and foster local support in Greece. The examples highlight the importance of community engagement for successful implementation of RES projects.

Projects like the “Tilos” hybrid system, the “Sifnos Renewable Energy Cooperative”, and the “Kozani Solar Park” show that extensive community consultation, educational campaigns, and transparent decision-making processes significantly enhance local support and the successful implementation of RES projects.

Moreover, informing and educating local populations about the benefits, the operation, and the potential impacts of RES projects helps in gaining their support. Examples from the regions of Metsovo and Thessaly highlight how educational workshops and collaboration with local institutions foster positive attitudes toward RES projects.

Table 6. Examples of community engagement activities leading to successful implementation of RES projects in Greece.

Location	Type	Community engagement activities	Outcome
Tilos (island)	Hybrid (wind & solar)	Extensive community consultation, public meetings, educational campaigns, and workshops.	Strong local support, successful implementation, and improved energy independence.
Sifnos (island)	Renewable Energy Cooperative	Cooperative model with local ownership, regular meetings, transparent decision-making, and educational sessions.	High community support, successful establishment of the cooperative, and active local involvement.
Kozani (mainland)	Solar Park	Public consultations, collaboration with local government, educational campaigns, and informational sessions.	Positive reception, job creation, and local economic development.
Metsovo (mainland)	Wind energy	Multiple meetings, informational sessions, involvement of local university in impact studies, and public education.	Broad acceptance and successful implementation.
Karystos (Evia island)	Wind farm	Public meetings, informational campaigns, addressing environmental concerns, and involving local stakeholders.	Some delays and adjustments, but improved engagement led to better community relations.
Thessaly (mainland)	Solar farm	Educational workshops, community involvement in planning, local economic incentives, and ongoing consultation.	Generally positive reception, with continuous monitoring of land use impacts.
Milos (island)	Geothermal energy	Informational sessions, public consultation, collaboration with local authorities, transparent planning processes.	High community engagement and support for geothermal energy development.
Crete (island)	Solar and wind	Regular community meetings, educational outreach, involvement of local schools, and collaboration with local NGOs.	Improved community understanding and support, successful implementation of projects.
Patras (mainland)	Urban solar initiative	Community workshops, participatory planning, collaboration with local businesses, and public feedback sessions.	Increased local participation and successful integration of solar panels in urban areas.
Volos (mainland)	Wind farm	Public forums, transparent decision-making, regular updates to the community, and addressing specific local concerns.	Enhanced community trust and smoother project implementation.

Table 7 provides examples of various reasons for local opposition to RES projects in Greece, such as environmental concerns, impacts on local livelihoods and landscapes, and inadequate community in-

volvement. Cross-cutting reasons for local opposition leading to delays in the implementation of RES include:

(**i**)**.** environmental and ecological concerns, i.e., worries about environmental degradation, impact on wildlife, and disruption of natural landscapes, leading to significant delays and legal challenges in RES projects implemented in Mount Vermio, Arcadia, and Thrace;

(**ii**)**.** cultural and historical preservation concerns, due to the perceived threat to cultural heritage and landscape aesthetics, leading to local resistance to projects located near historical or culturally significant sites, such as those in the Mani Peninsula and Pelion;

(**iii**)**.** economic and livelihood impacts, namely concerns about loss of agricultural land and displacement of local livelihoods, as seen in the opposition to projects in Crete and Arcadia.

Table 7. Examples of reasons for local opposition leading to delays in the implementation of renewable energy projects in Greece.

Location	Type	Reasons for opposition	Outcome
Mount Vermio (mainland)	Wind farm	Concerns about environmental degradation, impact on local wildlife, disruption of natural landscapes, and inadequate consultation.	Significant delays, legal challenges, and reassessment of project plans by developers.
Arcadia (Peloponnese)	Wind project	Impact on agriculture, noise, visual impact, effect on bird populations, and insufficient compensation for local communities.	Protests, legal actions, and modifications to project scale and plans to address local concerns.
Karystos (Evia island)	Wind farm	Environmental degradation, impact on local wildlife, tourism concerns, and lack of adequate environmental assessments.	Delays, additional environmental assessments, and improved engagement with local communities.
Mani Peninsula (Peloponnese)	Wind farm	Visual impact, disruption of historical sites, cultural heritage concerns, and inadequate mitigation measures.	Heightened scrutiny, rigorous impact assessments, and revised project plans to mitigate opposition.
Aetolia-Acarnania (mainland)	Wind project	Concerns over landscape changes, effects on local flora and fauna, and insufficient community involvement in planning.	Legal challenges, protests, and demand for more comprehensive environmental studies.
Crete island	Solar Park	Loss of agricultural land, insufficient compensation, displacement of local livelihoods, and inadequate stakeholder engagement.	Project delays, negotiations for better compensation, and revised consultation processes.
Thessaloniki (mainland)	Wind farm	Environmental concerns, noise pollution, visual impact, and potential negative effects on local tourism and property values.	Protests, legal appeals, and requirement for additional mitigation measures and community dialogue.
Thrace (mainland)	Wind and solar project	Impact on local ecosystems, biodiversity concerns, and perceived lack of direct benefits to the local population.	Sustained opposition, demand for better local benefits, and more robust environmental protections.
Pelion (mainland)	Wind project	Visual impact, disruption of natural landscapes, potential harm to local tourism, and insufficient environ-	Opposition led to project reassessment, increased environmental protections, and enhanced community

		mental safeguards.	engagement.
Evros (mainland)	Wind farm	Impact on migratory bird routes, disruption of natural habitats, and insufficient community consultation and compensation.	Legal challenges, requirement for better environmental assessments, and improved local compensation offers.

Scope of the modeling analysis

The vision of transitioning towards a people-centered and 100% renewable-based energy system in Greece can only be realized if citizens are willing to engage with relevant stakeholders from the energy sector to co-design such a system.

Furthermore, citizens need to invest in RES, but before doing so, they need to be aware of both the economic and the environmental value stemming from their investments, as it is unlikely to invest in new technological capabilities having only environmental or other ancillary benefits for the energy system, e.g., energy security, as their primary goals.

In this regard, ongoing and future policy schemes are required to inform and convince citizens of the potential benefits and maximize the value of existing technological capabilities.

So far, there is limited evidence about how citizen preferences can inform political discussions about trade-offs between different energy system design options, specifically considering electricity generation and distribution systems consisting of RES technologies.

So far, energy models have increasingly been used to support decision-making, with high techno-economic sophistication but with weak or no representation of social aspects such as public preferences. Yet, knowing this could allow for preference-led electricity scenarios, based not only on cost-optimality or avoiding what people do not want, but on what they do want.

Considering the above, we aim at integrating citizen preferences into a highly resolved, bottom-up energy system model to enable the assessment of social preferences alongside other aspects like technical feasibility and cost.

In the context of the expected and increasingly participatory role of citizens and other societal actors in the combat against the climate crisis, driving changes in the energy system, and in particular in the supply side, we use the **OSeMOSYS-GR** model in the case of Greece to analyze preference-led energy system planning alternatives under various future-world evolutions.

Based on the case study specifications and the ENCLUDE scenario typology, we ask the following RQs:

RQ$_{2.1}$	*"How does citizen participation in power sector planning and decision-making affects the capacity requirements and the resulting electricity mix of decarbonization pathways under different potential evolutions of the future?"*
RQ$_{2.2}$	*"How do costs and the carbon footprint of centralized and decentralized systems compare between different future-world evolutions?"*
RQ$_{2.3}$	*"What are the potential socioeconomic benefits derived from citizen-led investments and how do these benefits compare among different policy mixes and potential future evolutions of the surrounding environment?"*

6.1.3. Decarbonizing the transport and the residential sectors in Western Europe under different "people-centered" storylines

Due to the aggregate regional levels of the IMAGE modeling framework, and consequently its supranational focus, the selected case study relevant for comparison with other case studies, is Western Europe. This allows for a comparison with the case studies of Denmark, France, and Greece from the other models with a national focus.

The case study of Western Europe is characterized by the passenger transport and residential system. The passenger transport system is largely car-based at around 38% of the passenger kilometers (pkms) travelled (about 27,000 pkm per capita per year). Bus travel is about 25%, walking and biking combined about 19%, air travel 9%, train 7%, and high-speed train 2% (based on the SSP2 reference scenario for 2015). The energy intensity of the different modes of transport is 1.85 MJ/pkm for air travel, 1.35 MJ per pkm for cars, 0.75 MJ per pkm for buses, 0.48 MJ per pkm for high-speed trains, and 0.36 MJ per pkm for trains.

For the residential sector, the energy use in Western Europe is roughly 10 EJ (based on the SSP2 reference scenario for 2015) including household appliances, lighting, cooking, water heating, space heating, and cooling. The most significant contribution to this energy use is space heating (over half the total residential energy use), and after that water heating (about a fifth of the total residential energy use).

With Western Europe as a case study having a supranational level of analysis, we use **IMAGE** and its aggregate scope, aiming to answer the following RQ, to provide decision-makers with a holistic perspective on the different patterns and trends of energy citizenship and their decarbonization potential under different transition pathways.

Based on the case study specifications and the ENCLUDE scenario typology, we ask the following RQ:

RQ$_3$	*"What decarbonization pathways are possible for different patterns and trends of energy citizenship in changes in consumption and technology in the transport and the residential sectors of the Western Europe?"*

6.2. Scenario design and transition pathways

In this segment, we delve into the specification process for the case studies described in the preceding chapters. This entails a meticulous exploration of the specific steps taken to define and quantify the variables involved in each case study, shedding light on the numerical parameters and assumptions that form the basis of the analytical approach that was followed.

Based on the case study specifications, as presented in **Section 6.1**, we employ the ENCLUDE scenario space framework to showcase its applicability to three (3) different model applications looking into diverse RQs, such as the decarbonization potential of further diffusion of small-scale PV systems by 2030, empowering prosumerism at the national level of three (3) Member States, energy planning and different resulting benefits from a people-centered 100% renewable-based transition at the national level of one Member State, and the decarbonization potential of different patterns and trends of energy citizenship in the transport and the residential sectors in Western Europe.

This ultimately allows us to create three (3) different scenario spaces consisting of transition matrices with the evolution of different exogenous variables, e.g., emission factors, evolution of relevant energy prices and costs, technological costs and relevant updated configurations, benefits for citizens and/ or other power actors involved, according to the ENCLUDE scenario space.

Overall, our aim is to offer transparency and clarity regarding the methodologies employed, ensuring a robust foundation for the subsequent analyses and conclusions drawn from the case studies.

6.2.1. *“Power to the People” transition pathways through empowering prosumerism and citizen adoption of photovoltaic systems*

Three (3) different policy schemes are studied, also considering the existing regulatory framework in Denmark, France, and Greece:

- *Feed-in tariff*: Prosumers are incentivized through fixed remuneration rates for the electricity they inject into the grid, allowing for the assessment of the uptake of rooftop solar PV installations under a regulated pricing mechanism. The expected benefits from an investment on solar PV systems under the FiT scheme for the prosumers, are calculated according to the following equation:

$$P_{resid}^{total} = \begin{cases} if\ E_{PV} > E_{resid} \rightarrow\ C_{grid} \cdot E_{resid} + (E_{PV} - E_{resid}) \cdot FiT \\ if\ E_{PV} < E_{resid}\ \rightarrow C_{grid} \cdot E_{residPV} \end{cases}$$

where P_{resid}^{total} are the expected benefits (€), C_{grid} are the charges for the total amount of electricity consumed (€ per kWh), E_{PV} is the total electricity generation from the PV system (kWh), E_{resid} is the total electricity demand of the household (kWh), FiT is the amount of the fixed price for the remuneration for the excess electricity provided to the grid (€ per kWh), and $E_{residPV}$ the total electricity consumed from the PV system (kWh).

- *Net metering*: Prosumers offset their electricity consumption with the surplus energy generated by their PV systems, without receiving financial compensation for the excess energy fed into the grid. Expected benefits at the end of each netting period are calculated according to the following equation:

$$P_{resid}^{total} = C_{grid} \cdot \min(E_{PV}, E_{resid}) + C_{PV} \cdot E_{residPV}$$

where P_{resid}^{total} are the expected benefits (€), C_{grid} are the charges for the total amount of electricity consumed (€ per kWh), E_{PV} is the total electricity generation from the PV system (kWh), E_{resid} is the total electricity demand of the household (kWh), C_{PV} are the charges for the total amount of electricity absorbed from the PV system (€ per kWh), and $E_{residPV}$ the total electricity consumed from the PV system (kWh).

- *Net metering with BESS*: This case explores the synergistic effects of combining rooftop solar PV installations with a BESS, enabling prosumers to store excess electricity produced for later use, enhancing self-consumption and grid stability (Barva & Joshi, 2024; Hassanzadeh et al., 2020). The expected benefits at the end of each netting period, are calculated according to the following equation:

$$P_{resid}^{total} = C_{grid} \cdot (E_{resid} - E_{grid}) + C_{PV} \cdot E_{residPV}$$

where P_{resid}^{total} are the expected benefits (€), C_{grid} are the charges for the total amount of electricity consumed (€ per kWh), E_{grid} is the total electricity absorbed from the power grid (kWh), E_{resid} is the total electricity demand of the household (kWh), C_{PV} are the charges for the total amount of electricity absorbed from the PV system (€ per kWh), and $E_{residPV}$ the total electricity consumed from the PV system (kWh).

Each policy scheme is customized according to the model-specific assumptions that govern the different cases and “*future-world*” narratives under study; for example, FiT price and netting periods as set in each Member State, evolution of prices, evolution of electricity demand, etc., also in line with the principles and key traits of the “*Power to the People*” storyline.

It is noted that all the scenarios are conducted under the principles that characterize the "*Power to the People*" storyline as defined in Tsopelas et al. (2023). Hence, the model-specific assumptions (parameterization) of ATOM follows for each different specified case study separately (**Table 8**):

Table 8. Parameterization of ATOM for the policy schemes and the different "future-world" narratives under study, at the national level of the specified case studies (i.e., Denmark, France, and Greece), and in the context of the "*Power to the People*" storyline.

Denmark					
Parameters	***"Future-world" narratives***	***FiT***	***Net metering***	***Net metering with BESS***	***Justification***
Initial PV Cost (€/W_p)	"Unified World"	0.88	0.88	0.88	IEA (2018)
	"Familiar World"	0.88	0.88	0.88	
	"Fragmented World"	0.88	0.88	0.88	
PV Cost Annual Change Factor (%)	"Unified World"	-6.05	-6.05	-6.05	According to historical data and "future-world" narratives, IEA (2018)
	"Familiar World"	-4.05	-4.05	-4.05	
	"Fragmented World"	-1.05	1.05	1.05	
Initial FiT Value (€/MWh)	"Unified World"	62	-	-	Wikberg (2019)
	"Familiar World"	62	-	-	
	"Fragmented World"	62	-	-	
FiT Annual Change Factor (%)	"Unified World"	False	-	-	We assume that fixed price is constant toward 2030
	"Familiar World"	False	-	-	
	"Fragmented World"	False	-	-	
Initial Electricity Price (€/kWh)	"Unified World"	0.2703	0.2703	0.2703	Country Economy (2024a)
	"Familiar World"	0.3811	0.3811	0.3811	
	"Fragmented World"	0.5755	0.5755	0.5755	
Regulated Charges (€/kWh)	"Unified World"	0.0116	0.0116	0.0116	Energinet (2024)
	"Familiar World"	0.0116	0.0116	0.0116	
	"Fragmented World"	0.0116	0.0116	0.0116	
Electricity Price Annual Change Factor (%)	"Unified World"	-0.53	-0.53	-0.53	Assumption based on "future-world" narratives
	"Familiar World"	-0.53	-0.53	-0.53	
	"Fragmented World"	-0.53	-0.53	-0.53	
Annual Electricity Demand (kWh)	"Unified World"	-	4332	4332	ODYSSEE-MURE (2021)
	"Familiar World"	-	4332	4332	
	"Fragmented World"	-	4332	4332	
Battery Efficiency (%)	"Unified World"	-	-	94	Assumption based on R&D progress for Unified World, Farhad & Nazari (2019)
	"Familiar World"	-	-	92	
	"Fragmented World"	-	-	92	
Inverter Efficiency (%)	"Unified World"	-	-	98	Park et al. (2020)
	"Familiar World"	-	-	96	
	"Fragmented World"	-	-	96	
Initial Battery Cost (€/kWh)	"Unified World"	-	-	408	According to market research, Farnell (2024)
	"Familiar World"	-	-	408	
	"Fragmented World"	-	-	408	
Battery Cost Annual Change Factor (%)	"Unified World"	-	-	-2.5	According to historical data and "future-world" narratives
	"Familiar World"	-	-	-1.5	
	"Fragmented World"	-	-	False	
Battery Subsidy Percentage (%)	"Unified World"	-	-	50	According to "future-world" narratives, Danish Energy Agency (2024)
	"Familiar World"	-	-	False	
	"Fragmented World"	-	-	False	

Inertia to Invest	"Unified World"	0.04	0.04	0.04	Estimated empirically according to "future-world" narratives
	"Familiar World"	0.02	0.02	0.02	
	"Fragmented World"	0.01	0.01	0.01	

France

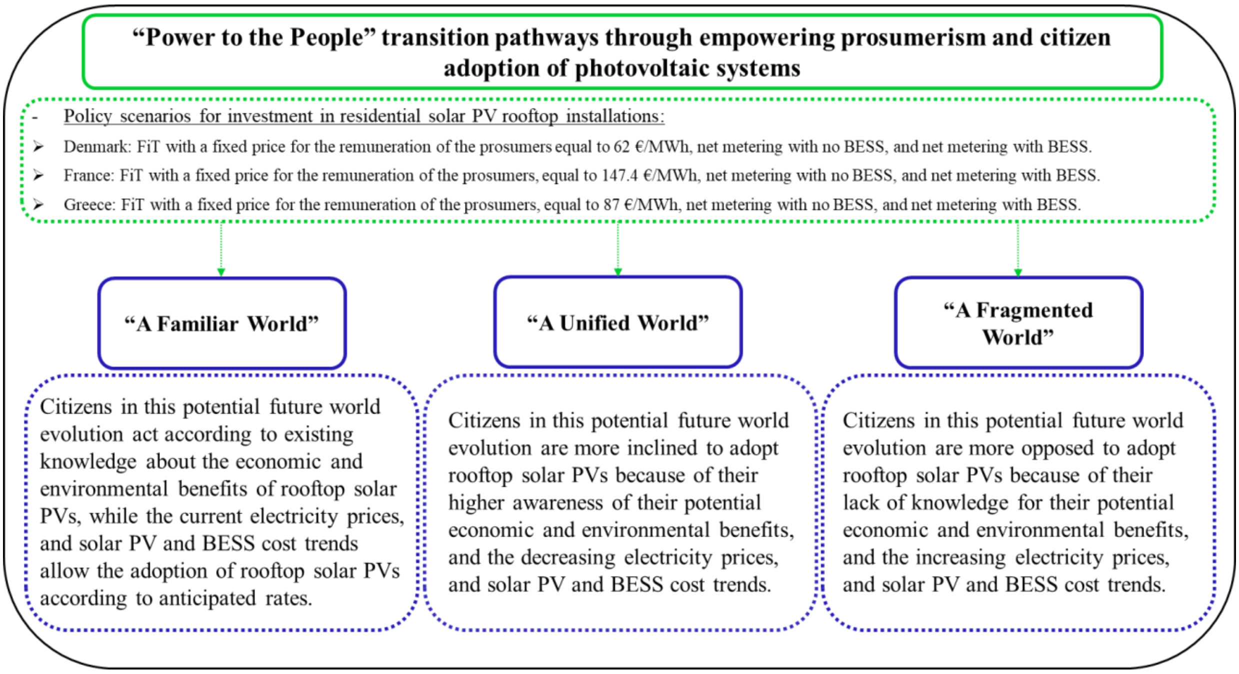
Parameters	***"Future-world" narratives***	***FiT***	***Net metering***	***Net metering with BESS***	***Justification***
Initial PV Cost (€/W_p)	"Unified World"	1.92	1.92	1.92	IEA (2022); Lilley (2024)
	"Familiar World"	1.92	1.92	1.92	
	"Fragmented World"	1.92	1.92	1.92	
PV Price Annual Change Factor (%)	"Unified World"	-5.73	-5.73	-5.73	According to historical data and "future-world" narratives, IEA (2022)
	"Familiar World"	-3.73	-3.73	-3.73	
	"Fragmented World"	1.73	1.73	1.73	
Initial FiT Value (€/MWh)	"Unified World"	147.4	-	-	Bellini (2024)
	"Familiar World"	147.4	-	-	
	"Fragmented World"	147.4	-	-	
FiT Annual Change Factor (%)	"Unified World"	False	-	-	We assume that fixed price is constant toward 2030
	"Familiar World"	False	-	-	
	"Fragmented World"	False	-	-	
Initial Electricity Price (€/kWh)	"Unified World"	0.1331	0.1331	0.1331	Country Economy (2024b)
	"Familiar World"	0.1648	0.1648	0.1648	
	"Fragmented World"	0.1964	0.1964	0.1964	
Regulated Charges (€/kWh)	"Unified World"	0.0627	0.0627	0.0627	Commission de Régulation de l'Énergie (2024)
	"Familiar World"	0.0627	0.0627	0.0627	
	"Fragmented World"	0.0627	0.0627	0.0627	
Electricity Price Annual Change Factor (%)	"Unified World"	-0.53	-0.53	-0.53	Assumption based on "future-world" narratives
	"Familiar World"	-0.53	-0.53	-0.53	
	"Fragmented World"	-0.53	-0.53	-0.53	
Annual Electricity Demand (kWh)	"Unified World"	-	4972	4972	ODYSSEE-MURE (2021)
	"Familiar World"	-	4972	4972	
	"Fragmented World"	-	4972	4972	
Battery Efficiency (%)	"Unified World"	-	-	94	Assumption based on R&D progress for Unified World, Farhad & Nazari (2019)
	"Familiar World"	-	-	92	
	"Fragmented World"	-	-	92	
Inverter Efficiency (%)	"Unified World"	-	-	98	Park et al. (2020)
	"Familiar World"	-	-	96	
	"Fragmented World"	-	-	96	
Initial Battery Cost (€/kWh)	"Unified World"	-	-	457	According to market research, Ultimatron France (2024)
	"Familiar World"	-	-	457	
	"Fragmented World"	-	-	457	
Battery Cost Annual Change Factor (%)	"Unified World"	-	-	-4.0	According to historical data and "future-world" narratives
	"Familiar World"	-	-	-3.1	
	"Fragmented World"	-	-	False	
Battery Subsidy Percentage (%)	"Unified World"	-	-	50	According to "future-world" narratives, Solar Power Europe (2020)
	"Familiar World"	-	-	False	
	"Fragmented World"	-	-	False	
Inertia to Invest	"Unified World"	0.04	0.04	0.04	Estimated empirically according to "future-world" narratives
	"Familiar World"	0.02	0.02	0.02	
	"Fragmented World"	0.01	0.01	0.01	

Greece

Parameters	***“Future-world” narratives***	***FiT***	***Net metering***	***Net metering with BESS***	***Justification***
Initial PV Cost (€/W_p)	“Unified World”	0.833	0.833	0.833	According to market research, Taxheaven (2023), “Solar on Rooftops” program
	“Familiar World”	0.833	0.833	0.833	
	“Fragmented World”	0.833	0.833	0.833	
PV Price Annual Change Factor (%)	“Unified World”	-4.28	-4.28	-4.28	According to historical data and “future-world” narratives, Michas et al. (2020)
	“Familiar World”	-1.28	-1.28	-1.28	
	“Fragmented World”	2.28	2.28	2.28	
Initial FiT Value (€/MWh)	“Unified World”	87	-	-	Article 4/L.4414/2016.A'149
	“Familiar World”	87	-	-	
	“Fragmented World”	87	-	-	
FiT Annual Change Factor (%)	“Unified World”	False	-	-	We assume that fixed price is constant toward 2030
	“Familiar World”	False	-	-	
	“Fragmented World”	False	-	-	
Initial Electricity Price (€/kWh)	“Unified World”	0.1244	0.1244	0.1244	Public Power Corporation (2024)
	“Familiar World”	0.1817	0.1817	0.1817	
	“Fragmented World”	0.2444	0.2444	0.2444	
Regulated Charges (€/kWh)	“Unified World”	0.0508	0.0508	0.0508	Stavrakas et al. (2019)
	“Familiar World”	0.0508	0.0508	0.0508	
	“Fragmented World”	0.0508	0.0508	0.0508	
Electricity Price Annual Change Factor (%)	“Unified World”	-0.53	-0.53	-0.53	Assumption based on “future-world” narratives
	“Familiar World”	-0.53	-0.53	-0.53	
	“Fragmented World”	-0.53	-0.53	-0.53	
Annual Electricity Demand (kWh)	“Unified World”	-	4739	4739	ODYSSEE-MURE (2021)
	“Familiar World”	-	4739	4739	
	“Fragmented World”	-	4739	4739	
Battery Efficiency (%)	“Unified World”	-	-	94	Assumption based on R&D progress for Unified World, Farhad & Nazari (2019)
	“Familiar World”	-	-	92	
	“Fragmented World”	-	-	92	
Inverter Efficiency (%)	“Unified World”	-	-	98	Park et al. (2020)
	“Familiar World”	-	-	96	
	“Fragmented World”	-	-	96	
Initial Battery Cost (€/kWh)	“Unified World”	-	-	552	According to market research
	“Familiar World”	-	-	552	
	“Fragmented World”	-	-	552	
Battery Cost Annual Change Factor (%)	“Unified World”	-	-	-4	According to historical data and “future-world” narratives, Michas et al. (2020)
	“Familiar World”	-	-	-2.91	
	“Fragmented World”	-	-	False	
Battery Subsidy Percentage (%)	“Unified World”	-	-	100	Taxheaven (2023), “Solar on Rooftops” program
	“Familiar World”	-	-	90	
	“Fragmented World”	-	-	50	
Inertia to Invest	“Unified World”	0.04	0.04	0.04	Estimated empirically according to “future-world” narratives
	“Familiar World”	0.02	0.02	0.02	
	“Fragmented World”	0.01	0.01	0.01	

Considering specifications of the “*people-centered*” storylines and the potential evolutions of the “*future-world*” narratives, the ENCLUDE scenario space for a “*Power to the People*” storyline that empowers prosumerism and further citizen adoption of small-scale photovoltaic systems in the European Union by 2030 is specified (**Figure 22**).

This scenario design allows us to explore three (3) different combinations of the "*Power to the People*" transition pathways under study, for a potential evolution of a (**i**). "*Familiar World*", (**ii**). "*Unified World*", and (**iii**). "*Fragmented World*".



"Power to the People" transition pathways through empowering prosumerism and citizen adoption of photovoltaic systems

- Policy scenarios for investment in residential solar PV rooftop installations:
  - Denmark: FiT with a fixed price for the remuneration of the prosumers equal to 62 €/MWh, net metering with no BESS, and net metering with BESS.
  - France: FiT with a fixed price for the remuneration of the prosumers, equal to 147.4 €/MWh, net metering with no BESS, and net metering with BESS.
  - Greece: FiT with a fixed price for the remuneration of the prosumers, equal to 87 €/MWh, net metering with no BESS, and net metering with BESS.

"A Familiar World"

Citizens in this potential future world evolution act according to existing knowledge about the economic and environmental benefits of rooftop solar PVs, while the current electricity prices, and solar PV and BESS cost trends allow the adoption of rooftop solar PVs according to anticipated rates.

"A Unified World"

Citizens in this potential future world evolution are more inclined to adopt rooftop solar PVs because of their higher awareness of their potential economic and environmental benefits, and the decreasing electricity prices, and solar PV and BESS cost trends.

"A Fragmented World"

Citizens in this potential future world evolution are more opposed to adopt rooftop solar PVs because of their lack of knowledge for their potential economic and environmental benefits, and the increasing electricity prices, and solar PV and BESS cost trends.

Figure 22. The ENCLUDE scenario space for a "Power to the People" storyline that empowers prosumerism and further citizen adoption of small-scale photovoltaic systems in the European Union by 2030.

6.2.2. *Combining "Power to the People" with "People to the Streets" storylines towards people-centered and 100% renewable-based national energy systems*

"People-centered" storyline descriptions

Storylines and scenario logic

Decarbonized futures can be described by different storylines according to different viewpoints. Despite the shared decarbonization objective, their envisioned end-state aims and governance choices, including the actors to carry out the change, are in fact fundamentally different (Lilliestam & Hanger, 2016).

Given that citizens are considered as key actors in this transition, it is important to better understand how their perspectives and decision-making can affect future energy system design.

Xexakis & Trutnevyte (2021) found that French, German, and Polish citizens with different demographical and political characteristics have positive views in terms of individual technology preferences toward hydropower, rooftop and open field solar PV systems, offshore wind power, biomass, and electricity savings and efficiency.

Furthermore, they observed moderate or positive views for onshore wind power as well as negative views on natural gas and coal with carbon capture and storage (CCS) and net electricity imports with regards to the national electricity supply.

Mey et al. (2024) showed that household electricity prices, electricity imports, and power generation technology choices are the key drivers of citizen preferences with regards to the design of future regional renewable electricity systems. According to their findings, if citizens were to decide, the future renewable power system would be decentralized, based on supply with high shares of rooftop PV systems, communally owned, not relying strongly on transmission, and leading to low household prices.

Furthermore, citizens prefer such a decentralized system over a more centralized, wind power- and transmission-heavy system relying on imports.

Decentralization of the power system allows a more varied and efficient participation of different stakeholders in the energy transition and provides many opportunities for citizens, especially those with a good knowledge of the energy market and consumption patterns, enabling them to make informed choices.

- Our first scenario, “***Decentralized planning***”, emerges from *protest against fossil fuel-based and centralised power structures*.

  It relies on bottom-up initiatives with **equity** as the key constraint and emphasizes **democratization** and **autonomy** through **decentralization** as the primary aim; and RES systems of a *small-scale* and *modular nature*- are most preferred by citizens and excellently suited for this.

  In this scenario, decentralization is considered as a *necessary precondition* for decarbonization; however, a democratized and decarbonized energy system cannot be achieved if *large corporations*, which already hold the largest share of energy infrastructure in the power market, act in collusion with policymakers to maintain control and *monopolize* the energy sector.

  To avoid an undemocratic energy system, *more than replacing technologies is required*; **societal change** is necessary to move away from a centralised energy system model.

  Hence, in this scenario, the focus falls upon reducing the role of corporations and promote citizen and cooperative energy as well as small- and medium-scale companies close to the people: moving towards an “***energy for the people by the people***” model.

  To ensure citizen control and local benefits of transition policies, *citizens’ preferences and acceptance levels* need to be reflected in the decision-making processes. In this regard, NGOs and citizen organizations actively voice their concerns about the dominance of larger companies in the energy sector, emphasizing the importance of preserving a competitive landscape that allows smaller entities to thrive, and this leads to a growing number of instances of strong and well substantiated local opposition against large-scale, and especially, wind power, projects.

  By *vocalizing these concerns through social media, organized protests, and community engagement*, citizens *increase their knowledge* about the energy system, *raise wider public awareness*, and *exert pressure on policymakers to prioritize their interests* as consumers and potential prosumers.

  Policymakers continue the efforts to create favorable conditions for investments in energy production from RES, *opening new possibilities for citizens* to engage in the energy market. This is done through the development of regulations and supportive measures.

  In the “*Decentralized planning*” scenario, higher public participation to electricity generation stems from self-production schemes (e.g., net metering or net-billing) employing local small-scale renewable energy (e.g., rooftop solar PV systems) coupled with energy storage (e.g., battery) installations and thus greedy energy majors are restricted.

  The growing local energy markets enable the liberalization of the energy market, and along with fast and efficient mechanisms for selling the surplus of self-produced electricity to the grid, provide important support to homeowners and businesses to generate their own electricity from RES.

  Overall, economic benefits are expected to remain the strongest motivation for utilization of RES, while considerations on the positive environmental impacts will be an important reason to generate own electricity from RES for a substantial number of citizens *with high levels of energy literacy*, *climate consciousness*, and *social value propositions*.

- Contrastingly, the *integrated and centralized energy production at the national level increases the security of supply but limits the opportunities for energy citizenship*. Our second scenario, “***Centralized planning***”, relies on **top-down** policy and aims at *replacing carbon-intensive technologies and practices with zero-carbon ones*, but in a **centrally controlled, secure way**.

  Security plays a *major role in the public and political debate*. Maintaining control over both the *stability of energy supply and over the pace and direction of the transition* are key features of energy and climate governance.

  Therefore, the *government respects security concerns by carefully implementing changes*, with policies closely following their detailed and elaborated master plans. In this context, the government *does not emphasize raising public awareness of the potential benefits of energy citizenship*.

  Therefore, *citizens’ lack of knowledge about RES leads to low level of social acceptance of new products, services, small-scale technologies, and innovative solutions in the energy field that could further open and promote numerous possibilities for energy citizenship initiatives*.

  As a result, the most important technological solutions and innovations are applied mostly for the *development of large-scale energy infrastructure*, without actual consideration for sustainability and out of citizens’ reach.

  In the “*Centralized planning*” scenario, *economic attractiveness mainly comes from large-scale investments in VRE*, e.g., onshore and offshore wind turbines and utility-scale PV systems, *with large-scale supply-side flexibility* (e.g., utility-scale BESS, pumped hydro, and electrolyzers) installations, thus ***limiting prosumerism capabilities***.

  In this regard, least preferred by citizens controllable large-scale solutions and electricity imports are the key means to achieve decarbonization. As onshore and offshore wind power plants multiply, the national government puts in place adequate regulations that *ensure that local communities in areas where wind parks will be sited will benefit from the operation of these wind parks*, thus somewhat *mitigating local opposition against wind power*.

  Emphasis is also given to the participation in the EU-wide electricity grid and the possibility of cross-European electricity trading, *rather than the creation of local energy grids and local trading micro-systems*. Smart grids development remains stagnant in the future, thus posing a major hurdle for energy citizenship. Citizens have little impact on the development of smart grids since this is a very specific and complex issue most people are indifferent to.

- Our third scenario, “***Fossil fuel-dependent planning***”, shares similarities with the “*Centralized planning*” storyline in terms of reliance on **top-down policy** and **ensuring national security in supply**; however, it presents notable differences as regards combating the climate crisis.

  In this scenario, *national policymaking totally disregards its commitments to the EU*’s *visions and targets* and fails to take the necessary- from a climate-neutrality perspective- actions to replace carbon-intensive technologies and practices with zero-carbon ones.

  Similarly to the “*Centralized planning*” scenario, *security plays a major role in the public and political debate* and thus the government respects security concerns by ***implementing reforms at a slower pace***.

  In the future, underlined *social distrust toward national and local energy policies becomes prominent*. Citizens’ lack of knowledge and trust with regards to the greening of the power system and whether that would be beneficial for them due to the high costs and environmental implications that it would require, leads to *low levels of social acceptance of low-carbon solutions*.

> Consequently, there is a strong resistance to change at the regional level, especially where the greening of the power sector is expected to cause the most drastic changes in the way people live, pushing citizens *to get involved in radical action such as protest movements and other forms of agitation against RES*.
>
> As a result, the resulting power system is dominated by fossil-fired centralised energy generation, with national boundaries clearly visible in the system's architecture.

"People-centered" scenario specifications

We explore least-cost capacity and electricity mixes that are subject to specific sociotechnical constraints. Considering the three (3) different scenarios, as presented above and describing the identified energy citizenship patterns and trends related to the "*Power to the People*" and the "*People to the Streets*" "*people-centered*" storylines, we develop **four (4) different cases** that are simulated with the use of the OSeMOSYS-GR model and follow the logic behind the described scenarios, i.e., "*Centralized case*" derived from the "*Centralized planning*" scenario, "*Decentralized case*" from the "*Decentralized planning*" scenario, and "*Gas-dependency case*" and "*Lignite-dependency case*" from the "*Fossil fuel-dependent planning*" scenario.

Furthermore, an additional case is created as a means of providing a baseline for the scenario space so that comparisons with the other cases can be made, i.e., the "*BAU case*", which describes a future power system as envisioned by the current governmental national energy and climate planning (i.e., NECP) and based on the anticipated citizen participation in the energy market and social acceptance of low-carbon energy projects.

The "*Centralized case*" implies system planning based on lower participation of citizens in the energy market and higher social acceptance of large-scale RES projects, especially wind onshore and wind offshore, while the "*Decentralized case*" entails system planning based on higher participation of citizens in the energy market and lower social acceptance of large-scale RES projects, thus leaving more space for small-scale applications.

On the other hand, both the "*Gas-dependency case*" and the "*Lignite-dependency case*" entail system planning based on lower participation of citizens in the energy market and lower levels of social acceptance of low-carbon energy projects compared to the "*BAU case*". The "*Gas-dependency case*" assumes a national security of supply planning based on imported natural gas, while the "*Lignite-dependency case*" assumes a national security of supply planning based on domestic lignite.

In terms of specifications, these cases differ in terms of the share of rooftop solar PV installations in the total PV capacity- to reflect the trends of the "*Power to the people*" storyline- and the share of fossil fuels or RES in the total capacity- to reflect the trends of the "*People to the Streets*" storyline- by 2030 and 2050, respectively.

The shares of rooftop solar PV systems in the total PV capacity in 2030 for the three (3) cases are estimated based on the NECP target of 1 GW. The respective shares in 2050 are estimated aiming at utilizing the maximum technical potential of rooftop solar PV installations in residential rooftops in Greece (i.e., ~12 GW) for the "*Decentralized case*" to show the most ambitious development of public participation in terms of prosumerism while the current share of rooftop solar PV in the total PV capacity (~7%) is used as a projection for the "*Centralized Case*" to present a poor development of future public participation.

Respectively, the shares of fossil fuels or RES in the total capacity mix are estimated considering the capacity targets of the NECP and adapting them based on the "future-world" narratives' logic as described above.

For example, wind power shares in the capacity mix are reduced by 2050 under the "*Decentralized case*" to illustrate higher public opposition to large-scale wind power projects in Greece, while they are increased by 2050 under the "*Centralized Case*" to showcase less social opposition to such projects.

Furthermore, the shares of net electricity imports in the total electricity mix are estimated based on the NECP projections in 2030 and 2050 and are assumed to be higher in the "*Centralized case*" and lower in the "*Decentralized case*" compared to the "*BAU case*".

"Future-world" narrative descriptions

Narratives and scenario logic

The degree to which a social innovation is adopted by the public heavily correlates to the contextual external circumstances of the social group under study.

Therefore, following the "*Diffusion of Innovations*" theory of Everett M. Rogers (Rogers, 1983), which provides a framework for comprehending the dissemination and adoption of novel ideas, technologies, and practices within societies and has found wide application across various disciplines, we can assume the traditional adoption curve (**Figure 23**) to simulate baseline transition pathways under the "*Familiar World*" narrative, as this curve describes the typical attitude of individuals toward innovation.

The adoption curve is a graphical representation of the process of innovation adoption across distinct groups within a social system, each characterized by varying levels of readiness to embrace new innovations.

More specifically, the adoption curve identifies *five (5) different adopter groups/ categories* in which individuals fall into and describe their attitude toward adopting new technologies or behaviors, namely:

- ***Innovators*** are risk takers who have the resources and desire to try new things, even if they fail.
- ***Early Adopters*** are selective about which innovations they adopt. They are considered those that other groups ask for new information and thus reduce other groups' uncertainty about an innovation by adopting it.
- ***Early Majority*** take their time before adopting a new idea. They are willing to embrace a new technology as long as they understand how it fits with their lives.
- ***Late Majority*** adopt in reaction to peer pressure, emerging norms, or economic necessity. Most of the uncertainty around an idea must be resolved before adoption.
- ***Laggards*** are traditional and make decisions based on past experiences. They are often economically unable to take risks on new ideas.

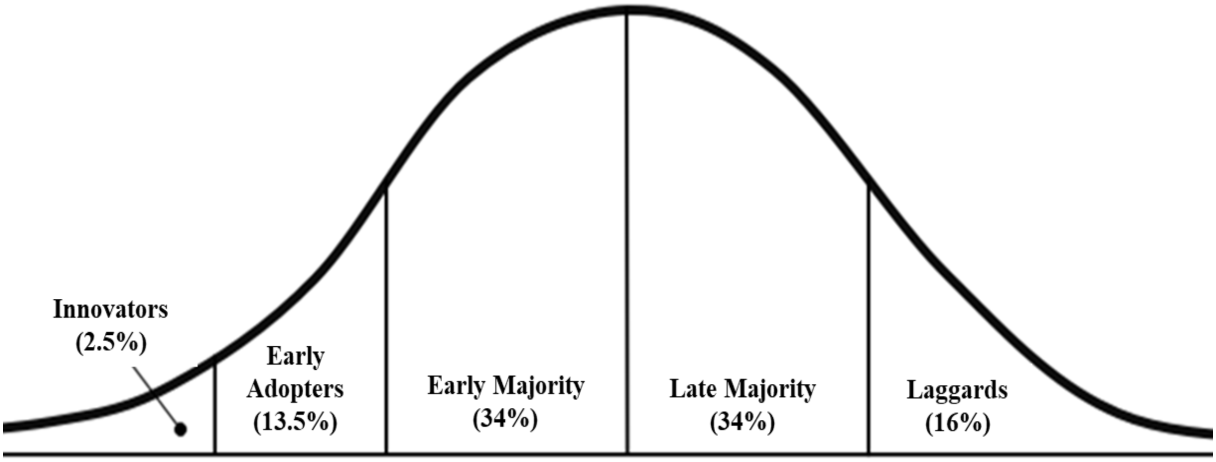


Figure 23. Adoption of innovation curve. Source: Rogers (1983).

To portray the differences between the different "*future-world*" narratives, the scenario space can be further informed and differentiated by incorporating various degrees of behavior adoption related to the decision-making process of becoming a prosumer.

Therefore, the adoption curve may be adapted to the needs of each narrative, by assuming a skewed distribution of the adoption curve and, thus, different percentages for the adopter groups.

As a result, two (2) new adoption curves are created (**Figure 24**) with the respective percentages for the different adopter groups; one (1) correlating to positive systemic changes (i.e., "*Unified World*"), that drive cooperation forward and assumes widespread early adoption of sustainable technologies and practices, and one describing a world in which growing disbelief is prevalent, which deters individuals from incorporating such practices into their lifestyle, and in which adoption of innovations is delayed (i.e., "*Fragmented World*").

By designing depictions of potential future-world narratives with adoption curves exhibiting both positive and negative skewness, that represent the eagerness- or lack thereof- of the public to welcome social innovations related to energy citizenship, such as prosumerism, we manage to add an informed people-centered aspect to our analysis.

In the context of this application, we simulate the capacity expansion of rooftop solar PV systems following the adoption trends assumed for each "future-world" narrative.

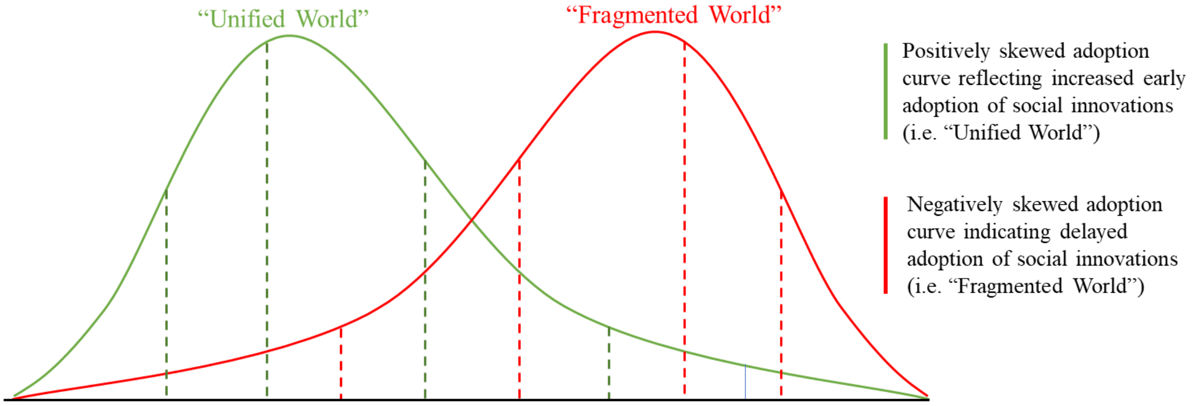


Figure 24. Skewed adoption curves representing the attitude towards social innovations under the "*Unified World*" and the "*Fragmented World*" narratives.

Below we provide a qualitative account of each "*future-world*" narrative, describing the evolution of the external environment related to the transition pathways analyzed in the power sector of Greece and allowing us to make assumptions related to the shares of fossil fuels or RES in the total capacity mix:

- "***A Familiar World***": Transition pathways developed under this narrative build on a potential evolution of the future in which citizens depend on national political decisions to invest in green solutions and thus take their time before adopting rooftop solar PV systems.

  As such, future planning of the power system follows the BAU specifications foreseen by current policy documents. The government keeps citizens informed about the energy transition, allowing them to become aware of its potential benefits. This enables less opposition to the planned energy projects in the context of the NECP implementation.

  However, uncertainty regarding citizens' preferences and acceptance levels which are not reflected in the national decision-making processes does not eliminate the possibility of a less fossil fuel-based and more decentralized planning, in case that citizens decide to unify and combat the BAU planning.

  In any case, the future evolution of the external environment allows the decarbonization of the power sector to be completed according to current national-level projections.

"***A Unified World***": Transition pathways developed under this narrative build on the premise that citizens come together united in the battle against the climate crisis and collectively oppose to the use of fossil-fuels in the energy mix, even with the use of CCS, as implied by the current NECP in Greece, thus leaving more room for RES.

Furthermore, citizens decide to become prosumers by investing in green solutions at a faster rate compared to the "*Familiar World*" narrative. The deployment of rooftop solar PV systems is mainly driven by behavioral changes and mutual accountability of citizens, governments, and companies.

Of course, the extent to which citizens invest in such solutions depends on the governance of the energy system, i.e., a centralized planning provides less space for citizen-led initiatives, while a decentralized planning provides more space for them.

In both cases, the more positive evolution of the future external environment allows achievement of decarbonization targets in the power sector to be completed even faster than in the current national-level projections.

"***A Fragmented World***": Transition pathways developed under this narrative build on a potential evolution of the future in which the energy crisis is persistent and thus individuals are characterized by distrust and skepticism and are mainly concerned about their energy security rather than combating the climate crisis.

As such, citizens are supportive of the governmental decisions to cut down capital expenditures on the energy transition and base the national energy planning on the existing fossil fuel infrastructure that may utilize either the imported natural gas at an increasing rate (*gas-dependent planning*), or the domestic lignite at an increasing rate and the imported natural gas at a decreasing rate (*lignite-dependent planning*), not caring about the climate change's repercussions.

In this context, they become *prosumers only in reaction to peer pressure or out of economic necessity and at a slower rate* compared to the "*Familiar World*" narrative. Overall, citizens' worsening economic situation due to the continuous rise of energy costs does not favor the spread of prosumerism.

"Future-world" scenario specifications

The people-centered scenarios are examined under different systemic externalities, which are captured by specific contextual factors, i.e., rooftop solar PV adoption rate by citizens, natural gas and electricity import prices, emissions penalties, and interconnectedness with neighboring countries.

A large increase in both demand and supply of PV panels is expected in the coming years- a continuation of the current trend. Solar PV installations have the potential to be widely embraced by citizens and thus become among the most socially acceptable technologies for generation of electricity.

The state and other public institutions play a significant role as forerunners in terms of further promoting positive attitude of citizens toward RES. We assume different trends for rooftop solar PV adoption for each "*future-world*" narrative between 2030 and 2050 (**Figure 25**).

Specifically, the "*Unified World*" narrative has the fastest adoption rate (logarithmic trend), while the "*Fragmented World*" narrative has the slowest rate (exponential trend).

The "*Familiar World*" narrative follows an intermediate adoption rate combining the trends of the other two narratives, depicted by a S-curve.

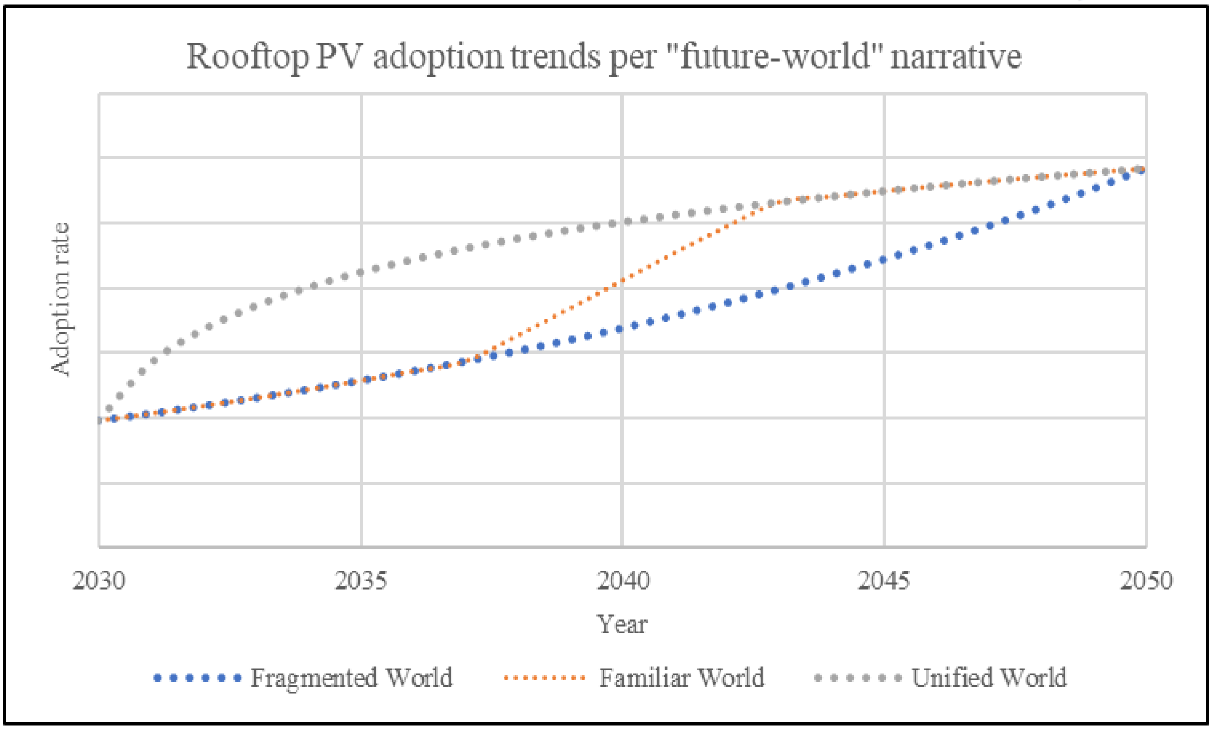


Figure 25. Rooftop solar PV adoption trends for the different “future-world” narratives between 2030 and 2050.

In the aftermath of their dramatic rise from 2021-2022, energy prices have now become a contentious political matter.

Energy prices affect the relative cost of RES-produced electricity which is generally expected to decrease in comparison to the electricity produced from fossil fuels. Natural gas price projections for the “*Familiar World*” narrative are derived from the NECP (**Table 9**).

Estimations for the “*Unified World*” consider national trends for the import price of natural gas before the 2022 energy crisis, while the projections for the “*Fragmented World*” follow national trends for the import price of natural gas during the 2022 energy crisis (Regulatory Authority of Energy, 2024).

Table 9. Natural gas price projections for the different “future-world” narratives in 2030 and 2050.

Projected natural gas prices (€/MWh)		
Year	2030	2050
“*Familiar World*”	38	40
“*Unified World*”	27	28
“*Fragmented World*”	158	164

Electricity import price baseline values for the neighboring countries under the “*Familiar World*” narrative are retrieved from ENTSO-e (2024).

Estimations for the “*Unified World*” consider electricity import price baseline values for the neighboring countries similar to those before the 2022 energy crisis, while the projections for the “*Fragmented World*” consider electricity import price baseline values for the neighboring countries similar to those during the 2022 energy crisis.

The trend used for projections until 2050 is derived from EU reference scenario 2020 (European Commission, 2020).

Emission Trading System (ETS) CO_2 emission allowance price projections for the “*Familiar World*” narrative are derived from NECP (**Table 10**).

Estimations for the "*Unified World*" consider global trends for economies with net zero emissions pledges, while the projections for the "*Fragmented World*" consider global trends for economies without net zero emissions pledges, as articulated in the World Energy Outlook 2023 (IEA, 2023b).

Table 10. Emission Trading System CO_2 emission allowance price projections for the different "future-world" narratives in 2030 and 2050.

Projected ETS CO_2 emission allowance price ($/tn$CO_2$)		
Year	2030	2050
"***Familiar World***"	80	150
"***Unified World***"	130	250
"***Fragmented World***"	50	90

The integration of the EU electricity market may have only a moderate impact on the development of energy citizenship, considering that the integration of the EU electricity market relies heavily on government actions and initiatives.

Citizens would primarily assume a more passive role in this development. Regarding interconnectedness with neighboring countries, it is assumed that in the "*Unified world*" countries become more extroverted and trade more electricity, which is reflected by a higher factor multiplied with the respective net electricity imports, while in the "*Fragmented world*" countries become more introverted and trade less electricity, i.e., a lower interconnectedness multiplier is used (**Table 11**).

Table 11. Multiplier reflecting interconnectedness with neighboring countries the different "future-world" narratives in 2030 and 2050.

Interconnectedness multiplier		
Year	2030	2050
"***Familiar World***"	1.00	1.00
"***Unified World***"	1.50	1.70
"***Fragmented World***"	0.85	0.75

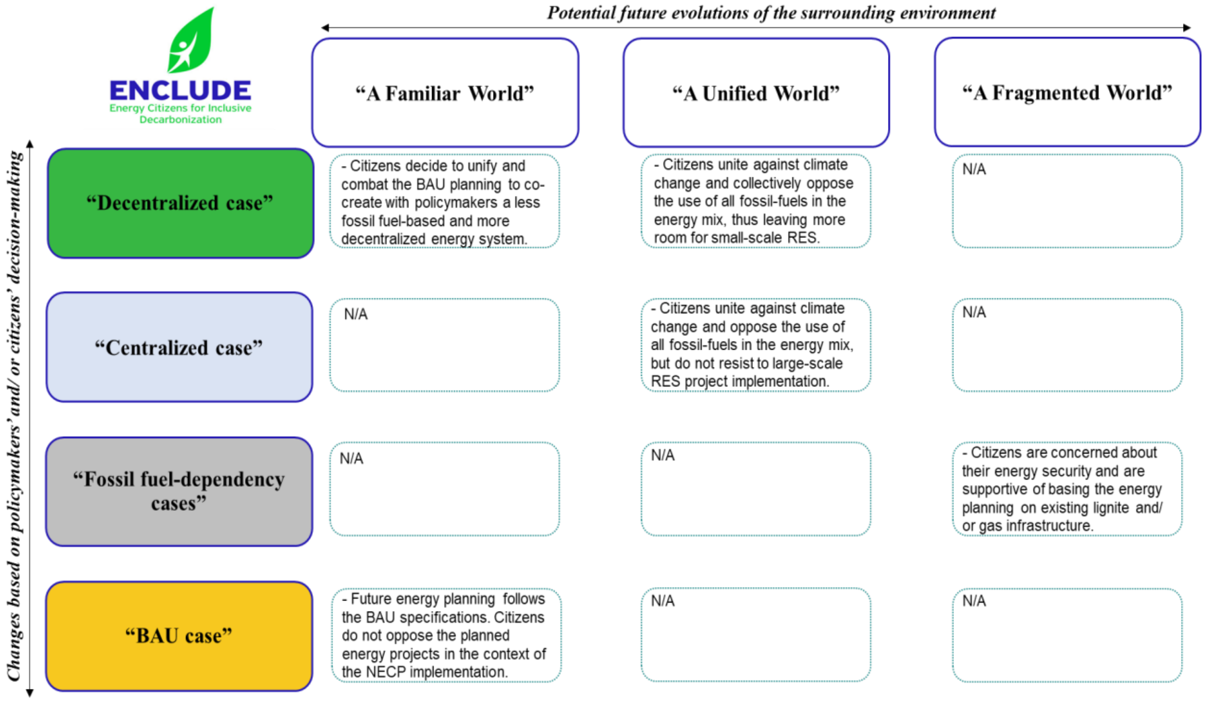
The ENCLUDE joint "*Power to the People*" and "*People to the Streets*" scenario space

Considering the specifications for both the "*people-centered*" storylines and the "*future-world*" narratives, the ENCLUDE scenario space for a joint "*Power to the People*" and "*People to the Streets*" storyline is developed and depicted in **Figure 26**.

In summary, the scenario space is split into two (2) parts:

(i). changes in the design principles of the energy system due to citizens' and/ or policymakers' decision-making based on the "*people-centered*" storylines, leading to five (5) different cases, i.e., "*BAU case*", "*Decentralized case*", "*Centralized Case*", "*Gas-dependency case*", and "*Lignite-dependency*" case, and

(ii). potential future evolutions of the surrounding environment based on three (3) "future-world" narratives, i.e., "*Familiar world*", "*Unified world*", and "*Fragmented world*". This allows us to explore a total of six (6) combinations of "*people-centered*" storylines and "*future-world*" narratives, i.e., "*BAU Familiar*", "*Decentralized Familiar*", "*Centralized Unified*", "*Decentralized Unified*", "*Gas Fragmented*", and "*Lignite Fragmented*" scenarios.



	"A Familiar World"	"A Unified World"	"A Fragmented World"
"Decentralized case"	- Citizens decide to unify and combat the BAU planning to co-create with policymakers a less fossil fuel-based and more decentralized energy system.	- Citizens unite against climate change and collectively oppose the use of all fossil-fuels in the energy mix, thus leaving more room for small-scale RES.	N/A
"Centralized case"	N/A	- Citizens unite against climate change and oppose the use of all fossil-fuels in the energy mix, but do not resist to large-scale RES project implementation.	N/A
"Fossil fuel-dependency cases"	N/A	N/A	- Citizens are concerned about their energy security and are supportive of basing the energy planning on existing lignite and/ or gas infrastructure.
"BAU case"	- Future energy planning follows the BAU specifications. Citizens do not oppose the planned energy projects in the context of the NECP implementation.	N/A	N/A

Figure 26. The ENCLUDE scenario space for a joint "Power to the People" and "People to the Streets" storyline.

6.2.3. *Decarbonizing the transport and the residential sectors in Western Europe under different "people-centered" storylines*

In the context of the IMAGE application, we focus on the transport and the residential sectors in Western Europe. For the "future-world" narratives, and the SSPs as a basis, we decided to use the SSPs as baselines for the IMAGE modeling.

Due to the complexity of the IMAGE model, we used (**Table 12**):

- SSP1 ("Sustainability- *Taking the Green Road*"), which advocates for a shift towards inclusive development and environmental stewardship, for the "*Unified World*" narrative,
- SSP2 ("*Middle of the Road*"), in which the world adheres to historical patterns with slow progress towards sustainability amidst persistent environmental degradation and moderate population growth, for the "*Familiar World*", and
- SSP4 ("*Inequality- A Road Divided*"), which highlights escalating disparities in human capital and economic opportunity, leading to heightened social unrest amidst rapid technological advancements, for the "*Fragmented World*".

This provides context from the "*future-world*" narratives (i.e., by using the SSPs as baselines), while focusing on the different patterns and trends of energy citizenship as have already been categorized under the "*people-centered*" storylines.

The behavioral actions of the "*people-centered*" storylines (**Table 2**), are narrowed down to the modellable actions in the transport and the residential sectors, and in the modeling parameters and implementation in IMAGE is described below (see summary in **Table 13**).

Table 12. The ENCLUDE "*future-world*" narratives as represented in the IMAGE modeling framework.

"Future-world" narratives	**Baseline SSP**	**Description**
"*Unified World*"	SSP1 "Sustainability - Taking the Green Road"	"*The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects predicted environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity*" (Riahi et al., 2017).
"*Familiar World*"	SSP2 "Middle of the Road"	"*The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceed unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall, the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain*" (Riahi et al., 2017).
"*Fragmented World"*	SSP4 "Inequality- A Road Divided"	"*Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Overtime, a gap widens between an internationally connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle- and high-income areas*" (Riahi et al., 2017).

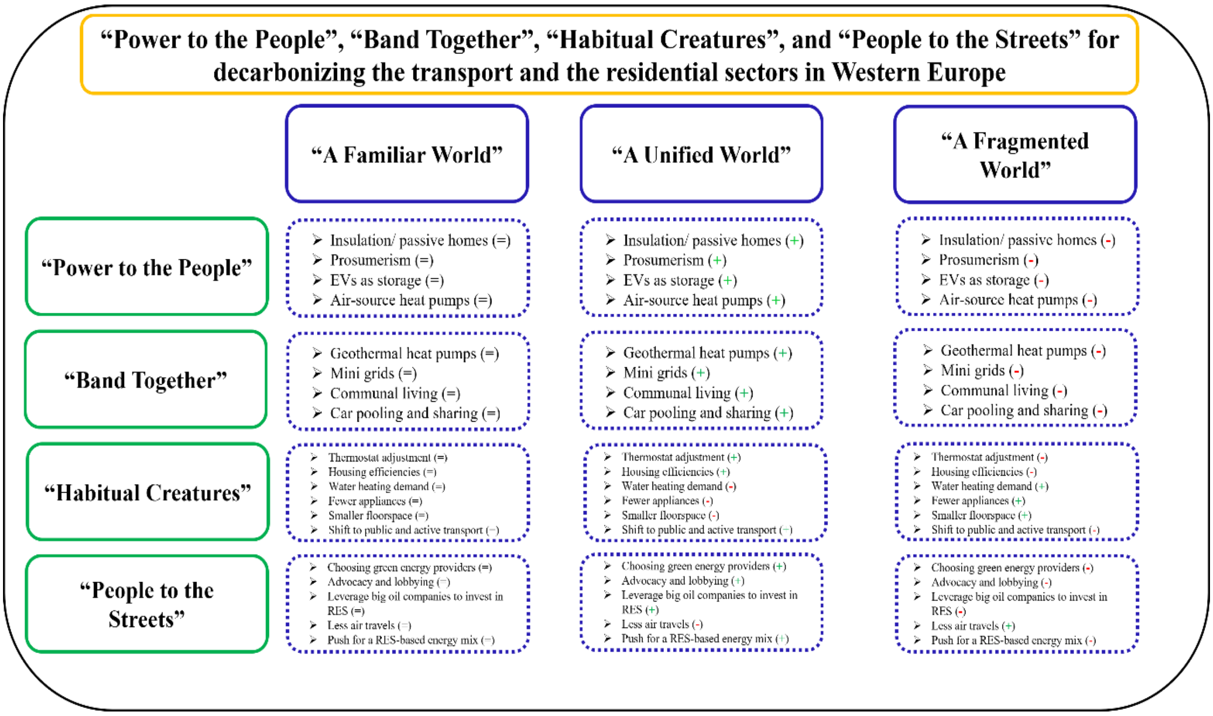
The behavioral actions for the "people-centered" storylines shown in **Table 13**, are a selection of the behavioral actions from **Table 2**, which were chosen to model in IMAGE based on the availability of variables and parameters in the TIMER-IMAGE sub-model. In particular:

- For the "*Power to the People*" storyline:
  - Insulation and passive homes are implemented by increasing the aggregate insulation levels via premium factors, in addition to increasing the capital turnover rates.
  - Furthermore, small-scale PV systems, representing prosumers, are implemented through higher architectural functional rooftop areas in IMAGE.

  - To represent using EVs as storage, we show the impact in transport emission reductions, by adjusting the additional technology costs, and, specifically, by assuming an optimistic cost development for EVs with close to 100% EV adoption by 2050.
  - Lastly, using an air-source heat pump for heating and cooling is represented by adjusting a heat pump premium in IMAGE to facilitate adoption of 50% by 2050.
- For the "*Habitual Creatures*" storyline:
  - Thermostat adjustment is modeled through a correction factor for Heating Degree Days (HDD) and Cooling Degree Days (CDD) with an adjustment of 2°C by 2050 with a gradual transition.
  - For housing efficiencies, a 'standby' factor is turned on to reduce energy use for various appliances. Assumptions for shorter showers are implemented by reducing the water heating demand by 25% by 2050 with a gradual transition.
  - For fewer appliances, ownership of clothing dryers was adjusted by reducing 40% by 2050 gradually.
  - For a smaller living space, we added a cap to the floorspace per capita of 36m^2 for urban and 38m^2 for rural areas by 2050.
  - For travel related measures, a shift to public transit and active travel was implemented by adjusting mode preferences towards bus, train, cycling, and walking away from cars and air travel.
- For the "*Band Together*" storyline:
  - Communal technologies are key themes. We model heat pumps, but instead of individual and air-sourced these are geothermal and collective installations for neighborhoods or communities. We apply a premium to encourage the heat pump adoption rates in IMAGE to reach a 50% adoption by 2050.
  - In this scenario, prosumerism would be more collective, and mini grids would be adopted by a neighborhood or community, optimizing energy production and consumption within. This is modelled in IMAGE as an increase in functional rooftop area.
  - For community living, such as shared gyms, laundry and dining areas would lead to less private floor space, and therefore lower floor space per capita. Therefore, we introduce a cap on the floor space per capita, with a gradual transition to a max of 36m^2 for urban areas and 43m^2 for rural areas by 2050.
  - Communal daily travel would also be relevant for this narrative. Carpooling, with multiple passengers' ride sharing, is implemented in IMAGE as a correction factor for passenger-kilometers, with 3% less in car travel. Car sharing in contrast, is mostly represented as an indirect effect on a shift to non-car modes, and less car ownership. Other impacts of this measure would be in the lower production of cars.
  - However, IMAGE focuses on the energy demand of driving cars and not the production. Therefore, this measure would in fact have a higher energy reduction than shown in this research.
- Lastly, for the "*People to the Streets*" storyline:
  - Various themes and actions around different influences on government and companies through activism, lobbying or lawsuits, are modeled through higher shares of renewable energy.

- Therefore, the assumptions from a “LowElec” scenario are taken, which include a multiplied capital floor cost of other technologies and learning rate, an additional premium factor for capital investments in electricity and a push for hydrogen usage.

Considering specifications of all the four (4) “*people-centered*” storylines and the potential evolutions of the “*future-world*” narratives, the ENCLUDE scenario space for exploring the impact of different manifestations of energy citizenship in decarbonization efforts in the Western Europe by 2050 is specified (**Figure 27**).



“Power to the People”, “Band Together”, “Habitual Creatures”, and “People to the Streets” for decarbonizing the transport and the residential sectors in Western Europe

	“A Familiar World”	**“A Unified World”**	**“A Fragmented World”**
“Power to the People”	➢ Insulation/ passive homes (=) ➢ Prosumerism (=) ➢ EVs as storage (=) ➢ Air-source heat pumps (=)	➢ Insulation/ passive homes (+) ➢ Prosumerism (+) ➢ EVs as storage (+) ➢ Air-source heat pumps (+)	➢ Insulation/ passive homes (-) ➢ Prosumerism (-) ➢ EVs as storage (-) ➢ Air-source heat pumps (-)
“Band Together”	➢ Geothermal heat pumps (=) ➢ Mini grids (=) ➢ Communal living (=) ➢ Car pooling and sharing (=)	➢ Geothermal heat pumps (+) ➢ Mini grids (+) ➢ Communal living (+) ➢ Car pooling and sharing (+)	➢ Geothermal heat pumps (-) ➢ Mini grids (-) ➢ Communal living (-) ➢ Car pooling and sharing (-)
“Habitual Creatures”	➢ Thermostat adjustment (=) ➢ Housing efficiencies (=) ➢ Water heating demand (=) ➢ Fewer appliances (=) ➢ Smaller floorspace (=) ➢ Shift to public and active transport (=)	➢ Thermostat adjustment (+) ➢ Housing efficiencies (+) ➢ Water heating demand (-) ➢ Fewer appliances (-) ➢ Smaller floorspace (-) ➢ Shift to public and active transport (+)	➢ Thermostat adjustment (-) ➢ Housing efficiencies (-) ➢ Water heating demand (+) ➢ Fewer appliances (+) ➢ Smaller floorspace (+) ➢ Shift to public and active transport (-)
“People to the Streets”	➢ Choosing green energy providers (=) ➢ Advocacy and lobbying (=) ➢ Leverage big oil companies to invest in RES (=) ➢ Less air travels (=) ➢ Push for a RES-based energy mix (=)	➢ Choosing green energy providers (+) ➢ Advocacy and lobbying (+) ➢ Leverage big oil companies to invest in RES (+) ➢ Less air travels (-) ➢ Push for a RES-based energy mix (+)	➢ Choosing green energy providers (-) ➢ Advocacy and lobbying (-) ➢ Leverage big oil companies to invest in RES (-) ➢ Less air travels (+) ➢ Push for a RES-based energy mix (-)

Figure 27. The ENCLUDE scenario space for all the ENCLUDE “people-centered” storylines towards decarbonization in Western Europe’s transport and residential sectors.

Table 13. Modeling parameters and implementation of the “people-centered” storylines for modeling in the IMAGE modeling framework.

“People-centered” storylines	***Themes***	***Behavioral actions***	***Model parameter***	***Model implementation***
“*Power to the People*”	Renovation and building	Insulation/ passive homes	Aggregate insulation level Capital turnover rates	Increase aggregate insulation level (premium factors) and capital turnover rates.
	Individual technologies	Rooftop PV	Functional rooftop area	PV roof area increase.
		EVs as storage	Additional passenger technology costs	Optimistic cost development for EVs with almost 100% adoption by 2050, with a gradual transition.
		Air-source heat pumps for heating and cooling	Heat pump premium	Adjust premium to facilitate heat pump adoption with 50% in 2050 with gradual transition.
“*Band Together*”	Communal technologies	Geothermal heat pumps for heating and cooling	Heat pump premium	Adjust premium to facilitate heat pump adoption with 50% in 2050 with gradual transition.
		Mini grids	Functional rooftop area	Increased area for rooftop PV potential.
	Communal living	Communal gym	Cap on floorspace per capita	Max 36 m^2 for urban areas and 43 m^2 for rural areas per capita with a gradual transition.
		Communal laundry		
		Communal dining		
	Communal daily travel	Car pooling	Correction factor passenger-kilometers	Adjusted passenger-kilometers with 3% less in car travel.
		Car sharing	Mode preferences	Shift to non-car modes because of higher cost per use.
“*Habitual Creatures*”	Incremental adjustments	Thermostat adjustment	Correction factor for HDD and CDD	Adjusted by 2-degrees C by 2050 with gradual transition.
		Housing efficiencies: LED lamps, smart metering, standby mode ap-	Standby factor to adjust energy use for these appliances	Flag on.

		pliances, heat recovery		
		Shorter showers	Water heating demand correction factor	Reduction by 25% by 2050 with a gradual transition.
	Housing choices	Fewer appliances	Dryer ownership	Reduction of 40% by 2050 with a gradual transition.
		Smaller floorspace	Cap on floorspace per capita	Max 36 m^2 for urban areas and 43 m^2 for rural areas per capita with a gradual transition.
	Travel	Shift to public and active transport	Mode preferences	Shift from car and airplanes to bus, train, high-speed train, cycling and walking, with a gradual transition.
"*People to the Streets*"	Public awareness campaigns	Choosing green energy providers	Factors for "LowElec" scenario	Capital floor cost of other technologies multiplied. Learning rate multiplied. Additional premium factor for capacity investments in electricity. Push for hydrogen usage.
	Advocacy and lobbying	Educate government about benefits of renewable energy and relevant strategies		
	Shareholder activism	Leverage big oil companies to invest in renewable energy		
	Community lawsuits	Less air travel to and from airports		
	Protest and demonstrations	Push for a renewable-based energy mix		

7. Model applications and results

The model application section of this deliverable is a crucial point in our investigation of the decarbonization potential of energy transition pathways influenced by "*people-centered*" storylines of energy citizenship.

This section focuses on the implementation of the modeling exercises stated in previous sections, while results obtained from the ATOM, OSeMOSYS-GR, and IMAGE modeling frameworks are also presented and analyzed in detail.

7.1. Empowering prosumerism and citizen adoption of small-scale photovoltaic systems at the Member State level by 2030

In this section, we present results from the *calibration* process as well as from the *forward-looking simulations* derived from the ATOM model for the three (3) different policy cases of interest, namely, FiT, net metering, and net metering with BESS, under the three (3) distinct "*future-world*" narratives, i.e., "*Familiar World*", "*Unified World*", and "*Fragmented World*", based on the specifications set in the context of the "*Power to the People*" storyline.

In addition, we assess the *decarbonization potential* of each policy case under each narrative, considering the carbon intensity of the power sector in each Member State. The analysis is performed for the cases of Denmark, France, and Greece, providing insights into the interplay between technology adoption, policy interventions, energy transition dynamics, and decarbonization targets, within diverse geographical, climatic, and socioeconomic contexts.

7.1.1. Calibration of ATOM based on historical data and past observations

In the context of the ENCLUDE WP5, ATOM's original geographical scope has been expanded to enable the simulation of small-scale solar PV adoption in the residential sectors of two (2) additional Member States, i.e., Denmark and France, allowing for a thorough comparison of the socioeconomic and regulatory factors that impact country-level adoption and diffusion patterns.

ATOM is calibrated using historical adoption and technoeconomic data stemming from the solar rooftop PV market of each Member State. Such historical data include past additions of solar PV (under or equal to 10 kW_p)[19] installed capacity, past installation costs of Building Applied Photovoltaics (BAPVs) and Building Integrated Photovoltaics (BIPVs), historical evolution of BESS capital costs, historical evolution of electricity prices that households are called to pay (including other regulated charges and taxes), and historical evolution of the fixed prices that prosumers are remunerated upon for the electricity they provide to the grid.

Through calibration, we define the final value ranges of the agent-related parameters to conduct the forward-looking simulations for the expected small-scale PV capacity additions by 2030. In addition, the "sensitivity analysis" module of the model is utilized to identify the agent-related parameters that mainly affect the model's outcomes, in terms of introducing uncertainty to the results.

Denmark

Historical adoption and technoeconomic data used for the calibration of ATOM in the case of Denmark are presented in **Figure 28**.

It is found that the cumulative capacity of small-scale solar PV systems in the Danish residential sector increased from 39 MW in 2012 to 526 MW by 2018 (IEA, 2018), with the most small-scale solar PV

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[19] Most common installations for residential buildings have an installed capacity of under or equal to 10 kW_p, while installations over 10 kW_p are usually characterized as "*commercial-scaled*" (or "*utility-scaled*" for installations over 1 MW_p).

capacity additions achieved from 2012 to 2015, when the largest values of fixed price for remuneration of prosumers was in effect.

In 2018, capital costs of residential solar PV installations had an average price of 1,075 €/kW$_p$ (IEA, 2018), while according to market research, costs of BESS for solar PV installations ranged from 478 €/kWh in 2012 to 430 €/kWh in 2018. At the time of writing this report, the price of BESS in Denmark is around 408 €/kWh (Farnell, 2024).

Finally, when it comes to the evolution of the household electricity price in Denmark, the tariff that households were called to pay, ranged from 0.2972 €/kWh in 2012 to 0.3123 €/kWh in 2018 (Country Economy, 2024a).

The fixed price that prosumers were able to choose to be remunerated (it is noteworthy that Denmark mainly promotes the adoption of small-scale solar PV systems by a net metering scheme with no remuneration for prosumers until today since the FiT policy scheme is about to be gradually abolished) spanned from around 191 €/MWh in 2012 to around 174 €/MWh by the end of 2018 (Wikberg, 2019).

According to Wikberg (2019), an annual reduction by 19 €/MWh in the fixed price was introduced by the national government in the late 2018, until it will be totally abolished.

As a result, a FiT scheme with a fixed price equal to 62 €/MWh is assumed for 2024 for the forward-looking simulations that will be conducted.

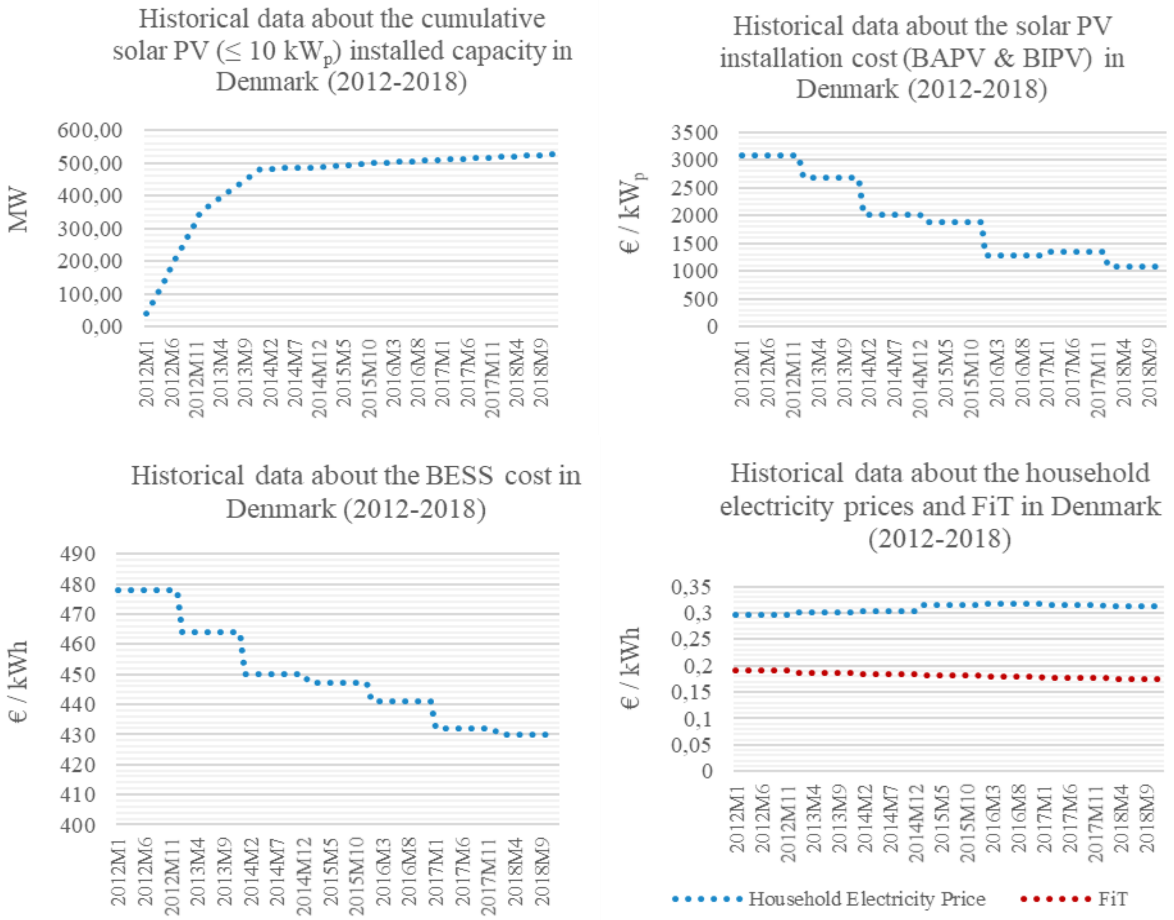


Figure 28. Historical adoption and technoeconomic data used for the calibration of ATOM in the case of Denmark for the period 2012-2018.

The results of the *sensitivity analysis* (**Figure 29**) indicate that the agent-related parameters that are responsible for the uncertainty ranges in the modeling results are the standard deviation of the expected payback period of the investment, which characterizes the scale of the "*Resistance towards PV* *investments*” agent-related parameter, and the mean value parameter of the global distribution that designates each agent’s threshold value for their resistance parameter, which shapes the “*Probability of investing*” agent-related parameter.

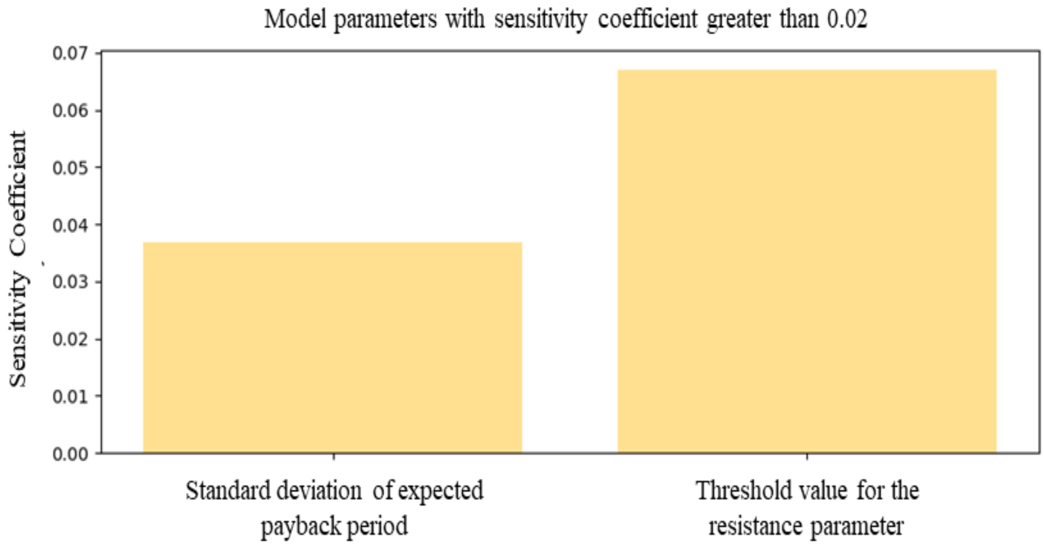


Figure 29. Sensitivity analysis results that indicate the agent-related parameters with sensitivity coefficient greater than 0.02 in the case of Denmark.

To calibrate ATOM in the case of Denmark, the historical data used span from the beginning of 2011 to the end of 2015. During that period, 499.57 MW of small-scale solar PV systems were installed in the Danish residential sector.

The reliability (*fitness*) of the calibration results is presented in **Figure 30**. While it is evident that the curve derived from the calibration results does not perfectly align with the curve representing the historical data, it is important to recognize that achieving complete alignment between the two (2) curves is unattainable, due to the mathematical background upon which the history matching process is based. In essence, this discrepancy arises due to inherent uncertainties and complexities in the modeling process, as well as the stochastic nature of the calibration algorithm.

Despite this, the reliability of the calibration results can still be assessed by evaluating the consistency and convergence of the two (2) curves across multiple runs of the calibration module. When the distance between the curves remains minimal over numerous iterations, it indicates a robust calibration process and boosts confidence to the reliability of the results. Therefore, while perfect alignment may not be feasible, the convergence of the curves serves as a validation criterion, affirming the reliability of the calibrated model outputs within an acceptable margin of error.

In the case of Denmark, it is apparent that the “*minimal*” distance between the past observations and the calibration results is quite “wide” after multiple iterations of the calibration module, hence, bigger guardedness about the reliability of the forward-looking simulations is recommended (compared to the case of France as it will be presented in the next subsection).

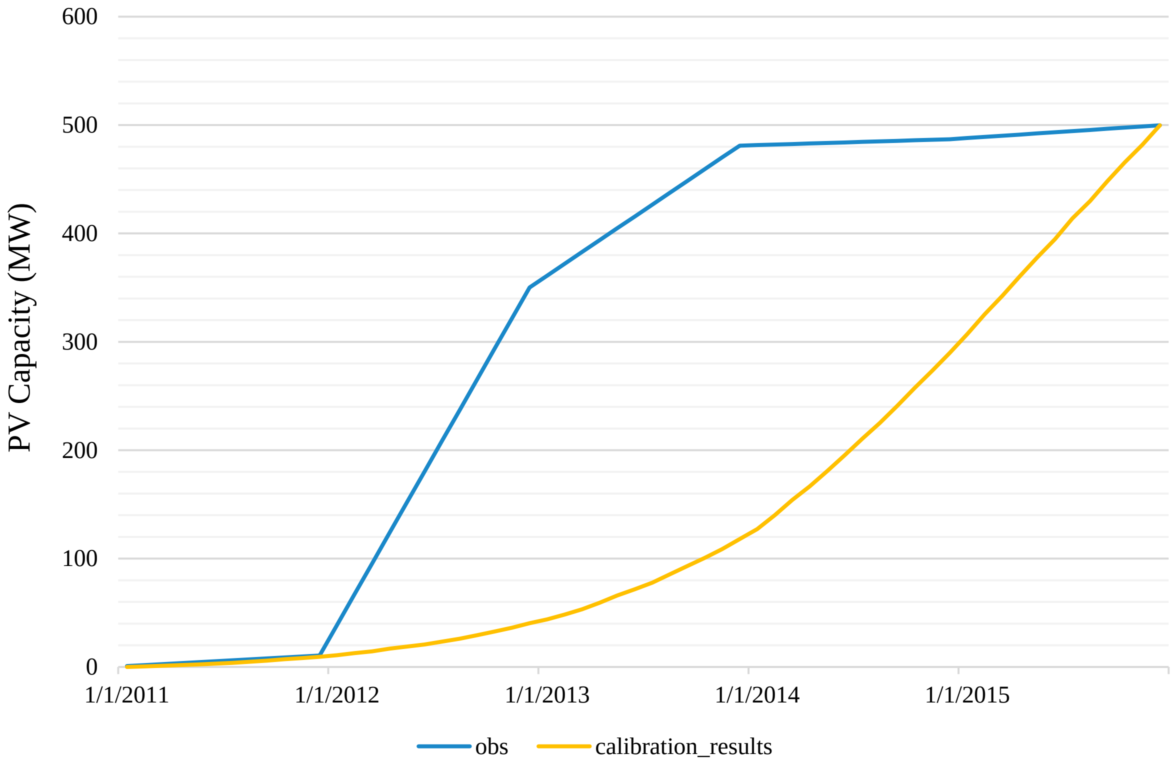


Figure 30. Optimal calibration results after several fitting iterations of the ATOM model (i.e., "calibration_results") against the historical data (i.e., "obs") of small-scale solar PV adoption during the period 2011-2015 in Denmark.

Finally, the calibration process ends with the determination of the *final value ranges* for the *agent-related parameters*, as presented in **Table 14**. These value ranges encapsulate the calibrated parameters that govern the behavior and decision-making process of the agents within the modeling framework of ATOM.

Table 14. Final value ranges of the agent-related parameters in the case of Denmark after the calibration process.

Agent-related parameter	Description	Min	Max
Beliefs	Global distribution's shape parameter that designates the agents' mean value.	56	68
	Global distribution's shape parameter that designates the agents' standard deviation.	15	25
Social learning	Global distribution's scale parameter that designates the agents' mean value.	39	45
	Global distribution's scale parameter that designates the agents' standard deviation.	3	8
Resistance towards PV investment	Global distribution's shape parameter that designates profitability's weight to the agents' resistance.	1.9	3.1
	Global distribution's scale parameter that designates profitability's weight to the agents' resistance.	0.2	0.9
	Global distribution's shape parameter that designates installed base's weight to the agents' resistance.	20.7	22.6
	Global distribution's scale parameter that designates installed base's weight to the agents' resistance.	5	12
Probability of investing	Global distribution's shape parameter that designates the agents' upper limit of resistance.	29	30.5
	Global distribution's scale parameter that designates the agents' upper limit of resistance.	6	12

Inertia to invest	No change in this parameter due to the impact that it will have in the model's outcomes (kept constant).	0.01

France

In the case of France, we follow a similar method to the one used in the case of Denmark. The historical adoption and technoeconomic data, used as inputs to the model in order to proceed with the forward-looking simulations, are illustrated in **Figure 31**.

More accurately, the cumulative capacity of the small-scale solar PV systems (equal and up to 10 kW_p installed capacity) in the French residential sector spanned from 130 MW in 2013 to 1,219 MW by the end of 2022 (IEA, 2022b), achieving a steadily increasing trendline up to today with an installation cost ranging from 1,200 €/kW_p to 3,000 € /kW_p, and an average typical cost for residential installations of BAPVs and BIPVs of around 2,200 €/kW_p (IEA, 2022b).

As for the historical evolution of the BESS costs, we conducted market research in well-known battery suppliers of France, concluding in a price evolution from around 657 €/kWh in 2013 to 579 €/kWh by the end of 2022. Currently, a typical cost for a solar battery in France is estimated around 457 €/kWh (Ultimatron France, 2024).

When it comes to the electricity price (including taxes and regulated charges) that households were called to pay, the price ranged from 0.144 €/kWh at the beginning of 2013 to 0.209 €/kWh by the end of 2022 (Country Economy, 2024b), while the average FiT tariff during the same time period ranged from around 292 €/MWh in 2013 to 181.4 €/MWh by the end of 2022 for installations up to 10 kW_p.

In addition, according to Fröding & Gasne (2024) and Oriol (2018), net metering is not allowed for prosumers in France, hence, the prosumers are remunerated for the electricity they inject to the grid according to the fixed price introduced by the French government, equal to 147.4 € in 2024 (Bellini, 2024).

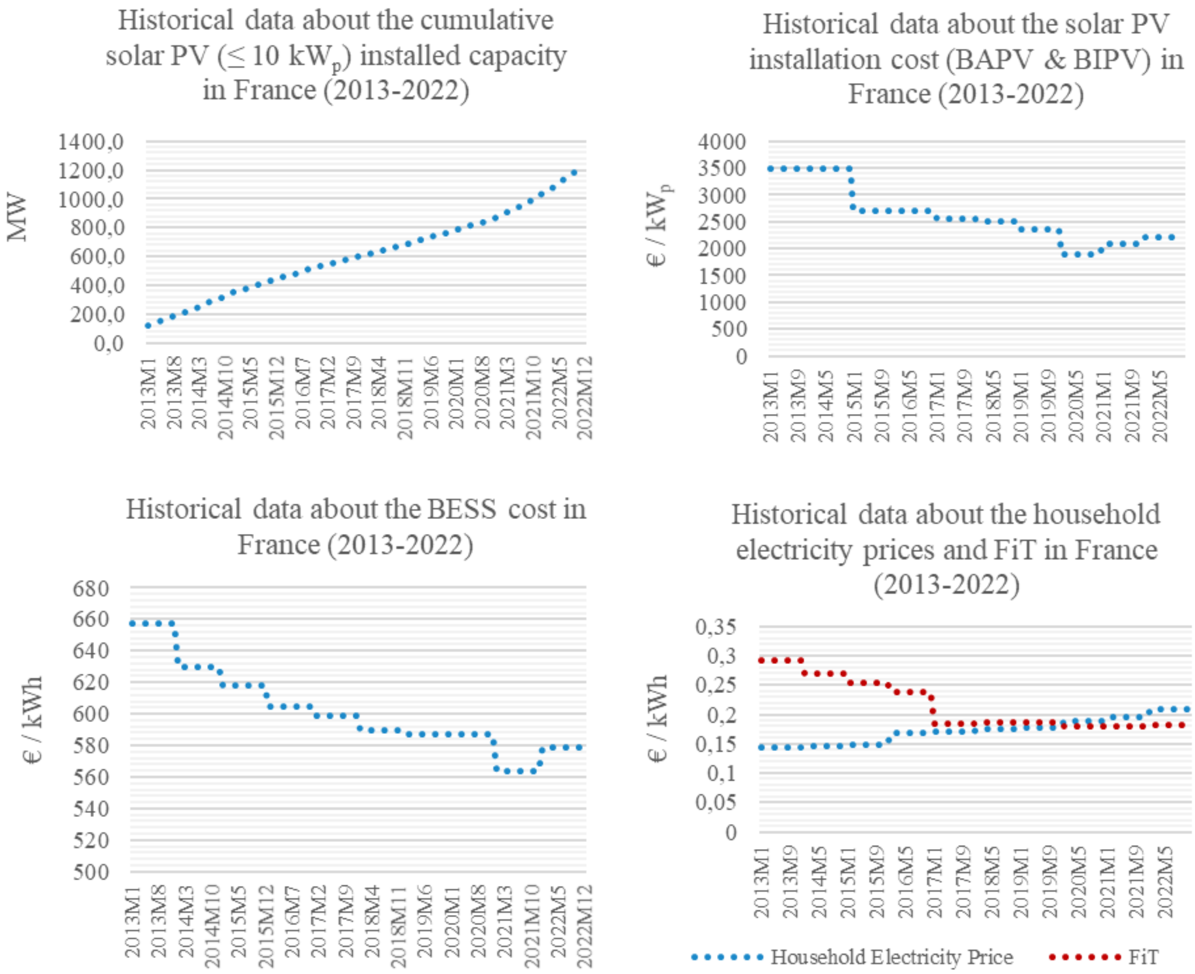


Figure 31. Historical adoption and technoeconomic data used for the calibration of ATOM in the case of France for the period 2013-2022.

The results of *sensitivity analysis* (**Figure 32**) indicate that the agent-related parameters responsible for uncertainty in the model's results are the mean value parameter of the anticipated size of the installed base, which characterizes the shape of the "*Resistance toward PV investment*" agent-related parameter, and the mean value parameter of the global distribution that designates each agent's threshold value for their resistance parameter, which characterizes the shape of the "*Probability of investing*" agent-related parameter.

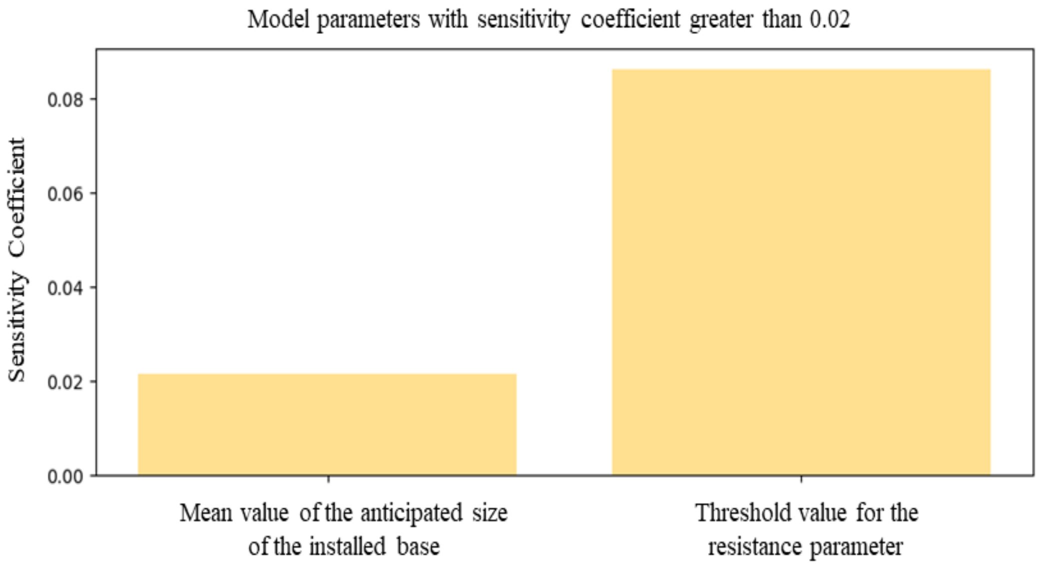


Figure 32. Sensitivity analysis results that indicate the agent-related parameters with sensitivity coefficient greater than 0.02 in the case of France.

The reliability (*fitness*) of the calibration results is depicted in **Figure 33**. Upon examination, it becomes apparent that, unlike with the case of Denmark, in the case of France, the disparity between the calibration results and past observations showcases a narrower "minimal" distance. This closer alignment indicates a higher degree of reliability in the forward-looking simulation results derived from ATOM.

Consequently, we can approach the final results with greater confidence. The latter underscores the importance of contextual nuances and data fidelity in calibration processes, emphasizing the need for careful interpretation and consideration of calibration outcomes when assessing the reliability of model predictions and informing decision-making processes.

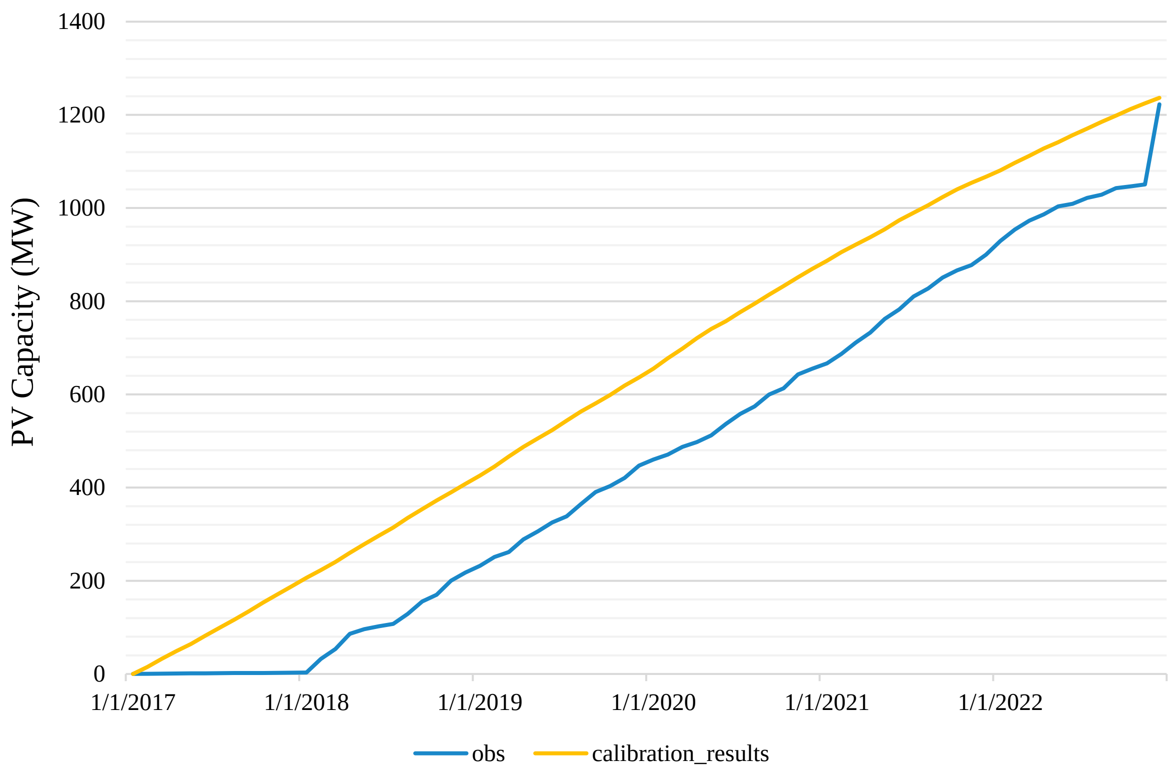


Figure 33. Optimal calibration results after several fitting iterations of the ATOM model (i.e., "calibration_results") against the historical data (i.e., "obs") of small-scale solar PV adoption during the period 2017-2022 in France.

Finally, after the calibration process, ATOM concludes by establishing the definitive *value ranges* for the *agent-related parameters* (**Table 15**). These value ranges serve as the encapsulation of the calibrated parameters, dictating the behavior and decision-making processes of the agents within the ATOM modeling framework.

Table 15. Final value ranges of the agent-related parameters in the case of France after the calibration process.

Agent-related parameter	Description	Min	Max
Beliefs	Global distribution's shape parameter that designates the agents' mean value.	130	151
	Global distribution's shape parameter that designates the agents' standard deviation.	10	30
Social learning	Global distribution's scale parameter that designates the agents' mean value.	30	50
	Global distribution's scale parameter that designates the agents' standard deviation.	1.2	5
Resistance towards PV investment	Global distribution's shape parameter that designates profitability's weight to the agents' resistance.	7.5	9.8
	Global distribution's scale parameter that designates profitability's weight to the agents' resistance.	4	6.8
	Global distribution's shape parameter that designates installed base's weight to the agents' resistance.	6.2	14.9
	Global distribution's scale parameter that designates installed base's weight to the agents' resistance.	6.1	20
Probability of investing	Global distribution's shape parameter that designates the agents' upper limit of resistance.	33	38.5
	Global distribution's scale parameter that designates the agents' upper limit of resistance.	10.1	20.1

Inertia to invest	No change in this parameter due to the impact that it will have in the model’s outcomes (kept constant).	0.01

Greece

Historical adoption and technoeconomic data for the calibration of ATOM in the case of Greece are illustrated in **Figure 34**.

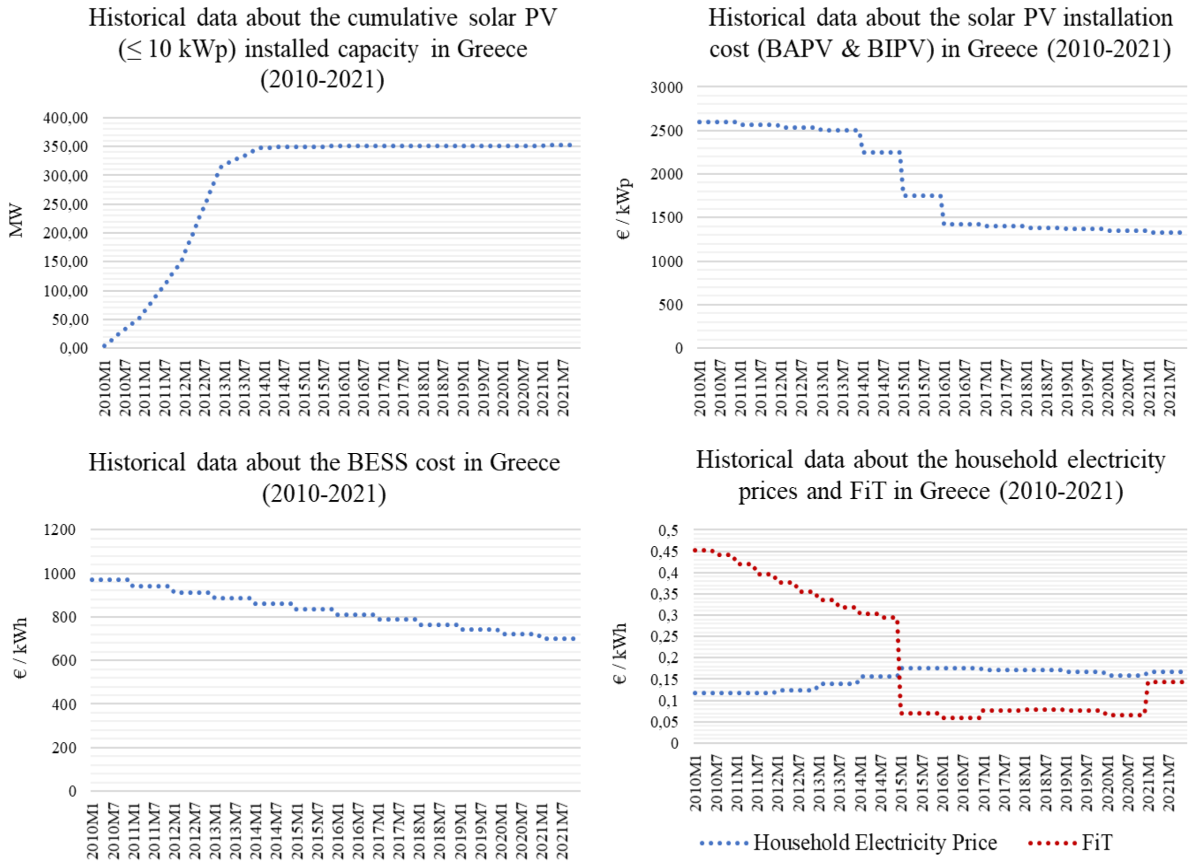
Specifically, the largest cumulative installed capacity of residential solar PVs in Greece was achieved from 2010 to 2013, when the FiT policy scheme was operational, with 348 MW installed at the end of 2013.

It is noted that the installed capacity by the end of 2021 was 352 MW (DAPEEP SA, 2022), while today (2024), according to official statistics derived from HELAPCO, the installed capacity of PV systems equal to or under 10 kW$_p$ is around 447 MW (HELAPCO, 2024). Moreover, PV installation costs from 2010 to 2021 ranged from approximately 2,600 €/kW$_p$ to 1,333 €/kW$_p$, respectively.

Furthermore, according to market research conducted in large commercial battery sellers in Greece, BESS costs from 2010 to 2021 spanned from 969 €/kWh to 700 €/kWh, which are slightly higher than the ones in the cases of Denmark and France. Today (2024), an average cost for a BESS in Greece is around 552 €/kWh.

Finally, the household electricity prices in the period of 2010-2021, ranged from 0.1181 €/kWh to 0.1674 €/kWh, respectively, while the electricity price households are currently called to pay is 0.1872 €/kWh (Country Economy, 2024c; Public Power Corporation, 2024).

During the same period (2010-2021), the available FiT spanned from 0.4469 €/kWh in 2010 (Papadelis et al., 2016) to 0.1436 €/kWh in 2021 with the historical highest of FiT been observed from 2010 to 2013, where the largest PV capacity additions were achieved.


Historical data about the cumulative solar PV (≤ 10 kWp) installed capacity in Greece (2010-2021)

Historical data about the solar PV installation cost (BAPV & BIPV) in Greece (2010-2021)

Historical data about the BESS cost in Greece (2010-2021)

Historical data about the household electricity prices and FiT in Greece (2010-2021)

Figure 34. Historical adoption and technoeconomic data used for the calibration of ATOM in the case of Greece for the period 2010-2021.

The results of the *sensitivity analysis* (**Figure 35**) for the case of Greece indicate that the agent-related parameters responsible for the uncertainty in the model's outcomes are the mean value parameter of the global distribution that assigns μ^{CF} to each agent, which characterizes the shape of the "*Beliefs*" agent-related parameter, the mean value of the anticipated investment payback period, which characterizes the shape of the "*Resistance toward PV investment*" agent-related parameter, and the mean value of the anticipated size of the installed base, which also characterizes the shape of the "*Resistance toward PV investment*" agent-related parameter.

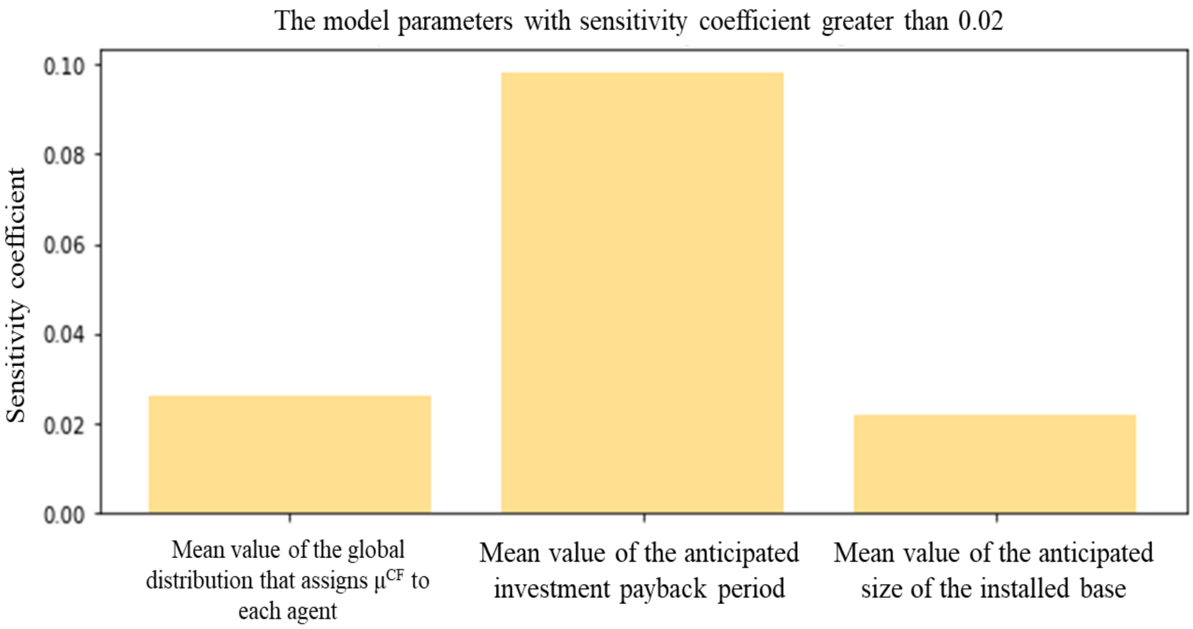


Figure 35. Sensitivity analysis results that indicate the agent-related parameters with sensitivity coefficient greater than 0.02 in the case of Greece.

The reliability (fitness) of the calibration results for the case of Greece is illustrated in **Figure 36**. Similarly to the case of France, results in the case of Greece show less disparity and as a result, calibration results showcase a narrow “minimal” distance from past observations.

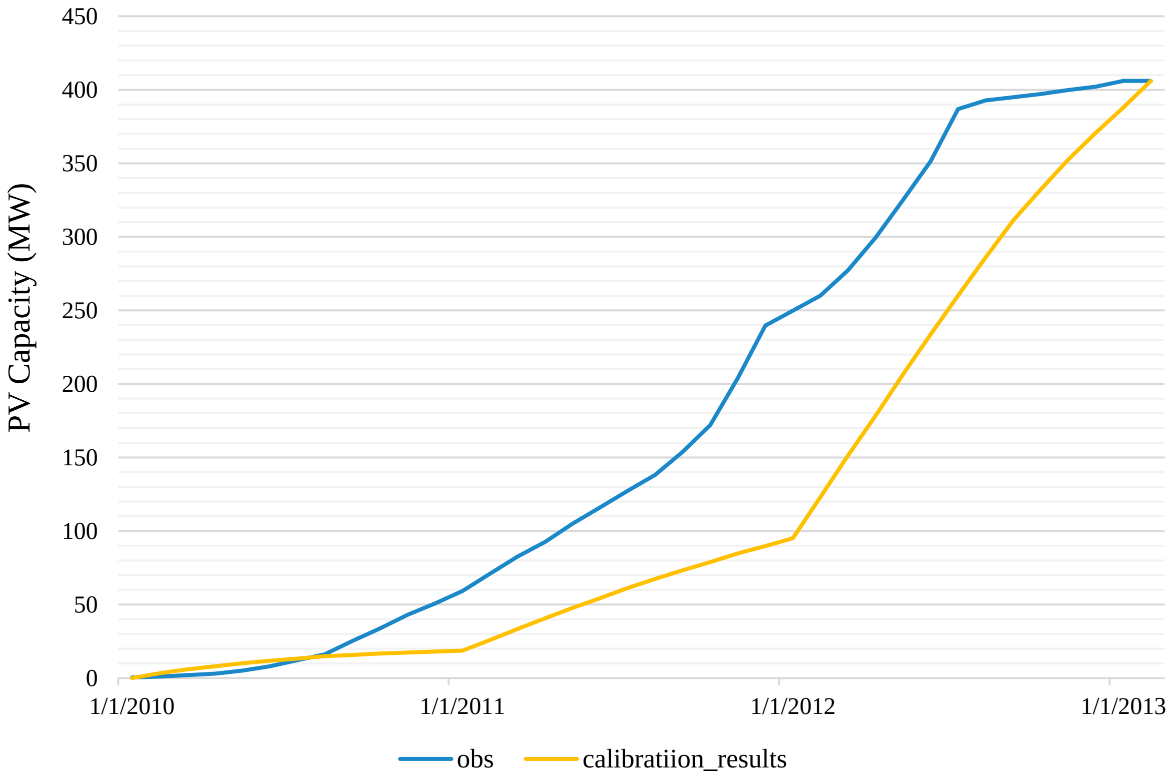


Figure 36. Optimal calibration results after several fitting iterations of the ATOM model (i.e., “calibration_results”) against the historical data (i.e., “obs”) of small-scale solar PV adoption during the period 2010-2013 in Greece.

Lastly, once again, the calibration process culminates with the definition of the final value ranges for the agent-related parameters for the case of Greece, as presented in **Table 16**. These value ranges surround the calibrated parameters that characterize the behavior and decision-making process of agents in the ATOM modeling framework.

Table 16. Final value ranges of the agent-related parameters in the case of Greece after the calibration process.

Agent-related parameter	Description	Min	Max
Beliefs	Global distribution's shape parameter that designates the agents' mean value.	114.5	122
	Global distribution's shape parameter that designates the agents' standard deviation.	1.8	19
Social learning	Global distribution's scale parameter that designates the agents' mean value.	7.2	26.5
	Global distribution's scale parameter that designates the agents' standard deviation.	0	5
Resistance towards PV investment	Global distribution's shape parameter that designates profitability's weight to the agents' resistance.	4.3	4.5
	Global distribution's scale parameter that designates profitability's weight to the agents' resistance.	1.1	1.5
	Global distribution's shape parameter that designates installed base's weight to the agents' resistance.	10	13.5
	Global distribution's scale parameter that designates installed base's weight to the agents' resistance.	1	8
Probability of investing	Global distribution's shape parameter that designates the agents' upper limit of resistance.	36.4	39.4
	Global distribution's scale parameter that designates the agents' upper limit of resistance.	1.8	7.8
Inertia to invest	No change in this parameter due to the impact that it will have in the model's outcomes (kept constant).	0.01	

7.1.2. Forward-looking simulations on citizen adoption in the European Union by 2030

In this section, we present the forward-looking simulations derived from ATOM under the "*Power to the People*" storyline, highlighting the decarbonization potential of the projected small-scale PV capacity addition trajectories. The analysis encompasses three (3) distinct policy cases: *FiT*, *net metering*, and *net metering with BESS*. Each case is evaluated within the unique geographical and socioeconomic contexts of Denmark, France, and Greece.

By examining the specific characteristics and variables relevant to each Member State, such as national household electricity prices, solar potential, and investment behaviors, we aim to provide a comprehensive understanding of how these policies can drive the adoption of small-scale solar PV systems and contribute to the respective national goals.

The outcomes will illustrate the effectiveness of each policy case in promoting renewable energy integration and reducing carbon emissions, thereby offering valuable insights for policymakers and other relevant stakeholders.

It should be noted that all simulations in each country were performed for 20 different sets of plausible values of the agent-related parameters, according to the final scenario space's value ranges, to represent 20 different, but realistic decision-making profiles, from willing to invest to risk-averse households.

In this way we are able to capture the behavioral and parametric uncertainty related to small-scale PV adoption by citizens. Uncertainty in the results is captured using error bars.

Projections for new PV capacity additions during the period 2024-2030 were scaled up at the national level using historical data and observations from the period that the previous policy schemes were operational in all three (3) countries.

Denmark

In the case of Denmark, the potential application of a FiT policy scheme (with a fixed price equal to 62 €/MWh) appears to have a greater impact on the adoption of small-scale solar PV systems in the residential sector.

This policy case prioritizes market-driven dynamics, allowing consumer decision-making to be influenced primarily by market forces (Cointe & Nadaï, 2018).

Results of the forward-looking simulations under the "*Unified World*" narrative for the three (3) different policy cases indicate estimated PV capacity additions by 2030 of around (**Figure 37**): (**i**). *FiT*: 440 MW, (**ii**). *net metering*: 274 MW, and (**iii**). *net metering with BESS*: 212 MW.

Error bars indicate that under a net metering policy scheme, uncertainty bounds are considerably lower, since the PV capacity additions of a net metering scheme span from 261 MW to 282 MW by the year 2030.

On the other hand, error bars indicate a higher uncertainty for the other two policy scenarios, since the PV capacity additions of a FiT scheme span from 415 MW to 455 MW by the year 2030, while the same results for the uncertainty of a net metering with BESS scheme range from 194 MW to 256 MW.

Forward-looking simulations demonstrate that in this "utopian" future world and under the FiT policy case, the aleatoric uncertainty gap between citizens who are willing-to-invest and those who are risk-averse is substantially reduced after mid-2028.

Moreover, it is observed that in this policy case and under this "future-world" narrative, early adoption is significantly larger, indicating the critical role of innovators in the diffusion of small-scale solar PV systems.

For the case of a net metering with BESS policy scheme, it is more probable to have risk-averse citizens since the "most probable" PV capacity additions (darker line) is closer to the lower uncertainty bound, in contrast with a net metering scheme where the darker line ("most probable") is closer to the upper uncertainty bound.

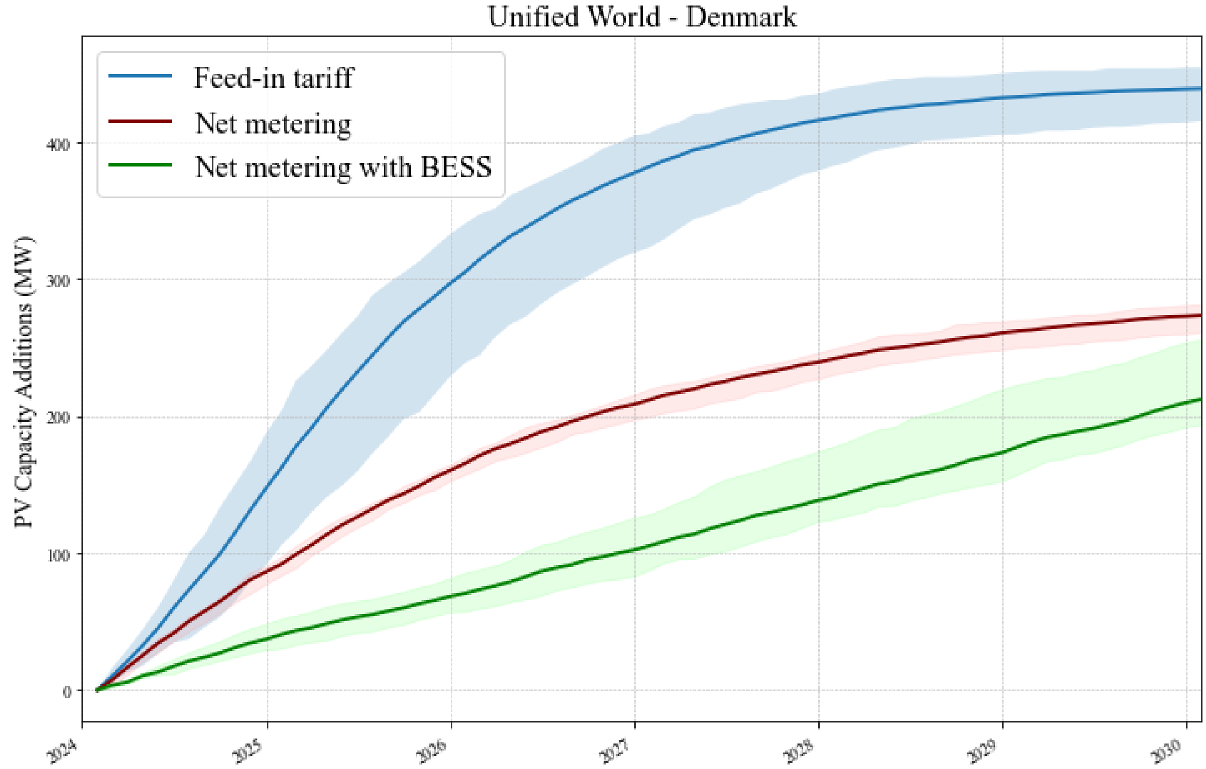


Figure 37. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Danish residential sector by 2030 for the three (3) policy cases and under the "*Unified World*" narrative. Uncertainty bounds are captured through error bars lighter colored.

Additionally, the total PV capacity additions under the "*Familiar World*" narrative for the three (3) policy cases by 2030, are estimated to be approximately (**Figure 38**): (**i**). *FiT*: 400 MW, (**ii**). *net metering*: 261 MW, and (**iii**). *net metering with BESS*: 110 MW.

It is noteworthy that even under the "*Familiar World*", the average estimated PV capacity additions for the net metering policy case is very close to the ones under the "*Unified World*" narrative.

More specifically, as abovementioned, under the "*Unified World*" narrative the estimated PV capacity additions resulting from the application of a net metering policy scheme is around 274 MW, while under the "*Familiar World*" narrative PV capacity additions are estimated to be around 261 MW.

This showcases that even under a "*utopian*" future world, citizens would have almost the same opinion about the expected profitability of the net metering scheme, which indicates that citizens feel that net metering is not able to provide them with significantly larger benefits than the ones they already have.

The case is different for the application of a net metering with BESS policy scheme, where the evolution of the future world seems to have a greater impact on the perspective of potential prosumers, since the disparity between the two "future-world" narratives for this policy case is wider.

Specifically, there is a disparity of around 100 MW between the results of these two "*future-world*" narratives.

This highlights the impact that a BESS subsidy has on the perception of the investment's profitability among citizens, since, in the "*Unified World*" narrative we assumed a 50% BESS subsidy, while under the "*Familiar World*" narrative we assumed no BESS subsidy.

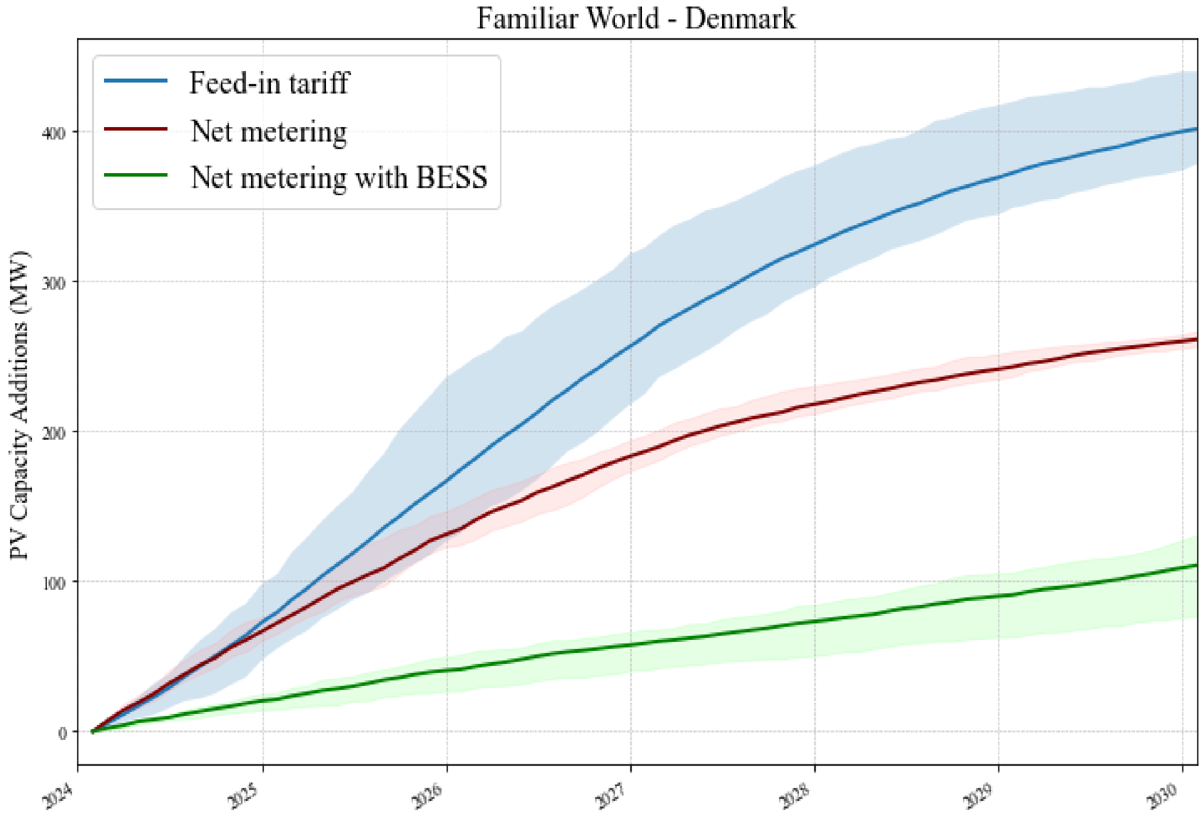


Figure 38. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Danish residential sector by 2030 for the three (3) policy cases and under the "*Familiar World*" narrative. Uncertainty bounds are captured through error bars lighter colored.

Finally, the projections for the PV capacity additions under a dystopian "Fragmented World" narrative for the three (3) different policy cases by 2030, are estimated to be approximately (**Figure 39**): (**i**). *FiT*: 120 MW, (**ii**). *net metering*: 132 MW, and (**iii**). *net metering with BESS*: 33 MW.

It is noteworthy that under a "dystopian" evolution of the future world, the application of a net metering policy scheme has a greater impact on the citizen adoption of rooftop PV systems. This showcases that citizens have a rooted perspective that the net metering policy scheme is able to provide them with greater benefits, under a "*Fragmented World*" narrative.

Moreover, results highlight that in the case of Denmark, where electricity prices are significantly high, net metering is able to provide citizens with significant economic benefits. This becomes even more apparent in the case of skyrocketing electricity prices under a "*Fragmented World*", compared to the "*Unified World*" and the "*Familiar World*" narratives, where electricity prices are considerably lower.

The latter speaks of the resilience that prosumerism and specifically a net metering scheme could have in the case of a pessimistic evolution of the future, since, at least, it could be a sustainable practice for citizens to cope with high prices.

On the other hand, under a "*Fragmented World*" narrative, the application of a FiT policy scheme is characterized by large uncertainty bounds (especially after 2027), since in a potential "dystopian" world evolution, where most citizens are risk-averse, PV capacity additions are estimated to be around 75 MW by 2030, while in the case of willing-to-invest citizens PV capacity additions could reach around 173 MW by 2030, which is higher than the upper bound of the net metering policy case (approximately 147 MW).

Overall, results show that under such an evolution of the future, citizens are not sufficiently motivated to invest in small-scale projects due to a lack of awareness, or confidence in their profitability, or due to their beliefs, which are not easily shifted, since under this particular version of the future, public is not as climate sensitive as in the other two (2) “future-world” narratives, or because they see governmental attention and resources primarily focused on large- and utility-scale PV systems (and generally RES projects).

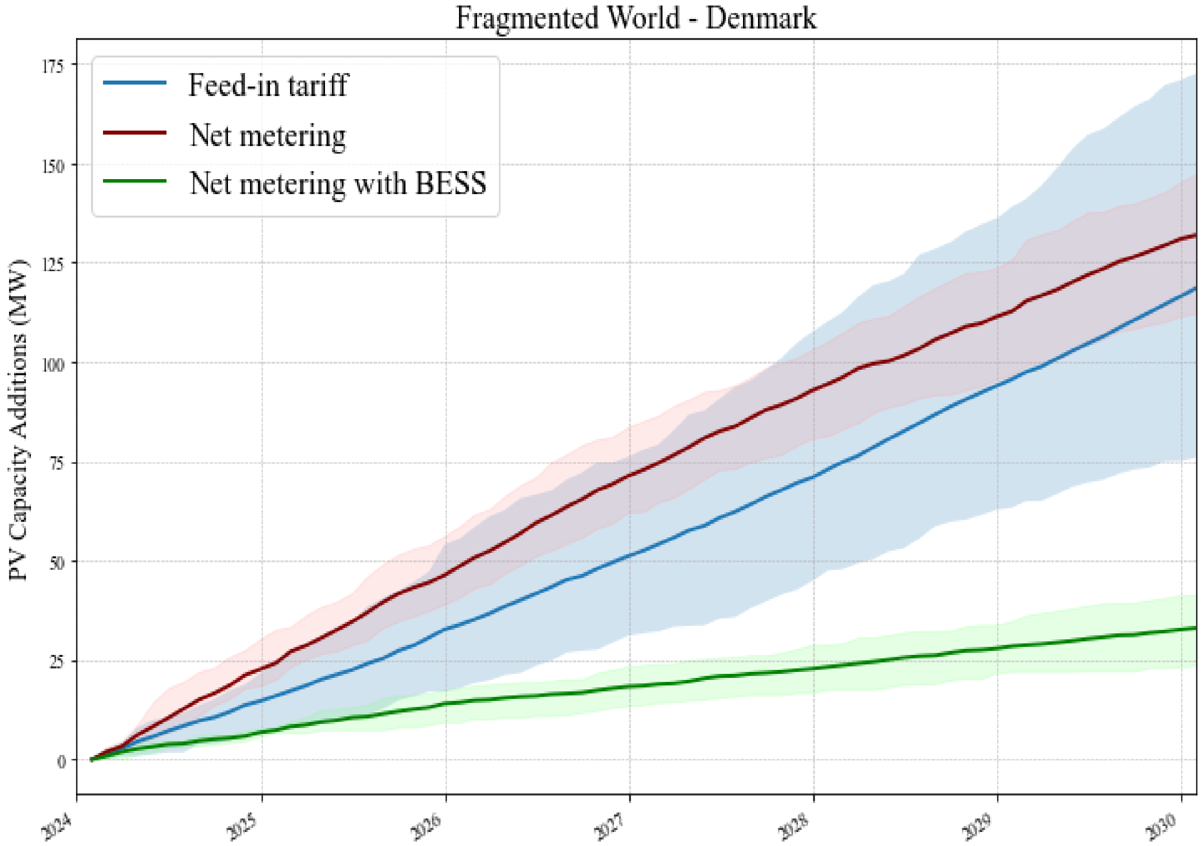


Figure 39. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Danish residential sector by 2030 for the three (3) policy cases and under the “*Fragmented World*” narrative. Uncertainty bounds are captured through error bars lighter colored.

Overall, the impact of the different “future-world” narratives on the adoption of small-scale solar PV systems in the Danish residential sector under all policy cases appears to be considerable.

More precisely, the PV capacity additions for the FiT policy case seem to be greatly affected by the different potential evolutions of the future.

This is also similar for the net metering with BESS case, where PV capacity additions are greatly affected by the potential evolution of the future world, while for this policy case, subsidies of BESS appear to have a great impact on citizens’ decision-making behavior.

On the other hand, in the case of the net metering scheme, even if there is no big difference between the “*Unified*” and “*Familiar World*” narratives, there is a large disparity between these two (2) potential future worlds evolutions and the “*Fragmented World*” narrative.

Moreover, the generally larger uncertainty bounds that characterize the decision-making process of Danish citizens, indicate that they have not a clear perception about their profitability of their investments.

However, in the case of the net metering scheme, with an hourly-based netting period, and especially in the “*Unified World*” and the “*Familiar World*” narratives, the uncertainty gap is very small. This shows that citizens have a clearer understanding of their investment’s benefits.

The latter is further strengthened when observing the same policy case in the “*Fragmented World*” narrative, where uncertainty is larger due to the different opinions among citizens. This deviation among citizens' beliefs has an impact on their "*resistance toward PV investment*" agent-related parameter.

Furthermore, when it comes to the decarbonization potential of the policy schemes under study, by taking into account specific characteristics of the Danish power sector, and more specifically, the power sector's carbon intensity (Our World In Data, 2024a), and the PV electricity generation output, we present an estimation of the carbon emissions reduction by 2030, resulting from the projected capacity additions of the small-scale PV systems in the Danish residential sector.

Under the "*Unified World*" narrative, as expected, the estimated carbon emission reduction is larger than under the other two (2) other "future-world" narratives, with FiT appearing as the policy scheme with the greatest decarbonization potential.

In particular, the decarbonization (emission reduction) potential of small-scale solar PV systems in the Danish residential sector by 2030 for the three (3) different policy cases under study in the context of the "*Unified World*" narrative is estimated to be approximately (**Figure 40**): (**i**)**.** FiT: 89,300 $tnCO_2eq.$, (**ii**)**.** net metering: 51,000 $tnCO_2eq.$, and (**iii**)**.** net metering with BESS: 35,000 $tnCO_2eq.$

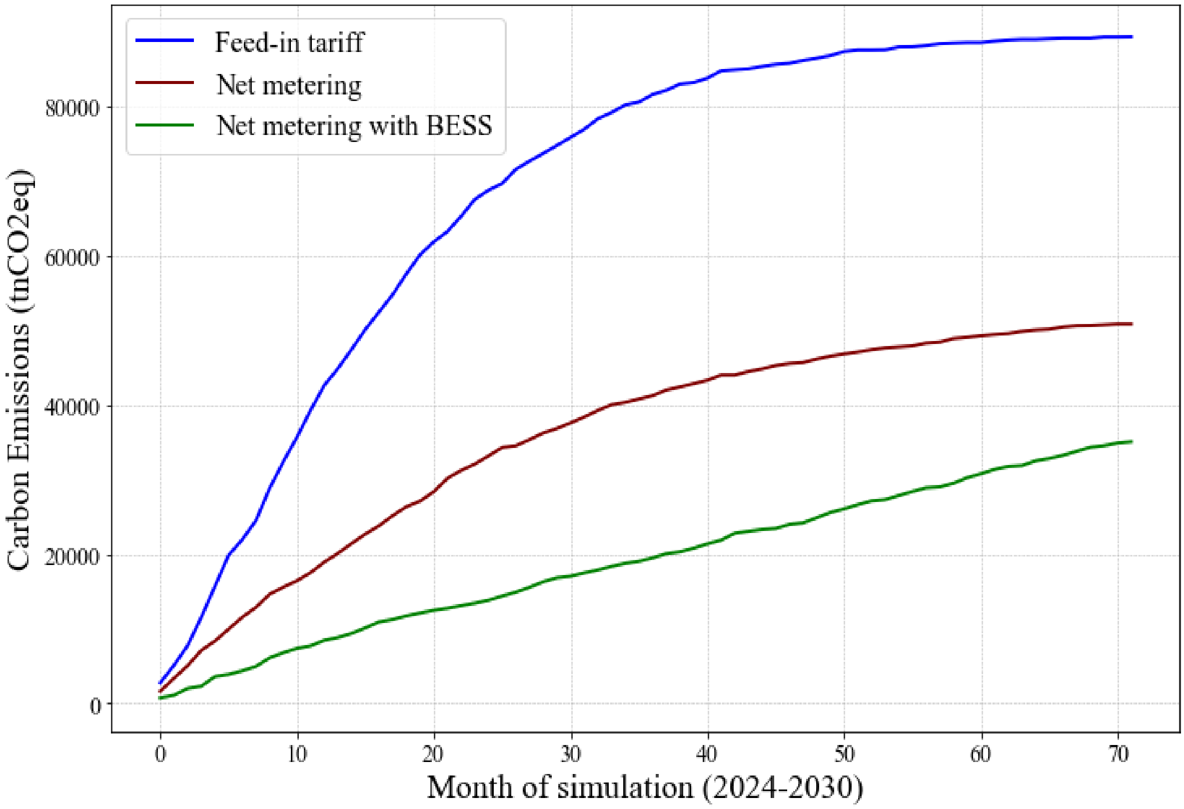


Figure 40. Estimated carbon emission reduction for the three (3) policy cases under study in the "*Unified World*" narrative, considering carbon intensity in the Danish power sector.

Furthermore, the decarbonization (emission reduction) potential of small-scale solar PV systems in the Danish residential sector by 2030 for the three (3) different policy cases under study in the context of the "*Familiar World*" narrative is estimated to be approximately (**Figure 41**): (**i**)**.** FiT: 73,500 $tnCO_2eq.$, (**ii**)**.** net metering: 48,200 $tnCO_2eq.$, and (**iii**)**.** net metering with BESS: 21,650 $tnCO_2eq.$

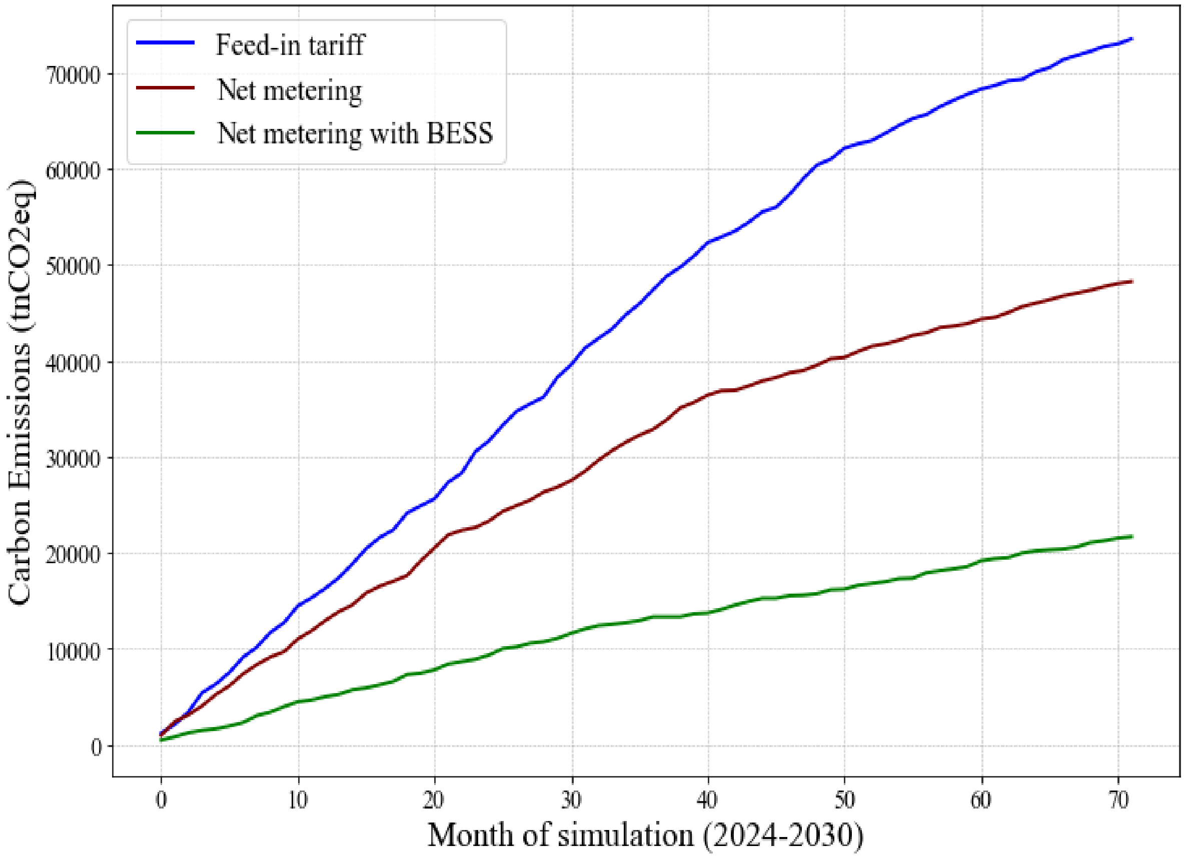


Figure 41. Estimated carbon emission reduction for the three (3) policy cases under study in the "*Familiar World*" narrative, considering carbon intensity in the Danish power sector.

Finally, expected CO_2 emission reduction under the "*Fragmented World*" narrative is less compared to the other narratives. Although the application of a net metering policy scheme under this narrative shows a greater impact on the decarbonization potential during its first years of application (until April of 2027), after this time, the application of a FiT policy scheme with a fixed remuneration of 62 €/MWh starts to have a greater impact on the decarbonization.

In particular, the decarbonization (emission reduction) potential of small-scale solar PV systems in the Danish residential sector for the three (3) policy schemes under study in the "*Fragmented World*" narrative by 2030 is estimated to be approximately (**Figure 42**): (**i**)**.** FiT: 24,000 $tnCO_2eq$., (**ii**)**.** net metering: 25,500 $tnCO_2eq$., and (**iii**)**.** net metering with BESS: 5,100 $tnCO_2eq$.

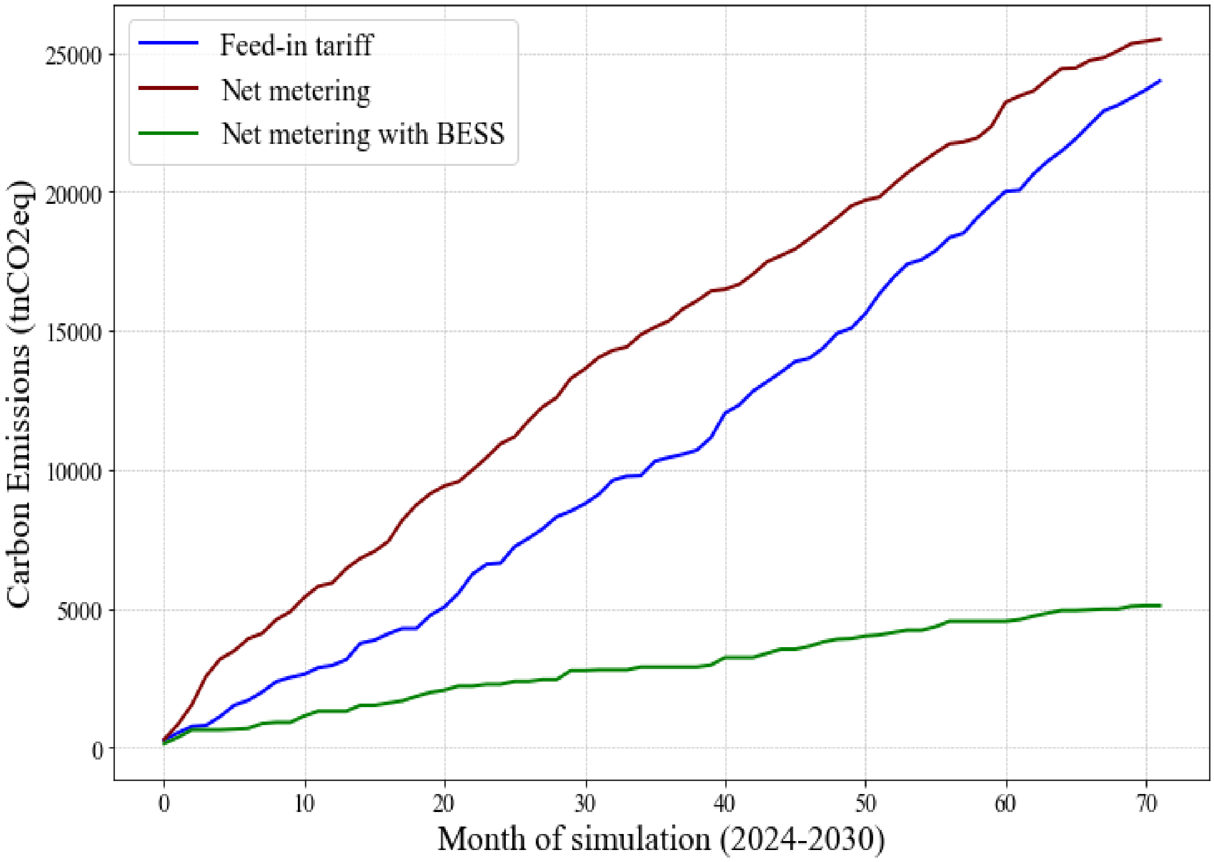


Figure 42. Estimated carbon emission reduction for the three (3) policy cases under study in the "*Fragmented World*" narrative, considering carbon intensity in the Danish power sector.

France

In the case of France, the implementation of a FiT policy scheme with a fixed price set at 147.4 €/MWh as reported by Bellini (2024), appears to exert a greater impact compared to the other two (2) policy schemes under study, i.e., net metering and net metering with BESS.

Results of the forward-looking simulations under the "*Unified World*" narrative for the three (3) different policy cases indicate estimated PV capacity additions by 2030 of around (**i**). *FiT*: 923 MW, (**ii**). *net metering*: 471 MW, and (**iii**). *net metering with BESS*: 266 MW (**Figure 43**).

Contrary to Denmark, we observe that in the case of France and under the "*Unified World*" narrative, uncertainty bounds for the FiT scheme are considerably larger, especially after mid-2025.

More specifically, the gap between the willing-to-invest and the risk-averse citizens is estimated to be around 355 MW, while the "pessimistic" (risk-averse) PV capacity additions are estimated to be approximately 773 MW by 2030, and the "optimistic" PV capacity additions by 2030 approximately 1,128 MW.

Furthermore, early adoption is also observed in the case of France under this "future-world" narrative.

However, we observe that the respective early adoption in the case of Denmark is considerably larger.

Although, the total PV capacity additions in the case of France are almost double than the ones for Denmark, which makes sense if we take into account the difference in population between the two (2) countries.

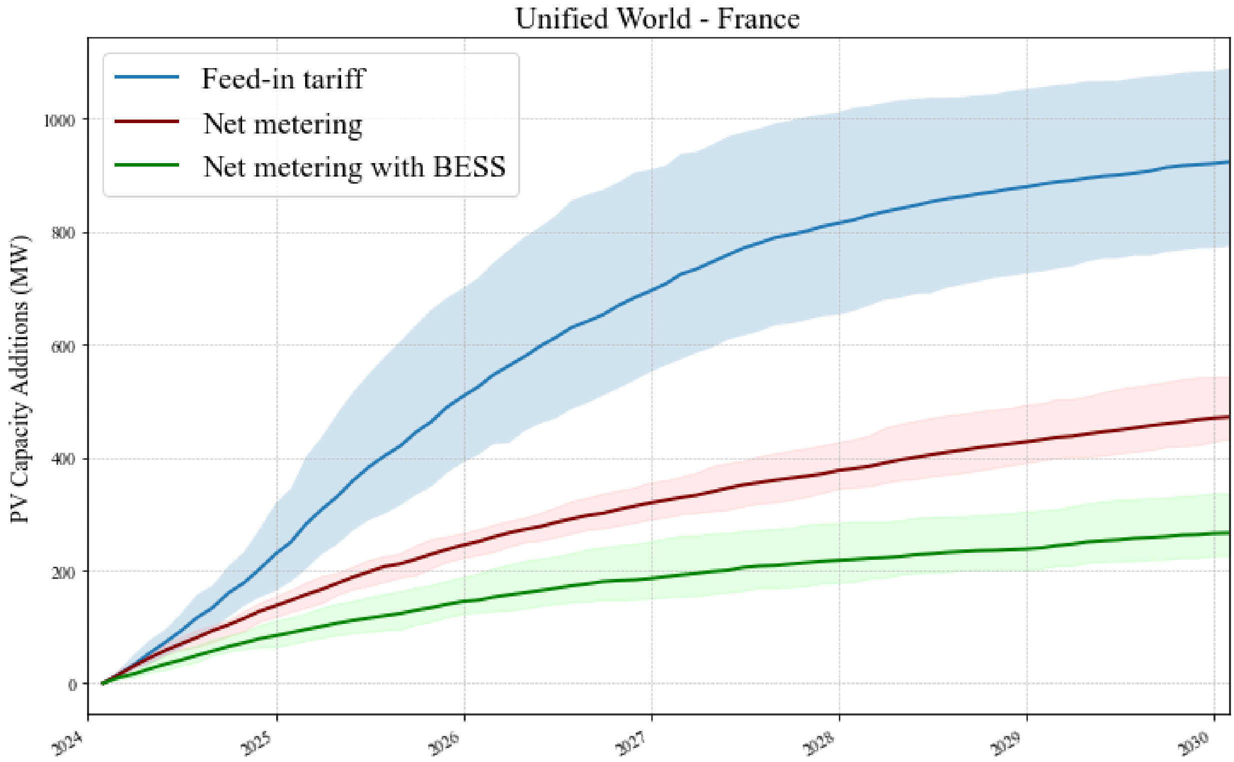


Figure 43. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the French residential sector by 2030 for the three (3) policy cases and under the "*Unified World*" narrative. Uncertainty bounds are captured through error bars lighter colored.

Additionally, the total PV capacity additions under the "*Familiar World*" narrative for the three (3) different policy cases are estimated to be approximately by 2030: **(i).** *FiT*: 671 MW, **(ii).** *net metering*: 379 MW, and **(iii).** *net metering with BESS*: 202 MW (**Figure 44**).

Once again, the FiT scheme shows the greater uncertainty, and more specifically, the estimated PV capacity additions under this case span from 599 MW to 786 MW by 2030. This indicates an uncertainty gap equal to 187 MW.

Moreover, contrary to the "*Unified World*" narrative, early adoption is not observed in the "*Familiar World*" narrative, which indicates the significantly smaller number of early adopters in a potential evolution of the future world that nothing changes and citizens are characterized by opinions and perceptions as we know them today (even if the early adoption in the case of France in a "utopian" world is less than the one observed in the case of Denmark).

It is noteworthy that a potential application of a net metering scheme under this "future-world" narrative, shows a greater impact for the first and a half year (until mid-2025), while after this time, net metering shows a smaller impact on citizen adoption.

Finally, the application of a net metering policy scheme with BESS shows less impact on the expected PV capacity additions when compared with the other two (2) cases.

This highlights once again the impact of a BESS subsidy on citizens' decision-making behavior, since we make the same assumption as in the case of Denmark (50% subsidy under the "*Unified World*" while no subsidy is assumed under the "*Familiar World*" narrative).

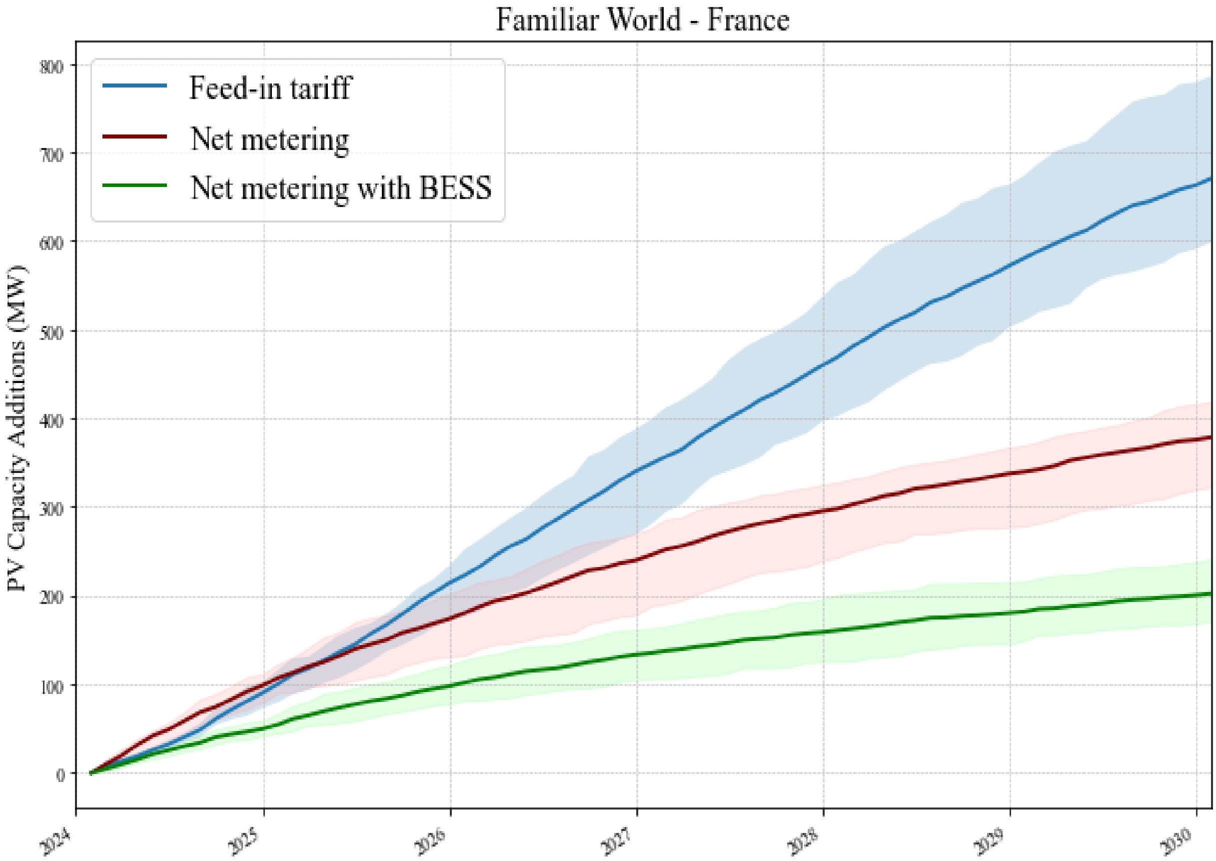


Figure 44. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the French residential sector by 2030 for the three (3) policy cases and under the "*Familiar World*" narrative. Uncertainty bounds are captured through error bars lighter colored.

Last but not least, the projections for the expected adoption of small-scale solar PVs under the "*Fragmented World*" narrative and for the three (3) different policy cases, is estimated to be around (**Figure 45**): (**i**). *FiT*: 246 MW, (**ii**). *net metering*: 184 MW, and (**iii**). *net metering with BESS*: 100 MW.

Under this dystopian evolution of the future, the application of a net metering scheme appears to have a greater impact on citizen adoption, similarly to the case of the "*Familiar World*" narrative.

However, while under the "*Familiar World*" narrative net metering shows larger PV capacity additions, under the "*Fragmented World*" narrative, net metering seems to have longer duration compared to the FiT scheme, and more specifically, until the middle of 2026. After this time, net metering drops below the FiT scheme.

Another observation is that the FiT policy case shows significantly greater uncertainty under this dystopian "future-world" narrative, contrary to the respective uncertainty under the "*Familiar World*" narrative.

In general, we observe that under a "*Fragmented World*" narrative, uncertainty gaps become larger, which makes sense in a manner that in this potential evolution of the future, electricity prices significantly increase, so more citizens get a clearer understanding of their investment's profitability and respective benefits.

Moreover, it is worth mentioning that under the "*Fragmented World*" narrative, the "pessimistic" case of PV capacity additions in the case of the FiT scheme, is considerably lower than in the "optimistic" case of the net metering scheme.

This indicates that even if it is more probable to achieve larger PV capacity additions with a FiT policy scheme, there is also a possibility to have larger PV capacity additions with a net metering scheme, if citizens are more willing to invest.

PV capacity additions in the "pessimistic" scenario in the case of the FiT scheme are approximately 175 MW, while additions in the "optimistic" scenario in the case of net metering are approximately 215 MW.

Finally, the application of a net metering policy scheme with BESS shows less impact on citizen adoption when compared with the other two (2) policy cases.

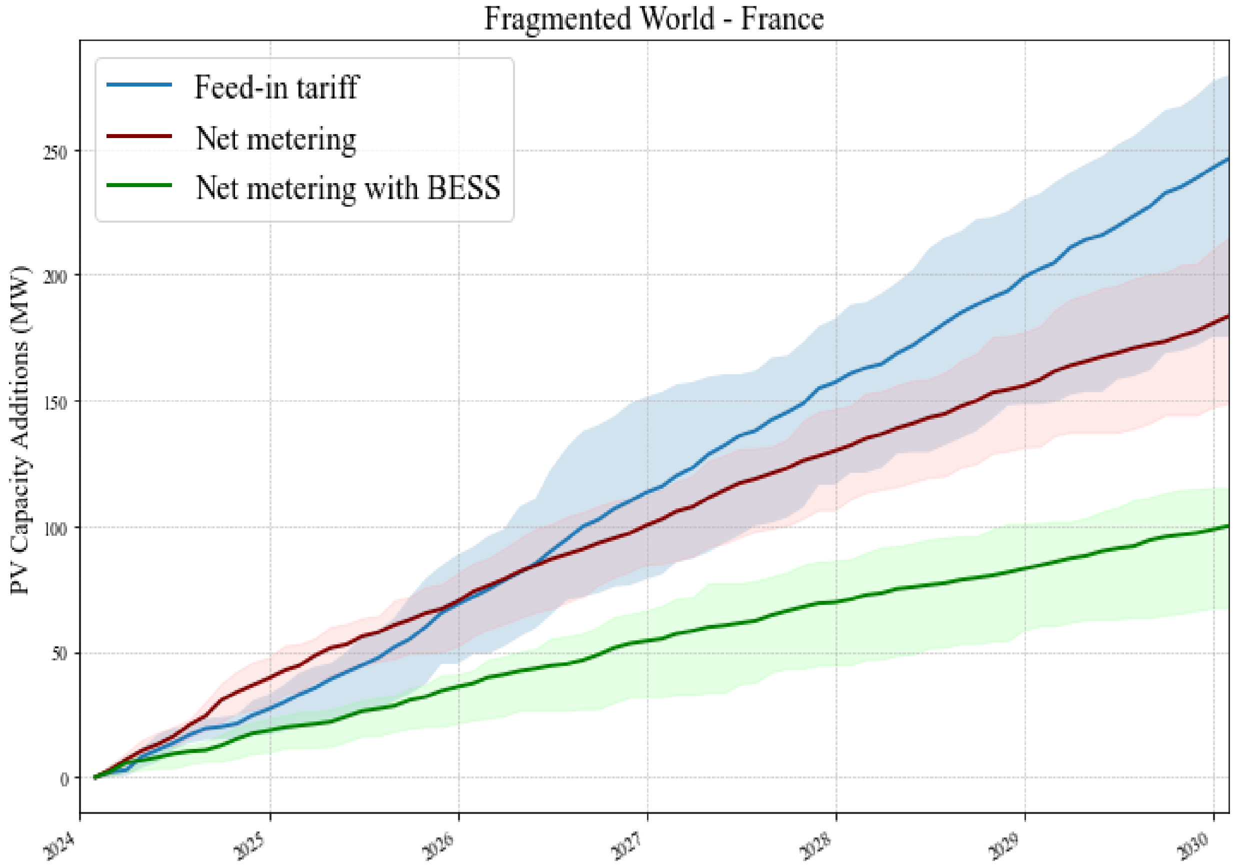


Figure 45. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the French residential sector by 2030 for the three (3) policy cases and under the "*Fragmented World*" narrative. Uncertainty bounds are captured through error bars lighter colored.

Overall, similarly to the case of Denmark, larger uncertainty gaps observed in the case of France, highlight that there is no clear perception about the profitability of investing in rooftop PV systems among French citizens.

As we mentioned in the case of Denmark, for many citizens prosumerism will be a way to reduce energy bills and help tackle climate crisis, while for other citizens prosumerism is not an option that can help them to reduce energy bills.

When it comes to the decarbonization potential of the policy cases under study in the case of France, and by also considering carbon intensity in the French power sector (Our World In Data, 2024a), we present an estimation of the carbon emission reduction.

Under the "*Unified World*" narrative, as expected, the estimated carbon emission reduction in the French residential sector is larger than under the other two (2) other "future-world" narratives, with FiT appearing as the policy scheme with the greatest decarbonization potential.

In particular, the decarbonization (emission reduction) potential of small-scale solar PV systems in the French residential sector by 2030 for the three (3) different policy cases under study in the context of the "*Unified World*" narrative is estimated to be approximately (**Figure 46**): (**i**). FiT: 124,200 $tnCO_2eq.$, (**ii**). net metering: 55,100 $tnCO_2eq.$, and (**iii**). net metering with BESS: 20,400 $tnCO_2eq.$

It is noteworthy that carbon emission reduction of the FiT scheme is more than two (2) times greater than the emission reduction that could come from the application of a net metering scheme.

Furthermore, carbon emission reduction under the FiT scheme is almost six (6) times larger than the reduction that could come from the application of a net metering scheme with BESS, under a "utopian" evolution of the future.

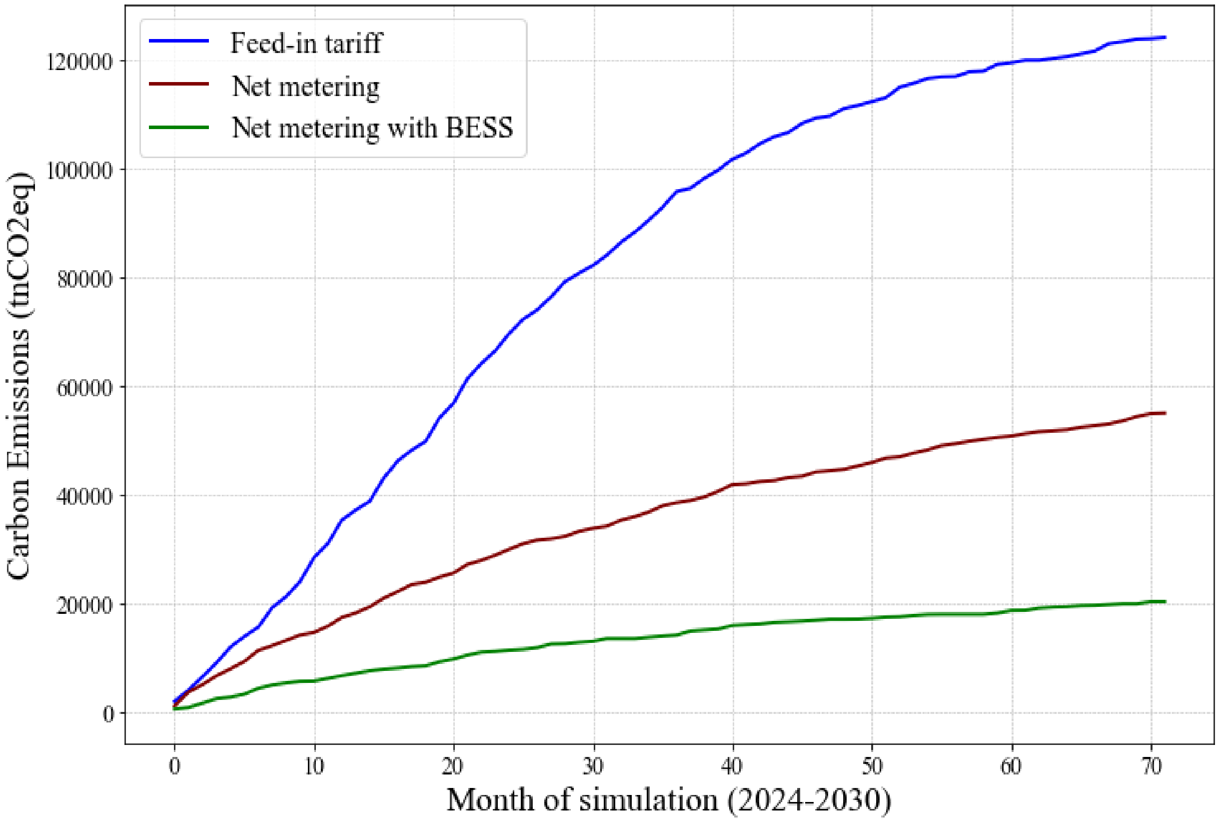


Figure 46. Estimated carbon emission reduction for the three (3) policy cases under study in the "*Unified World*" narrative, considering carbon intensity in the French power sector.

In accordance with the "*Familiar World*" narrative, the implementation of a FiT policy scheme is forecasted to lead to a significant emission reduction by 2030.

However, in the short-term (until 2025), net metering seems to have a carbon emission reduction potential close to the reduction potential that could result from the application of a FiT policy scheme with a fixed price equal to 147.4 € per MWh.

Similar to the case of the "*Unified World*" narrative, carbon emission reduction from the potential application of a FiT policy scheme are more than two (2) times and almost six (6) times larger by the reduction that could result from the application of a net metering and a net metering scheme with BESS, respectively.

Specifically, the decarbonization (emission reduction) potential of small-scale solar PV systems in the French residential sector by 2030 for the three (3) different policy cases under study in the context of the "*Familiar World*" narrative is estimated to be approximately (**Figure 47**): (**i**). FiT: 98,500 $tnCO_2eq.$, (**ii**). net metering: 41,600 $tnCO_2eq.$, and (**iii**). net metering with BESS: 16,600 $tnCO_2eq.$

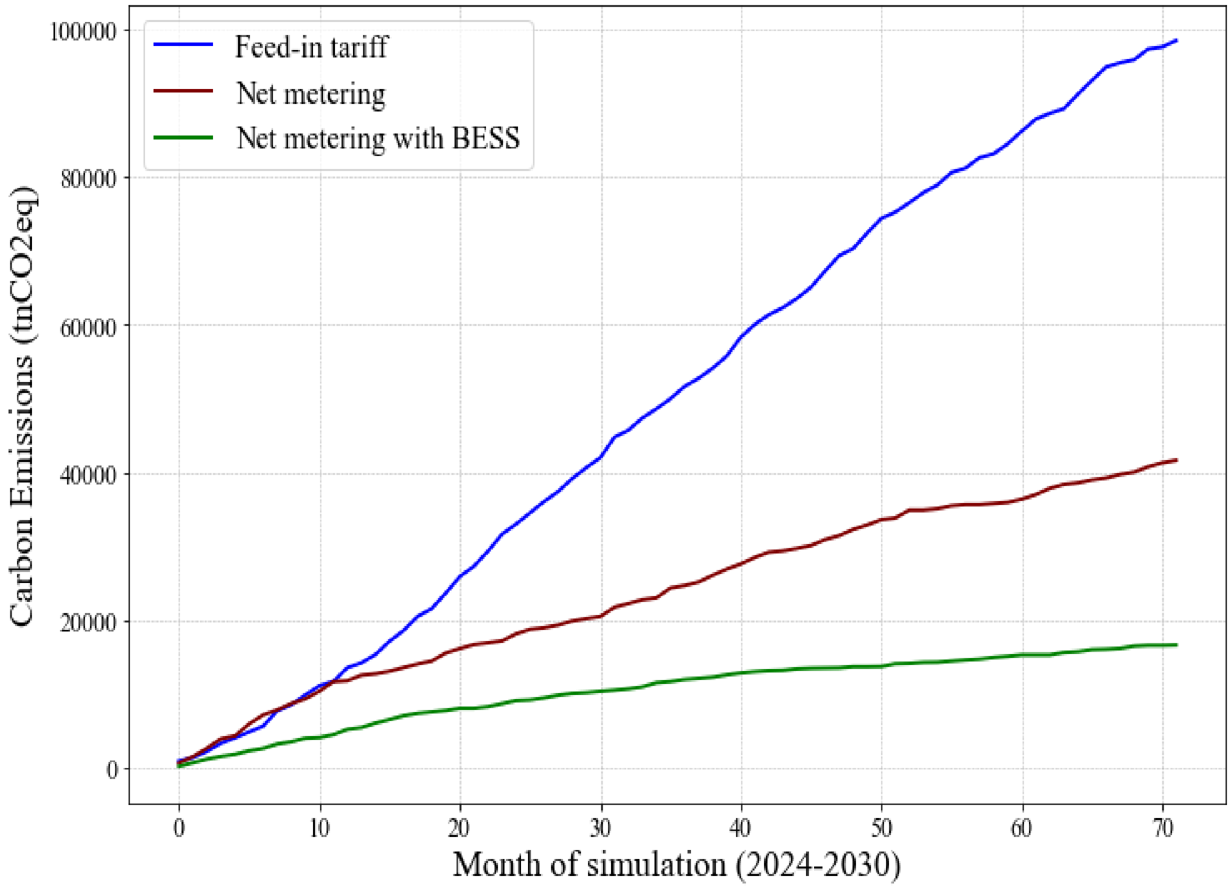


Figure 47. Estimated carbon emission reduction for the three (3) policy cases under study in the "*Familiar World*" narrative, considering carbon intensity in the French power sector.

Last but not least, under the "*Fragmented World*" narrative, the application of a net metering policy scheme initially has a greater decarbonization potential than the FiT scheme since it is able to contribute to a carbon emission reduction of around 4,900 tnCO$_2$eq. until June 2025.

However, by the end of 2030, the decarbonization (emission reduction) potential of small-scale solar PV systems in the French residential sector by 2030 for the three (3) different policy cases under study in the context of the "*Fragmented World*" narrative is estimated to be approximately (**Figure 48**): **(i).** FiT: 29,700 tnCO$_2$eq., **(ii).** net metering: 15,700 tnCO$_2$eq., and **(iii).** net metering with BESS: 9,500 tnCO$_2$eq.

Contrary to the "*Unified World*" and the "*Familiar World*" narratives, in the "*Fragmented World*" narrative, carbon emission reduction of the net metering scheme with BESS is almost three (3) times less than the respective reduction in the case of the FiT scheme.

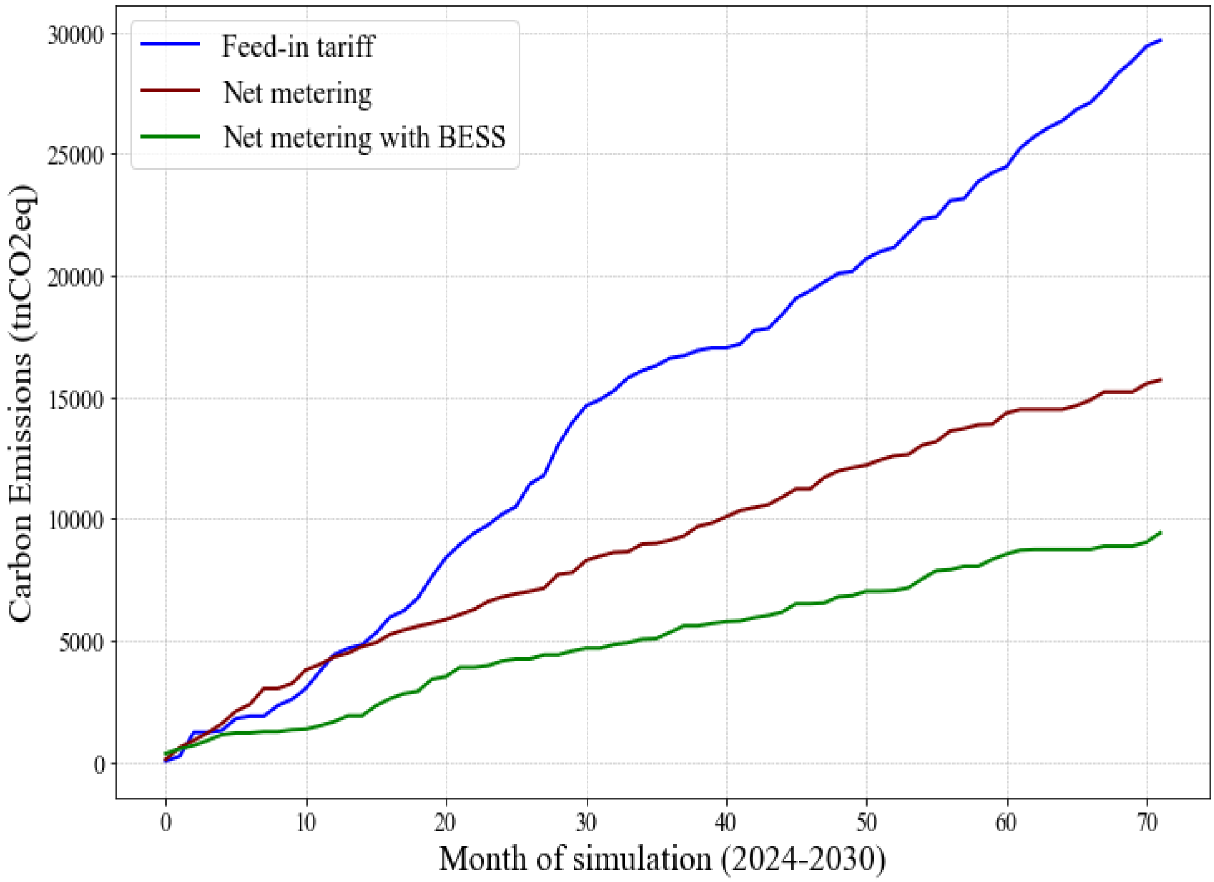


Figure 48. Estimated carbon emission reduction for the three (3) policy cases under study in the "*Fragmented World*" narrative, considering carbon intensity in the French power sector.

Greece

Once again, the greatest impact on the adoption of small-scale solar PV systems in the Greek residential sector appears to be achieved through the application of a FiT policy scheme with a constant fixed price of 87 € per MWh.

Forward-looking simulation results indicate that the expected PV capacity additions under the "*Unified World*" narrative for the three (3) policy cases by 2030 are around (**Figure 49**): **(i).** *FiT*: 290 MW, **(ii).** *net metering*: 120 MW, and **(iii).** *net metering with BESS*: 123 MW.

It is evident that contrary to the other case studies, uncertainty bounds in the forward-looking simulations in the case of Greece (not only under a "*Unified World*" narrative, but also for all the "future-world" narratives as we will present in the next paragraphs) are very narrow.

More specifically, for the policy cases of net metering and net metering with BESS this gap is almost zero.

This indicates that in this utopian potential evolution of the future world, Greek citizens who will invest in small-scale solar PV systems have a very clear understanding about the profitability of their investment.

Another important observation is that for the first time, a net metering scheme with BESS seems to have a greater impact on citizen adoption when compared to a potential application of a net metering scheme without BESS.

Similar to what we mentioned before, this showcases the impact of the BESS subsidy on citizens' decision-making behavior, and as a result, on adoption projections.

More specifically, in the case of Greece, we assumed a 100% BESS subsidy, which, as it shows in our modeling outcomes, has a very strong impact on citizens' perception about the profitability of the investment, which results to lower values for the "*resistance toward PV investment*" agent-related parameter (see **Section 4.1.1**).

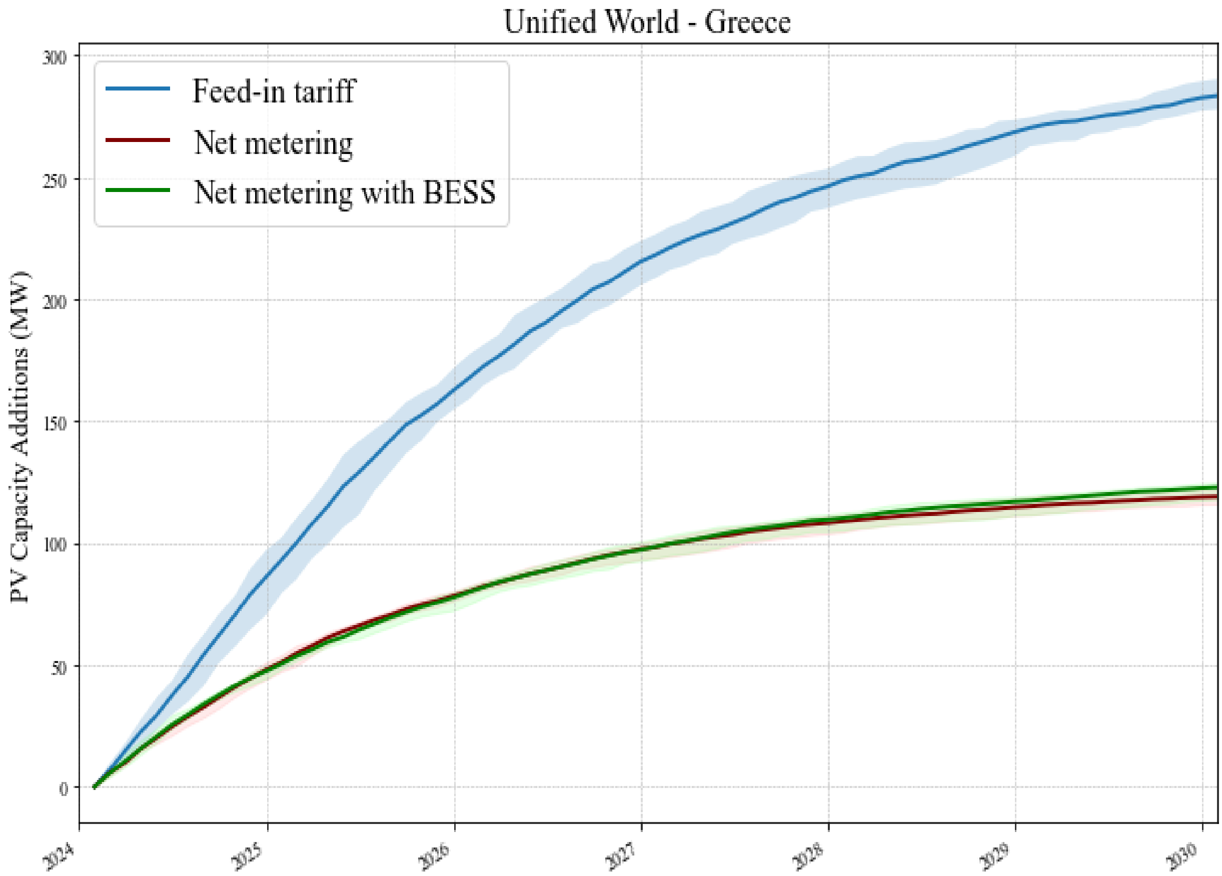


Figure 49. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Greek residential sector by 2030 for the three (3) policy cases and under the "*Unified World*" narrative. Uncertainty bounds are captured through error bars lighter colored.

Additionally, the total PV capacity additions under the "*Familiar World*" narrative for the three (3) policy cases by 2030 in the Greek residential sector, are estimated to be approximately (**Figure 50**): **(i).** *FiT*: 265 MW, **(ii).** *net metering*: 115 MW, and **(iii).** *net metering with BESS*: 115 MW.

In this case, we also see that the levels of the expected PV capacity additions under a net metering scheme are identical to levels of the respective PV capacity additions achieved in the case of the net metering scheme with BESS.

The latter highlights the impact of the BESS subsidy on citizens' decision-making behavior, since for this potential evolution of the future, we assumed a 90% BESS subsidy.

Moreover, as mentioned in the "*Unified World*" Greek case, the uncertainty gaps are very narrow, which indicates once again that citizens have a very clear perception of their investment's profitability.

It is also noteworthy that the adoption rate in this case, as described in the trajectories of the curves depicted in the adoption figures, is almost identical.

However, the total PV capacity additions are- as expected- steadily larger under the "*Unified World*" narrative, even if not with big disparity between the results (especially for net metering and net metering with BESS).

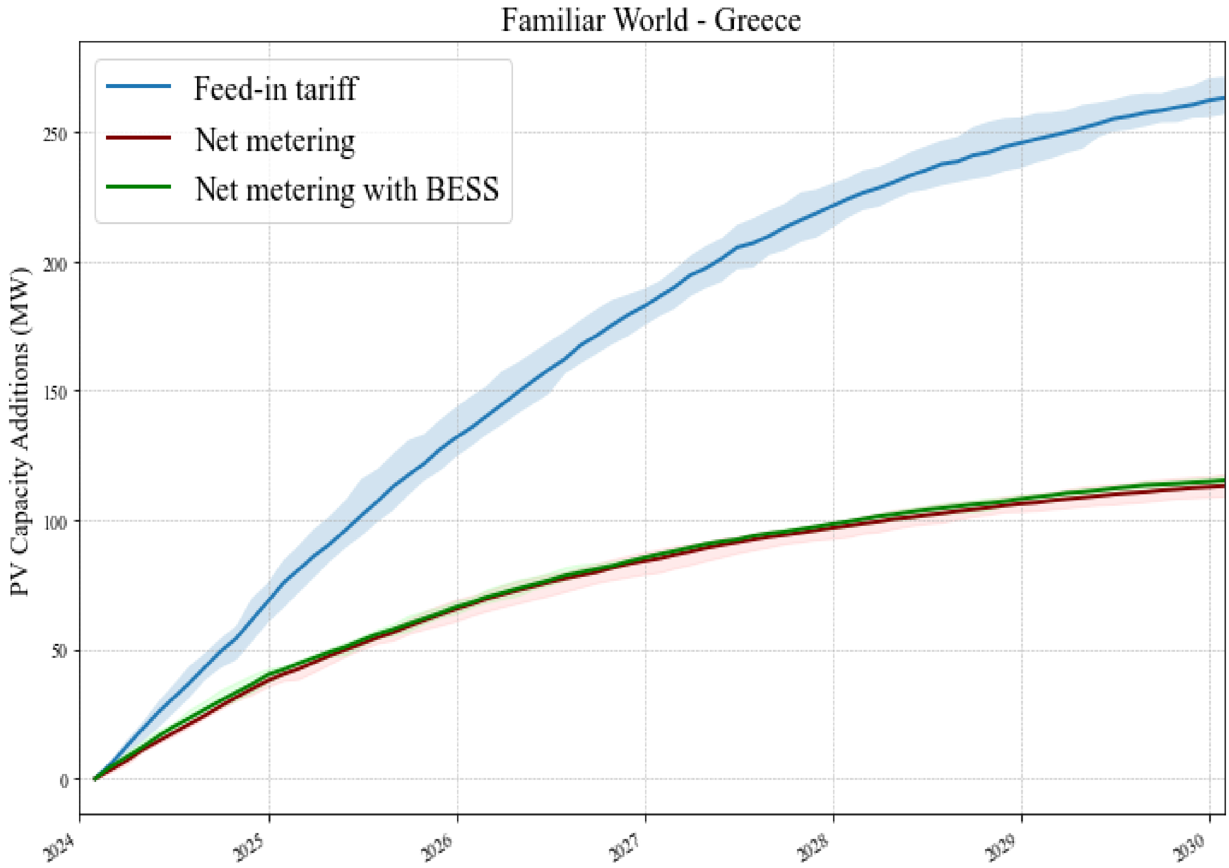


Figure 50. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Greek residential sector by 2030 for the three (3) policy cases and under the "*Familiar World*" narrative. Uncertainty bounds are captured through error bars lighter colored.

Finally, results of the forward-looking simulations under the "*Fragmented World*" narrative for the three (3) different policy cases under consideration indicate expected PV capacity additions by 2030 of around (**Figure 51**): (**i**)**.** *FiT*: 215 MW, (**ii**)**.** *net metering*: 98 MW, and (**iii**)**.** *net metering with BESS*: 92 MW.

While for the other two (2) "future-world" narratives the potential application of a net metering with BESS resulted to total PV capacity additions slightly larger when compared to the application of a net metering without BESS scheme, under a "Fragmented World" we observe that net metering is slightly over compared to the case of net metering with BESS.

This once again shows the impact of a BESS subsidy, since, in this case, we only assumed a 50% BESS subsidy.

Furthermore, we observe that under this narrative, the uncertainty gap is slightly larger for all the policy cases, while for the net metering with BESS is slightly larger.

This is attributed to the nature of this "future-world" narrative, similarly to what we observed in the other case studies (Denmark and France), where citizens are divided in terms of their beliefs about the economic and environmental benefits of their investment, and as a result they are hardly influenced by their close social circle.

We also notice that under the "Fragmented World" narrative, the trajectories of the curves indicate that there are considerably less early adopters of the technology, which is also aligned with the nature of this potential evolution of the future world, where citizens are not so willing to invest in a technology until they will be ensured for the outcomes of their investment.

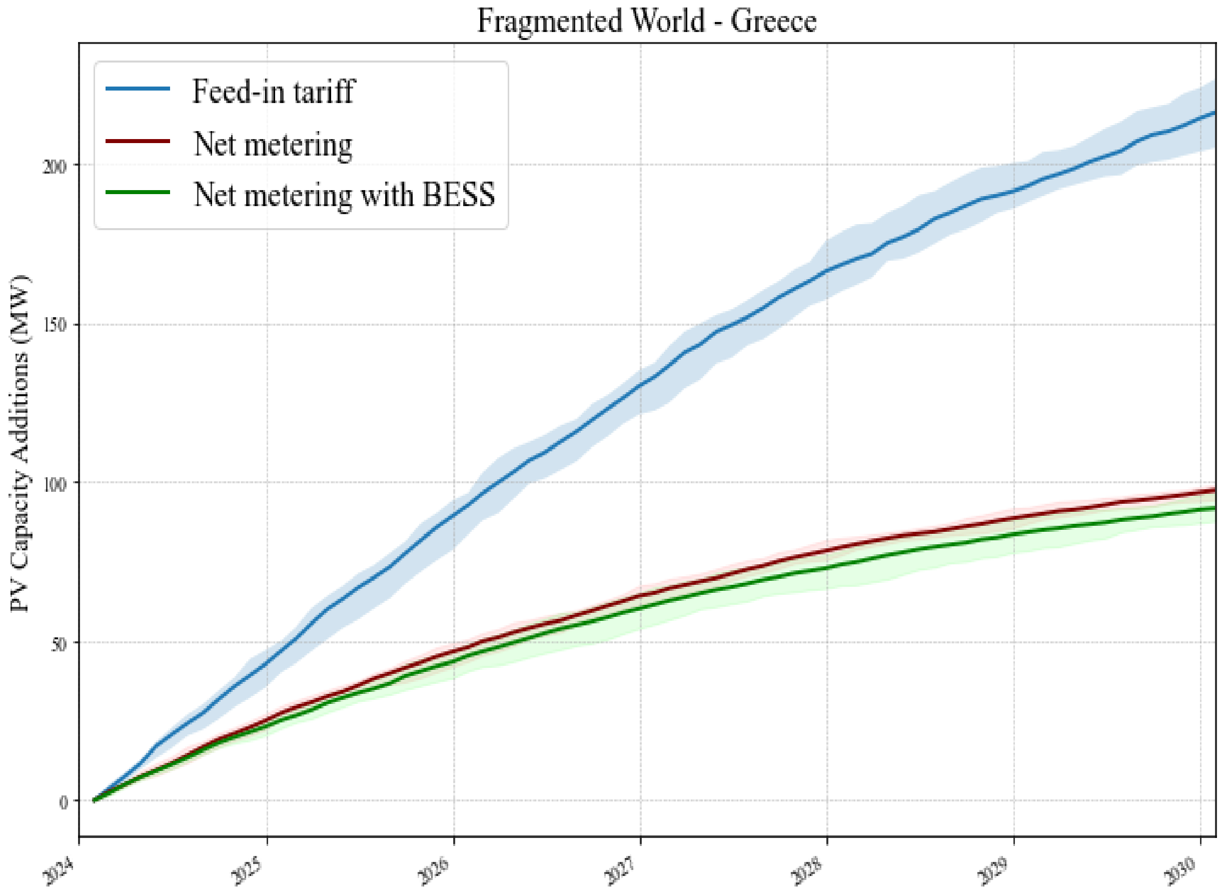


Figure 51. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Greek residential sector by 2030 for the three (3) policy cases and under the "*Fragmented World*" narrative. Uncertainty bounds are captured through error bars lighter colored.

In contrast with the other two (2) case studies (Denmark and France), in the case of Greece, we observe less uncertainty gaps for all the schemes under study.

This can mainly be attributed to citizens' beliefs about the investment's profitability.

In the cases of net metering and net metering with BESS, this is attributed to citizens' clearer perception about the profitability of their investment, which is further diffused to other citizens through their social circle.

However, even if the uncertainty is less, we observe that net metering and net metering with BESS are not able to achieve the total PV capacity additions that are able to be achieved through the application of a FiT scheme with a fixed price equal to 87 € per MWh.

As a result, in citizens' perspective, a FiT scheme with these levels of fixed price, appears to be more economically attractive for citizens and this is the reason for the larger adoption rates.

As for the decarbonization (emission reduction) potential of small-scale solar PV systems in the Greek residential sector by 2030 for the three (3) different policy cases under study in the context of the "*Unified World*" narrative is estimated to be approximately (**Figure 52**): (**i**)**.** FiT: 153,750 $tnCO_2eq.$, (**ii**)**.** net metering: 63,000 $tnCO_2eq.$, and (**iii**)**.** net metering with BESS: 72,450 $tnCO_2eq.$

As a result, we observe that the application of a FiT policy scheme is able to lead to carbon emission reduction over two (2) times bigger than the one that could be achieved under the application of net metering or net metering with BESS.

However, for the first time we notice that a net metering policy scheme with BESS under a potential "unified" evolution of the future is able to lead to larger emission reduction levels when compared to a net metering scheme without BESS, which is also aligned with the simulated results as presented above.

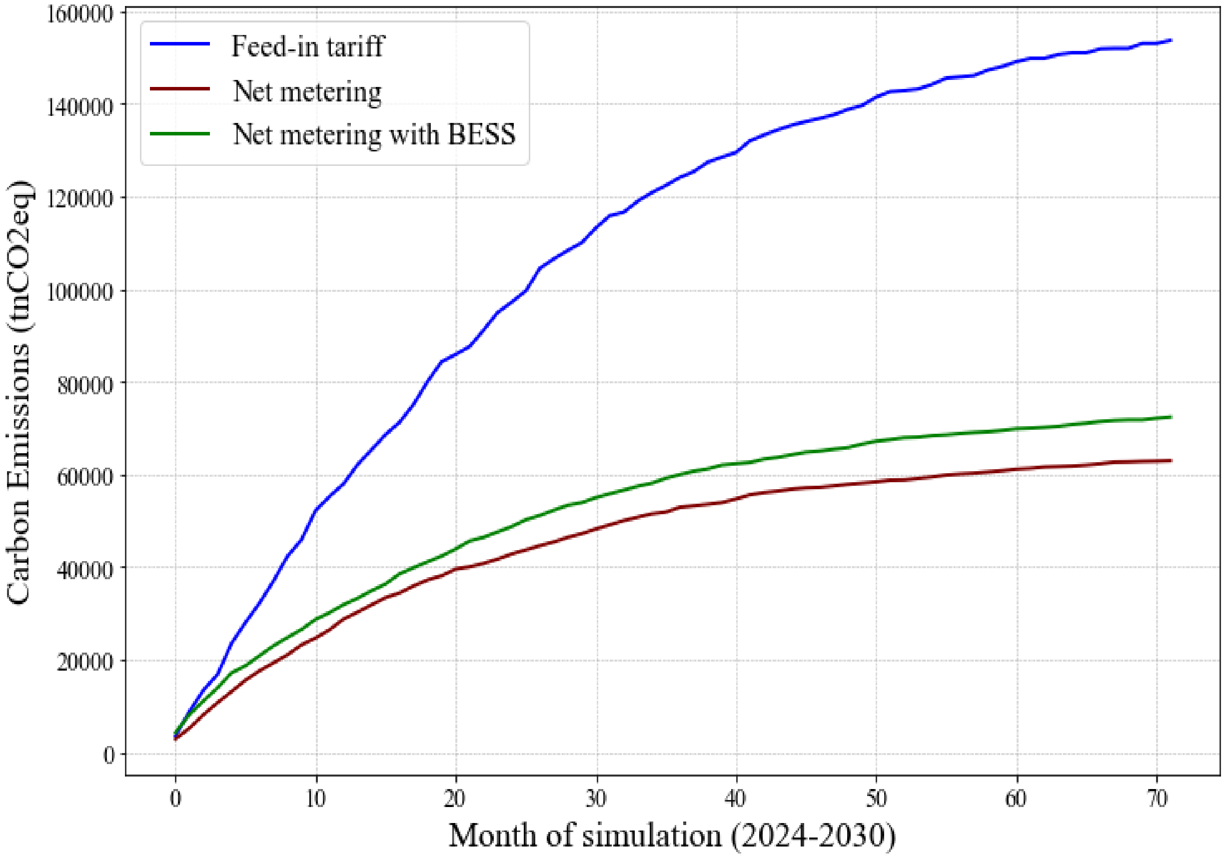


Figure 52. Estimated carbon emission reduction for the three (3) policy cases under study in the "*Unified World*" narrative, considering carbon intensity in the French power sector.

In the context of the "*Familiar World*" narrative, the application of the existing FiT policy scheme (with fixed price equal to 87 € per MWh) has the greatest impact on the decarbonization potential.

More precisely, the decarbonization (emission reduction) potential of small-scale solar PV systems in the Greek residential sector by 2030 for the three (3) different policy cases under study in the context of the "*Familiar World*" narrative is estimated to be approximately (**Figure 53**): (**i**)**.** *FiT*: 129,000 $tnCO_2eq.$, (**ii**)**.** *net metering*: 58,300 $tnCO_2eq.$, and (**iii**)**.** *net metering with BESS*: 53,250 $tnCO_2eq.$

Once again, the decarbonization potential of the FiT policy case is over two (2) times bigger than the decarbonization potential of net metering and net metering with BESS.

Also, we notice that the decarbonization potential of the net metering scheme is slightly greater than the decarbonization potential of net metering with BESS, which is attributed to the very small disparity between the two (2) policy cases in the total PV capacity additions and they are not apparent **in Figure 50**.

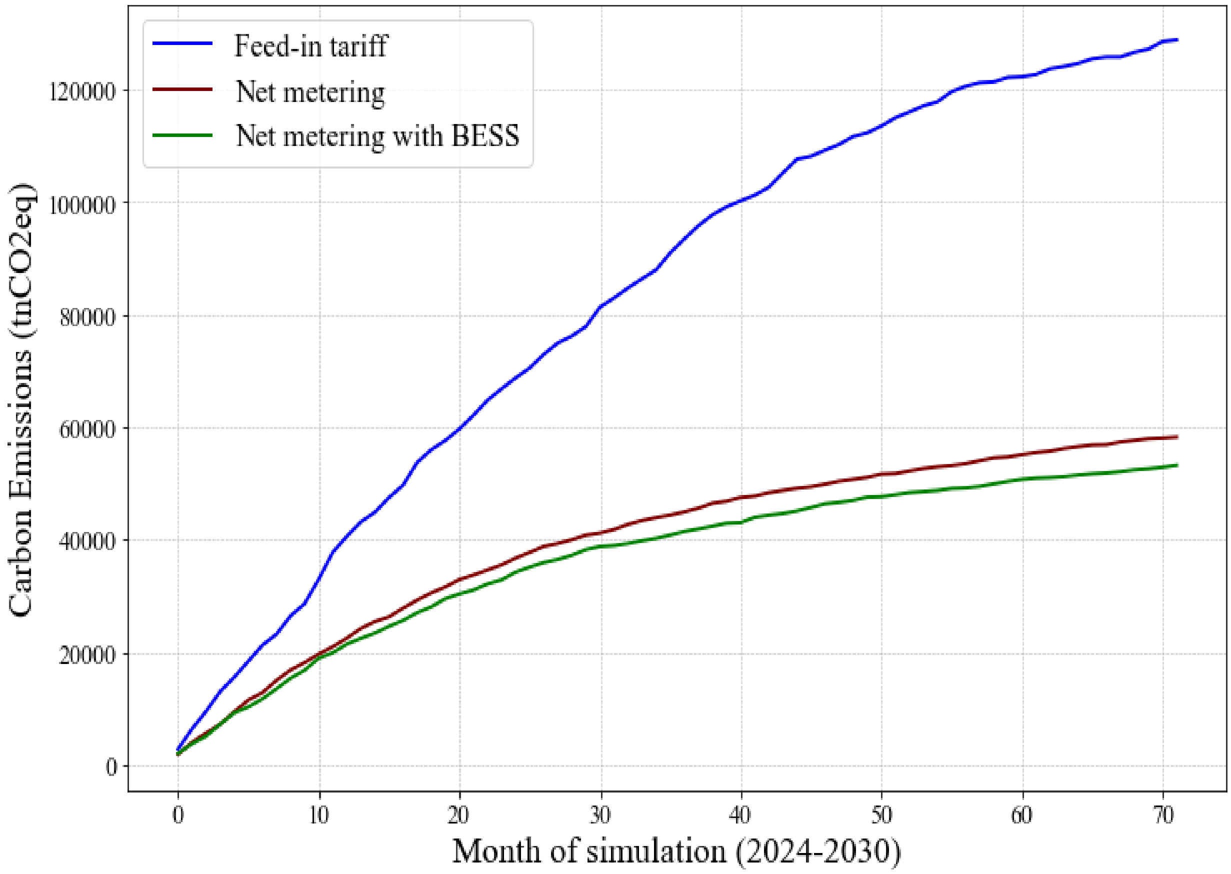


Figure 53. Estimated carbon emission reduction for the three (3) policy cases under study in the "*Familiar World*" narrative, considering carbon intensity in the French power sector.

Lastly, within the "*Fragmented World*" narrative, the implementation of the existing FiT policy scheme, once again, demonstrates the most significant impact on the decarbonization (emission reduction) potential in the Greek residential sector.

Specifically, the decarbonization (emission reduction) potential of small-scale solar PV systems in the Greek residential sector by 2030 for the three (3) different policy cases under study in the context of the "*Fragmented World*" narrative is estimated to be approximately (**Figure 54**): (**i**)**.** *FiT*: 82,000 $tnCO_2eq$., (**ii**)**.** *net metering*: 37,500 $tnCO_2eq$., and (**iii**)**.** *net metering with BESS*: 32,000 $tnCO_2eq$.

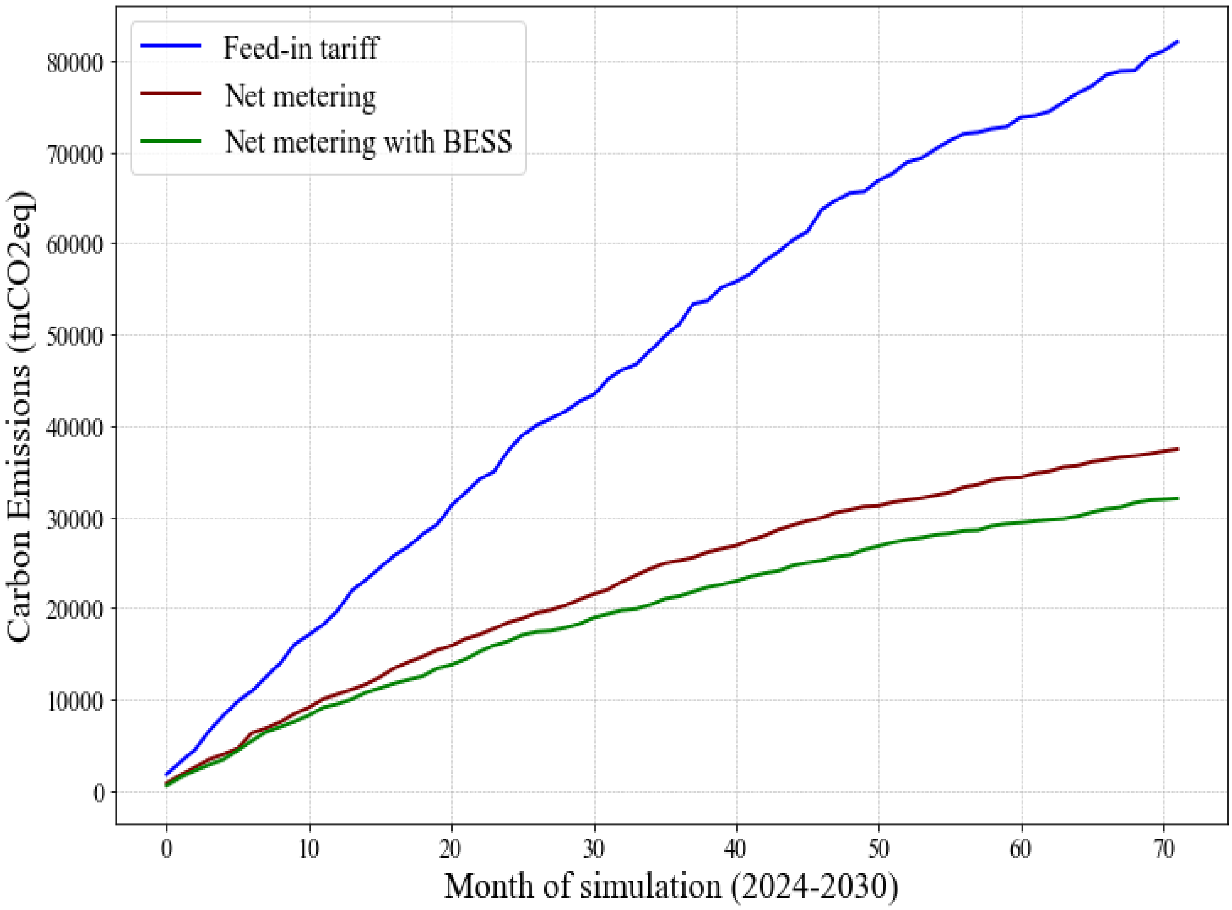


Figure 54. Estimated carbon emissions reduction for the three policy scenarios under the "*Fragmented World*" narrative taking into account the carbon intensity of the Greek power sector.

Cross-country comparison

In summary, **Table 17** showcases the expected capacity additions and the respective decarbonization (emission reduction) potential from the further citizen adoption of small-scale PV systems in the Danish, the French, and the Greek residential sectors by 2030, for the three (3) policy schemes under study, i.e., FiT, net metering, and net metering with BESS, under the three (3) ENCLUDE "future-world" narratives.

We observe that in the case of Denmark, simulation outcomes indicate the negative impact of the "*Fragmented World*" narrative in the expected PV capacity additions, whereas there is no big difference in the PV capacity additions between the "*Familiar*" and the "*Unified World*" narrative.

It is noteworthy that, in accordance with governmental decisions of the past few years, the FiT policy in Denmark is gradually phased out ("BEK no. 1044 of 27/05/2021"[20]), as the government aims to promote the adoption of small-scale solar PV systems through the full transition to a net metering policy scheme without direct compensation for prosumers (Martín et al., 2021; Wikberg, 2019). This shift reflects evolving policy priorities and the ongoing pursuit of sustainable energy transition objectives.

Within the framework of the net metering policy scheme, prosumers demonstrate a dearth of motivation to produce excess electricity due to the absence of remuneration during the designated netting periods (Ziras et al., 2021). Therefore, it is evident that the current net metering scheme in Denmark has a comparatively smaller impact on the expected capacity additions when compared to the deployment of the FiT policy scheme.

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[20] https://www.retsinformation.dk/eli/lta/2021/1044

In addition, our findings also show that in the case of the FiT scheme, and under a potential “unified” evolution of the future, there are considerably more early adopters in Denmark compared to France and Greece, where citizen adoption of small-scale solar PV systems is progressing more “steadily”.

However, under a “fragmented” evolution of the future world, the application of a net metering policy scheme has a greater impact on citizen adoption projections in the case of Denmark, compared to France and Greece, where the case is not the same.

This showcases the significant impact that electricity prices have on the perspective of citizens about the profitability of their investment. Specifically, under the “*Fragmented World*” narrative, Danish citizens perceive the greater profitability of a net metering with an hourly netting period and in which the excess electricity they provide to the grid is remunerated according to the retail electricity price.

This is contrary to the cases of France and Greece, where the electricity prices are not such elevated like in Denmark (see assumptions in **Section 6.2.1**), and as a result, net metering has less impact on citizen adoption.

As for the combination of the existing net metering policy scheme with BESS, results indicate a weaker potential in expected small-scale PV capacity additions. This is probably attributed to the fact that despite the relatively lower cost of BESS in Denmark (around 408 €/kWh) compared to the other Member States under analysis (Farnell, 2024), no subsidization is provisioned from the government for the installation of such systems (Danish Energy Agency, 2024).

In this context, it is noteworthy that, despite assuming a 50% subsidy for BESS systems under the “*Unified World*” narrative, the impact on the adoption of small-scale solar PV systems with BESS remains negligible. This phenomenon is attributed to the constrained profitability that prosumers can attain, even with a 50% subsidy, in comparison to the profitability achievable under a net metering scheme (Draheim et al., 2020).

In the case of France, now, modeling findings suggest that the FiT policy scheme holds considerable promise for accelerating the deployment of small-scale solar PV systems across different socioeconomic and environmental scenarios. On the other hand, the outcomes stemming from the net metering scheme underscore the limited influence of the policy on the further adoption of small-scale PV systems by 2030.

It is noteworthy that the French government, trying to provide prosumers with stronger financial incentives in order to promote prosumerism, attempts to incentivize the prosumers through the FiT policy scheme, while a net metering scheme is not regulated (Fröding & Gasne, 2024; Oriol, 2018).

Results highlight that even despite the assumed half subsidization of the BESS costs (under the “*Unified World*” narrative), a net metering policy scheme seems to have the least effect on the expected capacity additions by 2030 due to the lower profitability that prosumers are to perceive through the investment under these policy schemes (net metering and net metering with BESS).

However, it is also noteworthy that in the case of France, uncertainty bounds in the case of the FiT policy scheme, under the “*Unified World*” narrative, are considerably larger when compared with the respective uncertainty bounds in the cases of Denmark and Greece.

The latter implies that the perspective of citizens about the profitability of their investment under a FiT scheme, when electricity prices and PV capital costs are decreased, is divided since there are almost equally divided willing-to-invest and risk-averse citizens.

In addition, despite the larger adoption potential in the case of France (compared to Denmark), the estimated decarbonization (emission reduction) potential under the net metering and the net metering with BESS policy schemes are almost at the same levels with the case of Denmark. This is attributed to the lower carbon intensity of the French power sector, which is mainly based on nuclear energy; thus, there is a narrower margin for reduction compared to Denmark.

These findings suggest that, while the FiT policy scheme holds promise as a robust mechanism for further driving decarbonization efforts in the French residential sector, further exploration of complementary strategies may be necessary to fully address the complexities of reducing carbon emissions.

Lastly, in the case of Greece, modeling outcomes show that the existing FiT policy scheme can contribute to the greatest adoption potential, while the application of the existing net metering policy scheme- based on which no remuneration is provided to prosumers for the excess electricity injected into the grid- seems to have almost two (2) times less impact on the adoption of small-scale solar PV systems in the residential sector. This is mainly attributed to the fact that prosumers lack the incentive to generate surplus electricity as they are not reimbursed for it during the four-month netting period.

Also, uncertainty bounds for the policy schemes under study in the case of Greece are significantly smaller when compared to the respective behavioral uncertainty bounds in the cases of Denmark and France.

In general, the less the uncertainty, the stronger the citizens' perception of the profitability of their investment, which can then influence other citizens in their social circle.

Furthermore, decarbonization (emission reduction) potential from the further citizen adoption of small-scale PV systems in the Greek residential sector is ambiguous. On the upside, results present a significantly higher decarbonization potential, especially under the application of the FiT policy scheme, compared to Denmark and France.

On the downside, the higher decarbonization potential in the case of Greece, also considering its population, implies the considerably higher carbon intensity of the country's power sector (Our World In Data, 2024a) compared to the cases of Denmark and France. The latter highlights the importance of empowering prosumerism and the further citizen adoption of small-scale PV systems in Greece, especially considering the national targets, as have been set by the latest official version of the NECP.

Table 17. Citizen adoption and decarbonization potential of prosumerism in the Danish, the French, and the Greek residential sectors by 2030, for the three (3) policy cases under study, and under the three (3) ENCLUDE "future-world" narratives.

Denmark			
Capacity additions (MW)	FiT	*"Unified World"*	440
		"Familiar World"	400
		"Fragmented World"	120
	Net metering	*"Unified World"*	274
		"Familiar World"	261
		"Fragmented World"	132
	Net metering with BESS	*"Unified World"*	212
		"Familiar World"	110
		"Fragmented World"	33
Carbon emission reduction (tnCO$_2$eq.)	FiT	*"Unified World"*	89,300
		"Familiar World"	73,500
		"Fragmented World"	24,000
	Net metering	*"Unified World"*	51,000
		"Familiar World"	48,200
		"Fragmented World"	25,500
	Net metering with BESS	*"Unified World"*	35,000
		"Familiar World"	21,650
		"Fragmented World"	5,100
France			

Capacity additions (MW)	FiT	*"Unified World"*	923
		"Familiar World"	671
		"Fragmented World"	246
	Net metering	*"Unified World"*	471
		"Familiar World"	379
		"Fragmented World"	184
	Net metering with BESS	*"Unified World"*	266
		"Familiar World"	202
		"Fragmented World"	100
Carbon emission reduction (tnCO$_2$eq.)	FiT	*"Unified World"*	124,200
		"Familiar World"	98,500
		"Fragmented World"	29,700
	Net metering	*"Unified World"*	55,100
		"Familiar World"	41,600
		"Fragmented World"	15,700
	Net metering with BESS	*"Unified World"*	20,400
		"Familiar World"	16,600
		"Fragmented World"	9,500
Greece			
Capacity additions (MW)	FiT	*"Unified World"*	290
		"Familiar World"	265
		"Fragmented World"	215
	Net metering	*"Unified World"*	120
		"Familiar World"	115
		"Fragmented World"	98
	Net metering with BESS	*"Unified World"*	123
		"Familiar World"	115
		"Fragmented World"	92
Carbon emission reduction (tnCO$_2$eq.)	FiT	*"Unified World"*	153,750
		"Familiar World"	129,000
		"Fragmented World"	82,000
	Net metering	*"Unified World"*	63,000
		"Familiar World"	58,300
		"Fragmented World"	37,500
	Net metering with BESS	*"Unified World"*	72,450
		"Familiar World"	53,250
		"Fragmented World"	32,000

7.2. Combining "Power to the People" with "People to the Streets" storylines towards people-centered and 100% renewable-based national energy systems

Based on the case study specifications and the designed scenario space, we present the capacity and electricity mix, the capital investments per technology, the total costs of electricity supply, and the CO$_2$ footprint in the Greek power sector by 2050 for the two (2) "people-centered" storylines under study, i.e., "*Power to the People*" and "*People to the Streets*", and the three (3) different "future-world" narratives.

Specifically, under the "*Familiar World*" narrative, we compare the "*BAU case*" with the "*Decentralized case*"; under the "*Unified World*" narrative, we compare the "*Centralized case*" with the "*Decentralized case*"; while under the "*Fragmented World*" narrative, we compare the "*Gas-dependency case*" with the "*Lignite-dependency case*".

7.2.1. Capacity mix by 2050

Under the "*Familiar World*" narrative, modeling results exhibit an increase in total capacity by 2050 in the "*BAU case*" and the "*Decentralized case*" dominated by VRE sources, i.e., utility, commercial, and rooftop solar PV systems, as well as onshore and offshore wind power installations, and solutions adding flexibility to the power sector, i.e., electricity storage, pumped hydro, and electrolyzers (**Figure 55**).

A relative total capacity growth of 76.9 GW by 2050 compared to 2025 is projected in the "*BAU case*", while the respective growth in the "*Decentralized case*" is 101.6 GW. Higher public participation in the energy market and more local opposition to large-scale wind and CCS projects in the "*Decentralized case*" result in much higher capacity of solar rooftop and commercial PV systems and somewhat higher capacity of onshore and offshore wind projects compared to the "*BAU case*". As a result, solar and wind reach 33 GW and 23.9 GW in the "*BAU Case*" and 50.5 GW and 27.7 GW in the "*Decentralized case*" by 2050.

Furthermore, supply-side flexibility reaches 32.8 GW in the "*BAU Case*" and 42.5 GW in the "*Decentralized case*". The main difference between the two (2) cases lies in the growth of short-term electricity storage (i.e., utility and rooftop BESS) that reaches 14.4 GW in the "*BAU Case*" and 25 GW in the "*Decentralized case*".

It should also be noted that in the "*Decentralized case*", there are higher capacity requirements for behind the meter electricity storage than the "*BAU case*", due to the higher amount of onsite electricity generation.

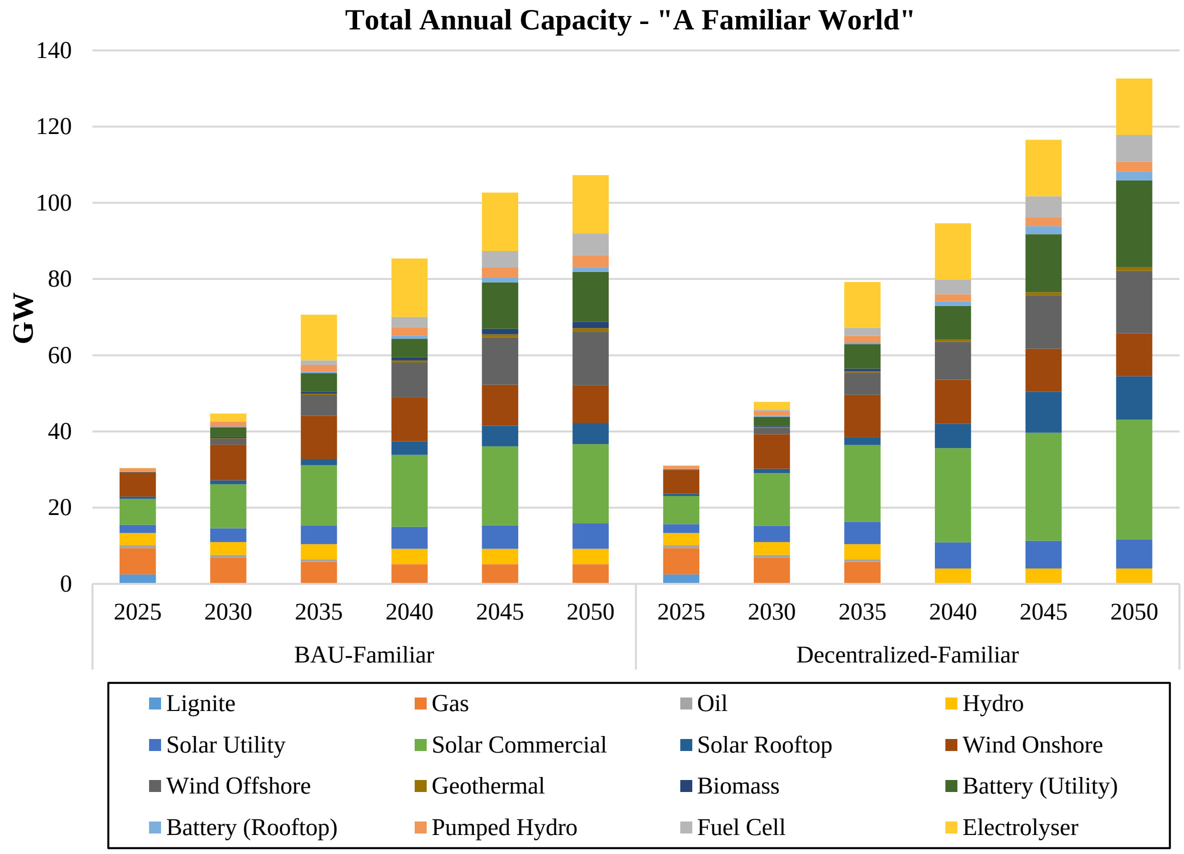

Figure 55. Total capacity mix in the Greek power sector by 2050 for the “BAU case” and the “Decentralized case”, under the “*Familiar World*” narrative.

Under the “*Unified World*” narrative, the results show once more an increase in total capacity by 2050 in the “Centralized case” and the “*Decentralized case*” dominated by VRE and supply-side flexibility technologies (**Figure 56**).

A relative total capacity growth of 71.7 GW by 2050 compared to 2025 is projected in the “*Centralized case*”, while the respective growth in the “*Decentralized case*” is 111 GW. In the “*Centralized case*”, the lower public participation in the energy market and less local opposition to large-scale wind projects result in much lower capacity of solar rooftop and commercial PV systems and somewhat higher capacity of onshore and offshore wind projects compared to the “*Decentralized case*”. As a result, solar and wind reach 28.4 GW and 33 GW in the “*Centralized case*” and 58.4 GW and 25.6 GW in the “*Decentralized case*” by 2050.

Therefore, the “*Centralized case*” describes a power sector with more balanced solar and wind capacity shares, while the “*Decentralized case*” describes a solar-dominated power sector.

In fact, the difference in the total VRE capacity growth between those two (2) cases lies mainly in the different shares of solar and wind technologies in the capacity mix, considering that solar-dominated systems have lower capacity factors than balanced/ wind-dominated systems. Therefore, larger VRE capacity is required in the “*Decentralized case*” to match the electricity generation potential of the “*Centralized case*”.

Furthermore, the difference in the total VRE capacity growth between the two (2) cases is also based to a lesser degree on the different amounts of imported electricity, which are higher in the “*Centralized case*”. Moreover, supply-side flexibility reaches 28 GW (i.e., 8.4 GW utility BESS, 0.4 GW rooftop BESS, 3 GW pumped hydro, and 16.2 GW electrolyzers) in the “*Centralized case*” and 45.9 GW (i.e., 28 GW utility BESS, 2.7 GW rooftop BESS, 3.1 GW pumped hydro, and 12.1 GW electrolyzers) in the “*Decentralized case*”.

The results show that the "*Centralized case*" requires much lower short-term flexibility and somewhat higher long-term flexibility than the "*Decentralized case*". This is in line with the results of other studies, who mention that short-term electricity storage requirements are significantly higher in solar-dominated systems than in balanced/ wind-dominated systems, and the timing of short-term electricity storage capacity requirements occurs sooner (Michas & Flamos, 2023; Nayak-Luke et al., 2021).

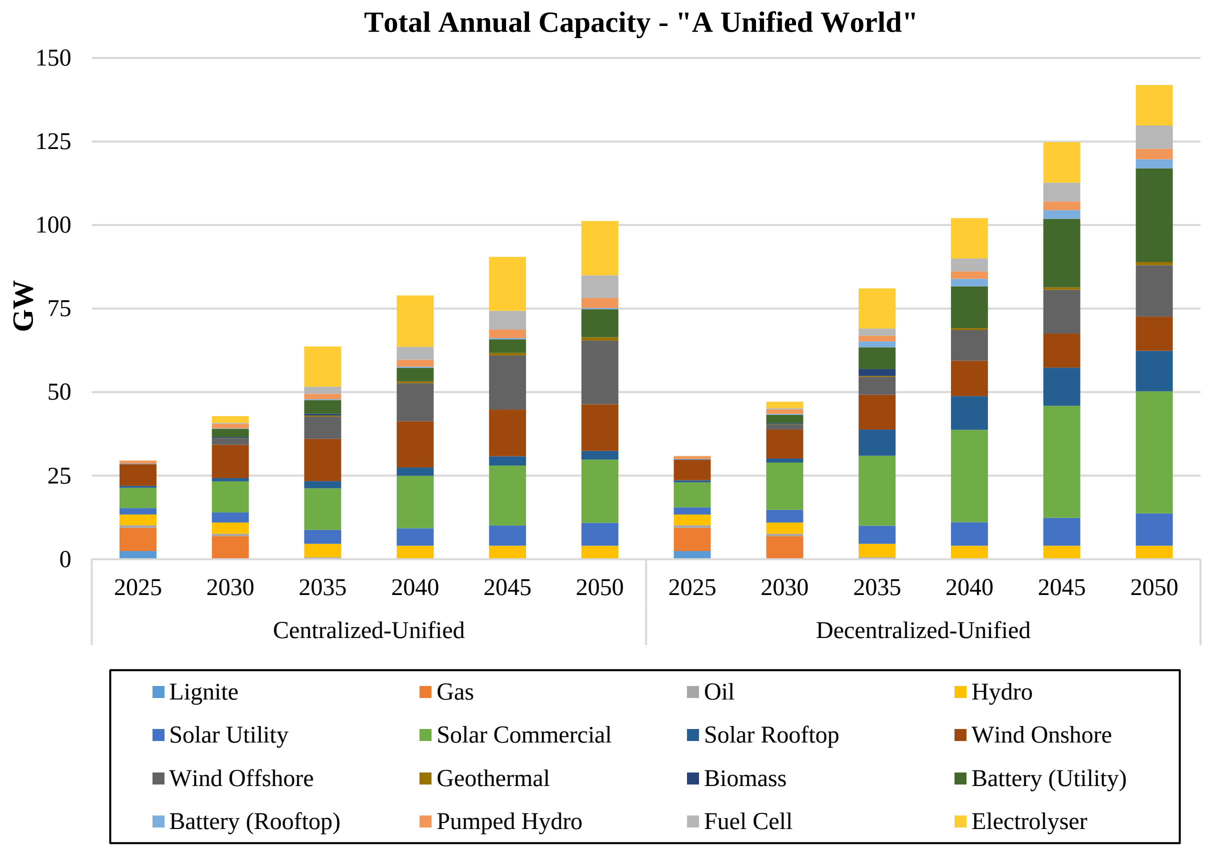

Figure 56. Total capacity mix in the Greek power sector by 2050 for the "Centralized case" and the "Decentralized case", under the "*Unified World*" narrative.

Under the "*Fragmented World*" narrative, the results present a more modest increase in total capacity by 2050 than the other two "*future-world*" narratives due to the continuation of gas and/ or lignite use for power generation (**Figure 57**).

A relative total capacity growth of 47.3 GW by 2050 compared to 2025 is projected in the "*Gas-dependency case*", while the respective growth in the "*Lignite-dependency case*" is 63.1 GW. As a result, solar and wind reach 26.8 GW and 18.1 GW in the "*Gas-dependency case*" and 31 GW and 22.5 GW of the total capacity mix in the "*Lignite-dependency case*" by 2050.

Moreover, supply-side flexibility reaches 11.8 GW (i.e., 1.2 GW utility BESS, 0.8 GW rooftop BESS, 3 GW pumped hydro, and 6.7 GW electrolyzers) in the "*Gas-dependency case*" and 22.9 GW (i.e., 8.5 GW utility BESS, 1.1 GW rooftop BESS, 3.1 GW pumped hydro, and 10.2 GW electrolyzers) in the "*Lignite-dependency case*".

Results show that there is more need for long-term flexibility rather than short-term flexibility similarly to the "*Centralized case*" results under the "*Unified World*" narrative.

It should be noted that the much lower flexibility requirements in these two (2) cases stem from the larger displacement of variable renewable electricity generation, which requires adequate flexibility to operate without large amounts of curtailment, by dispatchable electricity generation from gas- and/ or lignite-fired power plants, which can provide additional flexibility to the power sector by ramping up or down their electricity production levels.

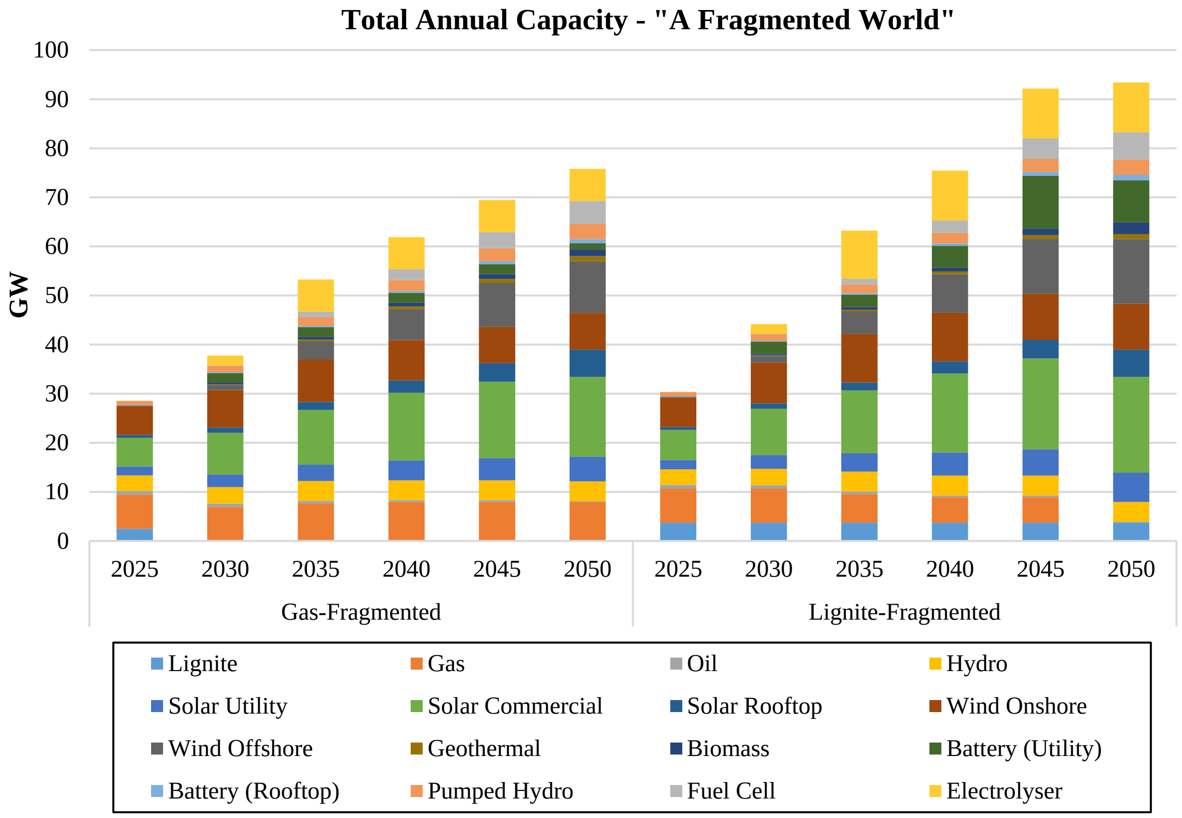

Figure 57. Total capacity mix in the Greek power sector by 2050 for the “Gas-dependency case” and the “Lignite-dependency case”, under the “*Fragmented World*” narrative.

7.2.2. Capital costs and investments by 2050

Under the “*Familiar World*” narrative, modeling results suggest that a carbon-neutral and decentralized power sector in Greece requires significant investments in VRE and storage technologies.

More specifically, the energy investment landscape in Greece will undergo changes as annual investments in the electricity supply will increase by 16.5% in the “*BAU case*” and 78.6% in the “*Decentralized case*” in 2050 compared to 2025. This is particularly evident in annual wind energy investments, which are projected to increase by 0.8 billion € in the “*BAU case*” and by 1.33 billion € in the “*Decentralized case*” in 2050 compared to 2025.

Wind power experiences substantial investment growth, averaging a total of 1.66 billion € in the “*BAU case*” and 1.85 billion € in the “*Decentralized case*” annually, indicating increased focus on and funding in this sector (**Figure 58**). This significant increase in wind energy investments is largely due to the development of offshore wind projects, which have much higher capital costs than onshore wind projects.

Similarly, investments in solar energy sources are projected to reach 0.84 billion € in the “*BAU case*” and 1.32 billion € in the “*Decentralized case*” on average, on an annual basis, benefiting in the latter case from the reduction in solar PV capital costs.

Solar rooftop and commercial PV systems occupy 18.9% and 65.3% of average annual investments in total solar power in the “*BAU Case*” and 24.3% and 63.6% of average annual investments in total solar power in the “*Decentralized case*”, thus showing the significantly higher capital investments required for decentralization of electricity generation.

Investments in electricity storage will reach an average of 0.46 billion € in the “*BAU case*” and 0.74 billion € in the “*Decentralized case*” on a yearly basis, with the larger share of this cost being attributed to utility-scale BESS. Investments in electrolyzers surpass 0.4 billion € on average annually, which will be required to meet the increasing hydrogen demand towards 2050.

Overall, modeling outcomes suggest a significant shift in investments towards VRE, particularly in wind and solar power, which also reflects Greece's commitment to clean and sustainable energy solutions.

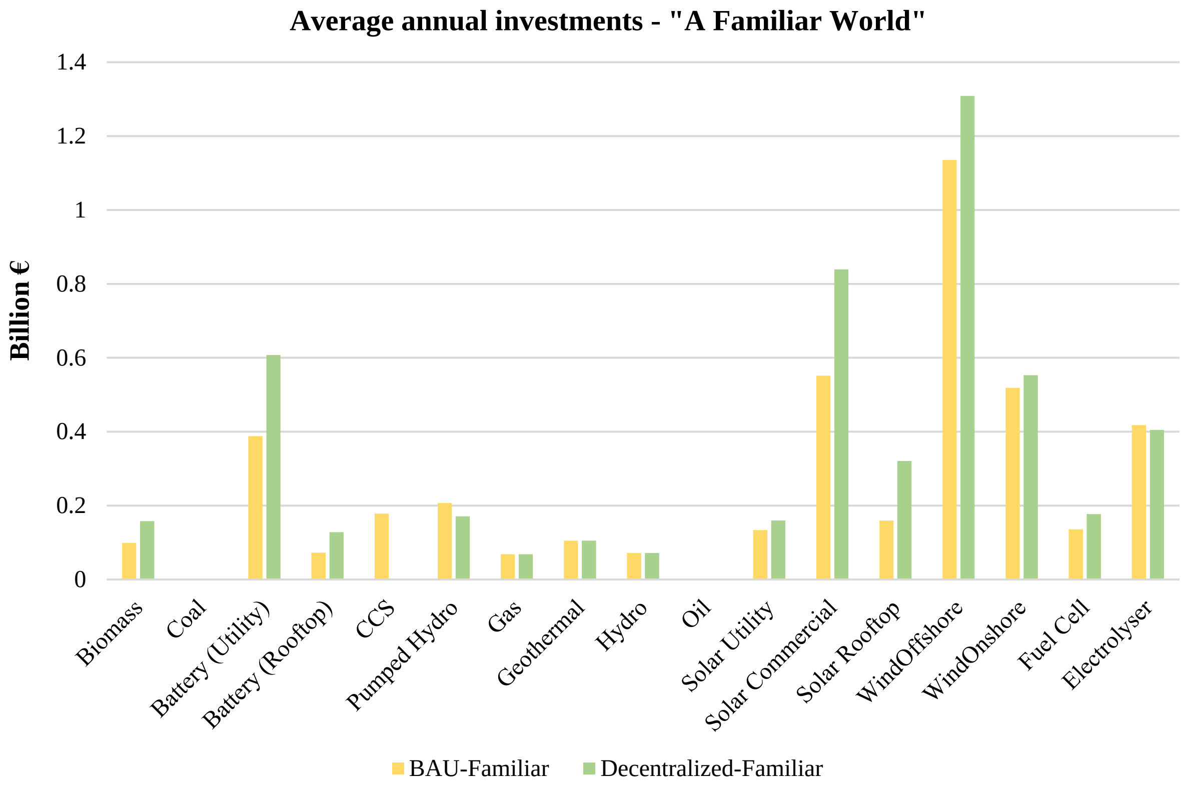

Figure 58. Average annual investments per technology for the "BAU case" and the "Decentralized case" over the period 2024-2050, under the "*Familiar World*" narrative.

Under the "*Unified World*" narrative, annual investments in the electricity supply will increase by 130.8% in the "*Centralized case*", and 83.6% in the "*Decentralized case*", in 2050 compared to 2025.

Similarly to the "*Familiar World*" narrative, annual wind energy investments are projected to increase by 1.6 billion € in the "*Centralized case*", and by 1.31 billion € in the "*Decentralized case*", in 2050 compared to 2025.

Wind power experiences substantial investment growth, averaging a total of 2.2 billion € in the "*Centralized case*" and 1.72 billion € in the "*Decentralized case*" annually, indicating increased focus and funding in this sector (**Figure 59**).

Similarly, investments in solar energy sources are projected to reach 0.68 billion € in the "*Centralized case*" and 1.54 billion € in the "*Decentralized case*" on average, on an annual basis. Solar rooftop and commercial PV systems occupy 12.1% and 68.2% of the average annual investments in total solar power in the "*Centralized case*" and 24.4% and 62.8% of the average annual investments in total solar power in the "*Decentralized case*".

On the other hand, investments in electricity storage will reach an average of 0.29 billion € in the "*Centralized case*" and 0.9 billion € in the "*Decentralized case*" on a yearly basis. Investments in electrolyzers will reach 0.44 billion € in the "*Centralized case*" and 0.33 billion € in the "*Decentralized case*" on average, annually.

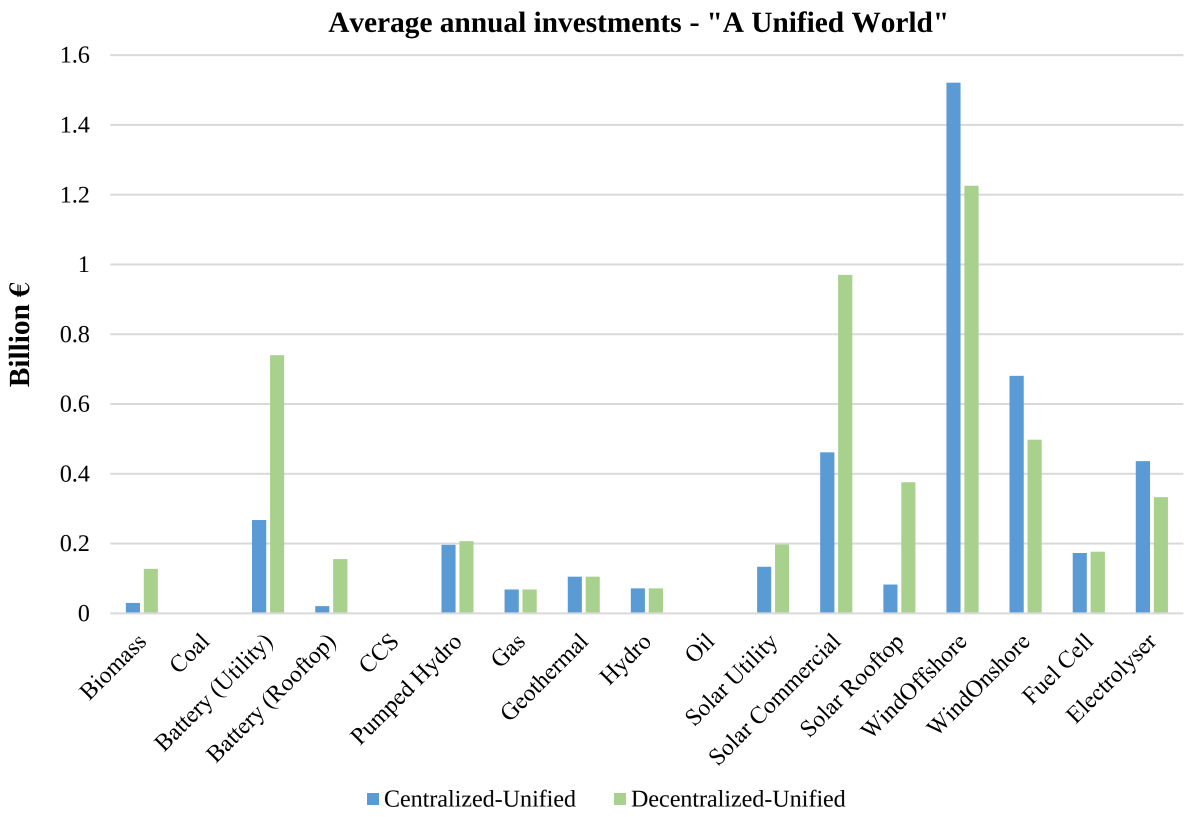

Figure 59. Average annual investments per technology for the “BAU case” and the “Decentralized case” over the period 2024-2050, under the “*Unified World*” narrative.

On an annual basis, under the “*Fragmented World*” narrative, investments in the electricity supply will increase by 136.3% in the “*Gas-dependency case*” and 166.1% in the “*Lignite-dependency case*” in 2050 compared to 2025.

However, total investments under this narrative will be much lower compared to the “*Familiar World*” and the “*Unified World*” narratives.

More specifically, wind energy investments are projected to increase averaging a total of 1.21 billion € in the “*Gas-dependency case*” and 1.5 billion € in the “*Lignite-dependency case*” annually (**Figure 60**).

Similarly, investments in solar energy sources are projected to reach 0.63 billion € in the “*Gas-dependency case*” and 0.75 billion € in the “*Lignite-dependency case*” on average and an annual basis.

On the other hand, investments in electricity storage will reach an average of 0.13 billion € in the “*Gas-dependency case*” and 0.34 billion € in the “*Lignite-dependency case*” on a yearly basis. Investments in electrolyzers will reach 0.18 billion € in the “*Gas-dependency case*” and 0.28 billion € in the “*Lignite-dependency case*” on average annually.

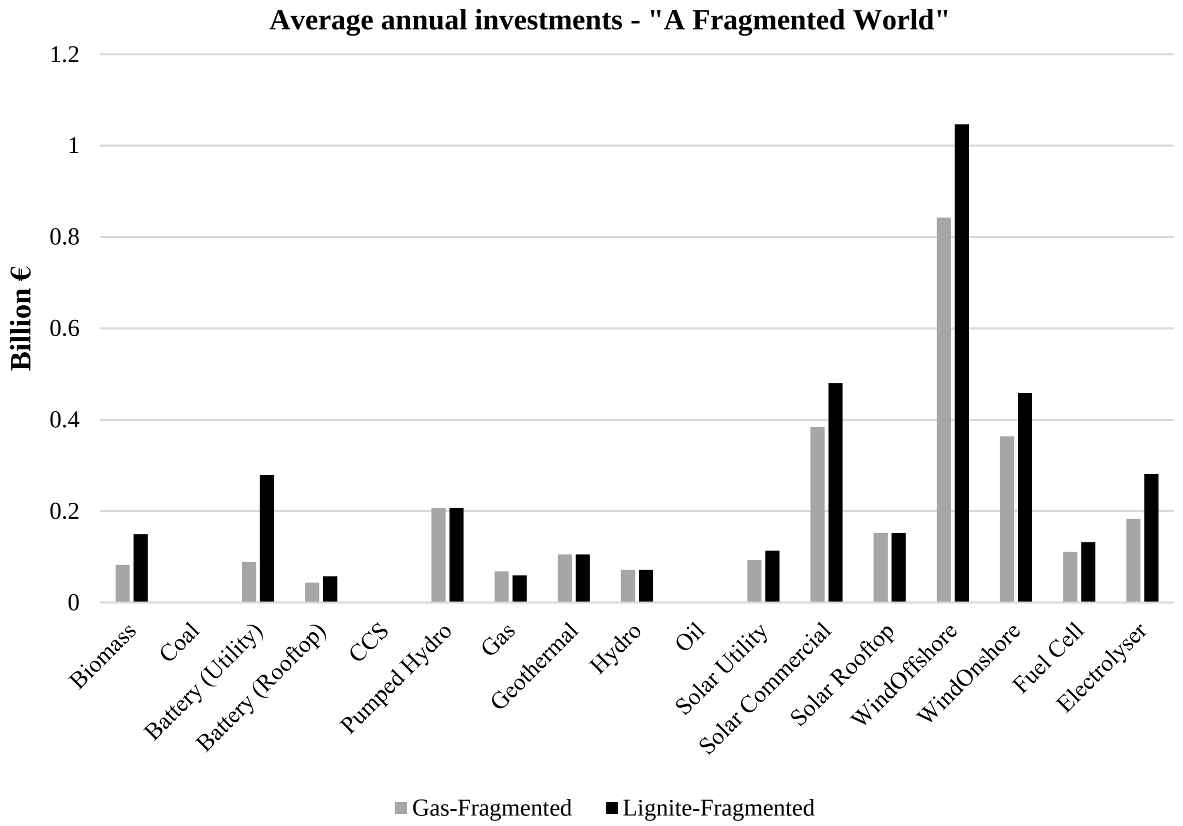

Figure 60. Average annual investments per technology for the "BAU case" and the "Decentralized case" over the period 2024-2050, under the "*Fragmented World*" narrative.

7.2.3. *Power generation by 2050*

Under the "*Familiar World*" narrative, results show an increase in electricity generation by 2050 in both the "*BAU case*" and the "*Decentralized case*", which are dominated by VRE sources (**Figure 61**).

A relative electricity generation increase of 0.379 EJ by 2050 compared to 2025 is projected in the "*BAU Case*", while the respective increase in the "*Decentralized case*" is 0.425 EJ. In the "*BAU Case*", lignite and oil are discontinued after 2027 and 2039, respectively, while natural gas and biomass remain in the electricity mix until 2050, since the remaining gas- and biomass-fired power plants are retrofitted with CCS.

On the contrary, in the "*Decentralized case*", the timeline for phasing out natural gas and biomass- is earlier, i.e., natural gas is phased out after 2037, while biomass is discontinued after 2039.

The reduction of fossil-fired electricity generation is mainly offset by the increase in power produced by VRE. In the "*BAU case*", solar power increases by 246% in generated electricity by 2050 (0.169 EJ) compared to 2025 (0.049 EJ). In the "*Decentralized case*", solar power demonstrates a notable growth with a 391% increase in generated electricity by 2050 (0.258 EJ) compared to 2025 (0.053 EJ).

As shown in both cases, this underscores a substantial shift towards solar power as a pivotal component of the national power supply mix. With regards to the contribution of different solar technologies, commercial and rooftop solar PV generation increases by 206% and 848% by 2050 compared to 2025 in the "*BAU case*".

In the "*Decentralized case*", commercial and rooftop solar PV generation increases by 326% and 1769% by 2050 compared to 2025. The difference in rooftop solar PV generation between the two (2) cases highlights the significant untapped potential of prosumerism in Greece.

Moreover, wind power exhibits an even larger increase in electricity production compared to solar power. In the "*BAU case*", electricity generation from wind power increases by 389% until 2050

(0.261 EJ) compared to 2025 (0.053 EJ). In the "*Decentralized case*", electricity generation from wind power increases by 480% until 2050 (0.303 EJ) compared to 2025 (0.052 EJ). This signals a strong trajectory towards the increased adoption of wind power, both onshore and offshore.

Overall, we find that the "*BAU case*" achieves 64% and 70% of VRE-based electricity in the total electricity mix in 2030 and 2050, while the "*Decentralized Case*" achieves 66.3% and 85.1%, respectively. The main reason behind this discrepancy between the two (2) cases is the share of natural gas and electricity imports in the total electricity mix, which is assumed to be higher in the "*BAU case*".

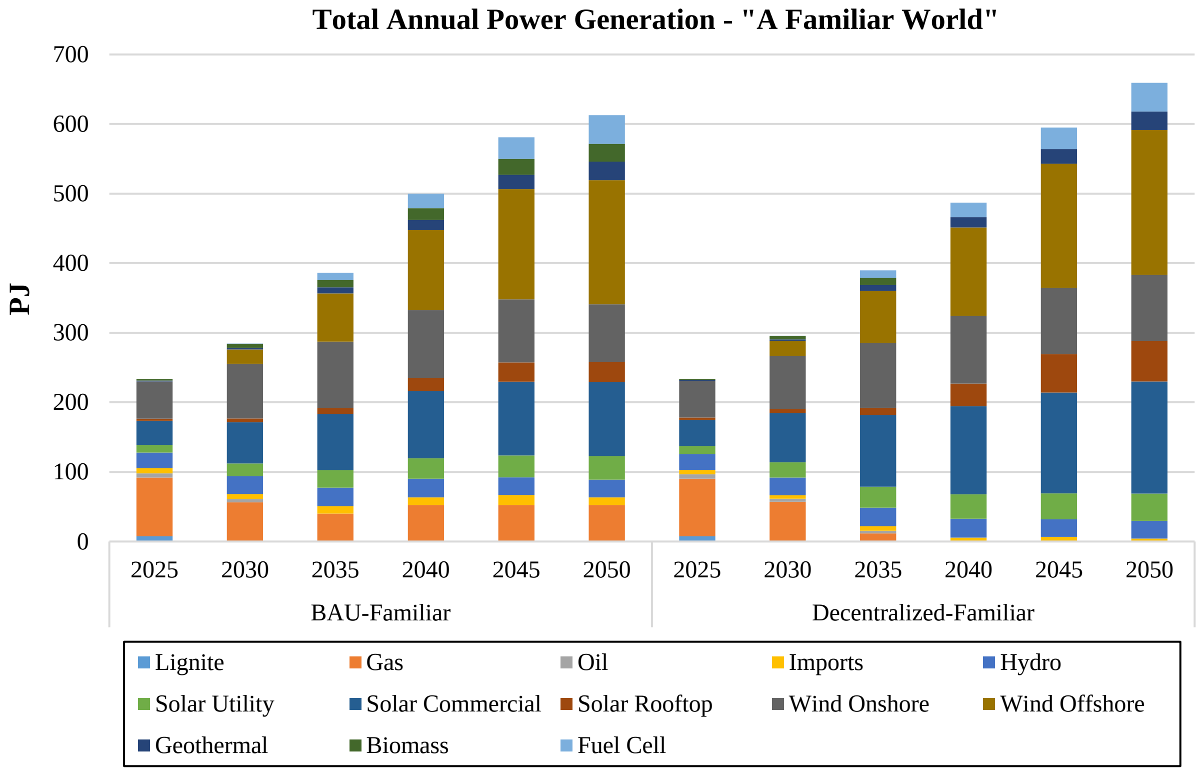

Figure 61. Total annual electricity generation mix in the Greek power sector by 2050 for the "BAU case" and the "Decentralized case" under the "*Familiar World*" narrative.

Under the "*Unified World*" narrative, results show an increase in electricity generation by 2050 in both the "*Centralized case*" and the "*Decentralized case*", which are again dominated by VRE sources (**Figure 62**).

A relative electricity generation increase of 0.41 EJ by 2050 compared to 2025 is projected in the "*Centralized Case*", while the respective increase in the "*Decentralized case*" is 0.446 EJ.

Furthermore, across the two (2) cases there is a consistent pattern of 100% reduction in electricity generation from lignite after 2025, gas after 2030, biomass and oil after 2035, signifying a complete phase out of traditional energy sources and complete dominance of VRE in the power mix.

The reduction of fossil-fired electricity generation is mainly offset by the increase in power produced by VRE. In the "*Centralized case*", solar power increases by 231% in generated electricity by 2050 (0.145 EJ) compared to 2025 (0.044 EJ). In the "*Decentralized case*", solar power demonstrates a remarkable growth with a 470% increase in generated electricity by 2050 (0.298 EJ) compared to 2025 (0.052 EJ).

With regards to the contribution of different solar technologies, commercial and rooftop solar PV generation increases by 390% and 1849% by 2050 compared to 2025 in the "*Decentralized case*". In the "*Centralized case*", commercial and rooftop solar PV generation increases by 211% and 371% by 2050 compared to 2025. Under this "*future-world*" narrative, wind power exhibits a much larger increase in electricity production compared to solar power under the “*Centralized case*” and a slightly smaller increase in electricity production compared to solar power under the “*Decentralized case*”.

Specifically, in the “*Centralized Case*”, electricity generation from wind power increases by 561% by 2050 (0.36 EJ) compared to 2025 (0.054 EJ). In the “*Decentralized case*”, electricity generation from wind power increases by 449% by 2050 (0.281 EJ) compared to 2025 (0.051 EJ).

Overall, we find that the “*Centralized case*” achieves 61.1% and 78.4% of VRE-based electricity in the total electricity mix in 2030 and 2050, while the “*Decentralized case*” achieves 63.8% and 85.2%, respectively. The main reason behind this discrepancy between the two (2) cases is the share of electricity imports in the total electricity mix, which are much higher in the “*Centralized Case*” (2.3 and 6.3 times higher in 2030 and 2050, respectively).

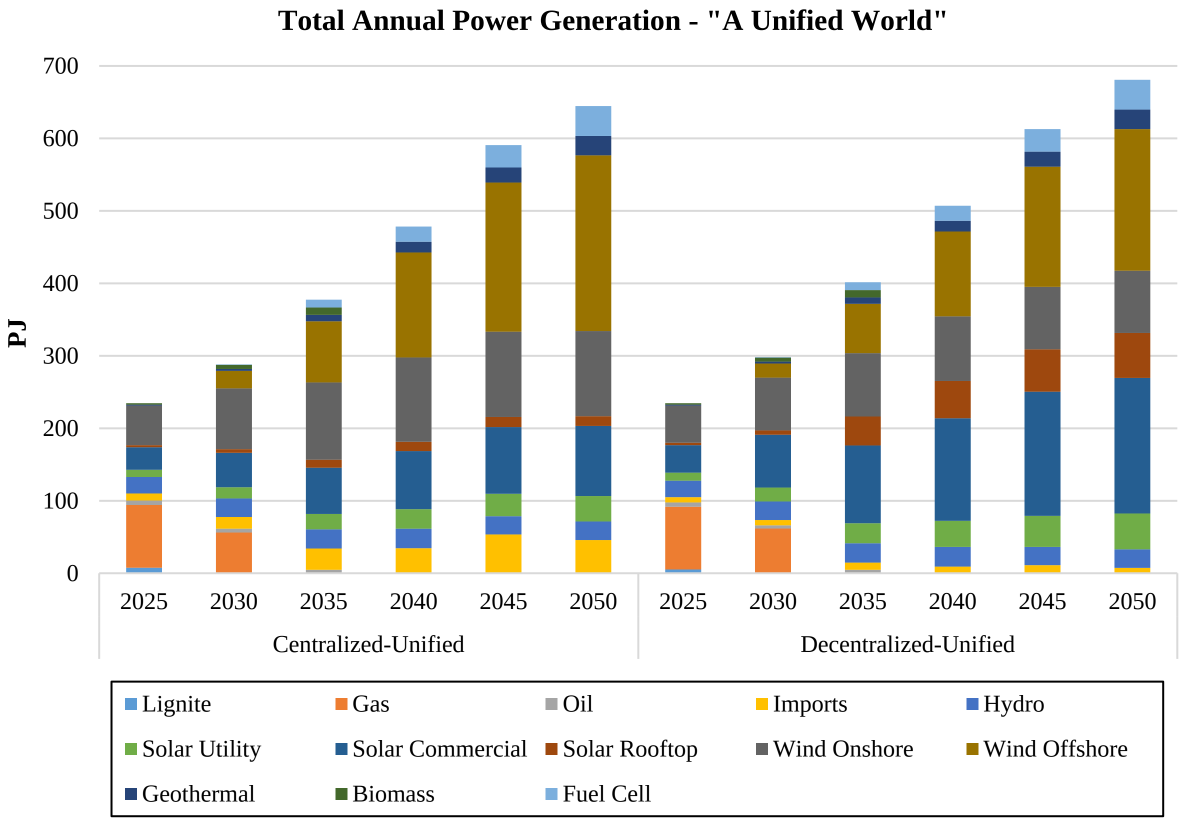

Figure 62. Total annual electricity generation mix in the Greek power sector by 2050 for the “BAU case” and the “Decentralized case” under the “*Unified World*” narrative.

Under the “*Fragmented World*” narrative, results show an increase in electricity generation by 2050 in both the “*Gas-dependency case*” and the “*Lignite-dependency case*”; however, variable renewable electricity production is offset by fossil-fired electricity generation to a larger extent (**Figure 63**).

A relative electricity generation increase of 0.384 EJ by 2050 compared to 2025 is projected in the “*Gas-dependency case*”, while the respective increase in the “*Lignite-dependency case*” is 0.37 EJ. In contrast to the “*Familiar World*” and “*Unified World*” narratives, fossil-fuel use for electricity generation is regularly continued until 2050 under the “*Fragmented World*” narrative.

In the “*Gas-dependency case*”, gas use increases by 91% in generated electricity by 2050 (0.157 EJ) compared to 2025 (0.082 EJ). In the “*Lignite-dependency case*”, lignite use increases by 167% in generated electricity by 2050 (0.072 EJ) compared to 2025 (0.027 EJ).

The increase of fossil-fueled electricity generation displaces a part of the power that would be produced by VRE. In the “*Gas-dependency case*”, solar power increases by 225% in generated electricity by 2050 (0.137 EJ) compared to 2025 (0.042 EJ). In the "*Lignite-dependency case*", solar power increases by 261% in generated electricity by 2050 (0.159 EJ) compared to 2025 (0.044 EJ).

In the "*Gas-dependency case*", electricity generation from wind power increases by 304% by 2050 (0.197 EJ) compared to 2025 (0.049 EJ).

In the "*Lignite-dependency case*", electricity generation from wind power increases by 386% by 2050 (0.246 EJ) compared to 2025 (0.051 EJ).

Overall, we find that the "*Gas-dependency case*" achieves 47.4% and 54% of VRE-based electricity in the total electricity mix in 2030 and 2050, while the "*Lignite-dependency case*" achieves 50.6% and 67%, respectively.

The main reason behind this discrepancy between the two (2) cases is the share of electricity provided by fossil fuels in the total electricity mix, which is higher in the "*Gas-dependency case*" especially after 2035 (2.2 times higher in 2050).

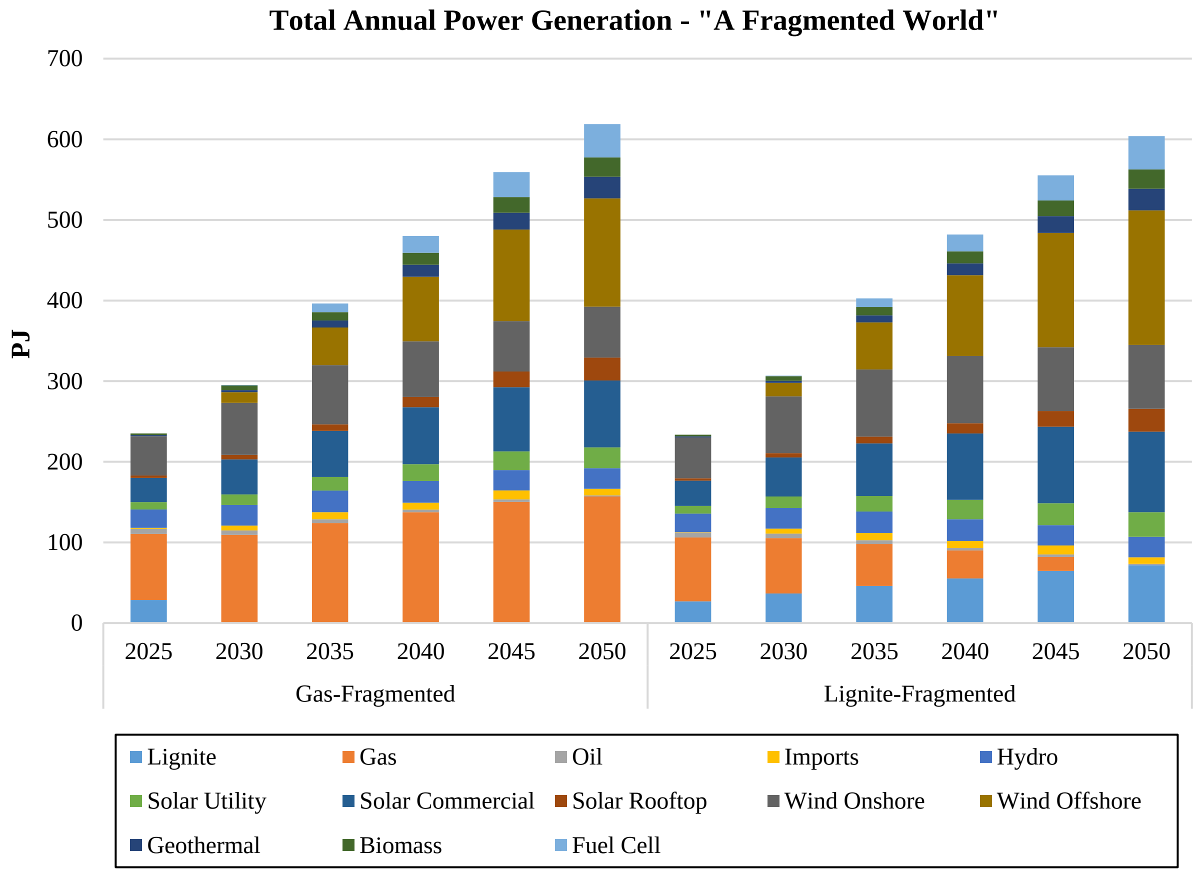

Figure 63. Total annual electricity generation mix in the Greek power sector by 2050 for the "BAU case" and the "Decentralized case" under the "*Fragmented World*" narrative.

7.2.4. CO$_2$ footprint by 2050

A decreased carbon footprint following a logarithmic trend is achieved across the "*BAU Familiar*", "*Decentralized Familiar*", "*Centralized Unified*", and "*Decentralized Unified*" scenarios due to the reduction of fossil-fueled electricity generation (**Figure 64**).

Under the "*Familiar World*" narrative, results show that the complete phaseout of fossil fuels leads to decarbonization in the power sector in 2040, while, under the "*Unified World*" narrative, decarbonization in the power sector is achieved after 2035.

On the contrary, the "*Gas Fragmented*" and "*Lignite Fragmented*" scenarios will lead to increased carbon footprints that follow exponential trends due to the extended fossil-fuel use until 2050. Specifically, carbon footprints of 0.39 Gton of CO_2 (4.7 times higher than the "*BAU Familiar*" scenario) and 0.56 Gton (6.7 times higher than the "*BAU Familiar*" scenario) are reached in the "*Gas Fragmented*" and "*Lignite Fragmented*" scenarios, respectively.

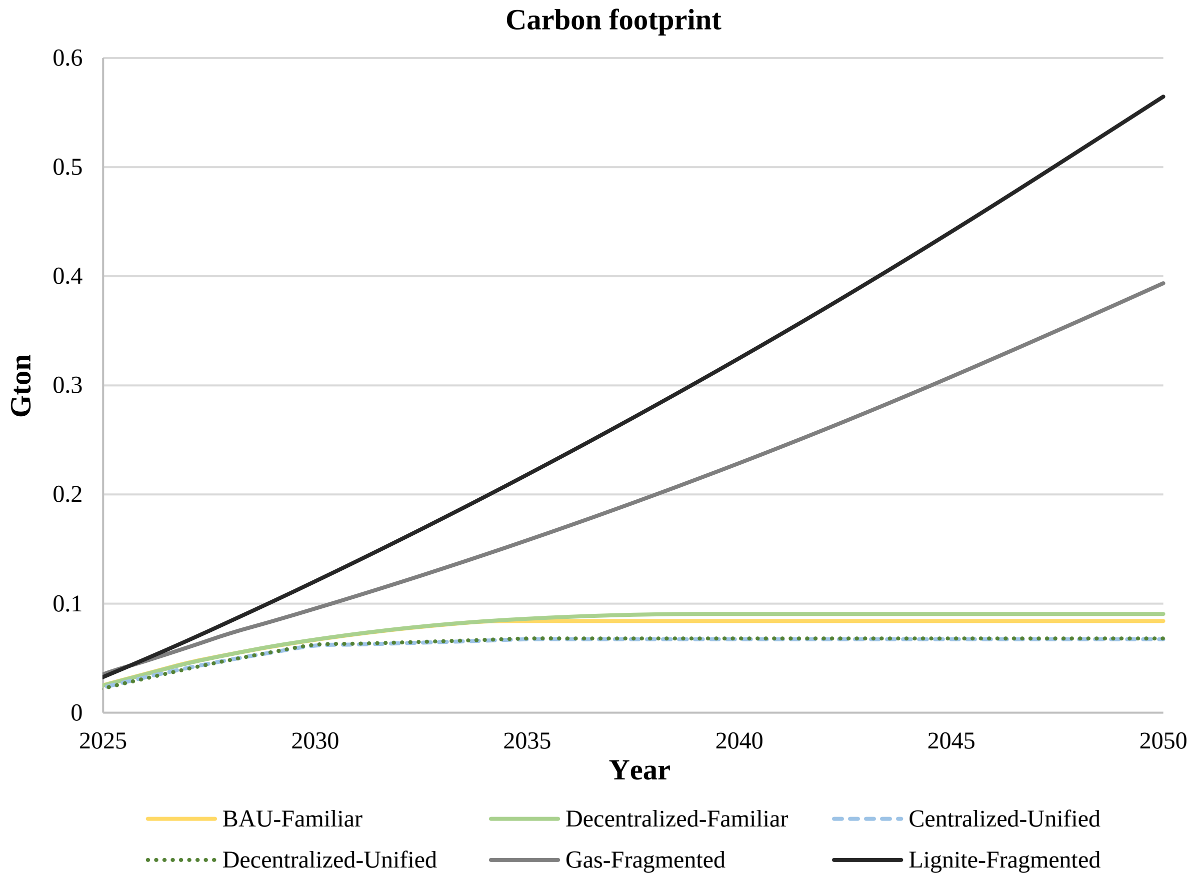

Figure 64. Total annual CO_2 footprint in the Greek power sector by 2050 for the "*BAU Familiar*", "*Decentralized Familiar*", "*Centralized Unified*", "*Decentralized Unified*", "*Gas Fragmented*", and "*Lignite Fragmented*" scenarios.

7.2.5. Total costs of electricity supply by 2050

Macroeconomic results under the "*Familiar World*" and the "*Unified World*" narratives imply that the energy transition will alter the cost structure in the power sector, cutting variable operating costs as well as costs owing to the emission penalties of the fossil-fired power plants, while boosting capital expenditures for green technologies.

By comparing the total cost of electricity supply between the "*BAU Familiar*" and the "*Decentralized Familiar*" scenarios, we see that decentralization of the electricity supply will require additional 22.5 billion € of capital investments, while 21.6 billion € of variable cost expenditures will be saved from this strategy.

Overall, the BAU energy planning will lead to cost savings of 4.8 billion € (**Figure 65**).

Under the "*Unified World*" narrative, results show that the "*Centralized Unified*" scenario is more economically efficient than the "*Decentralized Unified*" scenario by 24.3 billion €, due to the much higher capital investments required in the "*Decentralized case*".

Under this world narrative, the "*Centralized case*", which is based on higher amounts of imported electricity, benefits both from the better interconnections between Greece and its neighboring countries and the declining trend of electricity prices, ultimately resulting in 8 billion € of additional variable cost expenditures compared to the "*Decentralized case*".

On the contrary, the "*Centralized case*" saves 32.2 billion € of capital and fixed cost expenditures compared to the "*Decentralized case*".

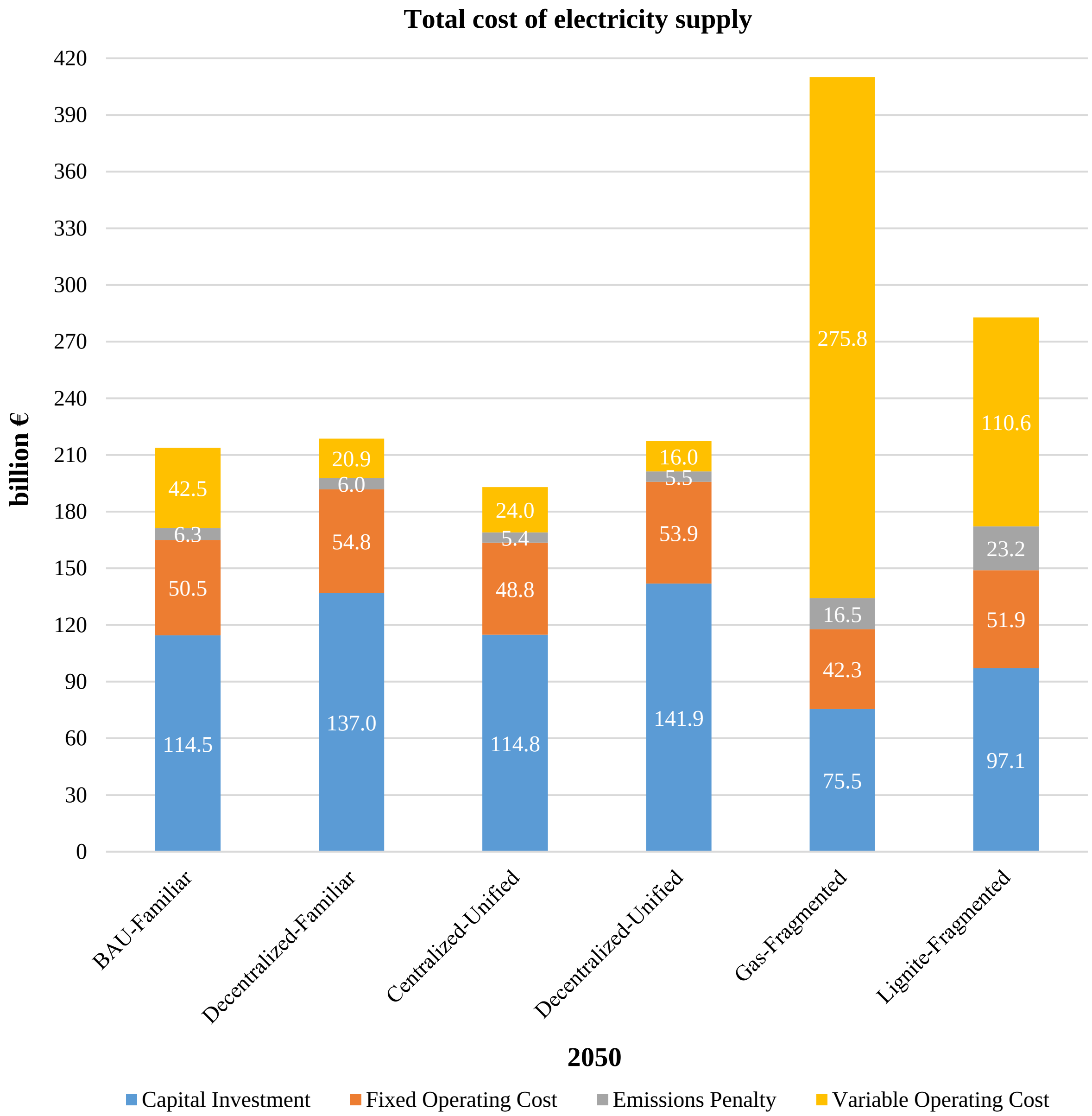

Figure 65. Total cost of electricity supply in the Greek power sector over the period 2024-2050 for the "*BAU Familiar*", "*Decentralized Familiar*", "*Centralized Unified*", "*Decentralized Unified*", "*Gas Fragmented*", and "*Lignite Fragmented*" scenarios.

7.2.6. Socioeconomic benefits for citizens

The results from the technoeconomic analysis on solar rooftop PV investments showcase different profitability levels across the scenarios and specific policy mixes in question (**Figure 66**).

More specifically, under the "*Familiar World*" narrative, the "*Decentralized case*" achieves higher profitability than the "*BAU case*", due to the larger capacity expansion of solar rooftop PV systems.

Under the "*Unified World*" narrative, the "*Decentralized case*" achieves ~2-3 times higher profitability than the "*Centralized case*", due to the even higher difference in the capacity growth of solar rooftop PV systems between the two cases.

As such it can be clearly shown that the "*Decentralized case*" presents ***a more democratized and equitable future*** in which ***socioeconomic benefits are distributed between a larger share of citizens and thus more people can catch up with the energy transition***.

Contrastingly, the "*Centralized case*" presents a *more individualistic and unfair future* in which socioeconomic benefits are distributed between *a smaller share of people* and thus ***more people are expected to be left behind amidst the energy transition***.

Under the "*Fragmented World*" narrative, citizens can benefit more than the "*BAU case*" because of the much higher wholesale and retail electricity prices. This is particularly evident in the "*Gas-dependency case*" in which the total system cost skyrockets, due to the more expensive natural gas imports, which in turn increases the wholesale and retail electricity prices.

A key difference lies between the "*Familiar World*" narrative and the "*Unified World*" narrative in terms of the profitability derived from the "*Decentralized case*". This difference stems from the adoption rate of solar rooftop PV which is higher in the "*Unified World*" narrative (logarithmic trend) compared to the "*Familiar World*" narrative (S-curve trend).

This highlights the imminence of citizen action since the earlier citizens start implementing solar rooftop PV investments the higher the potential socioeconomic benefits are going to be.

This finding is further strengthened due to the shift across the EU from policy instruments like FiT to the promotion of self-consumption, employing net metering and net billing regimes as a fundamental tool to mainstream solar rooftop PV installations.

Given that future installations will be mostly supported by the net billing scheme, which will largely displace the current net metering scheme, this policy change may result in potential profitability losses for citizens.

However, the potential profitability losses due to the suggested change in the policy mix are expected to be significantly lower than those that may occur due to the uncertainty in key contextual factors (e.g., prices).

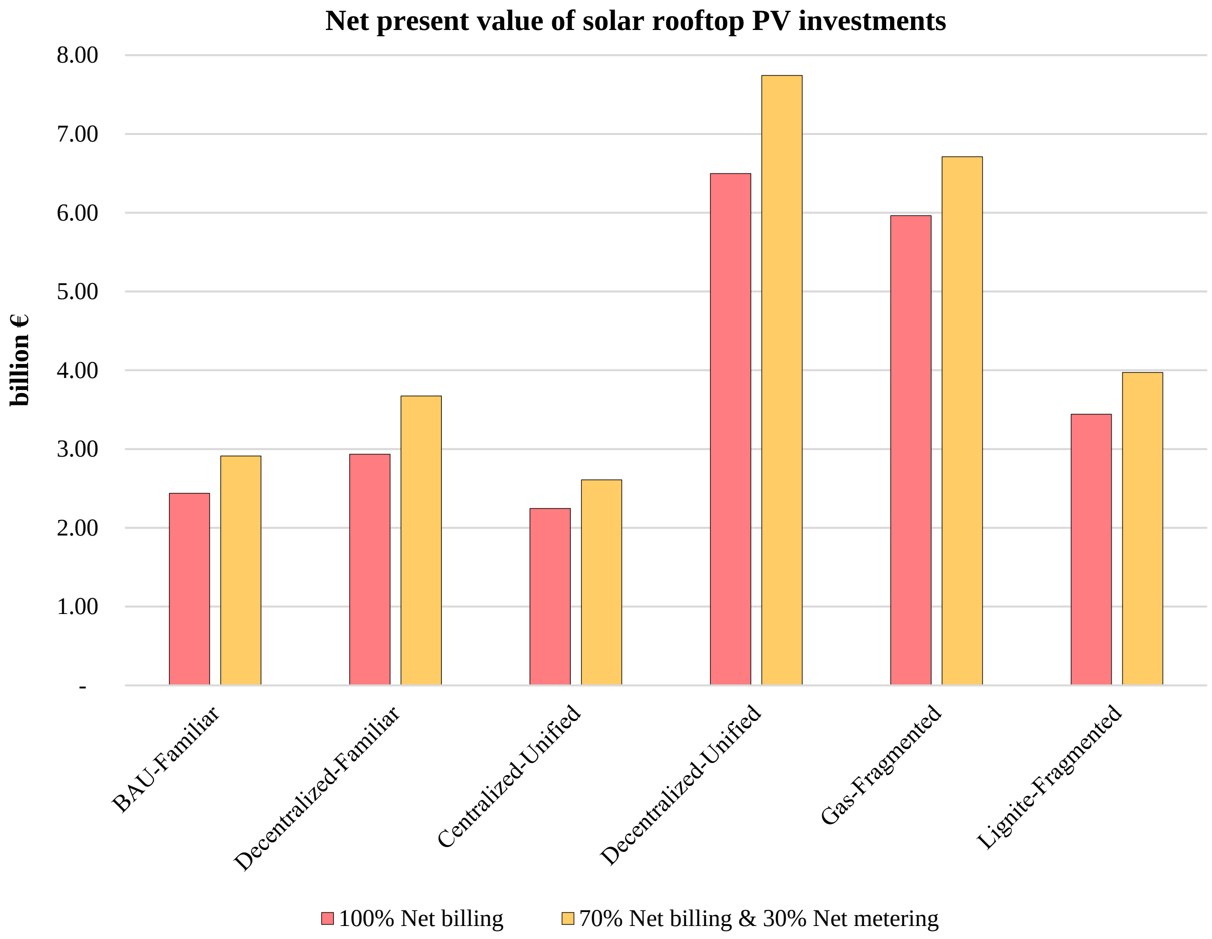

Figure 66. Net present value of rooftop solar PV investments over the period 2024-2050 for the "*BAU Familiar*", the "*Decentralized Familiar*", the "*Centralized Unified*", the "*Decentralized Unified*", the "*Gas Fragmented*", and the "*Lignite Fragmented*" scenarios.

7.3. Decarbonizing the transport and the residential sectors in Western Europe under different "people-centered" storylines

We present modeling outcomes on the decarbonization pathways (**Figure 67**), as derived from IMAGE model for twelve (12) scenarios, combinations of the three (3) ENCLUDE "*future-world*" narratives, and the four (4) "*people-centered*" storylines.

Decarbonization pathways present CO_2 emissions per capita from 2015 to 2050 in Western Europe for transport (left) and residential (right) based on the inputs detailed in **Table 12** (i.e., "*future-world*" narratives) and **Table 13** (i.e., "*people-centered*" storylines).

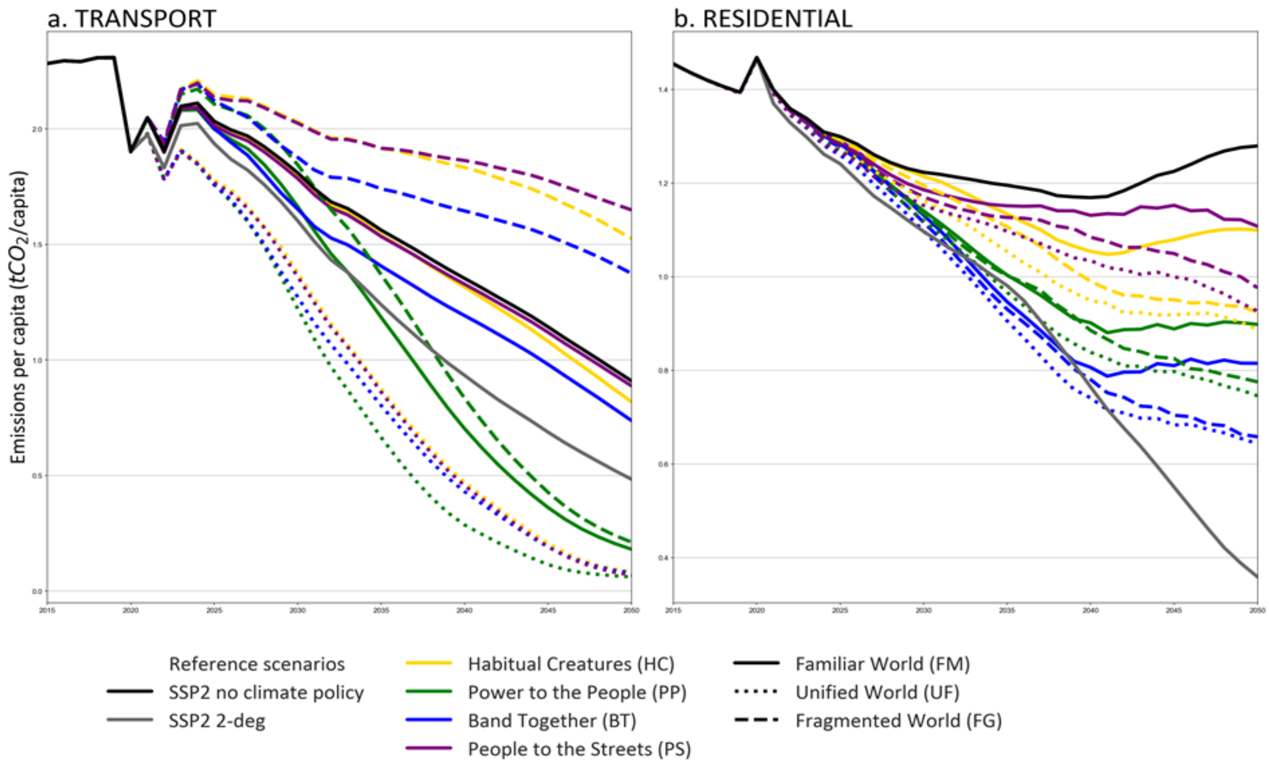

Figure 67. Decarbonization pathways in Western Europe under the ENCLUDE “people-centered” storylines and “future-world” narratives, as derived from the IMAGE model.

7.3.1. Decarbonization in the Western Europe’ transport sector by 2050

In the Western Europe’s transport sector (**Figure 67a**), a noteworthy drop in emissions is from the “*Power to the People”* storyline (in green) compared to the “*Familiar World” narrative* without climate policy (in black), where we assume high EV adoption (i.e., almost 100% by 2050) for electricity storage but also for driving. This pathway goes beyond the 2 °C target for 2050.

For the “*Habitual Creatures*” storyline, emission reduction is attributed to the shift to public and active transport directly, also shown in the modal split (**Figure A1** in **Appendix**), where the “*Habitual Creatures*” storyline is represented with the label “*HC_familiar*” in black.

For the “*Band Together*” storyline, emission reduction is due to car sharing and carpooling, with reduced car ownership, and consequently more public transit and active travel. This can be seen in the passenger mode split (**Figure A1** in **Appendix**), where under the “*Band Together*” storyline (represented with the label “*BT_familiar*” in green), there is a shift away from cars (shown in blue) towards buses and trains.

The total reduction of passenger-kilometers is shown in the passenger travel demand (**Figure A2** in **Appendix**), where the reduction is significantly lower compared to the other options, attributed to the car sharing and carpooling.

Finally, as expected, emission reduction under the “*People to the Streets*” storyline is less, because the focus is more on the energy system.

7.3.2. Decarbonization in the Western Europe’s residential sector by 2050

In the Western Europe’s residential sector, (**Figure 67b**), the “*Band Together*” storyline (in blue) shows the most significant reduction in emissions from the no climate policy scenario (in black) attributed to further communal geothermal heat pump adoption, communal living, and mini grids through higher PV adoption at scale.

The space heating energy demand (**Figure A3** in **Appendix**) and space cooling (**Figure A4** in **Appendix**) shows the impact of heat pump adoption and communal living on energy demand, almost having the energy use by 2050 compared to an SSP2 reference. However, the levels of emission reduction are still far from the 2 ^{o}C target for 2050.

The “*Power to the People*” storyline also shows substantial levels of emission reduction from high insulation levels, rooftop PV systems, and air-source heat pump adoption. The impact of the heat pump adoption is shown in energy demand for space heating, with about a third reduction in energy from SSP2 reference (**Figure A3** in **Appendix**).

For the “*Habitual Creatures*” storyline, the emission reduction levels are not as large, but still noteworthy, with incremental adjustments such as thermostat 2 ^{o}C increase (when warm), or decrease (when cold), housing efficiency and shorter showers, housing choices such as fewer appliances (i.e., dryer ownership) and smaller floorspace. The effects of the thermostat adjustments and smaller floorspace is visible in the space heating energy demand (**Figure A3** in **Appendix**) and space cooling (**Figure A4** in **Appendix**).

Lastly, results under the “*People to the Streets*” storyline show the indirect impacts of public awareness campaigns, advocacy and lobbying and shareholder activism, community lawsuits, and protest and demonstrations. We show this by assuming higher capital floor costs for other technologies, learning rates multiplied, higher capacity investments in electricity and a push for hydrogen usage.

8. Conclusions, recommendations, and further research

To realize the goal of a sustainable and just transition by 2050, the European Union has acknowledged the importance of citizens and other members of society in recent strategic and legislative frameworks. In this context, individuals are expected to become prosumers and contribute within energy communities or other collective targeted actions, impacting the emission reduction trajectory and governance of the energy system.

Therefore, transitions must meet the criteria of technological viability, economic feasibility, and social and political acceptability, taking into account individual preferences, degrees of acceptance, and changes in behavior and lifestyle.

Considering the above, the concept of energy citizenship has become increasingly important in recent literature. Energy citizenship is deemed compatible with and can make a significant contribution to scenario-based analyses, which aim to develop transition pathways towards desired energy futures and the goal of climate neutrality.

However, simply creating narratives and scenarios is not enough. Policymakers need modeling tools which can analyze the relationship between economic decision-making and behavioral change to make informed decisions and get assistance.

Despite the increasing importance of modeling approaches, most tools primarily focus on technoeconomic or cost optimization methods and consider the social dimension of the energy transition as a secondary aspect or represented with stylized assumptions (van den Berg et al., 2019).

They view society as a broader social context and have limitations in incorporating the dynamics of sociotechnical factors, such as policy preferences, behavioral patterns, or social acceptance of specific technologies. Consequently, they do not adequately consider the complex interaction between sociotechnical aspects and other crucial elements such as energy, economy, and environment.

The impact of sociotechnical factors on the speed of the energy transition is significant. This emphasizes the growing recognition of the importance of these aspects and their dynamics, making them essential in developing modeling tools.

Therefore, to investigate the sociotechnical pathways that would lead Europe to achieve climate neutrality by 2050, it is crucial to develop new or improve existing modeling methods to meet pressing needs.

8.1. Modeling storylines of energy citizenship under different “future-world” narratives at the national and the supranational levels

Energy citizenship has a diverse range of manifestations that can have a substantial impact on decarbonization efforts in different contexts and scales within the EU. This deliverable focuses on incorporating a quantitative aspect into the research around the concept of energy citizenship and its manifestations at the national and the supranational levels.

To do so, we utilize three (3) modeling tools to investigate the relationship between different manifestations of energy citizenship and their emission reduction potential in macro-scale energy systems. To achieve this goal, we employed a multi-method approach that combined the strengths of energy system modeling with a framework for transformative scenario design based on social innovations and storylines of energy citizenship and narratives of potential evolutions of the future.

More specifically, our approach consisted of five (5) main methodological steps. These steps involved identifying patterns and trends of energy citizenship, as described in **Deliverable 5.1**, and formulating the ENCLUDE “*people-centered*” storylines and “*future-world*” narratives, as outlined in **Deliverable 5.2**. This led to the creation of the ENCLUDE scenario space and the simulation of case-specific decarbonization pathways at both the local (**Deliverable 5.3**) and the national/ EU level (presented in this report).

Before applying the ENCLUDE modeling ensemble to the case studies, we performed a gap analysis to identify previously unexplored patterns and trends of energy citizenship that were not accounted for by our modeling tools. This analysis took into account the "*people-centered*" storylines and the "*future-world*" narratives, as well as the knowledge gained from the work done in the ENCLUDE **WP3**, and feedback from relevant end-users and stakeholders.

During this process, we not only found out additional model developments, modifications, and adjustments, but we also obtained a thorough comprehension of the connection between the identified patterns and trends of energy citizenship (both on the individual and the collective levels), sociotechnical dynamics and decarbonization pathways, and the capabilities of the ENCLUDE modeling ensemble.

By utilizing the previous work and following the overarching framework established within **WP5**, our main objective, in this report, was to create transition scenarios and decarbonization pathways for macro-scale case studies in different geographical and socioeconomic contexts.

To tailor our approach to the specific attributes of the examined case studies and to conform with the identified patterns and trends of energy citizenship, we enhanced the existing modeling ensemble that was introduced in **Deliverable 5.1**.

This expansion involved the integration of two (2) additional modeling tools. In this report, we showcased one of these new features: the OSeMOSYS-GR model based on the OSeMOSYS model generator. This addition improved the capabilities of the ENCLUDE modeling ensemble, allowing more comprehensive investigations of the various manifestations of energy citizenship at the national level.

Overall, three (3) different models, i.e., the ABM **ATOM**, the CEM **OSeMOSYS-GR**, and the IAM **IMAGE**, were used to simulate the case-specific decarbonization pathways outlined in this deliverable.

Using the **ATOM** model, we investigated the "*Power to the People*" storyline and the decarbonization potential of prosumerism within different geographical and socioeconomic contexts across the EU, with a specific focus on Denmark, France, and Greece.

For this specific application, **ATOM** evaluated the adoption potential of small-scale solar PV systems, considering a diverse range of agent-related factors, including inertia towards PV investments, resistance to adopt small-scale solar PV systems, and propensity to engage in prosumer activities, as well as market-related parameters, such as capital costs associated with solar PV systems, household electricity prices, feed-in tariffs, etc.

Utilizing the **OSeMOSYS-GR** model, we computed the potential impact wielded by citizen-led energy sectoral planning and decision-making processes, underscoring citizens preferences and acceptance as catalysts for contributing in decarbonization efforts in the Greek power sector.

Specifically, we assessed key energy, environmental, and economic impacts of active participation in the energy market under the "*Power to the People*" storyline and energy transition movements under the "*People to the Streets*" storyline within the future Greek electricity system. We did not only describe the technical prerequisites but also provided insights on the nuanced socioeconomic and behavioral factors influencing the transition towards a decarbonized power sector while stimulating inclusive participation and equitable distribution of benefits across society.

With regards to the supranational case study, we first identified the themes, behavioral actions, motivations, and enabling factors of the "*people-centered*" storylines (i.e., "*Power to the People*", "*Habitual Creatures*", "*Band Together*", and "*People to the Streets*") using insights on factors influencing emergence of CEIs from **WP3**. With the **IMAGE** model, we then provided insights into the potential long-term decarbonization pathways of energy citizenship at the supranational level, and specifically in Western Europe.

Harnessing the capabilities of **IMAGE**, we delineated the complex connections between environmental shifts and broader human development dynamics and the inherent uncertainties surrounding environmental transformations by combining each one of the "*people-centered*" storylines with each one of the "*future world*" narratives (i.e., "*Familiar World*", "*Unified World*", and "*Fragmented World*").

8.2. Decarbonization potential of energy citizenship at the national and the European levels

As part of this report, we aimed at creating the ENCLUDE scenario space for model applications at the national and the European levels based on previous modeling work we performed and already presented in **Deliverable 5.3**, and the further expansion and adjustment of the SSPs' qualitative descriptions to formulate a new set of three (3) qualitative descriptions of potential future-world evolutions, the ENCLUDE *"future-world"* narratives.

Specifically, by combining the "*people-centered*" storylines with the "*future-world*" narratives, we developed a framework for transformative scenario design, and we broadened our scenario typology by introducing alternative scenarios that delve into the uncertainty surrounding future societal, governance, and climatic conditions.

These scenarios depict the evolution of sociotechnical aspects that are challenging to quantify, such as behavioral change, social acceptance, and social norms, serving as a foundation for further scenario-based research and modeling applications.

This method enabled us to capture the impact of different external systemic changes including shifts in governmental institutions, organizational dynamics, and broader societal transformations on citizen-led energy transitions at a national and a supranational scale.

8.2.1. Empowering prosumerism and citizen adoption of small-scale photovoltaic systems at the Member State level by 2030

Modeling work under **Deliverable 5.3**, where we conducted a technoeconomic assessment and an assessment of the decarbonization potential of prosumerism at the local (household) level (for 11 cities across the EU), led us to a paradox. More specifically, we identified that even under a potential "*Fragmented World*" narrative, citizens' profitability from investing in small-scale solar PV systems and the resulting decarbonization potential by 2050 are significantly higher compared to the "*Unified World*" narrative.

These results showcased that even in a "*fragmented*" future world, prosumers are protected from the risk of elevated electricity prices, and they could strongly support decarbonization efforts in the residential sector. These benefits are mainly attributed to the increased electricity prices and emission factors assumed under the "*Fragmented World*" narrative, combined with the timing of the investment, which was assumed to take place in the baseline year of the analysis, i.e., 2024.

However, this was a "static" analysis shedding light on interesting insights regarding the profitability potential and the resilience of prosumer-empowering policy schemes in the EU. Expanding this work, in this deliverable, we increased the dynamic nature of our work by better modeling the investment horizon of citizens, which was assumed to take place in any year from 2024 to 2030.

Thus, by following an ABM modeling approach, which allows for more "*real-world*" and dynamic representations of different enabling factors, like, for example, capital costs of investing, decision-making behavior of citizens, etc., under the specifications of each "*future-world*" narrative, we managed to expand the "static" technoeconomic-based modeling work of Deliverable 5.3 into a more realistic and holistic evaluation of the adoption potential of small-scale PV systems.

To achieve this, we utilized the agent-based model **ATOM**, which based on the plausibility of its results compared to historical data and observations, simulates the expected effectiveness of various policy schemes on technology adoption (small-scale solar PV systems, BESS, heat pumps, EVs, etc.) in the residential sector, for the geographical and socioeconomic contexts of interest. The model's main novelty mainly lies in obtaining realistic uncertainty bounds and splitting the total model's output uncertainty in its major contributing sources, while also accounting for structural uncertainty.

In this study, we delved into *how different policy schemes could empower prosumerism and further citizen adoption of small-scale PV systems in different Member states by 2030, under a "Power to the People" storyline and different potential evolutions of the future.*

Modeling simulations led to different projections for small-scale PV capacity additions by 2030 in the Member States under study, i.e., Denmark, France, and Greece, as follows:

- Under the "*Familiar World*" narrative: In the case of Denmark and the FiT policy, projected capacity additions were computed at around 400 MW by 2030, while in the cases of France and Greece results projected expected capacity additions of 671 MW and 265 MW, respectively.

  On the other hand, for the net metering policy, projected PV capacity additions by 2030 were computed at around 261 MW in the case of Denmark, 379 MW in the case of France, and 115 MW in the case of France.

  Finally, for the net metering policy scheme with BESS total PV capacity additions by 2030 in the case of Denmark were projected at around 110 MW, while they were found at around 202 MW and 115 MW in the cases of France and Greece, respectively.
- Under the "*Unified World*" narrative: PV capacity additions by 2030 in the case of Denmark and the FiT policy were found at around 440 MW, while PV capacity additions in the cases of France and Greece were found at around 923 MW and 290 MW, respectively.

  On the other hand, in the case of the net metering policy, projected PV capacity additions by 2030 in the case of Denmark were computed at around 274 MW, while in the cases of France and Greece, were computed at around 471 MW and 120 MW, respectively.

  Lastly, in the case of the net metering policy with BESS, total projected PV capacity additions by 2030 in the case of Denmark were found at around 212 MW, while they were found at around 266 MW and 123 MW in the cases of France and Greece, respectively.
- Under the "*Fragmented World*" narrative: In the case of Denmark and the FiT policy, total PV capacity additions by 2030 were computed at around 120 MW, while in the cases of France and Greece, they were computed at around 246 MW and 215 MW, respectively.

  On the other hand, in the case of the net metering policy, the projected PV capacity additions by 2030 in the case of Denmark were computed at around 132 MW, while in the cases of France and Greece they were computed at around 184 MW and 98 MW, respectively.

  Finally, in the case of the net metering policy, the total project PV capacity additions by 2030 in the case of Denmark were found at around 33 MW, while they were found at around 100 MW and 92 in the cases of France and Greece, respectively.

As expected, modeling results showed that the overall adoption potential is higher under the "*Unified World*" narrative for all the three (3) policy schemes under study.

In addition, our modeling results also showed that the decarbonization potential of small-scale solar PV systems in the Member States under study, is considerably higher once again under the "*Unified World*" narrative, in all the three (3) policy schemes under study.

Our results also point out that the greater potential for further emission reduction due to prosumerism is achieved, as expected, in Greece, whose power sector is more carbon intensive (as it is mainly based on natural gas), compared to Denmark and France, whose power sectors are mainly based on wind and nuclear energy, respectively.

Moreover, by comparing our results across the case studies, useful cross-cutting findings regarding citizens' decision-making behavior and the expected uncertainty when it comes to further adoption of small-scale PV systems can be extracted:

- Higher uncertainty bounds are observed in the case of the FiT policy scheme. FiT schemes are generally characterized by a more "*static*" nature, which leads to more uncertainty, mainly due to the guardedness of citizens towards the skyrocketing evolutions of electricity prices compared to the fixed price for their remuneration. As a result, this uncertainty could be characterized as "*epistemic*" since it is attributed to the nature of the policy scenario.

  Higher uncertainty bounds, thus, in the case of the FiT policy scheme are mainly attributed to citizens feeling less secure about the fixed tariffs, which may be higher than the electricity prices that citizens are called to pay in the beginning but may result to a considerably lower amount when compared with the price that they will be called to pay after a few years.

  The latter is further enhanced if considering that the resulting uncertainty bounds were derived by assuming a zero annual change factor for the fixed tariff in our model parameterization.

- On the other hand, the less "*static*" (or more "*dynamic*") nature of the net metering scheme, in which the profitability of the investment for citizens is linked to the amount of the electricity prices that citizens are called to pay, results to lower levels of uncertainty in our modeling outcomes.

  The latter, as also highlighted by our modeling results, makes citizens feel more secure and confident about their decisions, despite the fact that economic benefits and profitability levels are lower compared to the case of the FiT policy.

As a result, and even if total PV capacity additions and levels of emission reduction achieved under the FiT policy are higher in all the different transition pathways under study, the net metering scheme (without or with a BESS subsidy) is characterized by less behavioral uncertainty in the projected adoption results, which could be a valuable insight to decision-makers when they design instruments to further promote the adoption of rooftop PV systems.

In this context, modeling results also showed that especially in the case of net metering with a BESS subsidy, the lowest levels of capacity additions and emission reduction are achieved.

This is mainly attributed to the high capital costs of residential BESS technologies, especially when no subsidization is provisioned, which also leads to higher levels of uncertainty. These expenses have a substantial impact on how citizens perceive the profitability of their investment, which has a negative effect on their decision-making behavior, and is, thus, reflected on the modeling results and the uncertainty levels achieved.

In terms of potential policy implications that could be extracted by our work in the context of this particular application, it is imperative, first of all, that policymakers establish precise and explicit NECP targets to encourage and further promote prosumerism. Setting clear objectives not only offers a strategic orientation but also guarantees accountability and quantifiable advancements towards the integration of renewable energy and active citizen participation.

Today, most Member States do not have a well-defined plan or strategy for the further promotion of small-scale solar PV systems, and they lack enough participation from stakeholders and institutional frameworks to facilitate their further growth (Climate Action Network, 2024).

Moreover, since the FiT scheme had a greater impact in terms of capacity additions and emission reduction achieved in the Member States under study, something that could further boost the success of the policy is the establishment of a fixed tariff offered to citizens for injecting electricity into the grid, as it is crucial, in general, to align fixed compensation with societal perspectives prosumers' perception on compensation methods (Le et al., 2022).

In this regard, the determination of a fixed compensation price should be guided by well-defined criteria that consider market dynamics, PV system costs, and prevailing electricity prices (Yamamoto, 2018).

Additionally, our results showed that policymakers should provide citizens with long-term fixed prices under a FiT policy scheme, as short-term fixed prices may have a negative effect on the psychology of prosumers since they create instability and additional uncertainty about the profitability of their investment.

On the other hand, by extracting policy-relevant implications in the case of the net metering scheme, it becomes apparent that the scheme’s profitability could be further boosted if it is combined with a BESS- as BESS typically provide grid stability and flexibility and let prosumers store their electricity needs for night use (Chatzigeorgiou et al., 2024; Kumar et al., 2022)- but only if further policy provisions, i.e., generous subsidies of >50%, and other BESS-specific regulations are envisioned.

Especially with regards to the further adoption of BESS, our results touch upon the “*psychological*” effect that a 100% subsidy could have on citizens’ decision-making behavior. More specifically, in the case of Greece, we found a considerable difference in the adoption of solar PV systems when coupled with BESS subsidization, under a 100% subsidy and a 90% subsidy.

It becomes apparent, thus, that even marginal deviations of the BESS subsidy may have a great impact on the citizens’ decision-making behavior when it comes to the adoption of rooftop PV systems, as, especially citizens who exhibit a high level of risk aversion, demonstrate a lack of clarity on the long-term profitability of their investment, and as a result, their attitudes and hesitancy toward investing stay unaltered.

In conclusion, citizens as prosumers or stakeholders in a future energy system have the power to influence and shape the future of electricity supply, even under a “*fragmented”* world. Their active participation brings numerous benefits, including enhanced decision-making and a more democratic energy paradigm, economic empowerment, energy autonomy, improved grid stability, etc.

As our modeling results also showed, their role in achieving energy security and financial stable and resilient systems cannot be understated, especially in the face of potential “*fragmented*” evolutions of the future, marked by extreme conditions and events, like conflicts, e.g., the Russia-Ukraine war, in which electricity prices skyrocketed due to the elevated prices of natural gas.

It is important, thus, that policymakers continue to support the growth of prosumerism through empowering citizen investments in small-scale PV systems and residential BESS and favorable policies and incentives, ensuring that citizens can reap the financial benefits and contribute to a more resilient and sustainable energy system.

8.2.2. Combining “Power to the People” with “People to the Streets” storylines towards people-centered and 100% renewable-based national energy systems

To analyze citizen preference-led energy system planning alternatives under various future-world evolutions, we utilized an energy system optimization and CEM framework, **OSeMOSYS-GR**, which was developed in the context of the work implemented under the ENCLUDE **WP5**.

In this study, we focused on the Greek power sector and examined *how citizen participation in power sector planning, along with their preferences and decision-making behavior could affect the capacity requirements and the resulting electricity mix of future transition pathways* and the *national targets of decarbonization and climate neutrality by 2050*. Modeling outcomes showed that:

- Under the "*Familiar World*" narrative, the "*Decentralized planning*" scenario will require 22.5 billion € of capital investments in the power sector more than the "*BAU planning*" scenario for additional 24.7 GW of electricity generation (17.5 GW of solar and 3.8 GW of wind more) and supply-side flexibility technologies (9.6 GW in front of the meter and 1 GW behind the meter battery storage more).

  The "*Decentralized planning*" scenario will achieve 2.3% and 15.1% of VRE-based electricity in the total electricity mix in 2030 and 2050 more than the "*BAU planning*" scenario.
- Under the "*Unified World*" narrative, the "*Centralized planning*" scenario will save 27.1 billion € of capital investments in the power sector that would otherwise be channeled for additional 39.3 GW of electricity generation (30 GW of solar less and 7.4 GW of wind more) and supply-side flexibility technologies (21.9 GW of battery storage less and 4.1 GW of electrolyzers more) in the context of the "*Decentralized planning*" scenario.

  Results show that the "*Centralized planning*" scenario will require much lower short-term flexibility and somewhat higher long-term flexibility compared to the "*Decentralized planning*" scenario. The "*Centralized planning*" scenario will achieve 2.7% and 6.8% of VRE-based electricity in the total electricity mix in 2030 and 2050 less than the "*Decentralized planning*" scenario.
- Under the "*Fragmented World*" narrative, the "*Fossil fuel-dependent planning*" scenario will require 13.5-29.6 GW of electricity generation and supply-side flexibility technologies less than the "*BAU planning*" scenario. Fossil fuel-dependent planning will achieve 13.4-16.6% and 3.2-16.1% of VRE-based electricity in the total electricity mix in 2030 and 2050 less than the "*BAU planning*" scenario.

We also assessed *how costs and carbon footprint of centralized and decentralized systems compare between different future-world evolutions*. Modeling outcomes showed that:

- Under the "*Familiar World*" narrative, the "*BAU planning*" scenario will lead to total cost savings of 4.8 billion € (2.3% of the "*BAU Familiar*" scenario total cost) compared to "*Decentralized planning*" scenario.
- Under the "*Unified World*" narrative, the "*Centralized planning*" scenario will lead to total cost savings of 24.3 billion € (11.4% of the "*BAU Familiar*" scenario total cost) compared to "*Decentralized planning*" scenario.
- Under the "*Fragmented World*" narrative, the "*Fossil fuel-dependent planning*" scenario carries the risk of leading to extremely high variable system costs, in case of future energy crises, that would lead to unbearable domestic electricity prices and energy impoverishment of citizens.
- Under the "*Fragmented World*" narrative, the "*Fossil fuel-dependent planning*" scenario also poses the risk of resulting in extremely high total carbon footprint from the power sector, which would lead to the breach of the country's Nationally Determined Contributions.

Lastly, we also explored *the potential socioeconomic benefits of a citizen-led transition and citizen investments, and how these compare among different policy mixes and potential future evolutions of the surrounding environment*.

We observed that more citizens can benefit from investments in green infrastructure and solutions in the "*Decentralized planning*" scenario compared to the "*Centralized planning*" scenario.

Furthermore, modelling results showcased ***timing of the investments as a key factor for the energy transition since the earlier citizens start implementing solar rooftop PV investments the higher the potential socioeconomic benefits are going to be***, due to the declining future electricity price trends.

This finding is further strengthened due to the shift from policy instruments like FiT to the promotion of self-consumption, employing net metering and net billing regimes as a fundamental tool to mainstream solar rooftop PV installations.

Overall, our modeling outcomes imply that citizens' preferences and acceptance levels with regards to power sector planning can have a significant impact on the future capacity growth of different energy technologies (e.g., small-scale solar power projects, large-scale utility wind power projects).

The combination of the energy planning and electricity mix findings with the different storylines including various citizens' preferences and acceptance levels provides tangible trends and patterns to be considered for future power sector planning strategies. Specifically:

- In the "*Decentralized planning*" scenario, we found that citizen awareness of small-scale RES benefits and their strong opposition to large-scale energy projects (i.e., CCS and wind power) leads to larger capacity expansion of commercial and rooftop solar PV installations combined with BESS and smaller capacity expansion of onshore and offshore wind.

  Furthermore, this scenario results in the complete phase out of fossil fuels and lower amounts of electricity imports from interconnected countries among all the examined scenarios.

  Despite the larger capital expenditures that it would require compared to the rest of the cases, the "*Decentralized case*" presents a ***more democratized and equitable future*** in which socioeconomic benefits ***are distributed between a larger share of citizens and thus more citizens can catch up with the energy transition***.
- In the "*Centralized planning*" scenario, we saw that citizens' lack of knowledge about small-scale technologies and innovative solutions in the energy field leads to smaller capacity expansion of commercial and rooftop solar PV systems combined with BESS and larger capacity expansion of large-scale energy infrastructure, mainly onshore and offshore wind.

  Similar to the "*Decentralized planning*" scenario, this scenario also results in the complete phase out of fossil fuels; however, higher amounts of electricity imports from interconnected countries are integrated to the electricity mix.

  Despite the smaller capital expenditures that it would require compared to the rest of the cases, we found that the "*Centralized case*" presents a ***more individualistic and unfair future*** in which socioeconomic benefits are distributed between ***a smaller share of people and thus more people are expected to be left behind amidst the energy transition***.
- In the "*Fossil fuel-dependent planning*" scenario, we observed that citizens' *distrust toward national and local energy policies* with regards to the greening of the power system results in a power system dominated by fossil-fired centralised energy generation, while there is less available space for VRE capacity growth.

  However, this scenario poses both economic and environmental risks for citizens and societal structures in general.

  Furthermore, this type of planning could widen the gap between "*winners*" and "*losers*" of the energy transition, since ***a minority of citizens (innovators) will highly profiteer by investing in solar rooftop PV systems due to the skyrocketing wholesale and retail electricity prices***, while the majority of citizens will not invest fast enough in solar PV systems, which could expose them more in energy vulnerability.

  Therefore, the importance of steering away from future-world evolution scenarios that lean towards somehow "dystopian" characteristics cannot be overstated.

In this context, citizens' preferences and acceptance levels should be reflected via public participation in the preparation of energy and climate strategies and the respective national decision-making processes, such as NECPs.

This is key to ensure that their concerns and needs are integrated into the policymaking process, leading to policies that properly address them. To achieve this objective, NGOs, citizen associations, and local communities should put pressure on the institutions not to neglect or downplay citizens' inputs.

However, before that, and especially in the case of Greece, *there is first a clear need to inform citizens on what a* “*green vs grey*” *future means and what entails for them and future generations*.

In our work, as have already been specified in the previous sections, we want to explore different energy planning futures in Greece under the “*Power to the People*” and the “*People to the Streets*” “*people-centered*” storylines.

To that end, people should not remain ignorant and should first get informed of “*what kind of power*” could be given to them and “*for what reason*” they should advocate in the streets.

Our work, thus, serves this this purpose; to get people better informed on the potential characteristics of a “green” and a “grey” future, so that at least people are really given a selection of choice.

As a result, different policy-based strategies or citizen-led initiatives, e.g., protests and demonstrations, public awareness campaigns, advocacy and lobbying, and shareholder activism, can be employed by different energy system actors (i.e., citizens, policymakers, market shareholders) to make sure that citizens are first well-educated and well-informed on the most predominant climate and environmental issues, and then that their preferences are adequately represented in the context of the energy transition.

Protests and demonstrations can raise public awareness and pressure governments and corporations to adopt sustainable practices, while grassroot movements can mobilize communities to demand climate action, advocate for RES, and oppose harmful projects. By capturing media attention and public support, protests amplify the urgency of the energy transition.

Public awareness campaigns can educate people about the benefits of RES and thus drive demand for green energy providers and technologies, which encourages further innovation and investment in sustainable solutions.

Effective campaigns are supported by funding for educational initiatives, social movements, and grassroot activism, ensuring the message reaches a broad audience and inspires collective action towards a sustainable future.

Advocacy and lobbying can influence policy and regulatory decisions to support sustainable practices. Advocacy raises public awareness and builds support for RES, while lobbying targets lawmakers to enact supportive legislation. By pushing for favorable policies, subsidies, and incentives, advocates and lobbyists create a conducive environment for RES growth.

Through shareholder activism, investors can use their influence to push for sustainable business practices. By leveraging voting rights and engaging with corporate management, shareholders can advocate for greater investment in RES, stricter environmental policies, and better transparency regarding sustainability goals. This activism holds companies accountable for their environmental impact and encourages innovation in green technologies.

In addition, analyzing modeling results from another perspective, our outcomes highlight the significant untapped potential of prosumerism in Greece. In this direction, the government should:

(i). develop a concrete roadmap with clear and ambitious long-term targets towards the further capacity expansion of rooftop solar PV systems,

(ii). base the capacity targets on a comprehensive analysis of rooftop solar PV potential, considering key impediments such as informational gaps, alignment issues between owners and tenants, misconceptions about solar PV reliability, etc.,

(iii). use the revision process of its NECP to concretize sub-targets related to number of individual/collective prosumers, small-scale projects, energy communities, etc., and

(iv). put in place self-consumption schemes with consistent monitoring and adjustment to boost the adoption of rooftop solar PV installations.

We also show that a decentralized power sector will require more short-term flexibility, especially behind the meter, to improve night-time use of electricity, thus increasing self-consumption rates. In this case, the distribution grid capacity should be increased to accommodate a significant amount of electricity from solar PV and relevant BESS installations.

Furthermore, our results imply that the decentralization of electricity generation will require significantly higher capital investments in VRE compared to more centralized system alternatives. To catalyze decentralization, ongoing and future policy schemes are required to inform and convince citizens of the potential benefits as well as maximize the value of relevant technological solutions.

In this context, the Greek government should ensure prosumers are compensated for the electricity they contribute to the grid through self-consumption support schemes like net metering (but not in its existing structure, as currently net metering in Greece does not compensate prosumers for the excess electricity they produce) and net billing. By promoting local initiatives, citizens can help tailor funding mechanisms to the specific needs of their regions, ensuring that financial resources are allocated more directly to address local priorities.

In this regard, citizens may actively champion the implementation of decentralized finance, a financial ecosystem built on blockchain technology that aims to provide financial services without relying on traditional intermediaries such as banks, brokerages, or exchanges.

Finally, to minimize the gap between “winners” and “losers” in the energy transition, the Greek government should also bridge the gap between the society and rooftop solar PV systems by:

a. launching public awareness campaigns to highlight the benefits of this technology,

b. developing training programs for administrative staff and policymakers at both the regional and the local levels,

c. establishing programs to ensure enough qualified installers,

d. funding local and regional agencies to enhance the use of renewable energy in their respective areas, and

e. implementing mandatory rooftop solar PV installations on all new or under renovation residential (or even commercial) buildings.

8.2.3. Decarbonizing the transport and the residential sectors in Western Europe under different “people-centered” storylines and manifestations of energy citizenship

With the application of the IMAGE model, we took a broader but more aggregated approach by modeling different energy citizenship trends across all the “*people-centered*” storylines in the context of the different “*future world*” narratives.

These “*people-centered*” storylines were first described in terms of themes, behavioral actions, motivations and enabling factors, and the connection to the results from **Deliverable 3.2** (see **Table 2** for a qualitative description). Then, they were modelled with specific changes to the parameters in the IMAGE model (see **Table 13** for quantitative assumptions).

The “*Habitual Creatures*” storyline includes less technological-related behavioral changes, mostly driven by cost-savings and intrinsic motivation for sufficiency and health, which are enabled mostly by design, social norms, and marketing.

In the “*Power to the People*” storyline, conversely, there are more technological-related behavioral changes, mostly driven by autonomy and energy security concerns, and enabled by subsidies, funding, regulation, and improved R&D.

On the other hand, the “*Band Together*” storyline encompasses collective behavioral changes with a mix of technological and non-technological characteristics. These are mostly motivationally driven by cost-savings, social cohesion, and optimized use of time and space. Furthermore, they would be enabled by infrastructure, flexibility for initiatives, cooperation for improved communication, necessary knowledge, and social norm shifts.

Finally, the "*People to the Streets*" storyline includes behavioral changes with less direct effect on energy demand. With a more systemic focus, these changes are driven mostly by an emphasis on technological solutions, seeking responsibility from companies and government, but also through social cohesion to start social movements. They are enabled by campaign funding, lobbying organizations, shareholder activist groups, functional government, and policymakers.

Using the IMAGE model, in this study, we explored *the potential decarbonization pathways of different patterns and trends of the concept of energy citizenship leading to changes in consumption and technology in Western Europe*. The decarbonization pathways were modeled based on the "*people-centered*" storylines in the context of the different "*future world*" narratives (**Figure 67**).

The overarching trends showed that the decarbonization potential is the highest in the transport sector for the "*Power to the People*" storyline and in the residential sector for the "*Band Together*" storyline, compared to the other "*people-centered*" storylines.

Overall, the behavioral actions are more significant in the residential sector than in the transport sector, as "*People to the Streets*", "*Habitual Creatures*", "*Power to the People*", and "*Band Together*" (in increasing order of magnitude) all deviate substantially from the SSP2 no climate policy reference scenarios. However, these changes are still far away from a 2 ^{o}C reference scenario, while in transport, the "*Power to the People*" storyline would go beyond the 2 ^{o}C reference scenario.

Overall, comparing the qualitative "*people-centered*" storyline trends included in **Table 2** and the quantitative decarbonization pathway results allows for informed strategies about which types of behavioral actions should be enabled, how, and what impact they could have.

For example, our results show that, in the transport sector, measures under the "*Power to the People*" storyline (e.g., EVs as storage), which can be enabled by subsidies on vehicles and storage, etc., have the highest decarbonization potential compared to measures under the other "*people-centered*" storylines (carpooling, shift to public and active transport, etc.).

Furthermore, our results show that, in the residential sector, measures under the "*Band Together*" storyline (geothermal heat pumps for heating and cooling, communal laundry, communal dining and cooking, etc.), which can be enabled by neighborhood initiatives and housing cooperation, etc., have the highest decarbonization potential compared to measures under the other "*people-centered*" storylines (insulation, air-source heat pumps for heating and cooling, thermostat adjustment, etc.).

To highlight some important enablers, regulation needs to be more flexible to incentivize energy citizens to adopt sustainable measures, and infrastructure should be improved and redesigned to increase opportunities and availability.

8.3. Limitations, exploitation, and further research

In this deliverable, we incorporated multiple national and supranational case studies across different geographical contexts and socioeconomic environments and used several models from the expanded ENCLUDE modelling ensemble to simulate various scenarios incorporating a multitude of energy citizenship trends.

Combined with the local case studies examined in **Deliverable 5.3**, our case study selection showcased great diversity of multi-scale energy-related and socioeconomic challenges for the transition to a greener future.

In this regard, different types of energy communities and initiatives and manifestations of energy citizenship were directly or indirectly represented in our modeling applications, which indicated a multitude of potential decarbonization pathways requiring various policy-induced measures or citizen-led solutions under different contexts.

Overall, we believe that our work can be exploited both within and outside of ENCLUDE by policy-makers and other relevant end-users from the field of policy and practice, who can use our findings to derive interesting and policy-relevant implications and recommendations.

Furthermore, our results can be taken up by researchers and other end-users from the field of academia that are interested in the ways that different patterns and trends of energy citizenship at both the individual and the collective level, can be integrated into the design of decarbonization pathways and simulated with computational models, at both the micro and the macros scales of analysis.

However, we recognize that our research comes with specific limitations:

First, we faced a lack of survey data concerning certain social and behavioral aspects, such as people's attitudes and lifestyles, which can hardly be quantified. For example, survey data gathered in the context of ENCLUDE, or previous relevant projects (e.g., **ECHOES**[21]) are not available as timeseries. This limited the potential of our modelling applications considering that our modeling tools typically require data that accounts for change over time. In this regard, a better availability of survey data on social and behavioral aspects could improve our modeling efforts.

Second, considering the wide spectrum of the potential applications that arise from the multifaceted nature of the concept of energy citizenship, each modeling framework has different capabilities to represent social aspects and hence, there are limits to what degree such aspects can be integrated. Specifically, the utilized CEM and IAM frameworks, i.e., **OSeMOSYS** and **IMAGE**, are not formulated in a way that technology preferences and behavioral changes can be inherently included. For example, as a linear programming modeling framework, OSeMOSYS cannot explicitly define merit-order assumptions on technology deployment (e.g., solar rooftop PV systems are always chosen in preference to utility-scale PV installations).

Full integration of social sciences into modeling architectures adds complexity, often unlikely and not desirable (Krumm et al., 2022). In this regard, indirect integration of social and behavioral aspects into **OSeMOSYS** and **IMAGE** was a better solution, for which various options emerge, e.g., direct model input via setting upper and lower limits or technology exclusion, monetization collected through discrete choice experiments expressed as willingness-to-pay, or a soft model coupling (Senkpiel et al., 2020).

In this work, we opted to quantify the qualitative "*people-centered*" storylines and formulate the scenario space by making plausible exogenous assumptions that followed their specifications. This form of integration of social aspects enabled a "*softer*" bridging approach, which did not require a restructuring of the simulation, or optimization process. However, this process was not straightforward due to methodological uncertainties and missing profound empirical data, forcing us to integrate social aspects ad-hoc and "*on top*" of the models through adjustments in scenarios and input parameters.

Third, actor heterogeneity is only addressed by **ATOM**- due to its ABM structure this is the most suitable choice- and is not accounted for explicitly in **OSeMOSYS** and **IMAGE**. In reality, there are a variety of actors (e.g., individuals, institutions, larger societal groups, but also media, opinion leaders, lobby groups, or political parties) who have different interests and pursue different objectives. Future modeling activities on social and behavioral aspects should therefore seek to differentiate more strongly between different types of decision-making profiles and consider how they interact and influence the perception and likelihood of their decisions.

To encounter the limitations of single models in representing social and behavioral aspects, a coupling between the different modeling frameworks would allow us to scale the local- or national-level results up to the national, or even supranational level. For example, soft-linking **ATOM** with **OSeMOSYS** or **IMAGE** presents the opportunity to provide behavioral insights and account for actor heterogeneity

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[21] https://echoes-project.eu/

with regards to technology adoption. Even though, such a coupling can provide a better integration of social aspects in **OSeMOSYS** and **IMAGE**, due to the ability to capture behavior dynamics and interaction of agents, **ATOM** can also benefit from this, as it lacks the macroeconomic perspective of CEMs or IAMs which offers a broader scope of examination.

On an individual level, as further research, the **ATOM** modeling framework will be expanded to provide forward-looking simulations about the adoption and decarbonization potential of more geographical and socio-economic contexts, like Portugal and Spain. Considering these countries' policy frameworks with regards to self-consumption schemes, **ATOM** will be further developed to simulate the PV capacity additions of small-scale solar PV systems in the residential sector under *net billing* (*with BESS*) policy schemes.

Furthermore, ATOM could be expanded to simulate the adoption potential of other technologies, like heat pumps or EVs. In this case, agent- and market-related parameters that characterize these technologies must be identified and further explained through proper mathematical equations.

By expanding **ATOM**, more comprehensive decarbonization pathway assessments will be feasible, offering valuable insights for policymakers, stakeholders, and communities, and helping to design effective strategies for promoting renewable energy adoption.

In addition, as further research when it comes to **OSeMOSYS-GR**, a more detailed assessment of the future energy demand evolution is required to capture the behavioral uncertainty mostly related to citizens' use of energy directly or indirectly, especially in the residential and transport sectors, i.e., their housing and travelling choices.

As a next step, specific demand profiles for housing and mobility will be developed in cooperation with **WP4** to formulate several "*what if*" scenarios relevant to the- already identified under the work conducted in the context of **WP4**- strategic energy citizens' clusters.

In the context of **Deliverable 5.5**, these profiles will provide a baseline for the last round of modeling simulations within ENCLUDE and enable the investigation of different routes to reach decarbonization targets while demonstrating which clusters are more crucial and responsive to accelerate decarbonization.

For further research with **IMAGE**, a decomposition analysis of emissions into contributions from consumption and technology changes, for different transport modes and residential energy services would shed more light in the supranational decarbonization pathway results.

Moreover, this deliverable was the first step to combine research outcomes from different types of energy system models, ABMs, CEMs, IAMs, utilizing the strengths of the models for applications at different aggregation, details, specificity, etc. A stronger coupling of these models with **IMAGE** could be explored in the future.

Overall, as a general note, and based on the modeling work that we have been carried out as part of ENCLUDE WP5, while computational tools assist in the generation of system knowledge and provide highly valuable insights on interactions in energy systems and markets for decision-makers, they will only ever be a part of the entire "*solution*". To provide orientation and transformational knowledge to decision-makers, interactive and iterative decision support tools are needed, which can be used in transdisciplinary research settings to co-design recommendations for energy system transformation pathways with actors from society outside the research ecosystem (Huckebrink & Bertsch, 2021).

Finally, to support efforts across Europe on transparency, associate source code, datasets, and detailed documentations, along with suitable open licenses (where possible) to enable the models' use, modification, and republication, will be uploaded on the TEESlab UPRC's GitHub page, while case study results will be made available on the ENCLUDE Interactive Policy Platform (as developed in the context of the **WP7**).

Appendix

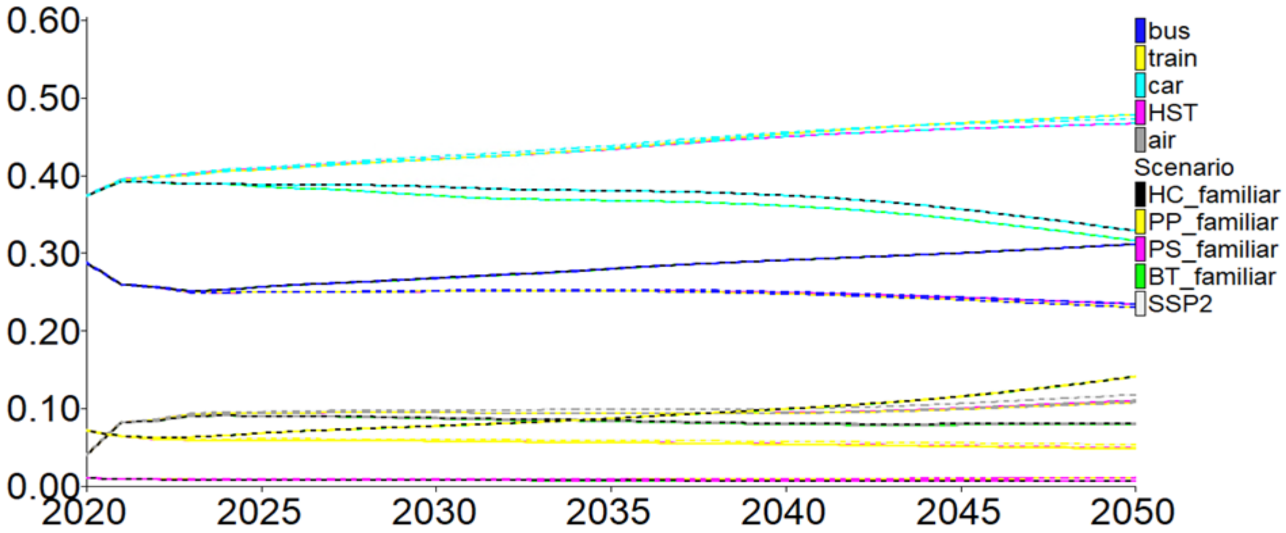

Figure A1. Passenger travel mode split (as a fraction of total passenger-kilometers) in Western Europe.

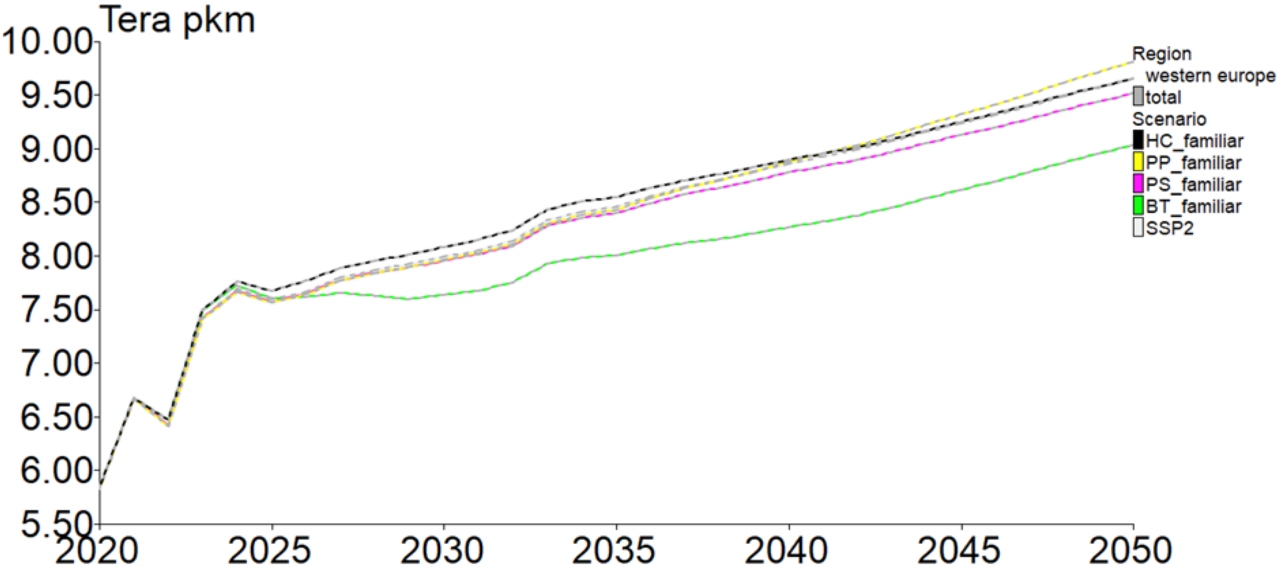

Figure A2. Passenger travel demand in Western Europe.

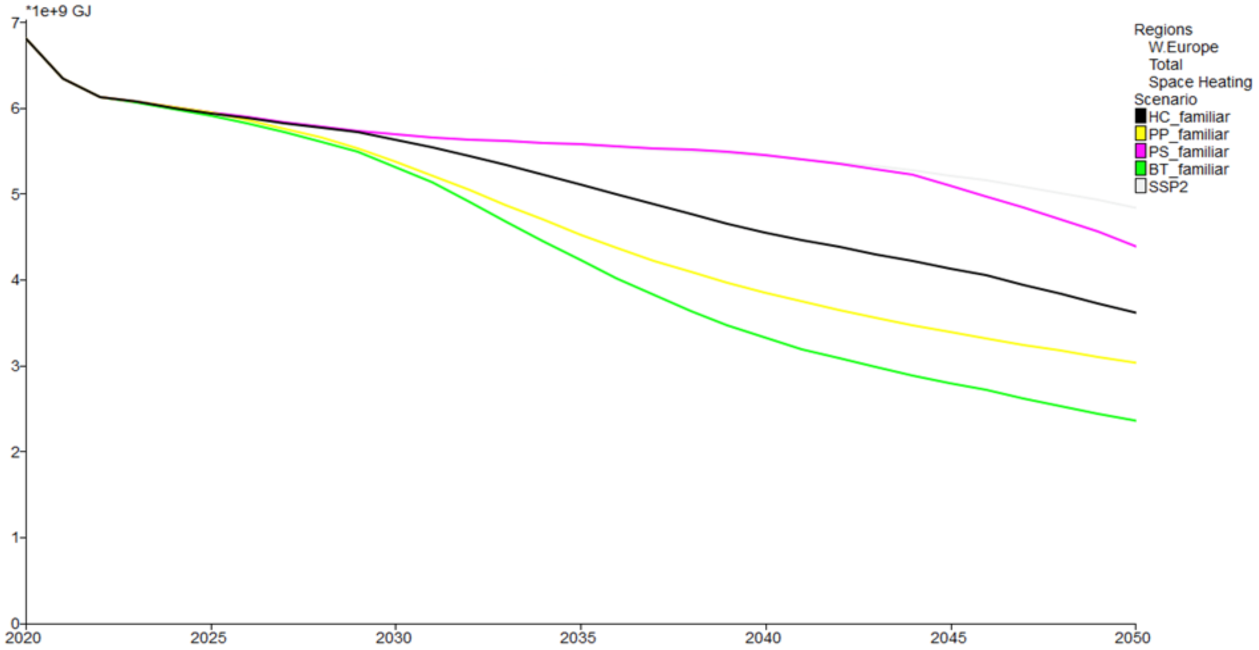

Figure A3. Energy demand for space heating in Western Europe.

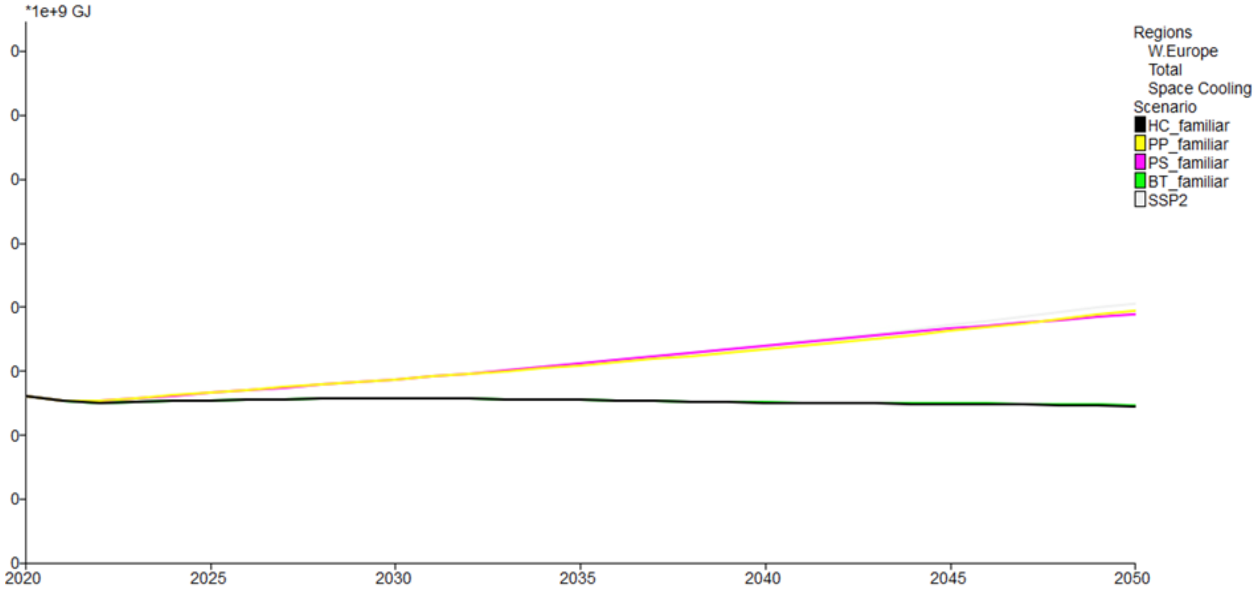

Figure A4. Energy demand for space cooling in Western Europe.

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