ENCLUDE

Energy Citizens for Inclusive Decarbonization

Decarbonization potential of strategic energy citizen clusters

WP5 – The impact of energy citizenship in decarbonization pathways

30/09/2024

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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

No changes with respect to the work described in the amended Grant Agreement.

2. Dissemination and uptake

This report may easily be used both within and outside of the project, by researchers interested in the fields of data-driven clustering techniques, energy system modeling, and energy citizenship. Hence, this report will be disseminated through the usual social media channels in order to communicate the key results and insights in an easily digestible manner. Also, it is envisaged that 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 fifth and final deliverable under Work Package 5 of the ENCLUDE project and builds on the work- based on country-specific data- done previously under Work Package 4, and specifically in Deliverable 4.2 and clustering of energy citizens, and in Deliverable 4.3 and profiling of energy citizens.

In this deliverable, we aim at understanding the relationship among patterns related to citizens' energy behaviors and decarbonization pathways. To do so, we integrated results of clustering and profiling into energy system modeling and simulations tools, by translating the clusters' characteristics and energy behaviors into inputs for the ENCLUDE modeling ensemble. This integration enables the quantification of the decarbonization potential of different citizen groups, thus demonstrating which clusters are more crucial and responsive toward accelerating decarbonization efforts.

This deliverable presents the model applications corresponding to two (2) different geographical contexts and socioeconomic environments. To simulate the different transition pathways, two (2) models were employed, namely: *ATOM* (Agent-based Technology adOption Model) and *OSeMOSYS-GR* (Open-Source energy MOdeling SYStem for GReece).

Modeling applications presented in this report include:

(**i**)**.** Exploring transition pathways of empowering prosumerism and citizen adoption of small-scale photovoltaic systems in Greece and the Netherlands by 2030, considering citizens' energy consumption patterns and extracting insights on citizens' decision-making behavior (using the *ATOM* model).

(**ii**)**.** Exploring the impact of citizens' energy behaviors on different planning and system design alternatives in the Greek power sector, considering the evolution of capacity requirements, the resulting electricity mix, and the achievement of national targets by 2050 (using the *OSeMOSYS-GR* model).

4. Evidence of accomplishment

This report serves as evidence of accomplishment.

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Executive Summary

Climate change is a multifaceted challenge that requires the confluence of various disciplines, including environmental science, social sciences, and engineering. The integration of these diverse perspectives is essential to capture the complexity of the energy and climate system and the socioeconomic structures that contribute to and are affected by climate change. However, current climate change mitigation strategies have predominantly emphasized the technical and infrastructural aspects of the energy transition, often overlooking the critical sociopolitical dimensions that underpin the success of these efforts.

A successful energy transition constitutes a deeply societal matter that has created the imperative to address its societal implications. In this regard, the European Union outlines policies that envision a central role for citizens in the energy transition and a more decentralized and democratic energy system that could encourage renewable energy production and empower citizens to engage and take responsibility for energy production and consumption. Aiming to realize this vision, the sociopolitical concept of "*energy citizenship*", consistently resurfaces in recent scientific and political discourse, due to its potential to bridge the gap between energy transition policies and social participation by emphasizing the role that citizens can play through their engagement and involvement in the energy system, as well as the impact they can have on the European Union's future energy landscape.

Nevertheless, contemporary energy modeling practices and scenario-based research approaches, used at a large extent by policymakers to assess and design policies and regulations to address climate-related challenges, focus primarily on cost optimization and technoeconomic implications of the energy transition, often disregarding social aspects, matters of inclusivity and equity, as well as citizens' preferences. Omitting such considerations may result in monolithic modeling exercises and oversimplified models that while they produce cost-optimized and computationally neat decarbonization pathways, they lack the necessary depth to inform policymakers about the broader societal dimensions crucial for a sustainable and inclusive energy transition. In this regard, a comprehensive and integrative approach that encompasses not only technological innovations and policy reforms but also profound behavioral changes across society is imperative.

In the context of ENCLUDE and particularly within "*Work Package (WP) 5: The impact of energy citizenship in decarbonization pathways*", we integrated the concept of "*energy citizenship*" into energy modeling to create more comprehensive and socially informed modeling exercises. This allowed us to explore the multi-scale relationship between the various expressions of energy citizenship and their potential impact on decarbonization efforts under a variety of scenarios and external conditions. To this end, in previous deliverables an ensemble of modeling tools was developed and implemented, producing insights regarding the decarbonization potential of energy citizenship at different scales of analysis and decision-making contexts across the European Union, i.e., local, regional, national, and supranational.

In this fifth and final deliverable of WP5 ("*D5.5: Decarbonization potential of strategic energy citizen clusters*"), we expanded our modeling tools to account for insights originating from "*WP4: Identification of citizens' clusters for decarbonization*". Through the use of machine learning algorithms, WP4 identified clusters of energy citizens utilizing data on energy consumption and carbon emissions for specific Member States. This resulted in the identification of commonalities within the utilized dataset and a subsequent categorization of citizens in distinct groupings. The citizen clusters were then analyzed based on sociodemographic characteristics and cognition-related attributes in order to produce a set of citizens' profiles that can be used to draw narratives for energy scenario development.

Leveraging this work, in this deliverable we integrate WP4 clustering and profiling results into energy system modeling and simulation tools, by translating the clusters' characteristics and energy behaviors into inputs for the ENCLUDE modeling ensemble. This integration quantifies the decarbonization potential of different citizen groups, and demonstrates which clusters are more crucial and responsive

towards accelerating decarbonization efforts. Targeting these clusters with tailored policies and interventions can significantly enhance the overall effectiveness and efficiency of decarbonization initiatives.

More specifically, this deliverable presents the model applications corresponding to two (2) different geographical contexts and socioeconomic environments, with our aim being, eventually, a sound and robust understanding of the relationship between patterns related to citizens' energy behaviors and decarbonization pathways. To simulate the different scenarios, two models of the ENCLUDE ensemble were employed, namely:

- ATOM (**A**gent-based **T**echnology ad**O**ption **M**odel),
- 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 key overarching messages:

Adoption of rooftop solar photovoltaic (PV) systems in the housing sector for different energy citizen clusters in Greece and the Netherlands

Citizens are increasingly becoming individual owners of solar photovoltaic (PV) assets, thus consuming their own electricity and playing a supportive role in driving the energy transition. Considering that and building upon the work conducted in WP4, we used ATOM to evaluate the adoption potential of small-scale solar PV systems in the residential sector in Greece and the Netherlands toward 2030. Specifically, we explored how different policy schemes can empower prosumerism and further citizen adoption of small-scale PV systems for different citizen clusters as well as their decarbonization potential.

Our results show that the 2030 national target for total small-scale PV capacity in Greece cannot be achieved using an individual policy scheme and thus a combination of policy schemes is required. Contrastingly, the respective Dutch target seems achievable under the application of an individual policy scheme, therefore there is no need for a combination of policy schemes in order to reach the target. Overall, we provide policy recommendations for the further expansion of small-scale PV systems by 2030, also considering citizen attributes and context-specific characteristics.

Power sector capacity buildout based on electricity consumption patterns of different energy citizen clusters in the housing and mobility sectors in Greece

Citizens' adoption rate of electrification technologies and their energy use patterns will significantly impact the future energy system's design in terms of capacity and flexibility requirements. Drawing from the need for better understanding of the potential impacts wielded by citizen groups with different profiles in terms of their sociodemographic characteristics, energy consumption levels, etc., we integrated different citizen groups' energy consumption patterns into OSeMOSYS-GR. This allowed us to assess their energy consumption alongside other aspects like technical feasibility and cost in order to explore decarbonization pathways in the Greek power system by 2050.

Our results demonstrate that citizens' energy-sufficient behaviors not only reduce housing and mobility costs by consuming less and adapting energy services to citizens' needs (e.g., appropriately sized products), but also mitigate system costs by avoiding unnecessary infrastructure investments. This, in turn, can mitigate energy price increases and further reduce citizens' energy costs by reducing their bills. We provide policy recommendations for the development of sufficiency policies for the housing and mobility sectors which can lead to a more secure, fair, and less costly transition to carbon neutrality with fewer strategic dependencies.

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List of Abbreviations/ Acronyms

ABM	Agent-based model/ modeling
ANIMO	grAssroot iNnovation dIffusion MOdel
ATOM	Agent-based Technology adOption Model
BAU	Business as usual
BESS	Battery energy storage system
CCS	Carbon capture and storage
CEM	Capacity expansion model
CO_2	Carbon dioxide
COP21	UN Climate Change Conference
DREEM	Dynamic high-Resolution dEmand-sidE Management model
EC	European Commission
EU	European Union
EV	Electric vehicle
FiT	Feed-in tariff
GHG	Greenhouse gas
IAM	Integrated assessment model/ modeling
IMAGE	Integrated Model to Assess the Global Environment
LCA	Life Cycle Assessment
NECP	National Energy and Climate Plan
OSeMOSYS	Open-Source energy Modeling SYStem
OSeMOSYS-GR	Open-Source energy Modeling SYStem for GReece
PV	Photovoltaic
RES	Renewable energy sources
RQ	Research question
TEESlab	Technoeconomics of Energy Systems laboratory
UK	United Kingdom
VRE	Variable renewable energy
WP	Work package

1. Introduction

Climate change stands as one of the most critical challenges that humanity faces today, presenting significant threats to ecosystems, economies, and human well-being. The increasing concentration of greenhouse gases (GHG) in the atmosphere is leading to rising global temperatures, which in turn results in more frequent and severe weather events, rising sea levels, and disruptions to agricultural systems. The consequences of inaction include among others biodiversity loss, population displacement, economic instability, and heightened human health risks. Addressing climate change has become one of the most urgent imperatives of our time, and the transition to a low-carbon economy is essential for limiting global warming.

In response to the climate crisis, 196 Parties signed the Paris Agreement at the UN Climate Change Conference (COP21) in 2015. This marked a significant milestone, as nations worldwide committed to limiting global warming to well below 2ºC above pre-industrial levels, and to pursue efforts to limit it to 1.5ºC. This landmark accord has catalyzed a range of policies and initiatives aimed at reducing GHG emissions, enhancing climate resilience, and supporting sustainable development.

Acknowledging the significance of climate change, the European Union (EU) has committed to mitigating it through numerous policies and international agreements. The EU introduced the European Green Deal in 2019 (European Commission, 2019). The Green Deal aims to make Europe the first climate-neutral continent by 2050, encompassing a broad spectrum of measures to promote renewable energy sources (RES), improve energy efficiency, reduce emissions, and foster innovation, with a view to ensure zero net GHG emissions by 2050, economic growth decoupled from resource use, and that no person and region is left behind.

Complementing the Green Deal, the "Fit for 55" legislative package and the European Climate Law are legally binding the EU to align short-term actions with long-term climate goals, ensuring a consistent and robust pathway towards achieving climate neutrality (European Parliament, 2021; European Commission, 2021b). The "Fit for 55" package introduces new measures and goals aiming to accelerate the EU's energy transition and achieve an at least 55% net domestic GHG emissions reduction by 2030. When fully implemented, this package could enable the EU to surpass this target, potentially reaching a net reduction of around 57% by 2030 (European Commission, 2023).

Additionally, the European Commission (EC) introduced the "REPowerEU" plan in March 2022 as a response to the energy crisis due to the Russian invasion of Ukraine and concerns regarding energy security in the EU. "REPowerEU" requires a collaborative effort by Member States in order to avoid energy supply disruptions, release pressure on energy markets and prices, and pursue the structural reform of the European energy system through increased deployment of RES (European Commission, 2022). Thanks to the "Fit for 55" package and REPowerEU, the EU is steadily reducing reliance on fossil fuel imports by investing in RES and electrifying end uses. In 2022, a record 60GW of wind and solar photovoltaic (PV) capacity was installed in the EU and the sales of heat pumps reached new highs (European Commission, 2021a).

However, the pace of GHG emission abatement must increase to meet the 2030 targets, as the level of progress by Member States in recent years falls significantly short of the effort required to meet both the medium and the long-term EU targets (European Commission, 2023). Given the complexity of climate change, achieving this goal requires a multifaceted approach, encompassing technological innovation, policy reform, and behavioral change (Kleanthis et al., 2022). So far, climate change mitigation efforts have mostly focused on the technical and infrastructural aspects of the energy transition. While technological innovations are undeniably necessary, they cannot halt climate change on their own, as it also involves societal aspects. In this context, the role of citizens is becoming increasingly important through their engagement, involvement, and shaping of the future energy landscape.

The need for citizen engagement has been acknowledged within the EU's strategic and legislative frameworks. In 2015, the Energy Union strategy was introduced, recognizing that by taking ownership of the opportunities allowed by the energy transition, citizens can actively participate in the energy market and thus benefit from new technologies to reduce their energy bills (European Commission, 2015). In 2019, the EC launched the “Clean Energy for all Europeans”, a policy package supporting citizens in the context of the energy transition and allowing for new forms of consumer participation in the market and cross-border cooperation (European Commission, 2016). More specifically, it established a legislative framework which gave the right to consumers, prosumers, and energy communities to produce, store, consume, and sell their own energy. In 2021, the Social Climate Fund and Just Transition Fund were also created to support vulnerable households and communities (European Commission, 2021b).

Overall, the EU envisions a central role for citizens in the energy transition and a more decentralized and democratic energy system which would encourage renewable energy production and empower citizens to engage and take responsibility for energy production and consumption. This has created the imperative to address the societal implications of the energy transition. In this context, the sociopolitical concept of “*energy citizenship*”, has been increasingly mentioned in recent scientific and political discourse (Wahlund & Palm, 2022).

Energy citizenship can be broken down into a set of emerging patterns and trends. In *Deliverable 5.1* “D5.1: Report on models’ adjustments and modifications to match emerging energy citizenship patterns and trends and patterns” under ENCLUDE’s “Work Package (WP) 5: The impact of energy citizenship in decarbonization pathways”, 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 (Tsopelas et al., 2022), as follows:

- the active participation of citizens in the energy market through "*prosumerism*", the increasing adoption of energy efficiency and smart technologies, and other related solutions,
- behavioral aspects of citizens and the impact of lifestyle changes in their daily lives,
- collective initiatives and expressions of energy citizenship, such as the formation of energy communities, cooperatives, ecovillages, or collective decision-making through housing association boards, etc.,
- political activities, such as participation in social movements and civil society initiatives that advance democratic visions of energy transition, contribution to energy sector planning and decision-making through participatory design of potential future energy landscapes, etc.

1.1. Energy citizenship and citizen clustering

Citizens consume significant amounts of energy each year and their energy consumption is dependent on patterns related to their energy behaviors and lifestyle changes in their daily lives. To better understand patterns related to citizens’ energy consumption, measurements of the changes of citizens’ energy behavior are required to gather data regarding energy usage, carbon dioxide (CO_2) emissions, etc. Clustering methods can categorize the collected datasets in order to identify diverse groups that share commonalities (Goggin & Zunder, 2024). For instance, clusters might be based on readiness to embrace energy citizenship actions falling within the identified patterns, energy consumption and CO_2 emission profiles, or responses to collective energy initiatives, revealing possible unexpected common characteristics among different demographics.

Understanding these groupings can inform policymakers about which citizen profiles have significant decarbonization potential and thus aid in predictive modeling. It can facilitate the development of inclusive and equitable policies, considering the diverse energy profiles and socioeconomic backgrounds of citizens, and assist the development of policies targeting specific groups of citizens to facilitate behavioral change (Bogin et al., 2021). This targeted approach ensures more effective engagement and increased participation in sustainable practices, such as the adoption of RES and energy-efficient solutions.

Clustering analysis has been widely used in the research community to provide solutions to energy- and climate-related challenges. Pereira et al., (2021) aggregated and analyzed the energy consumption of different types of energy community end-users, each one with different energy consumption and generation profiles, using clustering and classification methods in order to identify end-users' profiles and develop a web-based platform with services aiming to help manage energy communities. Arnold et al., (2024) analyzed 2,930 German citizens' preferences for smart energy technologies and services of future smart districts. They grouped citizens into three (3) distinct clusters, each with varying preferences for smart energy technologies and services, also differentiating citizens in terms of their sociodemographic characteristics, providing insights regarding the technical design of future smart districts and smart cities.

Petricli et al., (2024) used household-level survey data derived from a Turkish metropolis and investigated different factors (e.g., cognition-related and sociodemographic) that affect citizens' environmental behavior. By combining different machine learning clustering algorithms, they found five (5) distinct green citizen typologies based on different levels of environmental concern, human-nature relatedness, and sustainable consumption behavior. The authors argued that targeting the underlying factors can help policymakers and service providers craft effective policies encouraging behavioral change and bridging the attitude-behavior gap.

Kaur & Gabrijelčič (2022) applied data-driven unsupervised learning methods to categorize smart meter users into clusters, whose individuals exhibited comparable consumption patterns based on their daily routines. To evaluate their clustering technique, they utilized real-world electricity consumption data from 5,038 consumers in Slovenia. Their method prioritized reducing the data's dimensionality and focused on identifying key behavioral patterns and sources of variability to optimize the clustering algorithm and its parameters. Their findings suggest that factors such as time of day, day of the week, daily variability, and seasonality differences between clusters could inform the development of new strategies for energy management and grid planning.

On a smaller scale, Kazaki & Papadopoulos (2018), used clustering techniques to analyze smart meter data from the campus of Democritus University, in Xanthi, Greece. The researchers employed the K-means++ algorithm to cluster energy consumption data, which helped in identifying patterns of electricity usage across different periods and thus generating representative load curves. This approach allowed for a better understanding of the campus's energy performance and contributed to more efficient energy management strategies, aligning with European energy policies aimed at improving the efficiency of public buildings. The load profiles created through clustering could be further used to optimize energy distribution and reduce consumption costs in similar public infrastructure.

On the same scale, Ruiz et al., (2020) applied time-series clustering techniques to analyze and group energy data from buildings at the University of Granada in Spain. In their approach they tested and compared several clustering methods such as k-Means, k-Medoids, and hierarchical clustering. Their methodology identified consumption patterns to improve non-trivial energy system knowledge acquisition from raw energy data to be used in energy models with the aim of better understanding how buildings are consuming energy and identifying possible features and behaviors hidden in data.

Our literature review on data-driven clustering methods related to energy end-users shows the capacity of clustering techniques to complement energy modeling applications in order to improve energy system planning. However, many models currently underrepresent social and behavioral aspects related to end-users (Süsser, Ceglarz, et al., 2021). Most models adopt a technoeconomic or cost optimization approach, limiting their ability to include social aspects and dynamics such as policy preferences, or social acceptance (Chatterjee et al., 2022). As such, current models often treat the social dimension of the energy transition as an additional layer of analysis, considering society as a merely broader context, or, in the best of cases, as a perspective through which modelling results can be interpreted (Krumm et al., 2022a). This approach overlooks the interactions between societal factors and other elements like technology, economy, and environment (Süsser, Pickering, et al., 2021). Neglecting these factors may result in energy policy goals or implementation strategies that conflict with environmental policy or undermine social goals unknowingly (Sokołowski & Heffron, 2022).

In this regard, combining data-driven clustering techniques with energy system model applications enables the incorporation of social aspects in a meaningful manner and offers added value in various aspects of energy system planning, optimization, and operation. This approach sheds light on citizens' perspectives and provides a solution to current patterns of omittance, or disregard for social and behavioral factors that may lead to models generating overly optimistic and potentially misleading results, for example by suggesting transition speeds far exceeding any speeds observed, or pathways facing hard-to-overcome resource constraints (Süsser et al., 2022).

Specifically, utilizing results derived from clustering techniques can enable better representation of various consumer demand profiles (e.g., related to the housing or mobility sectors) in energy models. Clustering techniques group consumers with similar energy consumption patterns into representative clusters. This reduces complexity while maintaining accuracy, as only a limited number of representative profiles are used instead of modeling every individual consumer, and thus faster scenario evaluations can be enabled.

Furthermore, clustering allows energy models to simulate various demand scenarios, which helps in planning for contingencies and assessing different energy storage, or generation investment strategies under various demand conditions. Based on clustering results, sets of profiles can be introduced to draw narratives for more realistic scenario development.

In addition, with a clearer understanding of clusters, energy models can inform policymakers about which consumer groups or regions may need specific interventions, such as subsidies for energy efficiency measures or renewable energy incentives. This can significantly enhance the robustness of energy system models, thereby increasing their effectiveness in informing policy decisions and leading to the identification of tailored solutions within the examined contexts.

1.2. 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 contexts and scales, and thus it is crucial to better understand its impacts. 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 modeling trends and implications that may not be adequate for policymaking.

ENCLUDE's 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 WP5, 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 wide range of manifestations at different scales of analysis and decision-making contexts.

In previous deliverables under WP5, i.e., *Deliverable 5.3* and *Deliverable 5.4*, the foundation was laid by further modifying existing models, or even developing new ones, to assess the decarbonization potential of energy citizenship at the local, the regional, the national, and the supranational levels. A short overview of these two (2) deliverables is provided in the following paragraphs:

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

In Deliverable 5.3, we delivered transition pathways in different real-world case studies, focusing on the impact of energy citizenship at the local level. 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. Specifically, we appraised the profitability and decarbonization potential of "prosumerism" through household-level PV systems and different policy schemes in different cities across the EU by 2050, assessed the decarbonization potential of investing in energy efficiency solutions and adopting energy-related lifestyle changes at the municipality level, as well as showcased the value of collective citizen activities in contributing to meaningful changes over time.

"*D5.4: Report on the impact of energy citizenship at the national and EU levels*" in a nutshell (Manias et al., 2024)

In Deliverable 5.4, we delivered transition pathways focusing on the impact of energy citizenship at an upscaled level. By employing the ENCLUDE modeling ensemble once more, we aimed 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. Specifically, we explored the decarbonization potential through the further diffusion of small-scale PV systems across the EU, analyzed citizen preference-led energy system planning alternatives with a view to designing fully renewable-based national energy systems, and assessed the decarbonization potential of different patterns and trends of energy citizenship in the transport and the housing sectors in Western Europe at the upscaled (supranational) level.

Below an overview of the modeling tools comprising the ENCLUDE modeling ensemble is provided:

Table 1. The ENCLUDE modeling ensemble (Manias et al., 2024).

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 (BESS), heat pumps, electric vehicles (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**)	**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 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.

Complementing the modeling work performed under Deliverable 5.3 and Deliverable 5.4, as part of this deliverable ("*D5.5: Decarbonization potential of strategic energy citizen clusters*"), we aim to develop a comprehensive understanding of the decarbonization potential of different energy citizen clusters. By employing the established ENCLUDE modeling ensemble, we try to shed light on how different citizen groups could affect the shift to a decarbonized energy paradigm across the EU.

To do so, we also leverage previous work under ENCLUDE's "*WP4: Identification of citizens' clusters for decarbonization*", and, specifically, *Deliverable 4.2* and *Deliverable 4.3*. A short overview of these two (2) deliverables is also provided in the following paragraphs:

"*D4.2: Report on the identification of citizens' clusters for decarbonization*" in a nutshell (Naderian et al. (2024)

Deliverable 4.2 aimed to identify citizen clusters for decarbonization in different contexts by developing and testing clustering tools using machine learning algorithms. The citizen clustering analysis utilized datasets with various data types, including sociodemographic, cognition-related, energy consumption, energy behavior data, etc. This resulted in the identification of commonalities within the utilized dataset and the categorization of citizens in distinct groupings based on their energy consumption and carbon footprint levels.

"*D4.3: Report on bridging clusters for decarbonization with energy models*" in a nutshell (Naderian et al., 2024a)

Deliverable 4.3 aimed to analyze the citizen clusters identified in Deliverable 4.2 based on sociodemographics and cognition-related attributes such as age, education, house size, car fuel consumption, and climate change perception. Within-cluster analyses were carried out for each citizen cluster in order to produce a set of citizens' profiles that can be used to draw narratives for energy scenario development.

The aim of Deliverable 5.5 is to utilize the findings originating from the clustering work of Deliverable 4.2 and Deliverable 4.3 and couple them with energy system modeling and simulations, by translating the clusters' characteristics and energy behaviors into inputs for the ENCLUDE models. This integration will quantify the decarbonization potential of different citizen groups, demonstrating which clusters are more crucial and responsive towards accelerating decarbonization efforts. By targeting these clusters with tailored policies and interventions, the overall effectiveness and efficiency of decarbonization initiatives can be significantly enhanced.

In this deliverable, case studies corresponding to two (2) different geographical contexts and socioeconomic environments are modeled, with our aim being, eventually, a sound and robust understanding of the relationship between patterns related to citizens' energy behaviors and decarbonization pathways. We also provide information on the workings and capabilities of the ENCLUDE modeling ensemble. As such, the report 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 fields of academia and research that are interested in the ways that clustering results 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 with regards to the uptake of the clustering outcomes, in this deliverable we present results from the application of the **A**gent-based **T**echnology ad**O**ption **M**odel (**ATOM**) and the **O**pen-**S**ource **e**nergy **MO**deling **SYS**tem for **GR**eece (**OSeMOSYS-GR**).

1.3. Structure of this deliverable

The remainder of this deliverable is structured as follows:

- **Section 2** includes an overview of the methodology followed.
- **Section 3** describes the key findings from the clustering analysis under WP4 and the way that are leveraged in this deliverable.
- **Section 4** provides a description of the modeling tools' further modifications and adjustments that took place to integrate the clustering results of WP4.
- **Section 5** presents the specification of the analyzed case studies, along with respective parameters that were used, the developed scenarios, etc.
- **Section 6** presents the simulation results of the model application to the case studies.
- **Section 7** provides conclusions and recommendations of our work, summarizes limitations, and highlights next steps and areas for further research.

2. Working approach

This section provides an overview of the working approach followed in this deliverable, detailing the steps taken to achieve research objectives (Figure 1). Assessing the decarbonization potential of energy citizen clusters involved a multi-method approach, involving both semi-quantitative and quantitative methods. Furthermore, frequent coordination with WP4 took place to ensure the appropriate integration of outputs (clustering results) into WP5 inputs (energy scenarios). Using the insights from citizen clusters as input for the ENCLUDE modeling ensemble, we managed to formulate questions and explore scenarios that could provide recommendations for the development of policies and strategies that effectively promote decarbonization efforts across different segments of the population.

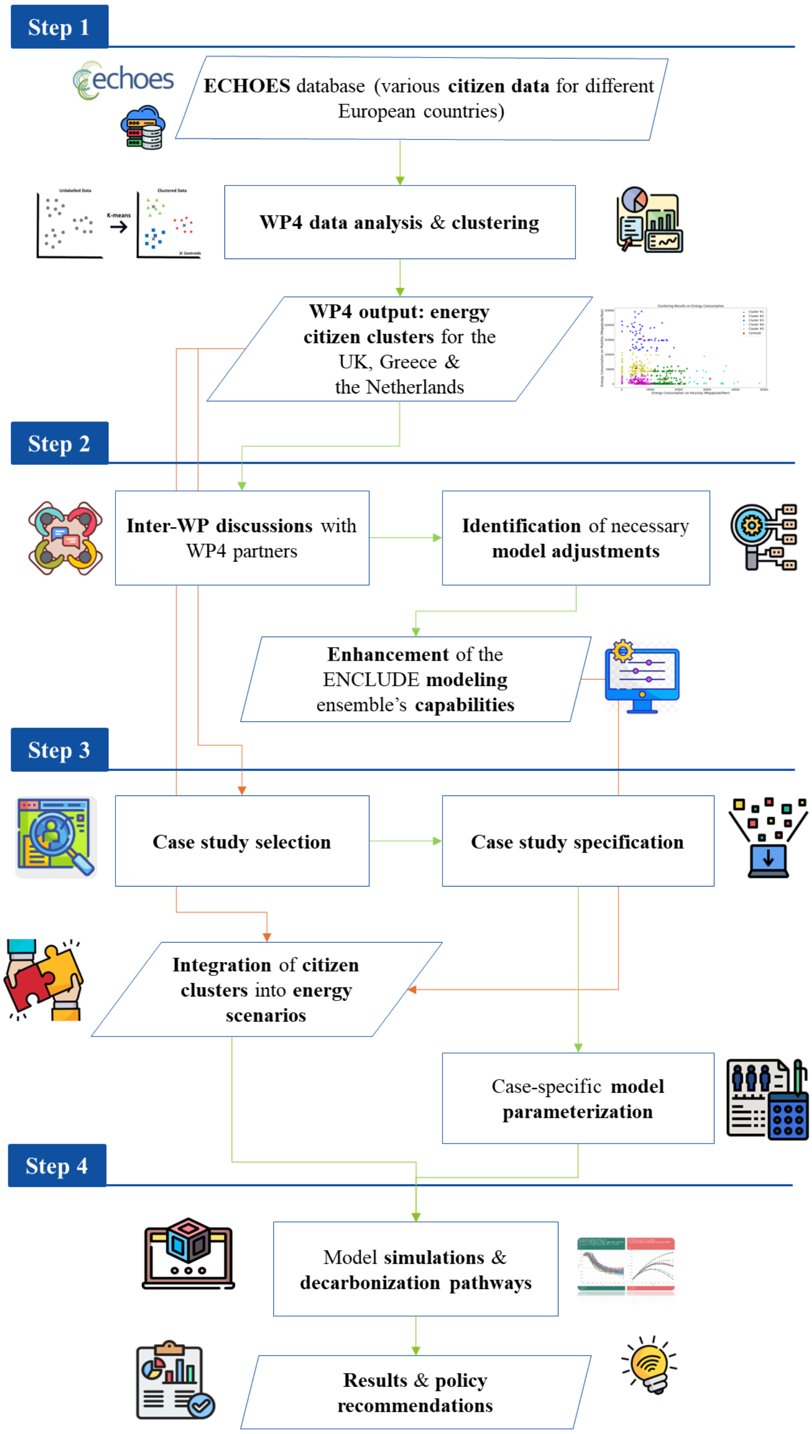

Figure 1. Multi-method approach as followed in the context of the ENCLUDE WP5 to assess the decarbonization potential of energy citizen clusters.

2.1. Step 1: Understanding the citizen clustering and profiling analysis

The first step of our work entailed understanding the origins and the process behind the semi-quantitative outputs of WP4, and mainly those in Deliverable 4.2 (Naderian et al., 2024b). The primary objective of WP4 was to extract meaningful clusters of energy citizens that span across various geographical contexts and socioeconomic environments in order to provide insight into citizen profiles and promote tailored policy interventions to accelerate decarbonization efforts.

To achieve this objective, Deliverable 4.2 (Naderian et al., 2024b) involved developing a machine learning model for clustering citizens based on data on energy consumption and CO_2 footprint. A detailed methodology was used to estimate the data regarding the total energy consumption in the housing sector (based on residency characteristics) and the mobility sector (based on transportation modes). Using a set of country-specific data from the ECHOES project[1], this approach was applied to data on citizens residing in the United Kingdom (UK), Greece, and the Netherlands.

As detailed in "*Step 2: Adjustments for the integration of clustering results into the models*", outputs of the clustering analysis, in terms of countries, sectors, and parameters of interest, highlighted areas for further development and enhancement of the ENCLUDE modeling ensemble. As detailed in "*Step 3: Case study selection and scenario design*", the application of the clustering analysis also guided the case study selection process as well as provided the relevant context for the formulation of the research questions (RQs) addressed by the modeling applications conducted in the context of this deliverable.

Better understanding of the citizen clustering analysis required the establishment of ongoing dialogue and feedback loops with WP4 colleagues. Therefore, several discussions between the two (2) WPs were held both online and in-person. In this regard, we organized several bilateral and trilateral (also including colleagues from "*WP1: Coordination, project management and ethics requirements*") online meetings from January 2024 until April 2024. Each meeting followed a structured agenda, covering updates on progress, identification of challenges, and setting short-term goals.

These meetings allowed for the alignment of objectives and timelines across both WPs. They also provided a platform for deep dives into technical aspects and facilitated knowledge sharing among the two (2) WPs. These meetings also facilitated a deep understanding of the application of the clustering methodologies, as well as the findings and conclusions discussed by WP4. We meticulously reviewed the data used as input, examined the energy citizen clustering and profiling processes, and analyzed the various parameters characterizing each identified cluster. We also had the opportunity to discuss about technical aspects related to WP5, such as required further model adjustments, the selection and specification of potential case studies, the incorporation of clustering outcomes into energy scenarios, etc.

Apart from online meetings, we also organized an in-person roundtable discussion with WP4 during the 6th ENCLUDE General Assembly meeting which took place on the 23rd and the 24th of May 2024 in Athens. The purpose of this discussion was to finalize the scope of the collaboration between the two (2) WPs. Specifically, we discussed how to best integrate the semi-quantitative energy citizen clustering and profiling outcomes of WP4 into quantitative inputs for the development of citizen-informed energy scenarios.

This collaborative process was further enhanced through reciprocal reviews of the deliverables produced by each WP. Specifically, Deliverable 4.2 (Naderian et al., 2024b) and Deliverable 4.3 (Naderian et al., 2024a) underwent review by WP5 colleagues, while Deliverable 5.4 (Manias et al., 2024) and this deliverable were reviewed by WP4 colleagues. Furthermore, during the development phase of both deliverables, preliminary findings were frequently shared between the two (2) WPs. This exchange facilitated the provision of constructive feedback, thereby enriching the comprehensiveness of our methodologies and the quality of our outputs. This iterative cooperation with WP4 colleagues underscored the value of

[1] https://echoes-project.eu/

interdisciplinary research, as it brought together expertise from different fields to enhance the robustness of our work.

2.2. Step 2: Adjusting the models to integrate the clustering results

After understanding the energy citizen clustering and profiling analysis, the next step was to identify further model adjustments for the ENCLUDE modeling ensemble. These were deemed necessary since the modeling applications conducted in this deliverable relied on the inputs received from WP4. From May 2024 to June 2024, our focus shifted towards refining the models to incorporate the newly identified data and parameters that would enable us to develop more sophisticated and accurate decision-support tools.

As detailed in "*Step 1: Understanding the citizen clustering and profiling analysis*", the required further model adjustments were also discussed between the two (2) WPs. During the discussions, we explored how the citizen clusters and profiles could be best integrated into the models to produce meaningful case study applications and address policy-relevant RQs. This collaborative effort allowed us to identify parameters previously overlooked by the models. Specifically, accounting for parameters related to citizens' energy consumption and CO_2 footprint levels was among the identified areas that called for further enhancement and improvement.

2.3. Step 3: Case study selection and scenario design

Geographical dimension adds an important value to the quantification of the decarbonization potential of energy citizenship, as already shown in Deliverable 5.3 (Fotopoulos et al., 2024) and Deliverable 5.4 (Manias et al., 2024). In this deliverable, the clustering results from Deliverable 4.2 (Naderian et al., 2024b) guided the selection process of the case studies and the formulation of the RQs addressed. This means that the selected case studies were confined to the countries whose citizens were included in the clustering and profiling analysis, namely the UK, Greece, and the Netherlands. We selected the two (2) Member States, namely Greece and the Netherlands for our analysis.

As detailed in "*Step 1: Understanding the citizen clustering analysis*", the case study selection was also discussed between the two (2) WPs. During the discussions, we jointly devised methods to appropriately scale clustering results derived from a limited number of survey participants at the national level. We integrated these scaled up outputs as inputs into our models in order to formulate different demand specifications for the design of citizen-informed energy scenarios and the case-specific model parameterization.

The method followed for the upscaling was initiated by identifying the historical national energy consumption and electricity demand for the housing and mobility sectors from the energy balances uploaded in Eurostat[2] for the time period 2018 (reference year in Deliverable 4.2) to 2021. For the years following this time period, we used the National Energy and Climate Plan (NECP) projections for Greece[3] and the Netherlands[4] toward 2050, to specify patterns of energy consumption and electricity demand in Greece and the Netherlands. After specifying the energy consumption and electricity demand patterns, we aimed to develop the energy scenarios. To do so, we scaled up the clustering results of Deliverable 4.2 at the national level by utilizing the following equations:

$$Scenario(Energy\ Consumption)_i = T_i * [\frac{C_j}{\sum C_j} * \ P_i * ECC_j + (1 - \frac{C_j}{\sum C_j}) * EC_i]$$

[2]https://ec.europa.eu/eurostat/cache/infographs/energy_balances/enbal.html?geo=EU27_2020&unit=KTOE&language=EN&year=2022&fuel=fuelMainFuel&siec=TOTAL&details=0&chartOptions=0&stacking=normal&chartBal=&chart=&full=0&chartBalText=&order=DESC&siecs=&dataset=nrg_bal_s&decimals=0&agregates=0&fuelList=fuelElectricity,fuelCombustible,fuelNonCombustible,fuelOtherPetroleum,fuelMainPetroleum,fuelOil,fuelOtherFossil,fuelFossil,fuelCoal,fuelMainFuel

[3] https://commission.europa.eu/publications/greece-draft-updated-necp-2021-2030_en

[4] https://commission.europa.eu/publications/netherlands-draft-updated-necp-2021-2030_en

$$Scenario(Electricity\ Demand)_i = \frac{ED_i}{EC_i} * \frac{C_j}{\sum C_j} * \ P_i * ECC_j + (1 - \frac{C_j}{\sum C_j}) * ED_i$$

where: i spans from 2018 (reference year) to 2050, j depicts the number of the cluster (1-3 for Greece and 1-4 for the Netherlands), T_i is the pattern for each year and is the number resulting from division of the annual energy consumption in year i with the annual energy consumption in the reference year, C_j is the population of each cluster, $\sum C_j$ is the sum of the population of all clusters, P_i is the national population for each year, ECC_j is the centroid energy consumption resulted from cluster j, EC_i is the energy consumption in year i, which has been extrapolated according to the Eurostat energy balances and NECP's projections, and ED_i is the electricity demand in year i, which has been extrapolated according to the Eurostat energy balances and NECP's projections.

$\frac{ED_i}{EC_i}$ is the share for each year and results from division of the annual electricity demand in year i (ED_i) with the annual energy consumption in year i (EC_i). This annual share was calculated for each year i based on the historical and future patterns of the share of electricity demand in the total energy consumption. We used this share instead of a pattern resulting from the division of the annual electricity demand in year i with the annual electricity demand in the reference year due to the unavailability of clustering results for electricity demand.

2.4. Step 4: Model application to the case studies

As the last step in our methodology, we fed the citizen-informed energy scenarios in our enhanced ENCLUDE modeling ensemble in order to generate forward-looking simulations and calculate the decarbonization potential of the citizen clusters at the national level. Simulations spanned different modeling horizons, reflecting both short-term and long-term targets, and produced decarbonization pathways informed by the clustering analysis, which provided complementary insights with regards to the transformative potential of energy citizenship. Modeling outcomes from this deliverable were further processed in order to demonstrate which clusters are more crucial and responsive towards accelerating decarbonization efforts and develop robust policy recommendations by targeting these clusters with tailored policies and interventions.

2.5. Analytical process for bridging citizen clusters into energy models

The following figure (Figure 2) provides an overview of the analytical process regarding the integration of WP4 results on energy citizen clusters into the energy models of WP5. In alignment with the methodological steps discussed in this section, our workflow entailed the identification of clusters' centroid values and population, their translation into energy consumption scenarios for housing and mobility, their conversion into electricity demand scenarios, and, finally, their integration into the ENCLUDE modeling ensemble.

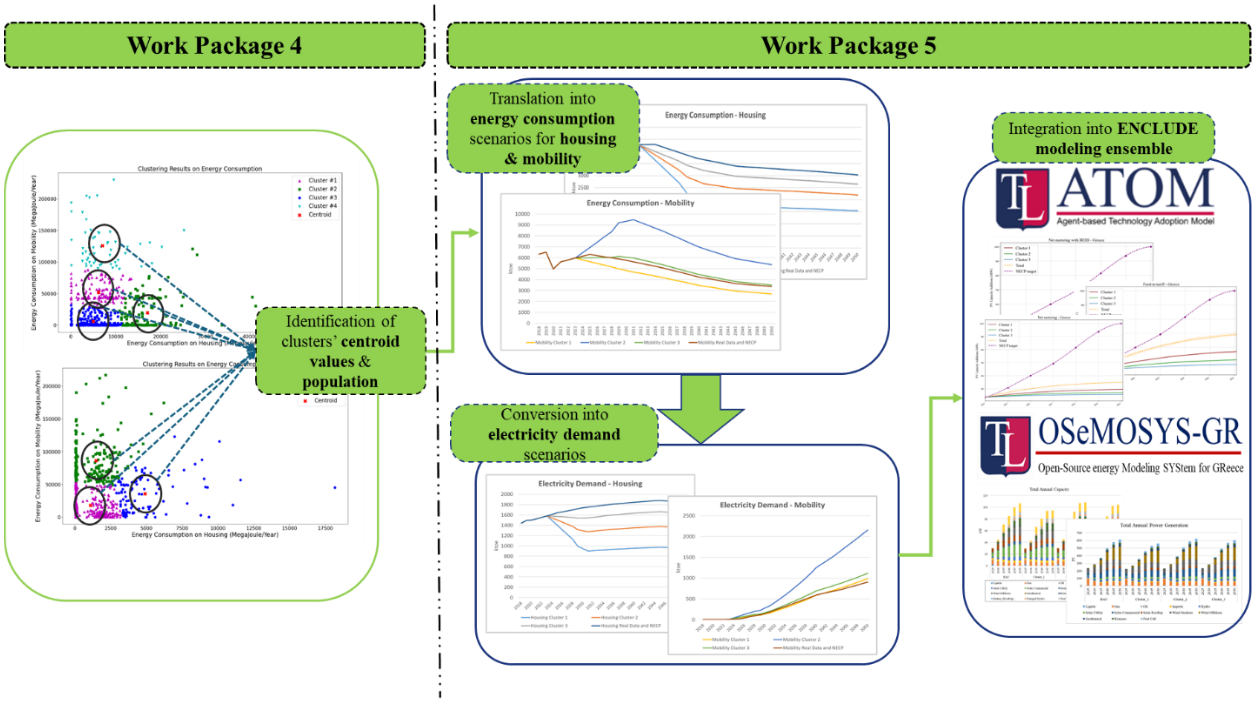

Figure 2. Overview of the analytical process for integrating clustering results into the ENCLUDE modeling ensemble.

3. An overview on citizen clustering analysis and energy citizen profiling

This section offers an overview of the citizen clustering analysis and the energy citizen profiling and summarizes their key findings. This overview provides a high-level understanding of the methods used and their results. More details about them can be found in Deliverable 4.2 (Naderian et al. 2024) and Deliverable 4.3 (Naderian et al., 2024a).

For the citizen clustering analysis, the ECHOES dataset was selected to categorize citizens based on their energy consumption and CO_2 footprint. The ECHOES dataset was developed through a Europe-wide survey covering 18,000 citizens' energy behaviors (Reichl et al., 2019).

Prior to the citizen clustering analysis, a Life Cycle Assessment (LCA) methodology was applied for estimating the annual energy consumption per capita for the housing and mobility sectors. LCA is regarded as one of the best methods for estimating energy consumption per capita in those two sectors as it considers various citizens' attributes, including their energy behaviors and the technologies that they use (Notter et al., 2013). Specifically, energy consumption calculations for the housing sector considered citizen data with reference to the greatest household energy expenditures, namely heating, cooling, hot water, cooking, and lighting and appliances. Energy consumption calculations for the mobility sector, considered citizen data related to private transport, motorcycles, public transport, and aviation.

The calculation of CO_2 footprint per capita utilized the energy consumption values derived from the application of the LCA method as well as emission factors for different types of fuel consumed for various activities within the housing and mobility sectors. The housing sector used emission factors for gas, oil, wood, heat pumps, and electricity, while the mobility sector used emission factors for petrol, diesel, hybrid, electricity, and gas.

In the context of the energy citizen profiling, citizen profiles were identified for each cluster or combination of two clusters based on within-cluster analyses for the selected countries. The within-cluster analyses built upon the clustering results for energy consumption and CO_2 emissions by evaluating each cluster based on its attributes. The within-cluster evaluation provided insights into the sociodemographic, energy consumption, and cognition-related factors (among others) that characterize the citizens within each identified group. Age, education, house size, car fuel consumption, and climate change perception were considered as key factors to evaluate each cluster, and the results were presented as histograms in Deliverable 4.3 (Naderian et al., 2024a). Based on the within-cluster statistics it was possible to identify citizens profiles for each cluster or combinations of clusters.

3.1. Citizen clustering process

After estimating both the energy consumption and the CO_2 footprint for each citizen, a clustering algorithm was applied to identify patterns and group similar data points. Specifically, the K-means clustering algorithm was employed to extract distinct citizen clusters, allowing for the classification of individuals based on their energy consumption and carbon footprint profiles.

K-means clustering algorithm is a machine learning-based method used for dividing a dataset into distinct groups or clusters based on their similarity. The algorithm works by initializing a set of k centroids showing the average position of all data points in each cluster, where k represents the number of desired clusters. Each data point in the dataset is then assigned to the nearest cluster centroid based on the Euclidean distance, forming k clusters.

Once all data points have been assigned to the cluster centroids, the centroids are recalculated by taking the mean of all data points within each cluster. The process of assigning points and recalculating the cluster centroids is repeated iteratively until the centroids no longer change significantly, indicating that the algorithm has converged.

3.2. Citizen clustering results and energy citizen profiles

In this section, we present the clustering outcomes derived from the application of the K-means algorithm to the data points on energy consumption and CO_2 footprint for Greece and the Netherlands, the two case study countries that were selected for the modeling applications in the context of this deliverable. More details about the case study selection are provided in **Section 5**. The clustering analysis of Greek citizen data resulted in three (3) distinct clusters, each representing a unique grouping based on their energy consumption patterns and related CO_2 footprint for the housing and mobility sectors. The clustering analysis of Dutch citizen data resulted in four (4) different clusters. The following sections offer more information on these clusters, providing the clusters' populations and centroid locations for energy consumption and CO_2 footprint for the housing and mobility sectors.

3.2.1. Clustering results and energy citizen profiles for Greece

Three (3) distinct groups of citizens can be identified based on their energy consumption patterns for the housing and mobility sectors in Greece. **Table** 2**2** displays the population and the centroid location of each cluster with regards to the energy consumption in the housing and mobility sectors.

According to the clustering results, energy consumption levels among Greek citizens exhibit relative consistency across housing and mobility sectors for the majority of individuals within *Cluster 1*. In contrast, significant variations in energy consumption between mobility and housing are observed in *Cluster 2* and *Cluster 3*, respectively.

Table 2. Clustering results based on energy consumption data for the housing and mobility sectors in Greece (Naderian et al. 2024).

Cluster	Population	Centroid location on housing energy (MJ)	Centroid location on mobility energy (MJ)
1	316	1,106.11	17,999.71
2	181	1,489.15	86,437.60
3	106	4,911.83	35,735.73

The CO_2 footprint clustering results exhibit similar patterns to those observed for energy consumption. *Cluster 1* has low to medium CO_2 footprints across both sectors, while *Cluster 2* and *Cluster 3* display more dispersed centroids for CO_2 footprints in the mobility and housing sectors, respectively. As shown in **Table 3**, nearly 72.6% of citizens (*Cluster 1*) maintain a low to medium CO_2 footprint, whereas 14.9% of citizens (*Cluster 2*) exhibit medium to high CO_2 footprints specifically in the mobility sector. 12.4% of citizens (*Cluster 3*) are associated with a high CO_2 footprint in housing.

Table 3. Clusters results based on CO_2 footprint data for the housing and mobility sectors in Greece (Naderian et al. 2024).

Cluster	Population	Centroid location on housing CO_2 footprint ($kgCO_2$/year)	Centroid location on mobility CO_2 footprint ($kgCO_2$/year)
1	438	127.41	1,888.73
2	90	118.36	8,236.55
3	75	509.80	2,603.62

Three (3) energy citizen profiles are defined for Greece based on within-cluster results, as presented in **Table 4**. In this case, each profile corresponds to each cluster. *Profile 1* represents citizens in *Cluster 1*, i.e., mostly young people with college degrees and low CO_2 footprint on housing and mobility. *Profile*

2 represents citizens in *Cluster 2*, namely mostly middle-aged people with medium to high level of CO_2 footprint and neutral to positive opinion regarding climate change.

Table 4. Energy citizen profiles based on CO_2 footprint clusters and within-cluster statistics for Greece (Naderian et al., 2024a).

Attribute	Profile #1	Profile #2	Profile #3
Age range	19-34	19-34 and 35-49	19-34
Education	College	College	College
Population %	72.63%	14.92%	12.45%
Energy on Mobility	Low to Medium	Medium to High	Medium to High
CO_2 Emissions (housing and mobility)	Low	Medium to high	Low to Medium
Climate Change Perception	Positive	Neutral to positive	Positive

3.2.2. Clustering results and energy citizen profiles for the Netherlands

Four (4) distinct groups of citizens can be identified based on their energy consumption patterns for the housing and mobility sectors in the Netherlands. **Table 5** displays the population and the centroid location of each cluster with regards to the energy consumption in the housing and mobility sectors.

According to the clustering results, energy consumption levels among Dutch citizens are relatively consistent across housing and mobility sectors for 44.1% of the population (*Cluster 3*). However, significant differences in energy consumption within the mobility sector are observed in *Cluster 1* and *Cluster 4*, which together represent 33.2% of the population. 21.9% of Dutch citizens (*Cluster 2*) exhibit medium to high energy consumption in housing.

Table 5. Clustering results based on energy consumption data for the housing and mobility sectors in the Netherlands (Naderian et al. 2024).

Cluster	Population	Centroid location on housing energy (MJ)	Centroid location on housing energy (MJ)
1	144	6,139.33	52,062.427
2	132	17,105.75	19,557.54
3	266	4,995.31	6,117.30
4	60	7,036.23	125,976.65

With regards to CO_2 footprint clustering results, as indicated in **Table 6**, nearly 40% of the citizens grouped (*Cluster 1*) exhibit a low to medium CO_2 footprint across housing and mobility sectors. In contrast, 40.8% of the citizens (*Cluster 3* and *Cluster 4*) have a medium to high CO_2 footprint in housing. Additionally, 20% of the citizens (*Cluster 2*) are characterized by a high CO_2 footprint in mobility.

Table 6. Clustering results based on CO_2 footprint data for the housing and mobility sectors in the Netherlands (Naderian et al. 2024).

Cluster	Population	Centroid location on housing CO_2 footprint ($kgCO_2$/year)	Centroid location on mobility CO_2 footprint ($kgCO_2$/year)
1	160	331.66	1,594.54
2	79	1,068.59	1,570.25

3	157	496.39	7,202.04
4	8	3,736.15	3,202.97

Three (3) energy citizen profiles are defined for the Netherlands based on within-cluster results, as presented in Table 7. *Profile 1* represents 39.6% of the population, consisting mainly of citizens with low level of CO_2 footprint on housing and mobility, mostly young and old people with college degrees. *Profile 2* represents 19.6% of the population, with high energy consumption and CO_2 footprint in the mobility sector, who have neutral to positive opinion about climate change. Members of this profile are young people with college or professional degrees. *Profile 3* is a combination of the citizens of *Cluster 3* and *Cluster 4*, with medium to high CO_2 footprint on housing. They are mostly middle-aged people with college degree, and they also have neutral to positive opinion about climate change.

Table 7. Energy citizen profiles based on CO_2 footprint clusters and within-cluster statistics in the Netherlands (Naderian et al., 2024a).

Attribute	Profile #1	Profile #2	Profile #3
Age range	19-34, >65	19-34	19-34,35-49
Education	Professional and College	College and Professional	College
Population %	39.60%	19.55%	40.84%
Energy on Mobility	Low to Medium	Medium to High	Low to Medium
CO_2 Emissions (housing and mobility)	Low	Medium to High	Low to Medium
Climate Change Perception	Positive	Neutral to Positive	Neutral to Positive

3.3. Key findings

For Greece, the analysis shows that the majority of citizens fall within the "*Low to Medium*" energy consumption range across both sectors, with a smaller group identified as "*Medium to High*" energy consumers, particularly in mobility. In contrast, the Dutch population exhibits a different clustering pattern, where a noticeable group of citizens demonstrates "*Medium to High*" energy consumption in housing, twice as large as those with high energy consumption in mobility. Overall, the citizen clustering analysis and energy citizen profiling laid the groundwork for developing tailored strategies aimed at reducing energy consumption and CO_2 emissions by addressing the specific needs and behaviors of different citizen groups (Naderian et al. 2024).

4. Further modifications and adjustments of the ENCLUDE modeling ensemble

After understanding the results derived from the citizen clustering and profiling analysis, further model developments, modifications, and adjustments took place so that the ENCLUDE modeling ensemble can simulate the case-specific decarbonization pathways. The selection of models from the ENCLUDE modeling ensemble was based on the premise that the clustering results should fall under the scope of the model and that the scale of the citizen clustering results should be the same as that of the model. In this regard, we selected two (2) out of the (5) modeling frameworks of the ENCLUDE modeling ensemble, i.e., ATOM and the OSeMOSYS-GR, for the model applications to the case studies. Both tools can use at least a part of the clustering results and can simulate energy scenarios at the national scale. More details about the case study selection are provided in **Section 5**.

In this section, we present the model modifications and adjustments, which will also be used to update earlier versions of the models' documentation in the EnergyCitizenship.eu platform[5] (as part of the work conducted in the context of ENCLUDE's "*WP7: Synthesis, Dissemination, Communication, and Exploitation*").

4.1. The ATOM modeling framework

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, battery energy storage systems (BESS), heat pumps, electric vehicles (EVs), etc.) in the residential sector for various geographical and socioeconomic contexts (Stavrakas et al., 2019).

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) (Papadelis & Flamos, 2019).

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.

Considering the different energy citizen clusters derived from Naderian et al. (2024), we employed ATOM in order to calculate the contribution of these clusters on the adoption potential of small-scale solar PV systems in the residential (housing) sectors of Greece and the Netherlands. Furthermore, we utilized ATOM to estimate the carbon emissions that could be avoided through the anticipated PV capacity additions and each cluster's contribution on the total decarbonization potential.

Specifically, different profiles of energy citizen clusters for Greece and the Netherlands were used as inputs in ATOM according to their electricity demand. Through this modeling exercise, we aim to provide valuable insights about the potential of empowering prosumerism in the residential sectors of the Member States by targeting specific energy citizen clusters; for example, lower-demand households.

More details about the ATOM modeling framework can be found in **Deliverable 5.4** (Manias et al., 2024).

[5] https://energycitizenship.eu/

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.

In this deliverable, we use OSeMOSYS-GR, a CEM 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.

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 and other flexible technologies like pumped hydro, large-scale and small-scale BESS 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.

In this deliverable, OSeMOSYS-GR utilized the insights provided by the energy citizen clustering and profiling analysis in order to compute the potential impacts wielded by citizen groups with different profiles in terms of their sociodemographic characteristics, energy consumption levels, etc. Specifically, the application of OSeMOSYS-GR leveraged the electricity demand data and projections for the housing and mobility sectors derived from the different citizen clusters and provided insights into key energy, environmental, and economic impacts of citizens' energy behaviors on the decarbonization pathways of the Greek power sector. To leverage the clustering analysis data, the model was further modified in order to capture different electricity demand projections in the housing and mobility sectors.

The OSeMOSYS-GR application aims to facilitate understanding in terms of which citizen clusters should be further targeted with tailored policies that could lead to the mitigation of the power sector's emissions and costs. It 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.

More details about the OSeMOSYS-GR modeling framework can be found in **Deliverable 5.4** (Manias et al., 2024).

5. Integration of energy citizen clusters into the case studies

In this section, we present the case study selection and specifications for the application of the ENCLUDE modeling ensemble. We also present the RQs we seek to answer through the model applications as well as background and contextual information and provide details on how we crafted the scenario design to address the RQs. This entailed parameterizing the utilized models to ensure their alignment with the clustering analysis, the selected case studies, and the overarching research objectives.

5.1. Case study selection and specification

The main source of information and data for the selection and specification of the case studies was those examined in the context of WP4 (Naderian et al. 2024). As already mentioned in Section 3 and Section 4, the rationale behind the case study selection process was based on the availability and scale of the clustering results provided by WP4 as well as their capability to be integrated into the ENCLUDE modeling ensemble. As mentioned in Section 4, the models employed in this deliverable, namely ATOM and OSeMOSYS-GR, have been previously calibrated for different European countries. However, it is important to note that the UK falls outside of their calibration scope and thus, the UK was not included as a case study in this deliverable.

This section delves into the selection of case studies chosen for analysis using the ENCLUDE modeling ensemble. Thus, we provide a cross-sectional overview of the prevailing conditions ("*status quo*") in the Netherlands and Greece, highlighting aspects relevant to each employed model (Figure 3). Our case studies showcase diverse socioeconomic conditions, e.g., income, employment rates, etc., which should be taken into consideration when studying the transition to fair and inclusive future societies. Furthermore, our selection spans across different policy landscapes, considering different legislative and regulatory frameworks, currently in operation in the selected Member States.

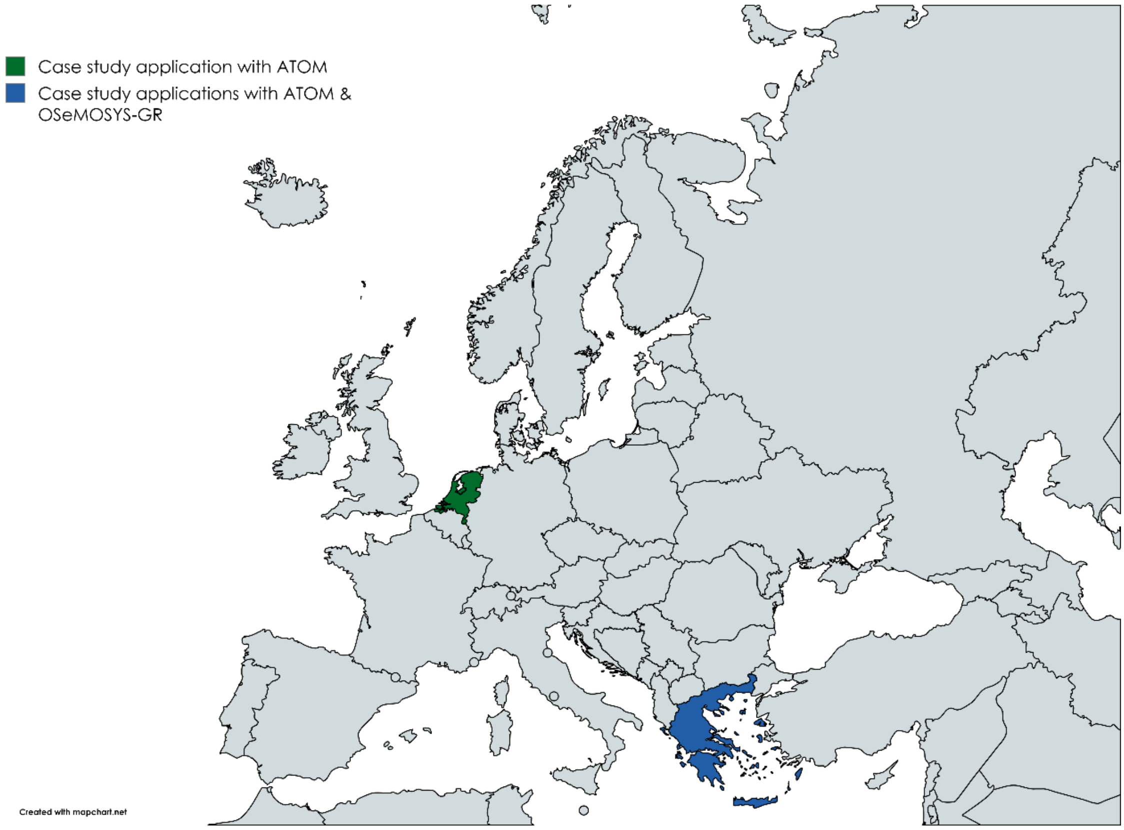

Figure 3. Selected case studies to be modeled using the ENCLUDE modeling ensemble at the national level (visualization developed using the online map-making tool "MapChart[6]").

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

5.1.1. Adoption of rooftop solar PV systems in the housing sector for different energy citizen clusters in Greece and the Netherlands

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., 2022b; 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 (Stavrakas & Flamos, 2020; 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 (Michas et al., 2019; Kontochristopoulos et al., 2021). Within this framework, the concepts of self-consumption and self-production are gaining significant value, particularly in the residential sector. Stavrakas et al. (2019) showed 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.

In this context, 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 Greece and the Netherlands. We provide a short policy background of prosumerism in both countries' residential sector below:

Greece

Greece has 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). Specifically, the average Global Horizontal Irradiation in Greece is around 1,639 kWh/m^2 (on an annual basis), which ranks Greece in the third (3^{rd}) position among the Member States (according to data retrieved by Global Solar Atlas[7]). Despite its abundant solar potential, Greece has not yet utilized the full potential of solar power integration since solar energy contributes only with 18.93% in power generation (Statista, 2024).

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.

So far, 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 feed-in tariff (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"[8], or based on a net metering scheme without any remuneration, according to "Law 5037/2023.OFG 78/28.03.2023"[9], and with a four-month netting period.

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

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

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

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.

The Netherlands

The Netherlands is located in Northwestern Europe and 26% of its area (around 10,500 km^2) is situated below sea level (van Alphen et al., 2022). It is not only a pioneering Member State in terms of solar PV per capita in the EU, but also worldwide.

According to data retrieved by Global Solar Atlas[10], the average annual Global Horizontal Irradiation of the Netherlands is approximately 1,057 kWh/m^2, which ranks the Netherlands in the 20th position among the Member States. However, despite of the lower ranking in terms of solar irradiation, it is noteworthy that the Netherlands is ranked first (1st) in terms of electricity generation from solar PVs per capita with 1,200 kWh/cap due to the elevated installed capacity that has already achieved (Our World In Data, 2024).

The installed capacity of solar PV systems in the Netherlands evolved from 650 MW in 2013 to 24.26 GW by the end of 2023 (StatLine, 2024; Zhang et al., 2023). From this capacity, 431 MW in 2013 to approximately 10 GW by the end of 2023 was attributed to residential solar PV installed capacity with over 2.5 million households having solar PV systems installed (StatLine, 2023; Stultiens, 2023).

According to Bódis et al. (2019), the rooftop area available in the Netherlands where residential solar PVs could be installed is equal to 283 km^2. That means that the Netherlands have a technical potential of residential solar PV systems of around 14 GW, which is translated to approximately 17,650 GWh per year. This electricity generation potential is capable to cover around 17% of the total electricity consumption of the country.

The latter highlights the need for more supportive policies in order to achieve a further diffusion of small-scale solar PVs in the Dutch residential sector. So far, the Netherlands aims to promote the adoption of small-scale solar PVs through a net metering scheme namely "Salderingsregeling" which started in 2004. Under this scheme, prosumers receive a compensation for the electricity they supply to the grid. However, the Dutch government aims to gradually phase the net metering scheme out by 2030 and transition to a FiT scheme with a fixed price lower than the retail price of electricity (Dutch Central Government, 2024; Nivera, 2024).

Along with the net metering scheme, a FiT scheme for the remuneration of residential prosumers namely "Postcoderoosregeling" used to be active from 2014 to 2020. This scheme was designed for collective solar energy projects within a specific postal code area. This scheme was particularly beneficial for those who could not install solar panels on their own property but wished to participate in a RES project. The last available fixed price under this policy scheme was equal to 109.7 €/MWh by the end of 2019 (Organisation for Economic Cooperation and Development, 2020).

Finally, with regards to BESS, Dutch government plans to allocate 100 million € in BESS subsidies in order to promote PV with storage. The initial estimate for the average subsidy will be equal to 0.215 €/kWh of discharged energy and the scheme is planned to begin by 2025 (Murray, 2024).

Based on the case study specifications, we ask the following RQs:

RQ$_{1.1}$	*"How could different policy schemes empower prosumerism and further citizen adoption of small-scale PV systems in Greece and the Netherlands by 2030 for the different citizen clusters that have been defined?"*

[10] https://globalsolaratlas.info/map?r=NLD&c=52.176306,5.29165,8

RQ ***1.2***	*"What are the carbon emissions that could be avoided (decarbonization potential) through the further empowering of prosumerism in Greece and the Netherlands by 2030 for the different citizen clusters that have been defined?"*

5.1.2. Power sector capacity buildout based on electricity consumption patterns of different energy citizen clusters in the housing and the mobility sectors in Greece

The European Green Deal sets strict benchmarks for the EU member states, including Greece, to transition towards climate neutrality. Greece has been making strides in reducing its reliance on fossil fuels, primarily lignite, which has historically been a major source of its electricity supply. Aiming to create a carbon-neutral energy system, the Greek NECP outlines the usage of variable renewable energy (VRE) capacity and modernizing energy infrastructure to meet increasing future electricity needs due to the electrification across various sectors, including housing, mobility, and industry (Michas & Flamos, 2023).

Electrification entails the adoption of EVs, heat pumps, and other electrification technologies that will lead to a paradigm shift in energy consumption and necessitate a comprehensive expansion of the power generation infrastructure (Calise et al., 2022). Furthermore, the continuous improvement in living standards, the evolution of consumption patterns, and the increasing use of energy-intensive technologies will further exacerbate the strain on the power system (Szajt et al., 2018).

In the mobility sector, the NECP-2019 set targets for EV adoption, aiming for 10.1% EVs in new passenger car registrations by 2024 and 30% by 2030 (Hellenic Ministry of Environment and Energy, 2019). In 2020, the Greek government passed a law promoting electromobility, which offers grants for purchasing electric cars, motorcycles, bicycles, and scooters. The law also allocates free-of-charge parking for EVs emitting less than 50 gCO_2/km, promotes public charging station installation, raises taxes on older high-emission vehicles, and mandates that only zero-emission vehicles are sold from 2030 onwards.

EV deployment in Greece has grown rapidly, from just 62 vehicles in 2014 to 18,575 in 2022, with a nearly sixfold increase between 2020 and 2022. Despite this growth, Greece still lags behind other European countries. In 2022, EVs made up just 0.3% of the total car fleet, compared to 2.3% in Europe. Additionally, only 7.9% of new car registrations were EVs, significantly lower than the European average of 21.6% (IEA, 2023).

Traditionally reliant on oil-based heating, especially in colder regions, the Greek housing sector has seen a shift towards heat pumps which are expected to increase its electricity demand. The Long-Term Renovation Strategy aims to cut oil use in housing heating by 90% by 2030, replacing it with natural gas, renewables, and electricity. By 2050, oil-based heating will be entirely eliminated and replaced by heat pumps, biomethane, hydrogen, and renewable electricity (Hellenic Ministry of Environment and Energy, 2021).

Electrification is a central pillar of this strategy, with a target to increase electricity use by 20% by 2030 (compared to 2015). Between 2010 and 2021, renewable heating and cooling grew from 19% to 31.1% of total demand, driven largely by heat pump adoption (IEA, 2023). According to the Greek NECP, electricity is projected to cover 47% and 81% of housing energy needs by 2030 and 2050, respectively (Hellenic Ministry of Environment and Energy, 2019).

Considering the above, it becomes clear that the success of Greece's energy transition hinges on active citizen engagement and the widespread adoption of the sustainable energy solutions in the mobility and housing sectors. In this context, citizens' adoption rate of electrification technologies and their energy use patterns will significantly impact the future energy system design in terms of capacity and flexibility requirements. By understanding and responding to the diverse behaviors and consumption patterns of different citizen groups, policymakers can ensure that the transition to a low-carbon economy is both efficient and equitable.

Drawing from the need for better understanding of the potential impacts wielded by citizen groups with different profiles in terms of their sociodemographic characteristics, energy consumption levels, etc., we aim at integrating different citizen groups' energy consumption patterns into OSeMOSYS-GR, to enable the assessment of their energy consumption alongside other aspects like technical feasibility and cost in order to explore the future development of the Greek power system.

Based on the case study specifications, we ask the following RQs:	
RQ$_{2.1}$	*"How do different citizen groups' energy consumption patterns affect the capacity and flexibility requirements as well as the resulting electricity mix of decarbonization pathways in the power sector by 2050?"*
RQ$_{2.2}$	*"How do different citizen groups' energy consumption patterns affect the capital investments and the carbon footprint of decarbonization pathways in the power sector by 2050?"*

5.2. Scenario design and transition pathways

In this section, we delve into the results of the specification process for the case studies described previously. Specifically, we shed light on the numerical parameters and assumptions that form the basis of the analytical approach that was followed in each case study. More details about the specification process are available in **Section 2**.

Based on the case study specifications, as presented in **Section 5.1**, we showcase the applicability of the ENCLUDE modeling ensemble to address the RQs, and thus explore the decarbonization potential of the further diffusion of small-scale PV systems by 2030 at the national level of two (2) Member States as well as the power system planning for a renewable-based transition at the national level of one Member State.

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

5.2.1. Adoption of rooftop solar PV systems in the housing sector for different energy citizen clusters in Greece and the Netherlands

In this section, we seek to describe how the different energy citizen clustering results were leveraged by ATOM in order to produce forward-looking simulations on the adoption potential of small-scale solar PV systems and estimations about avoided emissions (decarbonization potential) through prosumerism in the residential sectors of Greece and the Netherlands.

The different policy schemes simulated by ATOM in the context of our analysis are FiT, net metering, and net metering with BESS. We examine how these schemes affect the profitability of investing in small-scale solar PVs for potential prosumers in Greece and the Netherlands. More details about the modeling of these policy schemes in ATOM are available in Deliverable 5.4 (Manias et al., 2024).

To create projections for different citizen clusters in the Greek housing sector, we utilized relevant historical data, the clustering results on citizens' energy consumption (Naderian et al. 2024), and future patterns regarding energy consumption and electricity demand. **Figure 4** and **Figure 5** depict the historical data from 2018 to 2021 that were retrieved from Eurostat Energy Balances[11]. Furthermore, both

[11] https://ec.europa.eu/eurostat/cache/infographs/energy_balances/enbal.html?geo=EU27_2020&unit=KTOE&language=EN&year=2022&fuel=fuelMainFuel&siec=TOTAL&details=0&chartOptions=0&stacking=normal&chartBal=&chart=&full=0&chartBalText=&order=DESC&siecs=&dataset=nrg_bal_s&decimals=0&agregates=0&fuelList=fuelElectricity,fuelCombustible,fuelNonCombustible,fuelOtherPetroleum,fuelMainPetroleum,fuelOil,fuelOtherFossil,fuelFossil,fuelCoal,fuelMainFuel

figures present our extrapolations based on the Greek NECP's trends and each cluster's energy consumption levels in order to design the scenarios for the forward-looking simulations.

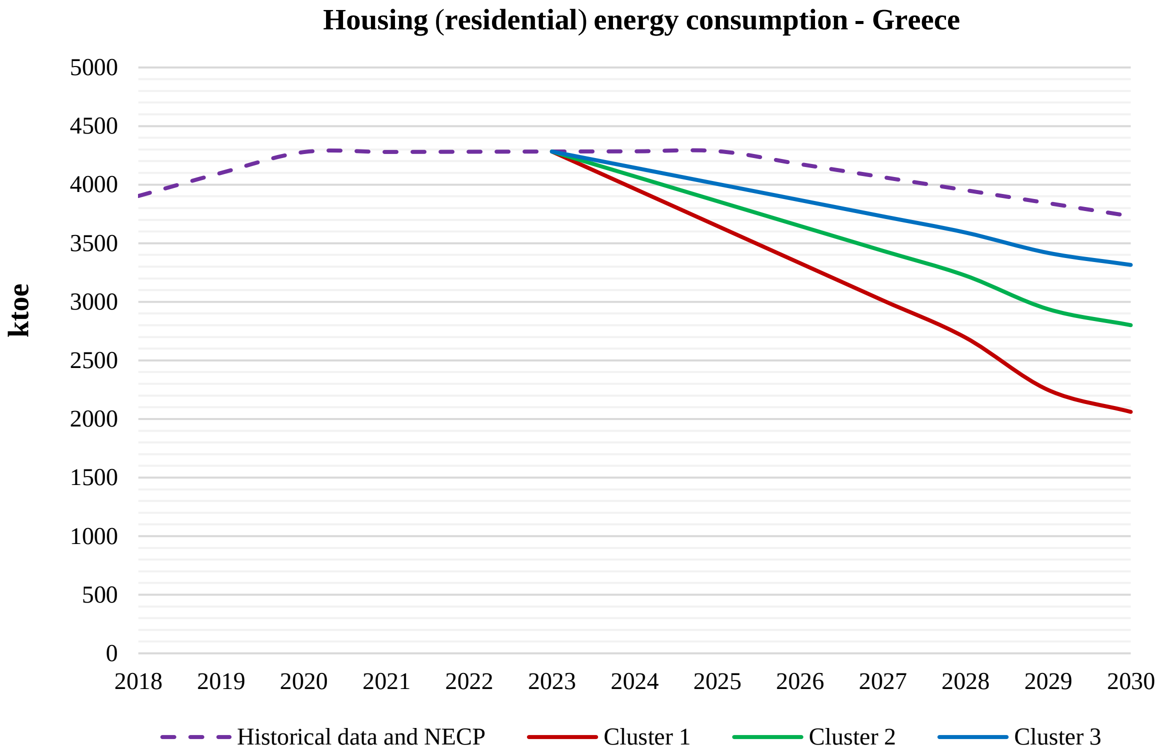

Figure 4. Energy consumption projections for different energy citizen clusters in Greece for the period 2024-2030.

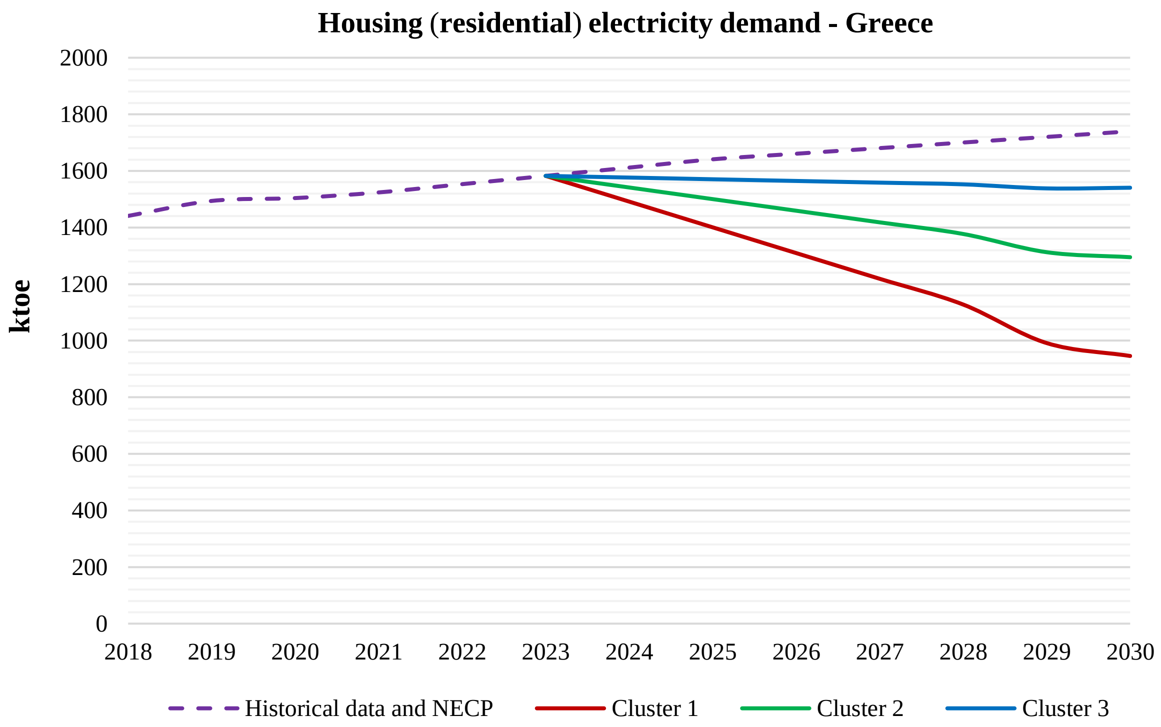

Figure 5. Electricity demand projections for different energy citizen clusters in Greece for the period 2024-2030.

The Greek NECP's projections result in the highest energy consumption and electricity demand among all scenarios with 3,731 and 1,740 ktoe by 2030. Our projections show that "*Cluster 1*" results in the lowest energy consumption and electricity demand with 2,061 and 946 ktoe by 2030. "*Cluster 2*" leads to higher energy consumption and electricity demand with 2,801 and 1,295 ktoe by 2030. Finally, "*Cluster 3*" is projected to have the highest energy consumption and electricity demand among all scenarios informed by the clustering analysis with 3,315 and 1,541 ktoe by 2030.

The electricity demand projections were used as inputs in ATOM in order to perform forward-looking simulations on the citizen adoption and the decarbonization potential of small-scale solar PV systems.

Figure 6 and **Figure 7** present the energy consumption and electricity demand projections for different citizen clusters in the Dutch housing sector by 2030. Additionally, both figures present the historical data of the energy consumption and electricity demand in the Netherlands from 2018 to 2021, as well as the energy consumption and electricity demand projections according to the EU Reference Scenario 2020 (European Commission, 2020) since there are no available projections in the latest Dutch NECP.

The EU Reference Scenario 2020 projections lead to the highest energy consumption and electricity demand among all scenarios with 8,259 and 1,639 ktoe by 2030. "*Cluster 1*" results in a medium level of energy consumption and electricity demand with 6,989 and 1,404 ktoe by 2030. "*Cluster 2*" and "*Cluster 4*" have similar patterns leading to energy consumption of 7,969 and 7,827 ktoe and electricity demand of 1,625 ktoe and 1,562 ktoe by 2030, respectively. "*Cluster 3*" results in the lowest energy consumption and electricity demand with 5,636 and 1,144 ktoe by 2030.

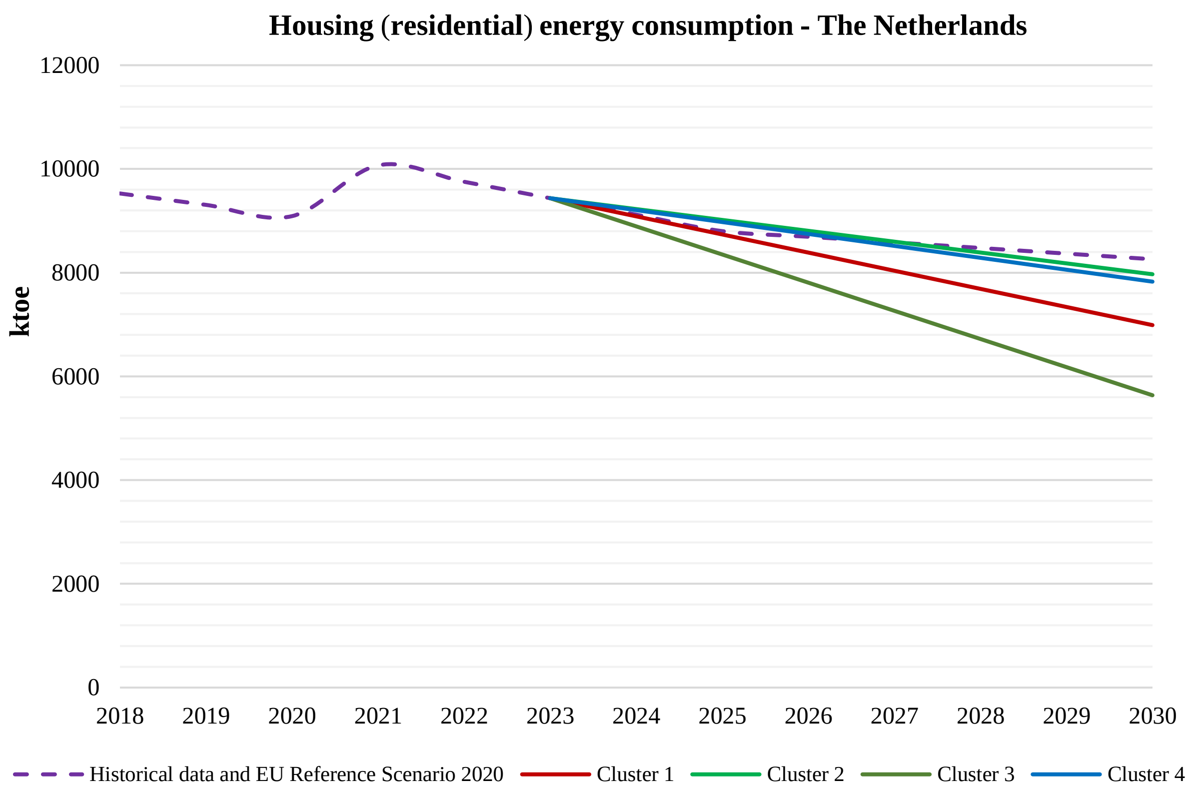

Figure 6. Energy consumption projections for different energy citizen clusters in the Netherlands for the period 2024-2030.

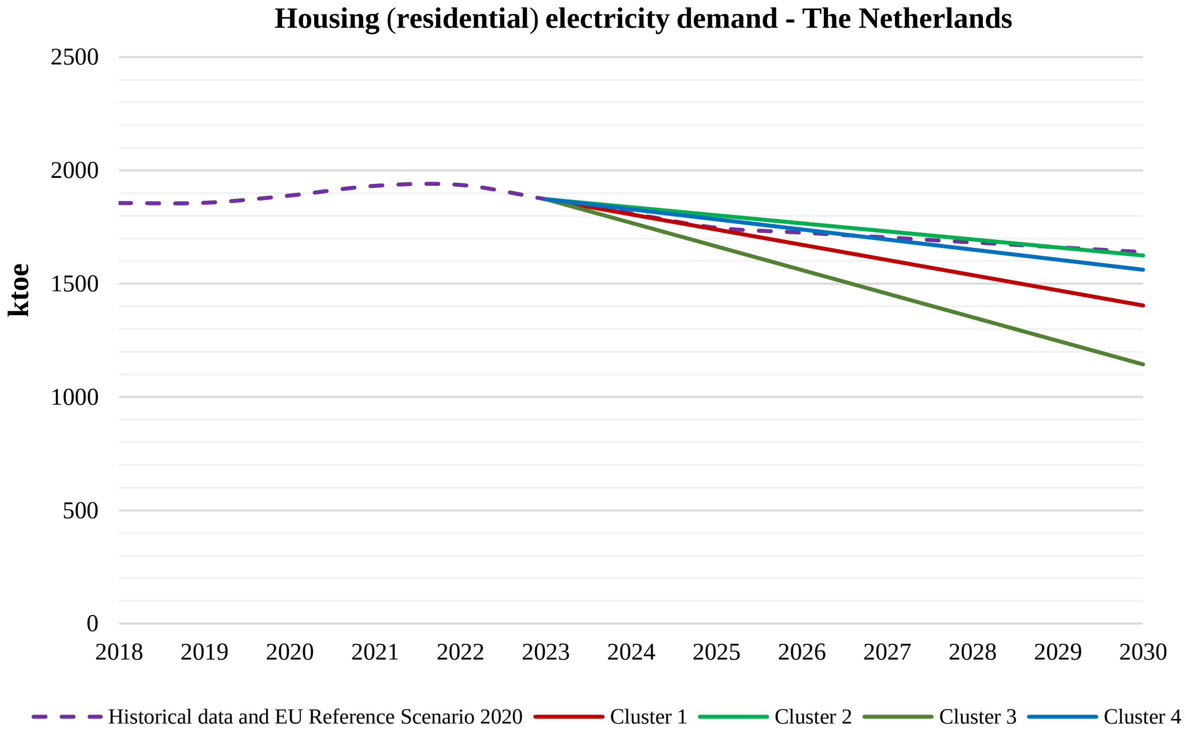

Figure 7. Electricity demand projections for different energy citizen clusters in the Netherlands for the period 2024-2030.

Table 8 presents the different electricity demand scenarios for both the Greek and the Dutch housing sectors, which were developed based on the projections for the different energy citizen clusters.

Table 8. ATOM parameterization for annual electricity demand considering the different policy schemes and the different energy citizen clusters in Greece and the Netherlands.

Greece					
Parameter	***Cluster***	***FiT***	***Net metering***	***Net metering with BESS***	***Justification***
Annual Electricity Demand (kWh)	*Cluster #1*	-	3,591.96	3,591.96	Eurostat Energy Balances, (Hellenic Ministry of Environment and Energy, 2023), Naderian et al. (2024)
	Cluster #2	-	5,096.70	5,096.70	
	Cluster #3	-	6,159.73	6,159.73	
Electricity Demand Annual Change Factor (%)	*Cluster #1*	-	-1.32	-1.32	Eurostat Energy Balances, (Hellenic Ministry of Environment and Energy, 2023)
	Cluster #2	-	-1.25	-1.25	
	Cluster #3	-	-1.30	-1.30	
The Netherlands					

Parameter	*Cluster*	*FiT*	*Net metering*	*Net metering with BESS*	*Justification*
Annual Electricity Demand (kWh)	*Cluster #1*	-	4,460.90	4,460.90	Eurostat Energy Balances, European Commission (2020), Naderian et al. (2024)
	Cluster #2	-	5,192.43	5,192.43	
	Cluster #3	-	3,409.87	3,409.87	
	Cluster #4	-	5,114.80	5,114.80	
Electricity Demand Annual Change Factor (%)	*Cluster #1*	-	-1.33	-1.33	Eurostat Energy Balances, European Commission (2020)
	Cluster #2	-	-1.12	-1.12	
	Cluster #3	-	-1.16	-1.16	
	Cluster #4	-	-1.43	-1.43	

5.2.2. Power sector capacity buildout based on electricity consumption patterns of different energy citizen clusters in the housing and mobility sectors in Greece

In this section, we seek to describe how the different energy citizen clustering results were leveraged by OSeMOSYS-GR in order to simulate the necessary capacity additions and capital investments for the decarbonization of the Greek power sector considering the electricity consumption patterns derived from the housing and mobility sectors.

To create projections for the different Greek energy citizen clusters, we utilized relevant historical data, the clustering results on citizens' energy consumption, and future patterns regarding energy consumption and electricity demand in the housing and mobility sectors.

The scenario design includes a business-as-usual (BAU) scenario, serving as a reference point against which the emissions and energy consumption trajectories of the scenarios based on the different energy citizen clusters are compared against. This comparison allows for the identification of potential margins for improvement to further decarbonize the energy system or lower its cost, as well as to inform strategic decisions regarding capacity additions. It can also shed light on necessary RES investments to meet national emission and sustainability targets.

The BAU scenario for this case study was constructed using projections by 2050 from the revised draft NECP published in November 2023 (Hellenic Ministry of Environment and Energy, 2023). These projections refer to energy consumption and electricity demand across both residential and mobility sectors, reflecting the electrification patterns at the national energy landscape.

Our scenarios build on key energy and climate targets as articulated in the revised draft NECP. According to the latest climate commitments, carbon neutrality in the Greek power sector should be achieved by 2040 and lignite phaseout should be completed by 2028. It should be noted that despite aiming at reaching carbon neutrality in the power sector by 2040, the revised draft NECP includes gas-fired power plants in the capacity and electricity mix by 2050, without explicitly mentioning the use of carbon capture and storage (CCS). As such, our BAU scenario as well as the rest of the scenarios informed by the clustering analysis which build on the BAU scenario assume that natural gas contributes to the electricity mix until 2050 with the use of CCS.

The scenarios informed by the clustering analysis correspond to the energy consumption and electricity demand patterns derived from the three (3) distinct clusters identified through the application of the K-means clustering algorithm to the Greek dataset. These clusters provide insights into the energy consumption patterns of both the housing and mobility sectors and reflect diverse demographic and behavioral profiles within the population. By generating specific energy trajectories for each cluster, these scenarios allow for a more granular understanding of sector-specific energy demands, which facilitates a more informed approach to future energy planning and sectoral decarbonization efforts.

A key challenge in our scenario design was to meaningfully and accurately represent the population of clusters at the national scale. To do so, each scenario informed by the clustering analysis assumed that a specific share of the total population of each country has the same energy consumption patterns as those directed by the respective cluster. This share was assumed to be equal to the proportion of the cluster's population in the total population of each country's citizens in the ECHOES dataset. This up-scaling process retained the original proportions of each cluster relative to the total sample and enabled us to create scenarios whose population sizes are reflective of the entire population on a larger, national scale.

In the following figures the patterns for all the scenarios under study are provided. **Figure 8** and **Figure 9** present the energy consumption scenarios for housing and mobility by 2050.

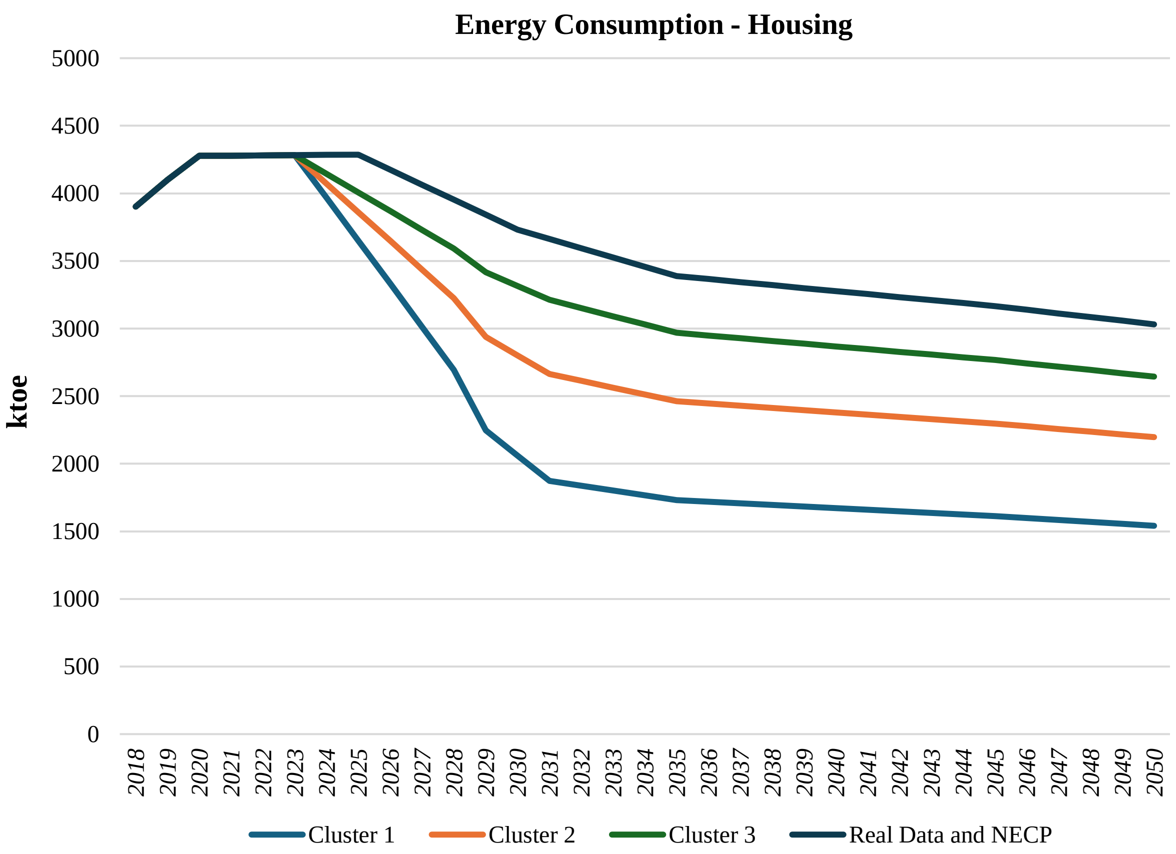

Figure 8. Energy consumption projections in the housing sector for different energy citizen clusters in Greece for the period 2024-2050.

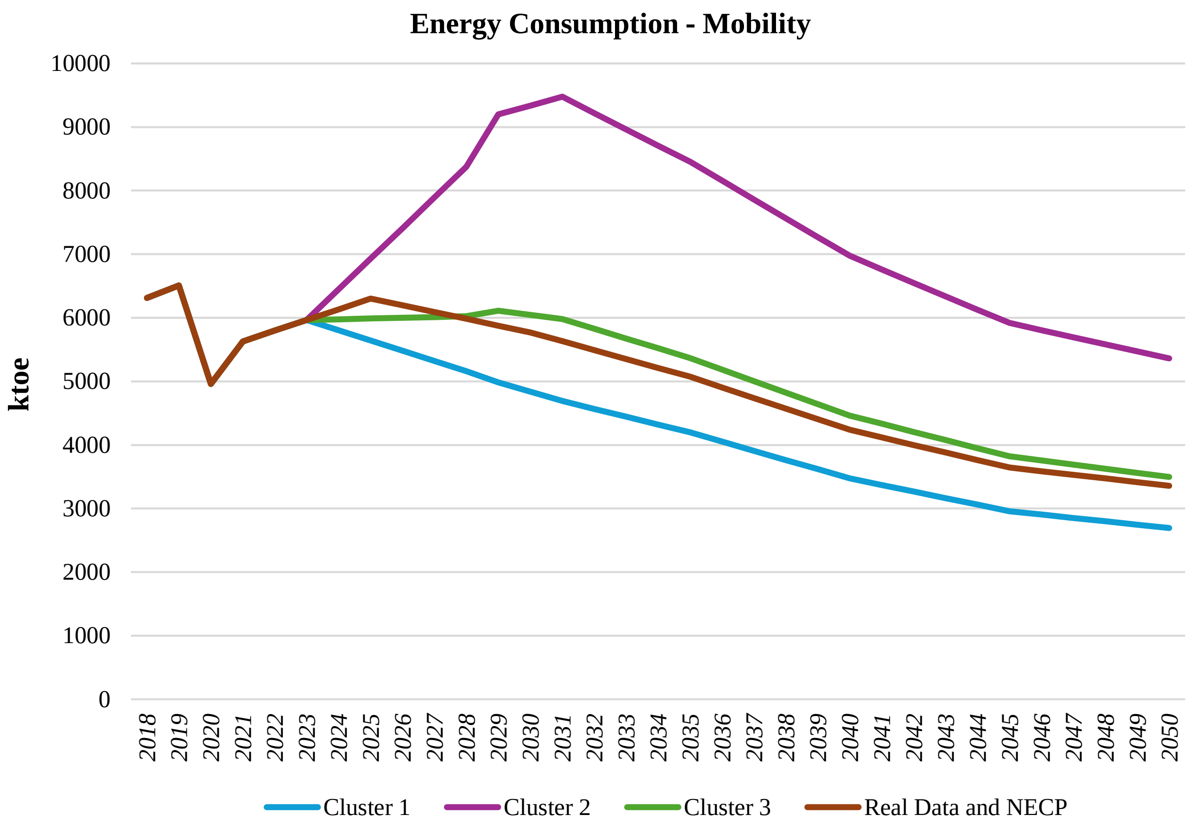

Figure 9. Energy consumption projections in the mobility sector for different energy citizen clusters in Greece for the period 2024-2050.

Our projections show that "*Cluster 1*" results in the lowest energy consumption in housing and mobility with 1,541 and 2,693 ktoe by 2050. "*Cluster 2*" leads to in a medium level of housing energy consumption (2,197 ktoe) and the highest energy consumption in mobility (5,363 ktoe) by 2050. Finally, "*Cluster 3*" is projected to have the highest housing energy consumption among all scenarios informed by the clustering analysis with 2,645 ktoe and a medium level of mobility energy consumption (3,497 ktoe).

Figure 10 and **Figure 11** present the electricity demand scenarios for housing and mobility by 2050.

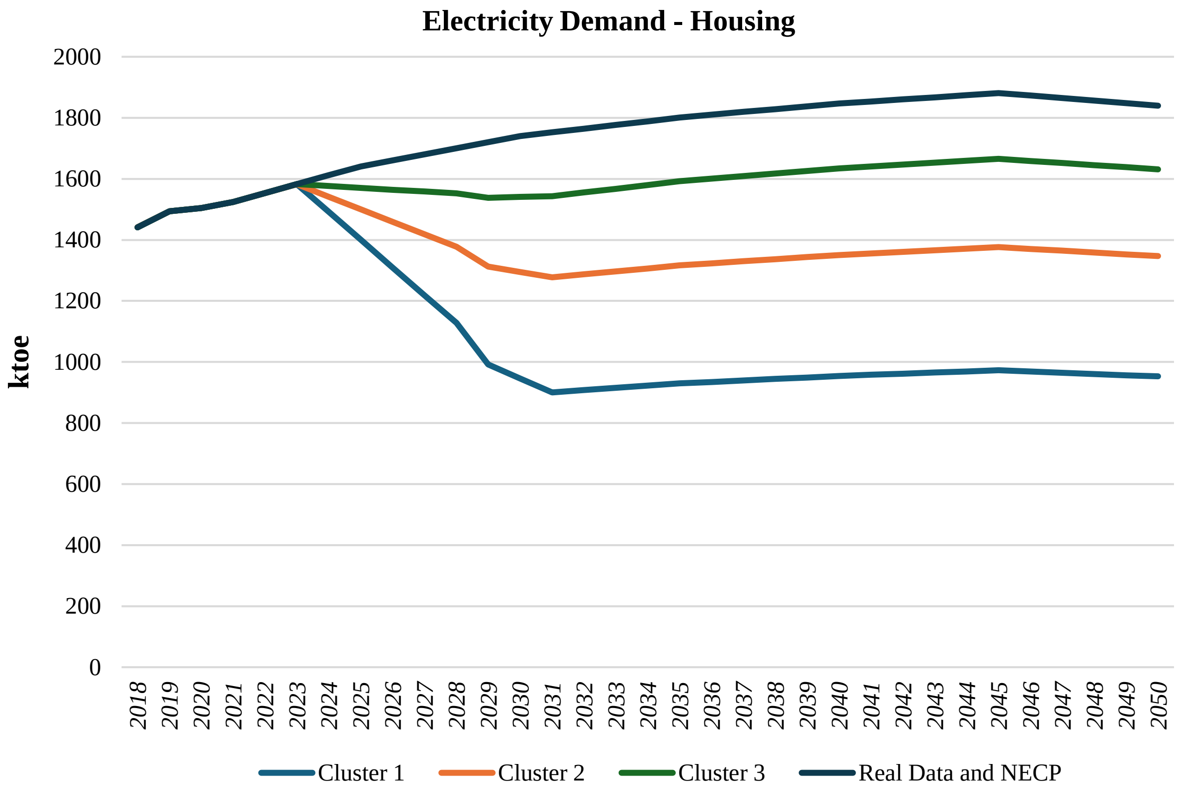

Figure 10. Electricity demand projections in the housing sector for different energy citizen clusters in Greece for the period 2024-2050.

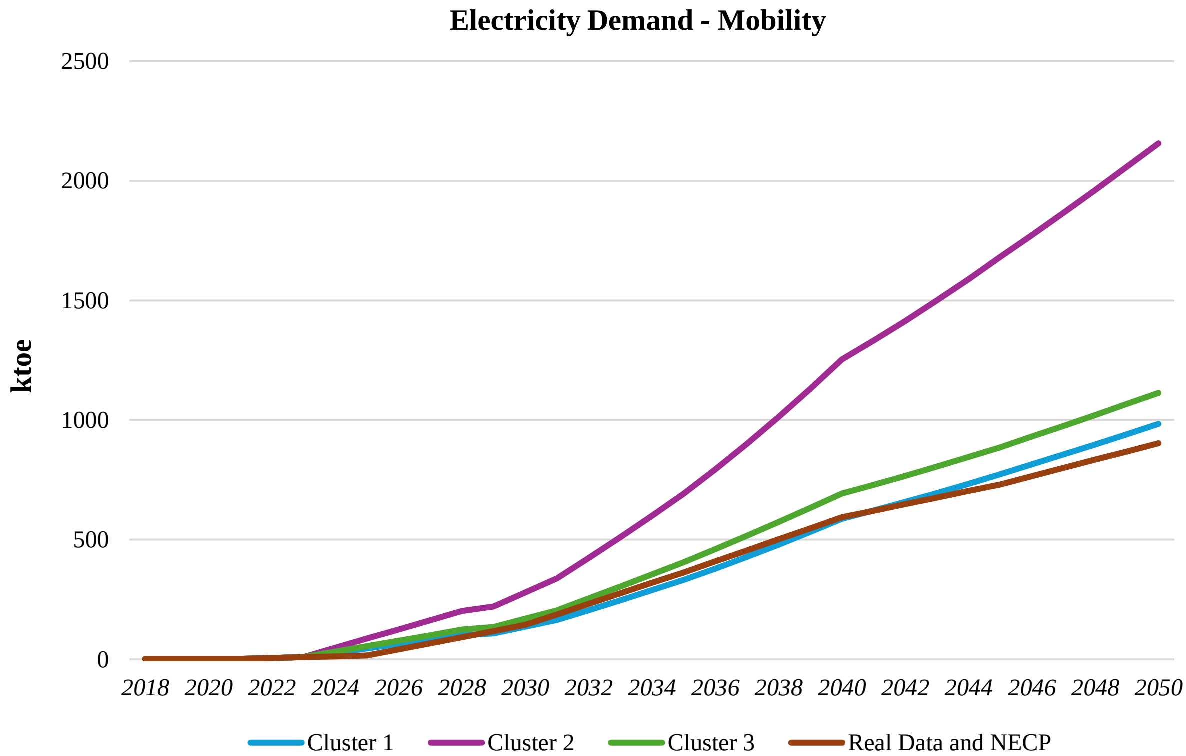

Figure 11. Electricity demand projections in the mobility sector for different energy citizen clusters in Greece for the period 2024-2050.

Our projections show that "*Cluster 1*" results in the lowest electricity demand in both the housing and the mobility sectors among all the Greek citizen clusters with 953 ktoe and 984 ktoe by 2050, respectively. "*Cluster 2*" leads in a medium level of housing electricity demand (1,347 ktoe) and the highest electricity demand in mobility (2,156 ktoe) by 2050. Finally, "*Cluster 3*" is projected to have the highest housing electricity demand among all the scenarios informed by the clustering analysis with 1,631 ktoe and a medium level of mobility electricity demand (1,113 ktoe).

Electricity demand projections in the housing and the mobility sectors were used as inputs in OSeMOSYS-GR in order to simulate the required capacity additions and capital investments for achieving decarbonization in the Greek power sector by 2050. Figure 12 depicts the electricity demand projections in the housing and the mobility sectors, labeled as "Residential Buildings" and "Road Transport", respectively. The "Other" segment of the bar chart represents the electricity demand for the rest of the end-use sectors, for which detailed cluster-based information has not been provided. The electricity demand for the "Other" category encompasses sectors such as commercial buildings, agriculture, industry, and other non-residential areas.

This figure incorporates the four (4) scenarios- one baseline scenario (denoted as "*BAU*") and three (3) scenarios derived from the identified clusters- offering a breakdown of electricity demand across different sectors. These scenarios provide the necessary specifications for the model application with OSeMOSYS-GR.

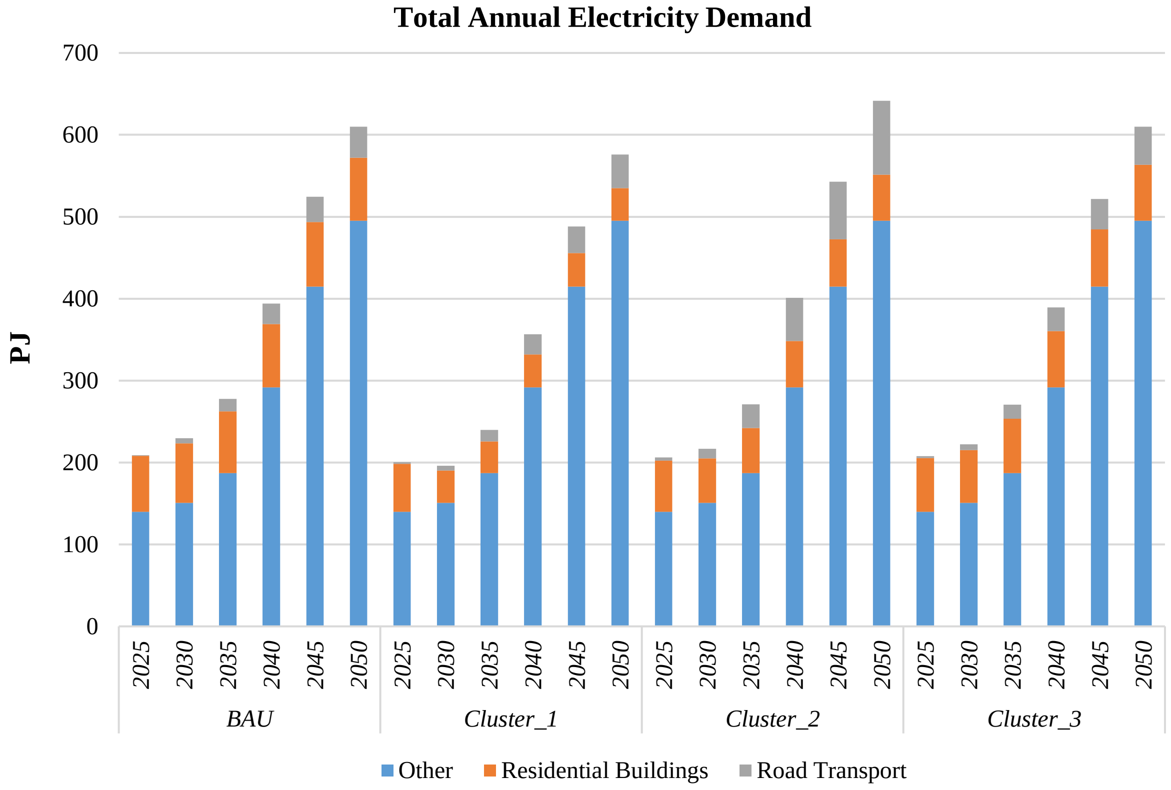

Figure 12. Total annual electricity demand by 2050 under the BAU scenario and the scenarios informed by the clustering analysis.

6. Model applications and results

This section offers a detailed account of the application of ATOM and OSeMOSYS-GR to the case studies in order to answer the RQs stated in previous sections (**Section 5**). It provides a comprehensive presentation of the results generated from the modeling exercises and aim key insights that can inform targeted policy interventions and strategic decision-making.

6.1. Modeling results on citizen adoption of rooftop solar PV systems in the housing sector for different energy citizen clusters in Greece and the Netherlands

We present the forward-looking simulations from ATOM in terms of capacity additions and avoided emissions due to citizen adoption of rooftop solar PV systems. This analysis is composed of three (3) different policy schemes: *FiT*, *net metering*, and *net metering with BESS*. Each policy scheme is assessed within the regulatory context of each country.

Considering contextual factors like the household electricity prices, the PV costs, the solar potential, and the investment behaviors, we sought to shed light on how the different citizen clusters impact small-scale solar PV adoption and decarbonization in the residential sector.

Modeling outcomes contribute to the assessment of the effectiveness of the policy schemes under study and increasing the understanding of how these schemes can affect the decision-making process of each citizen cluster, thus offering valuable insights for policymakers and other relevant stakeholders.

The forward-looking simulations for each Member State were performed for 25 different sets of plausible values for the agent-related parameters in order to represent 25 distinct, but realistic decision-making profiles, spanning from those citizens who are willing-to-invest to those who are risk-averse.

This process allowed us to capture the epistemic or aleatoric uncertainty related to the adoption of small-scale solar PV systems. This uncertainty in the modeling outcomes is depicted through error bars.

The projected solar PV capacity additions during the period 2024-2030 are upscaled according to the population of each citizen cluster, while the additions for the total population in each Member State are also depicted in the figures, using historical data and past observations.

The projected capacity additions were compared to the respective national targets in order to identify which policy schemes are most capable to contribute on the national target achievement by 2030. The forward-looking simulation of the capacity additions is cumulative to the already installed residential solar PV capacity that exists today in each Member State.

6.1.1. Greece

Currently, there is a residential solar PV installed capacity of approximately 435 MW (HELAPCO, 2024), while the Greek NECP target by 2030 is 1 GW residential solar PV installed capacity (Hellenic Ministry of Environment and Energy, 2023).

Applying a FiT scheme with a fixed price equal to 87 €/MWh appears to have the greatest impact on the adoption of small-scale solar PV systems in the residential sector. Specifically, the results under the *FiT* scheme indicate different levels of solar PV capacity additions towards 2030 for each cluster and for the whole population of Greece in total, of approximately (**Figure 13**): ***(i)***. "*Cluster 1*": 135 MW, ***(ii)***. "*Cluster 2*": 77.5 MW, ***(iii)***. "*Cluster 3*": 45 MW, and ***(iv)***. "*Total*": 256 MW.

The uncertainty bounds are very low for the scenarios informed by the clustering analysis since the capacity additions span from 130 MW to 140 MW ("*Cluster 1*"), 76.5 MW to 79.5 MW ("*Cluster 2*"), and 44 MW to 46.5 MW ("*Cluster 3*"), respectively. However, for the "*Total*" population, uncertainty bounds are much larger and can be easier observed in **Figure 13** since the capacity additions span from 247 MW to 270.5 MW.

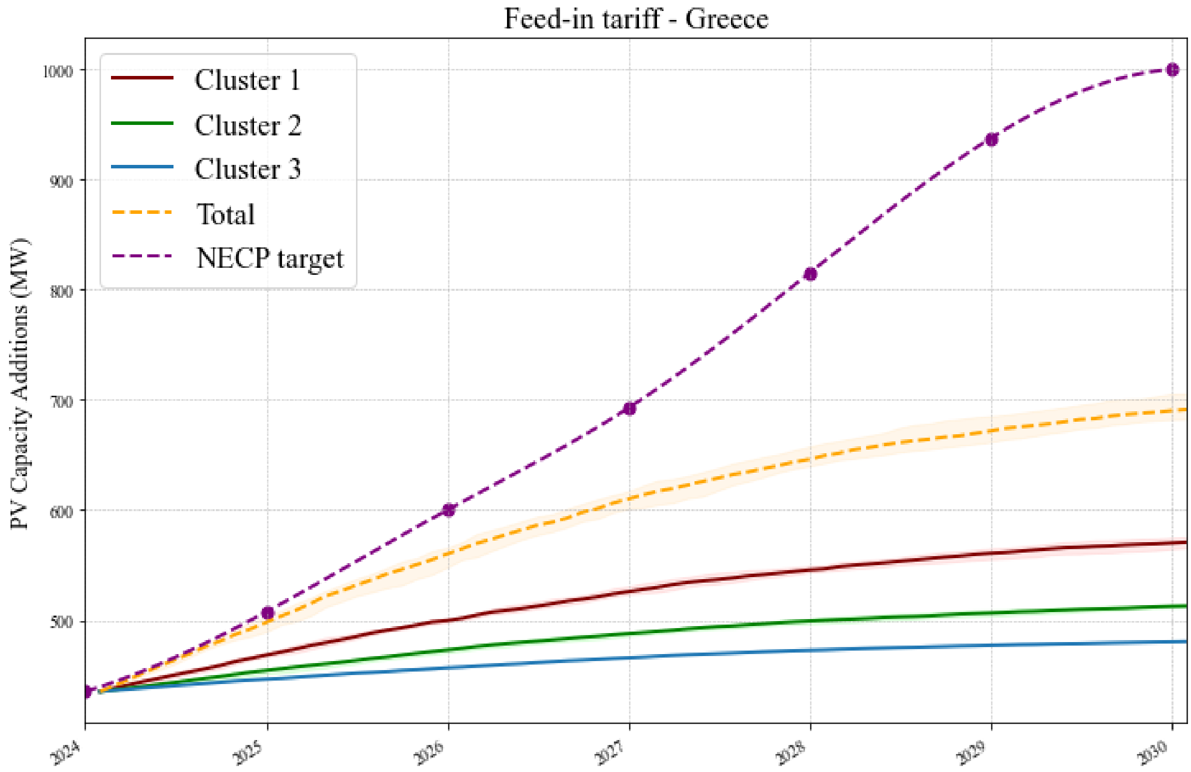

Figure 13. Results of the forward-looking simulations on the expected adoption of small-scale PV systems in the Greek residential sector by 2030 for the three (3) citizen clusters and for the whole population of Greece in total, compared to the Greek NECP's target and under the FiT policy scheme. Uncertainty bounds are captured through lighter colored error bars.

Additionally, the estimated PV capacity additions for the *net metering* policy scheme indicate different contributions for each cluster and for the whole population of Greece in total by 2030 since, as they are estimated to be around (Figure 14): ***(i).*** "*Cluster 1*": 60.5 MW, ***(ii).*** "*Cluster 2*": 35.2 MW, ***(iii).*** "*Cluster 3*": 21 MW, and ***(iv).*** "*Total*": 115 MW.

The uncertainty bounds of the PV capacity additions range from 60.5 MW to 61.2 MW for "*Cluster 1*", 35 MW to 36 MW for "*Cluster 2*", and 20 MW to 21.7 MW for "*Cluster 3*", respectively. The PV capacity additions for the "*Total*" population span from 111 MW to 118 MW by 2030.

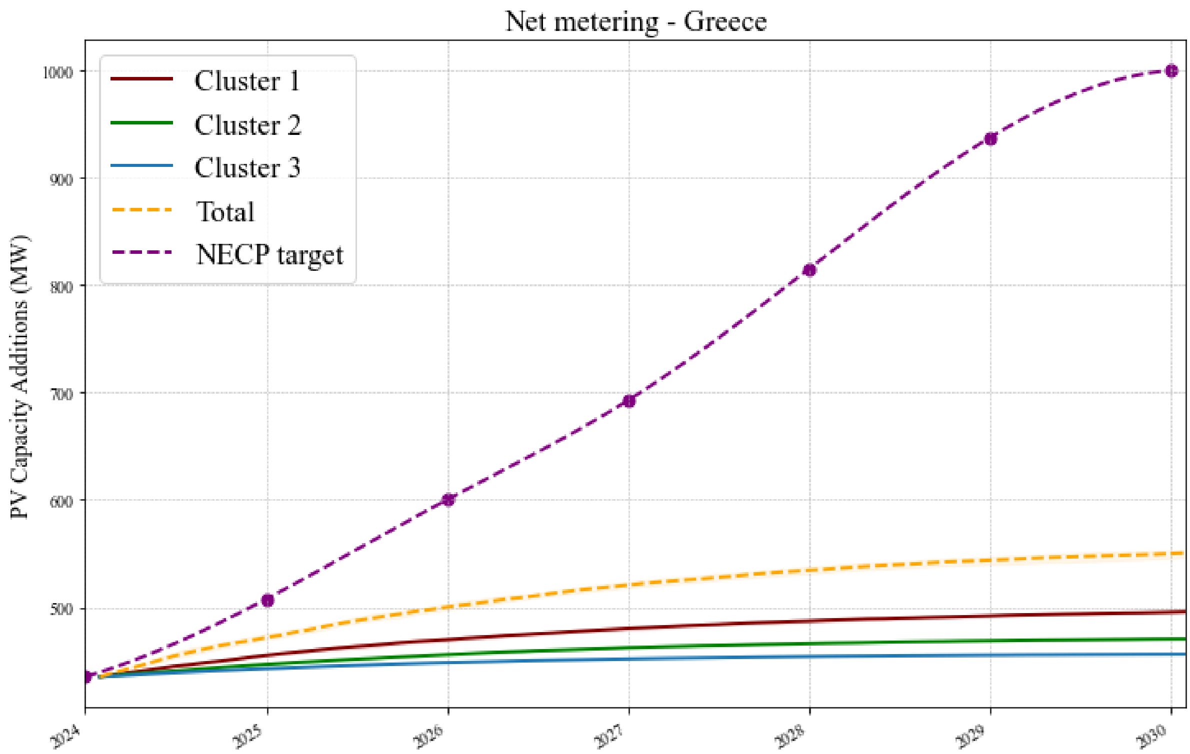

Figure 14. Results of the forward-looking simulations on the expected adoption of small-scale PV systems in the Greek residential sector by 2030 for the three (3) citizen clusters and for the whole population of Greece in total, compared to the Greek NECP's target and under the net metering policy scheme. Uncertainty bounds are captured through lighter colored error bars.

Finally, results under the *net metering with BESS* policy scheme, which assumes 90% BESS subsidy on the capital costs, present similar levels of PV capacity additions towards 2030 with the *net metering* policy scheme. These are estimated to be approximately (**Figure 15**): ***(i).*** "*Cluster 1*": 60.7 MW, ***(ii)***. "*Cluster 2*": 34.7 MW, ***(iii)***. "*Cluster 3*": 21 MW, and ***(iv)***. "*Total*": 114.5 MW.

Uncertainty bounds for this policy scheme are extremely low and thus cannot be observed in **Figure 15.** For "*Cluster 1*", the PV capacity additions by 2030 span from 59.35 MW to 63 MW. The PV capacity additions for "*Cluster 2*" and "*Cluster 3*" span from 34 MW to 35.2 MW and 20.65 MW to 21.5 MW, respectively. The uncertainty bounds of the PV capacity additions for the "*Total*" population range from 112 MW to 117.2 MW.

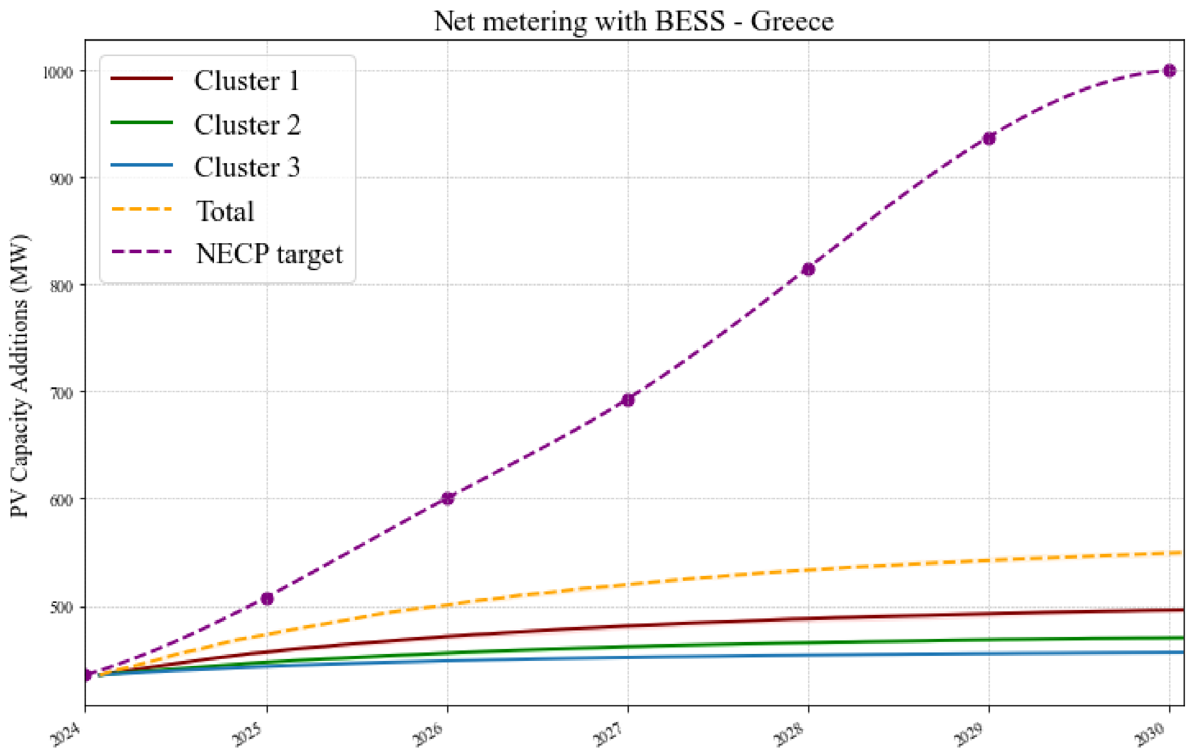

Figure 15. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Greek residential sector by 2030 for the three (3) citizen clusters and for the whole population of Greece in total, compared to the Greek NECP's target and under the net metering with BESS policy scheme. Uncertainty bounds are captured through lighter colored error bars.

According to the modeling results, the largest adoption of small-scale PV systems could be achieved under the FiT scheme; however, it would not be enough for achieving the national target by 2030. This finding highlights the insufficiency of supportive policy schemes when applied individually. Therefore, it is possible that a mix of different policy schemes needs to be applied in order to further enhance the adoption of small-scale solar PV systems in the Greek residential sector.

The uncertainty that governs the decision-making process of Greek citizens when adopting solar PV systems appears to be very low. This outcome shows the perception of Greek citizens toward PV investments, and more specifically, it highlights that on average, Greek citizens have a somewhat clear perception about the profitability potential of the investment. This becomes more obvious under the net metering and net metering with BESS policy schemes where the uncertainty bounds are generally lower when compared to the uncertainty bounds under the FiT scheme. This highlights the need for higher and long-term fixed prices to make citizens feel more certain about the profitability of their investments.

We also present estimations of the decarbonization potential of adopting small-scale solar PV systems by 2030 by considering the carbon intensity of the power sector according to the EU Reference Scenario 2020 projections (European Commission, 2020).

As expected, the FiT policy scheme shows the greatest decarbonization potential since the carbon emissions that could be avoided through this scheme is more than double when compared with the emissions that could be avoided under the net metering and net metering with BESS policy schemes.

More specifically, the potential application of a *FiT* scheme can lead to avoided emissions in the residential sector, of approximately (Figure 16): ***(i)***. "*Cluster 1*": 76,200 tnCO_2eq., ***(ii)***. "*Cluster 2*": 43,800 tnCO_2eq., ***(iii)***. "*Cluster 3*": 26,160 tnCO_2eq., and ***(iv)***. "*Total*": 125,400 tnCO_2eq. by 2030.

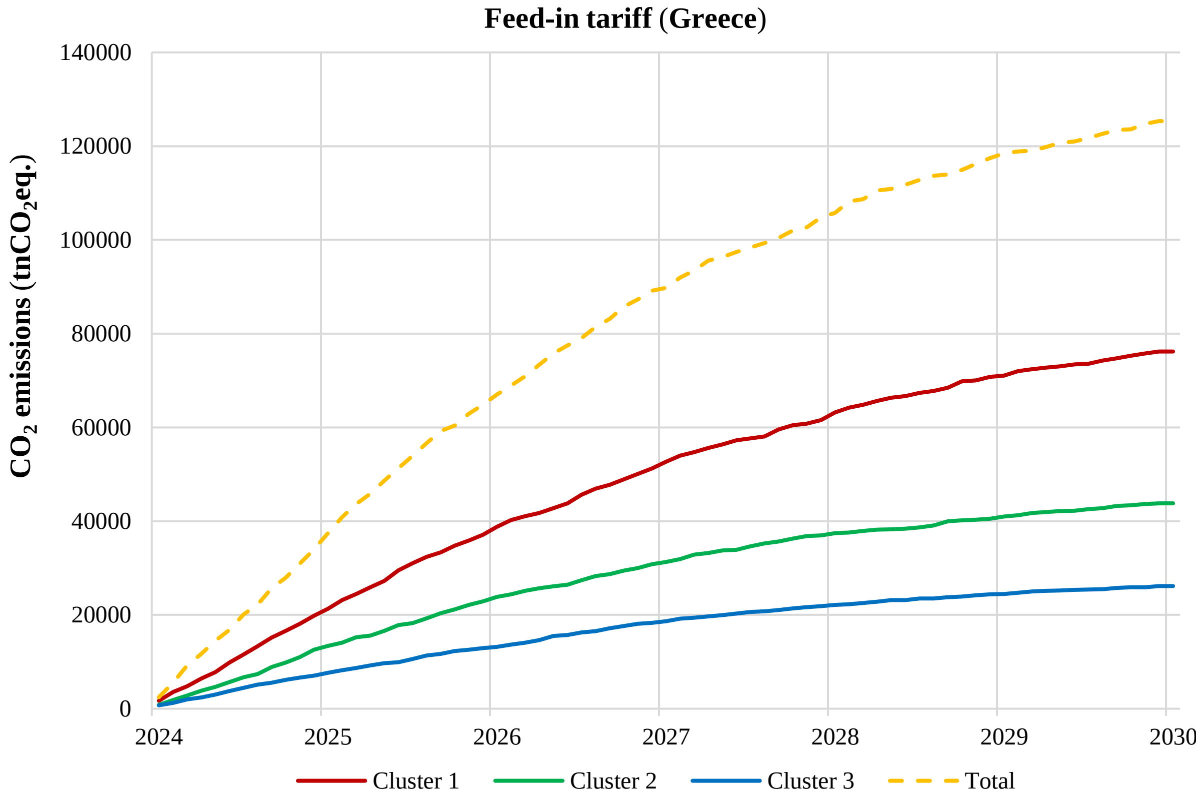

Figure 16. Carbon emissions that could be avoided through prosumerism in the Greek residential sector under the FiT policy scheme for the three (3) citizen clusters and for the whole population of Greece in total.

Furthermore, the carbon emissions that could be avoided under the *net metering* policy scheme for the three (3) citizen clusters, and for the whole population of Greece in total, are around (Figure 17): ***(i)***. "*Cluster 1*": 34,100 tnCO_2eq., ***(ii)***. "*Cluster 2*": 16,100 tnCO_2eq., ***(iii)***. "*Cluster 3*": 12,000 tnCO_2eq., and ***(iv)***. "*Total*": 57,400 tnCO_2eq. by 2030.

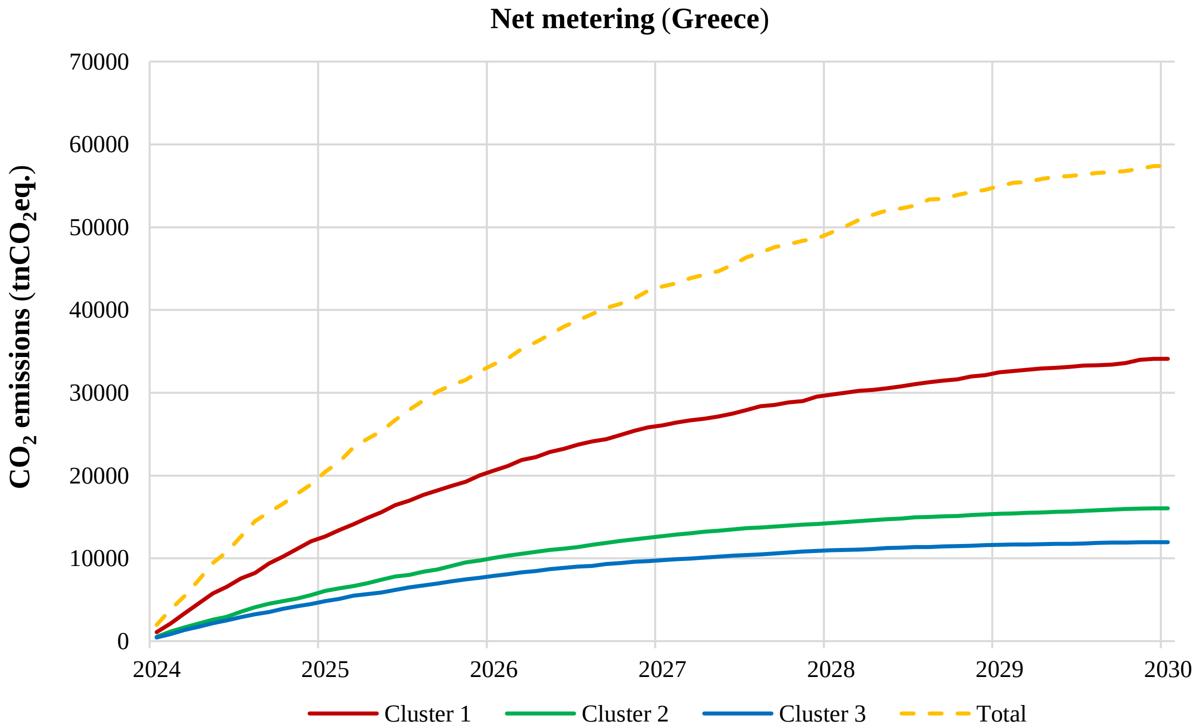

Figure 17. Carbon emissions that could be avoided through prosumerism in the Greek residential sector under the net metering policy scheme for the three (3) citizen clusters and for the whole population of Greece in total.

Lastly, the avoided carbon emissions through empowering prosumerism in the residential sector under the *net metering with BESS* policy scheme for the three (3) different citizen clusters, and for the whole population of Greece in total, are approximately (**Figure 18**): ***(i)***. "*Cluster 1*": 33,850 tnCO_2eq., ***(ii)***. "*Cluster 2*": 17,700 tnCO_2eq., ***(iii)***. "*Cluster 3*": 12,400 tnCO_2eq., and ***(iv)***. "*Total*": 53,050 tnCO_2eq. by 2030.

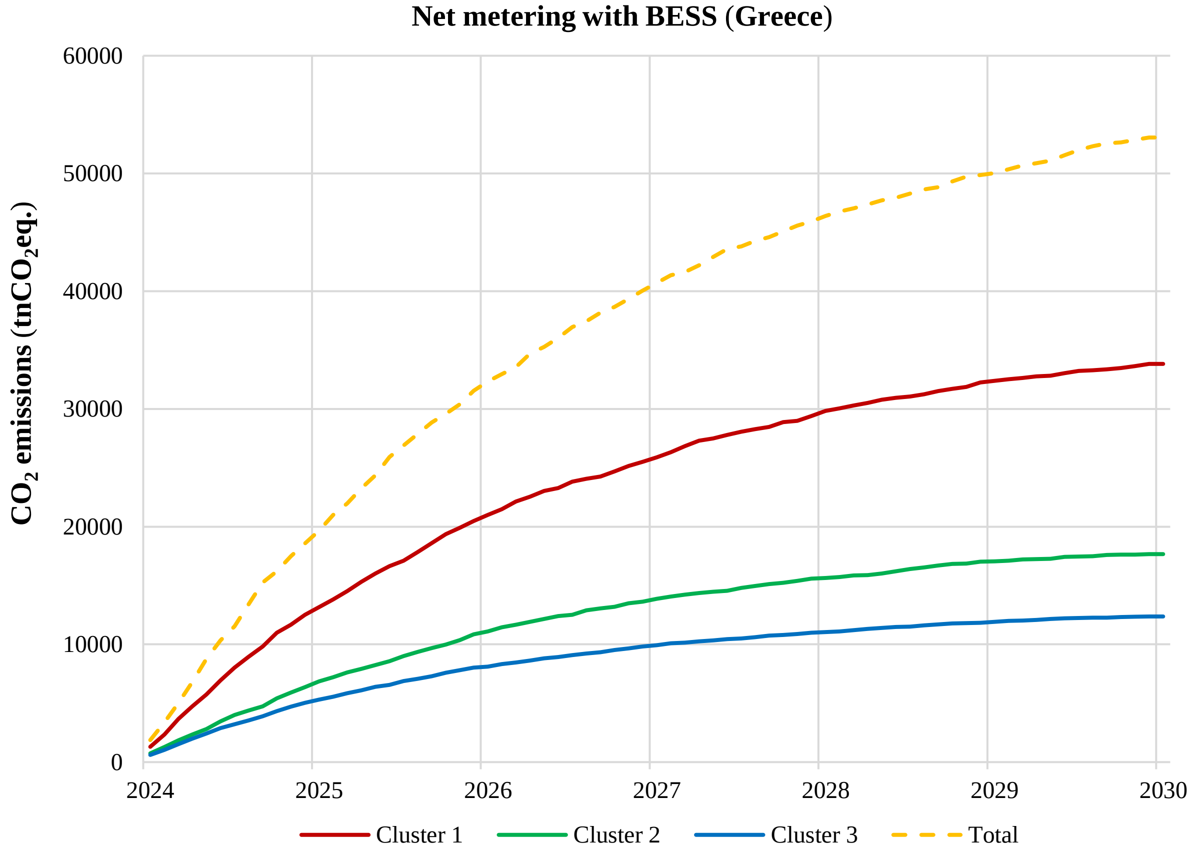

Figure 18. Carbon emissions that could be avoided through prosumerism in the Greek residential sector under the net metering with BESS policy scheme for the three (3) citizen clusters and for the whole population of Greece in total.

While the FiT policy scheme has the greatest potential for achieving decarbonization in the Greek residential sector by 2030, the potential combination of more supportive policy schemes that incentivize prosumers to invest in small-scale solar PV systems could increase the decarbonization potential of the residential sector.

From a cluster-based perspective, we see that "*Cluster 1*" results to higher capacity additions and avoided carbon emissions compared to the other two (2) Greek citizen clusters and thus contributes the most to small-scale solar PV adoption and decarbonization of the residential sector. This is mainly attributed to its higher population and lower electricity demand when compared to the other two (2) clusters.

6.1.2. The Netherlands

So far, the installed capacity of residential solar PV systems is approximately 10,106 MW (StatLine, 2023; Stultiens, 2023). We assume that the national target for the installed capacity of residential solar PV systems by 2030 equals to the technical potential for residential solar PV systems, i.e., approximately 14,000 MW (European Commission, 2017).

Applying a FiT scheme with fixed price equal to 109.7 €/MWh (the last available fixed price for residential prosumers which was abolished in 2020) appears to have the greatest impact on the potential adoption of small-scale solar PV systems (under or equal to 10 kW_p) in the Netherlands.

The PV capacity additions under the *FiT* policy case for the citizen clusters under study by 2030 are approximately (Figure 19): ***(i).*** "*Cluster 1*": 1,485.5 MW, ***(ii)***. "*Cluster 2*": 1,387.7 MW, ***(iii)***. "*Cluster 3*": 2,750 MW, ***(iv)***. "*Cluster 4*": 629.5 MW, and ***(v).*** "*Total*": 6,408 MW.

Figure 19 shows that "*Total*" population and "*Cluster 3*" result in larger uncertainty bounds than the rest of the other citizen clusters. The projected PV capacity additions by 2030 span from 1,400 MW to 1,742 MW for "*Cluster 1*", 1,265 MW to 1,572 MW for "*Cluster 2*", 2,610 MW to 3,128 MW for "*Cluster 3*", and 512 MW to 684 MW for "*Cluster 4*", respectively. The uncertainty bounds for the "*Total*" population span from 5,440 MW to 7,460 MW.

Modeling results show that a FiT scheme with a fixed price of 109.7 €/MWh could meet the 14 GW national target by 2030.

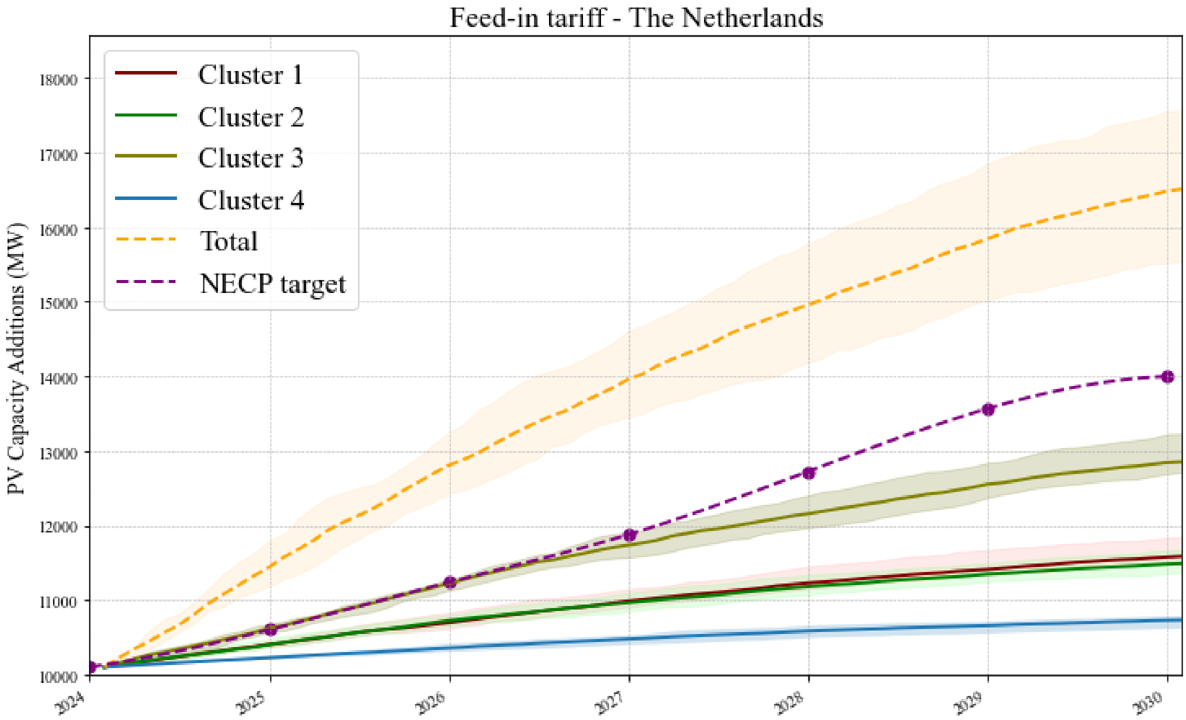

Figure 19. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Dutch residential sector by 2030 for the four (4) citizen clusters and for the the whole population of the Netherlands in total, compared to the set target and under the FiT policy scheme. Uncertainty bounds are captured through lighter colored error bars.

The PV capacity additions under the *net metering* scheme for the different Dutch citizen clusters and for the whole population of the Netherlands in total by 2030 are around (Figure 20): ***(i)***. "*Cluster 1*": 1,024.5 MW, ***(ii)***. "*Cluster 2*": 968 MW, ***(iii)***. "*Cluster 3*": 1,915.8 MW, ***(iv)***. "*Cluster 4*": 434 MW, and ***(v)***. "*Total*": 4,342 MW.

The PV capacity additions projected for "*Cluster 1*", "*Cluster 2*", "*Cluster 3*", and "*Cluster 4*" span from 880 MW to 1,072 MW, 959 MW to 1,017 MW, 1,669 MW to 2,206 MW, and 365 MW to 531 MW by 2030, respectively. Additionally, the PV capacity additions by 2030 for the "*Total*" population span from 3,609 MW to 4,705 MW. The lower uncertainty bound for the "*Total*" population indicates that there is also a possibility to not reach the target of the 14 GW by 2030 if no further economic incentives are provided to the potential adopters.

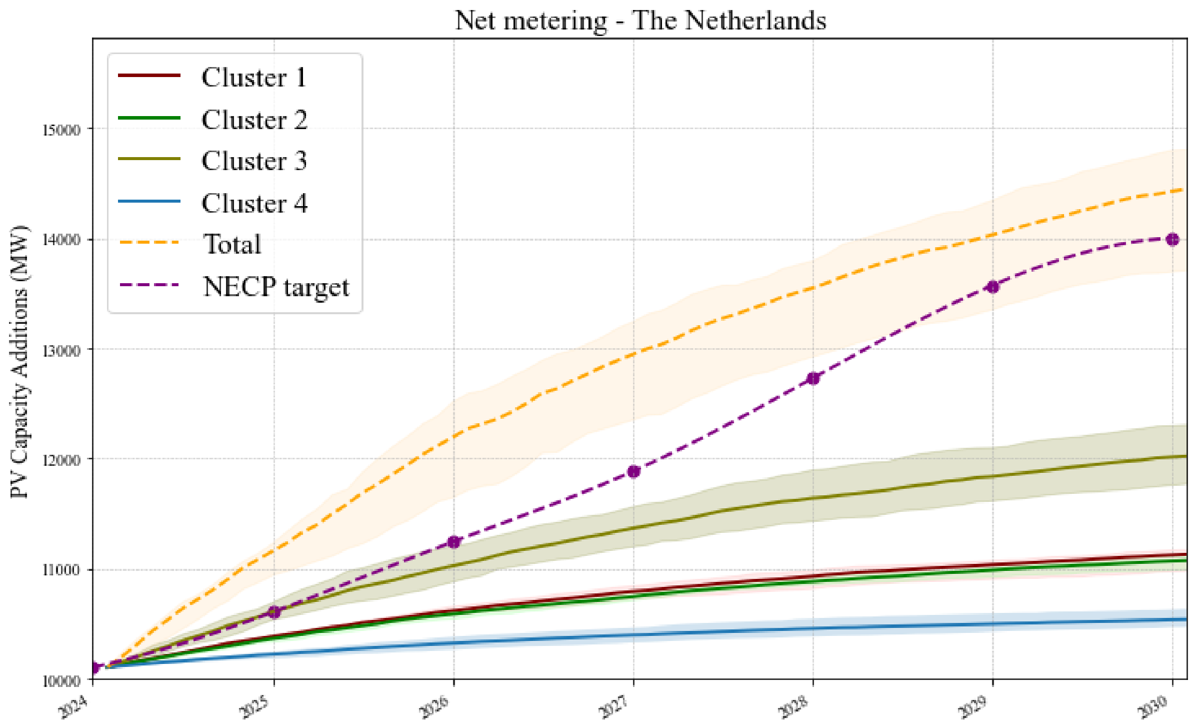

Figure 20. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Dutch residential sector by 2030 for the four (4) citizen clusters and for the whole population of the Netherlands in total, compared to the set target and under the net metering policy scheme. Uncertainty bounds are captured through lighter colored error bars.

The residential solar PV capacity additions under the *net metering with BESS* scheme by 2030 are estimated to be approximately (**Figure 21**): ***(i)***. "*Cluster 1*": 745.5 MW, ***(ii)***. "*Cluster 2*": 688.7 MW, ***(iii)***. "*Cluster 3*": 1,334.7 MW, ***(iv)***. "*Cluster 4*": 311.2 MW, and ***(v)***. "*Total*": 3,163.5 MW.

Uncertainty bounds for this policy scheme are considerably lower compared to the other two (2) policy schemes, while similar to the other two cases, uncertainty bounds are wider for "*Cluster 3*". The PV capacity additions projected for "*Cluster 1*", "*Cluster 2*", "*Cluster 3*", and "*Cluster 4*" span from 643 MW to 824.5 MW, 621.5 MW to 810 MW, 1,190 MW to 1,441 MW, and 286 MW to 342.5 MW by 2030, respectively. The uncertainty observed for the "*Total*" population in total is higher since PV capacity additions towards 2030 span from 2,870 MW to 3,500 MW.

Modeling results show that a net metering with BESS scheme could not meet the 14 GW national target by 2030.

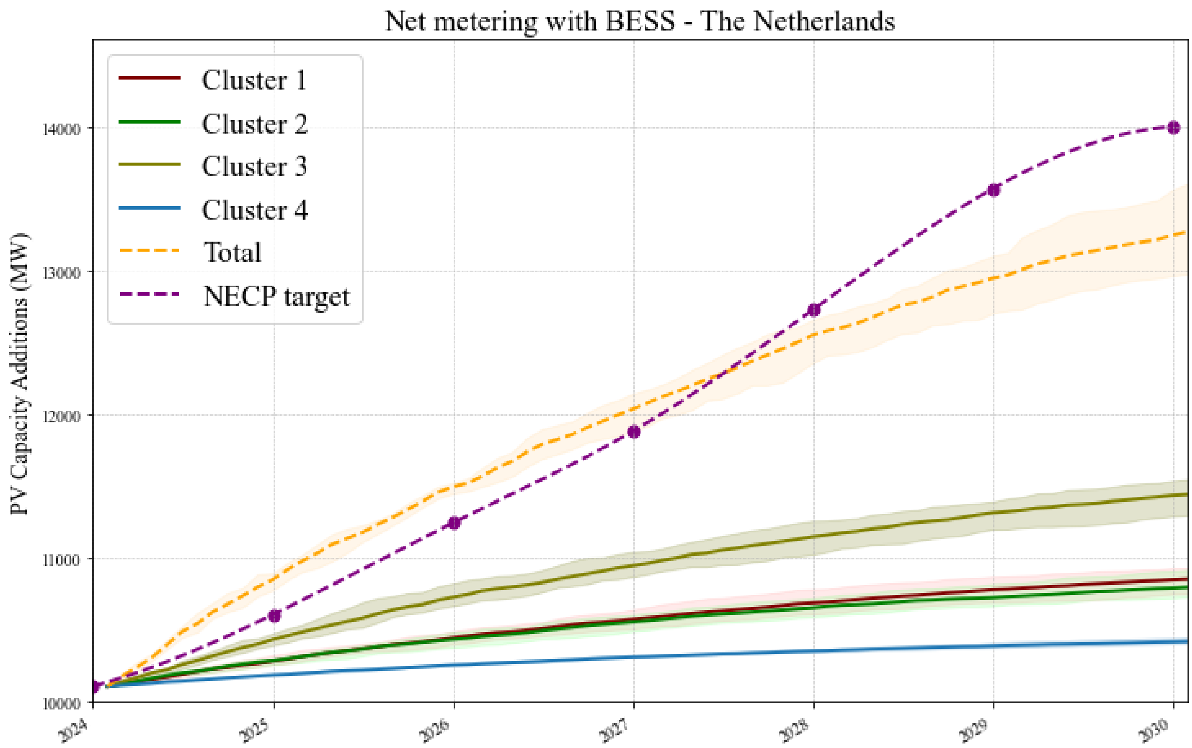

Figure 21. Results of the forward-looking simulations on the expected adoption of small-scale photovoltaic systems in the Dutch residential sector by 2030 for the four (4) citizen clusters and for the whole population of the Netherlands in total, compared to the target set and under the net metering with BESS policy case. Uncertainty bounds are captured through error bars lighter colored.

The target of 14 GW of residential solar PV installed capacity by 2030 could possibly be achieved even if the Netherlands continues to apply only the existing net metering scheme for small-scale solar PV systems. A potential application of a FiT scheme with a fixed price equal to at least 109.7 €/MWh (FiT in the Netherlands is not allowed for residential solar PV systems since 2020) would lead to overshooting the target and by a large margin. According to the modeling results, the projected PV capacity additions are approximately 2.5 GW over the 2030 target. In contrast to the Greek case study, there is no need to combine these two (2) schemes in order to achieve the 2030 target.

Nevertheless, the case is different if the existing net metering scheme is combined with BESS, assuming an 80% average subsidy on the capital cost of BESS according to recent statements of the Dutch energy and climate minister (Murray, 2024). In this case, the scheme seems to be capable of achieving the target until mid-2027, but after that time the PV capacity additions are not enough to reach the target. The projected PV additions are approximately 730.5 MW lower than the 2030 target.

Moreover, the uncertainty gaps for the PV capacity additions of the different Dutch citizen clusters are calculated to be higher when compared to the Greek case study, with "*Cluster 3*" having the largest uncertainty among all the clusters. This highlights that despite the higher PV capacity additions achieved by "*Cluster 3*", citizens who belong to this cluster have not a "clear" perspective about the profitability of the investment. This can be also attributed to the lower annual electricity consumption of "*Cluster 3*" citizens which results to higher ambiguity about the potential economic benefits of prosumerism. Another factor that affects the final PV capacity additions of the clusters is their populations. "*Cluster 3*" has the larger population since around 44% of the total population belongs to this cluster.

We also present the estimations for the avoided carbon emissions from the projected adoption of small-scale solar PV systems under the three (3) policy schemes. Similar to the Greek case study, this analysis is conducted by taking into account the carbon intensity in the Dutch power sector (according to the projections of the EU Reference Scenario 2020), and the solar PV output from the projected PV capacity additions.

More specifically, the potential application of a *FiT* scheme can lead to avoided emissions in the residential sector, of approximately (Figure 22): ***(i)***. "*Cluster 1*": 405,220 tnCO_2eq., ***(ii)***. "*Cluster 2*": 382,000 tnCO_2eq., ***(iii)***. "*Cluster 3*": 782,540 tnCO_2eq., ***(iv)***. "*Cluster 4*": 188,125 tnCO_2eq., and ***(v)***. "*Total*": 1,688,650 tnCO_2eq. by 2030.

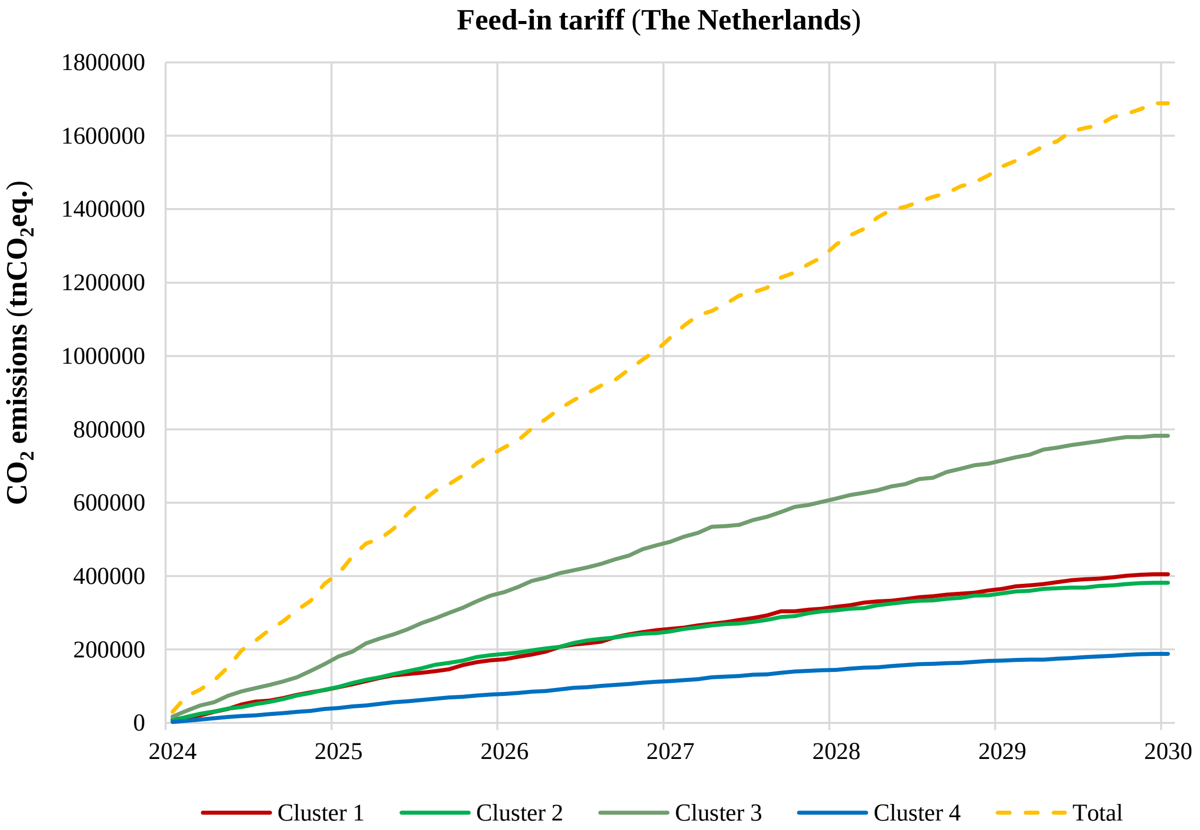

Figure 22. Carbon emissions that could be avoided through prosumerism in the Dutch residential sector under the FiT policy scheme for the four (4) citizen clusters and for the whole population of the Netherlands in total by 2030.

Additionally, for the *net metering* scheme, avoided carbon emissions through prosumerism in the Dutch residential sector for the different citizen clusters and for the whole population of the Netherlands in total by 2030 are estimated to be around (Figure 23): ***(i)***. "*Cluster 1*": 304,710 tnCO_2eq., ***(ii)***. "*Cluster 2*": 280,220 tnCO_2eq., ***(iii)***. "*Cluster 3*": 547,250 tnCO_2eq., ***(iv)***. "*Cluster 4*": 121,550 tnCO_2eq., and ***(v)***. "*Total*": 1,314,500 tnCO_2eq. toward 2030.

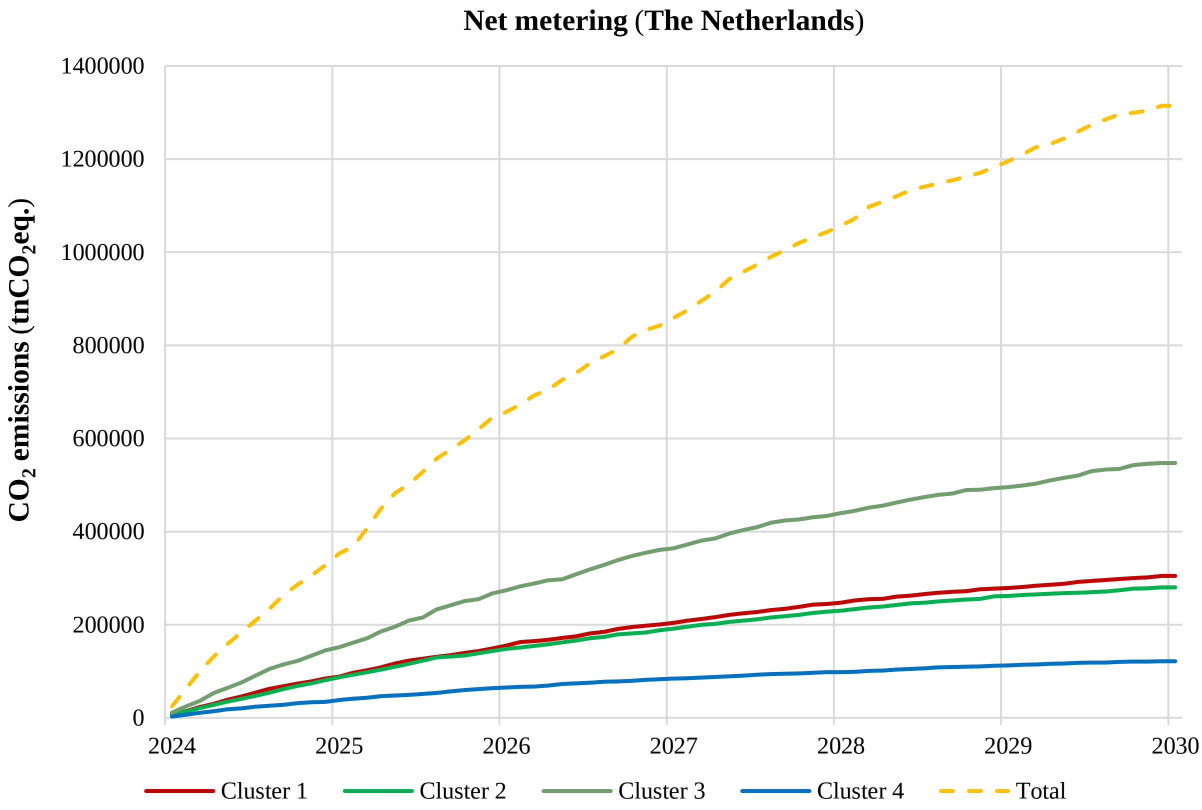

Figure 23. Carbon emissions that could be avoided through prosumerism in the Dutch residential sector under the net metering policy scheme for the four (4) citizen clusters and for the whole population of the Netherlands in total by 2030.

Last but not least, the contribution of each citizen cluster to the reduction of carbon emissions, as well as the carbon emissions that could be avoided through a *net metering with BESS* policy scheme for the whole population of the Netherlands in total, are estimated to be approximately (**Figure 24**): ***(i)***. "*Cluster 1*": 217,575 tnCO_2eq., ***(ii)***. "*Cluster 2*": 203,785 tnCO_2eq., ***(iii)***. "*Cluster 3*": 387,500 tnCO_2eq., ***(iv)***. "*Cluster 4*": 92,385 tnCO_2eq., and ***(v)***. "*Total*": 887,175 tnCO_2eq. by 2030.

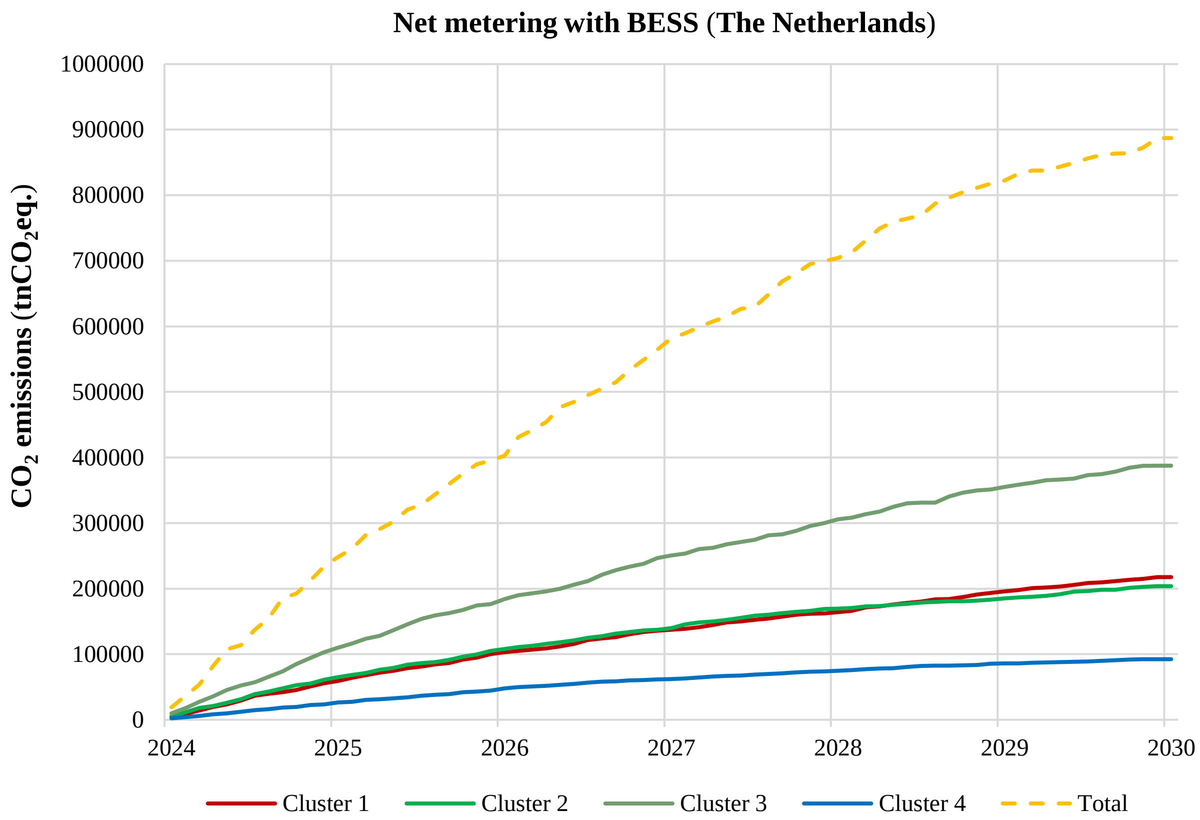

Figure 24. Carbon emissions that could be avoided through prosumerism in the Dutch residential sector under the net metering with BESS policy scheme for the four (4) citizen clusters and for the whole population of the Netherlands in total.

Similar to the Greek case study, the Netherlands have a strong decarbonization potential in the residential sector. This potential is especially evident for the FiT and net metering cases while it is also considerable for the net metering with BESS case. Specifically, prosumerism in the Dutch residential sector is capable to reduce the total carbon emissions of the country by 1% on average. This potential resulted mainly from the energy mix of the Dutch power sector since approximately 49% of the electricity production is based on fossil fuels (almost 40% from natural gas).

When it comes to the Dutch citizen clusters, citizens that belong to "*Cluster 3*" appear to have the most prominent role in the decarbonization of the residential sector since they contribute the most to the adoption of PV systems and thus to the reduction of carbon emissions. "*Cluster 3*" citizens are characterized by the lowest electricity demand among all clusters under analysis while their population is the largest. The same finding was derived from the Greek case study, in which the most impactful cluster was that with the lowest electricity demand and the largest population among all Greek citizen clusters. Therefore, policymakers should target citizen groups that combine such characteristics in order to increase the effectiveness of supportive policies for empowering prosumerism.

6.2. Modeling results on power sector capacity buildout based on electricity consumption patterns of different energy citizen clusters in the housing and the mobility sectors in Greece

This subsection delves into reporting results from the OSeMOSYS-GR model's application to the Greek case study based on the specifications and the designed scenario space detailed in Section 5. Specifically, we present the necessary capacity additions to decarbonize the power sector and the resulting electricity mix, the capital investments per technology, and the CO_2 footprint in the Greek power sector by 2050. We compare the results of the scenarios informed by the clustering analysis with those derived from the "*BAU*" scenario in order to provide insights for policymakers and other relevant stakeholders.

6.2.1. Capacity mix by 2050

In the "*BAU*" scenario, the anticipated total installed capacity of the Greek power sector is projected to increase by approximately 250%, reaching a total of 106.8 GW by 2050 compared to 2025. This substantial growth underscores both the rising electricity demand due to the electrification patterns and the critical opportunity to prioritize RES investments when developing the future energy system. The "*BAU*" scenario results in a total RES capacity of 63.8 GW by 2050.

The "*BAU*" scenario, aligned with projections from the revised draft Greek NECP, reveals that the expansion of total RES capacity is predominantly driven by VRE sources. These include utility-scale, commercial, and rooftop solar PV systems, as well as both onshore and offshore wind power installations. Additionally, technologies that enhance power system flexibility, such as BESS, pumped hydro, and electrolyzers, play a significant role, as illustrated in **Figure 25**.

The most significant capacity increases are anticipated in the solar commercial PV and offshore wind technologies, with each expected to add approximately 14 GW by 2050 compared to 2025. Notably, electrolyzers and fuel cells demonstrate a remarkable surge, with projections indicating 15.1 GW and 5.6 GW of capacity additions, respectively, by 2050 compared to 2025, highlighting the growing potential of hydrogen as a key fuel in the future energy mix.

Other supply side flexibility options, such as utility-scale and rooftop BESS as well as pumped hydro, are also expected to rise substantially, reaching a combined total of 17.1 GW by 2050. Specifically, capacity additions of 12.7 GW of utility-scale BESS, 1.1 GW of rooftop BESS, and 2.3 GW of pumped hydro are expected to take place by 2050 compared to 2025.

In contrast, the use of fossil fuels, specifically lignite and oil, is projected to be entirely phased out by 2028 and 2040, respectively. However, natural gas will continue to contribute with approximately 5.2 GW to the overall capacity by 2050 due to the use of CCS.

In the scenario informed by the first identified cluster (i.e., "*Cluster 1*"), representing the citizen group with the lowest energy expenditures in the housing and mobility sectors (see **Section 3** for further details), total capacity additions by 2050 are the smallest among all scenarios. Total capacity in this scenario is projected to reach only 94.3 GW by 2050, i.e., 12.5 GW less than the baseline scenario. Moreover, investment in RES is the lowest among all scenarios, with a total capacity of 56.6 GW by 2050, reflecting the more modest electricity consumption patterns of the citizens belonging to this cluster.

Citizens' energy-conscious behaviors regarding mobility and their positive climate change perceptions lead to a stabilization in capacity growth by 2045, with minimal differences observed between 2045 and 2050. Specifically, the total capacity is 93.9 GW in 2045 and 94.2 GW in 2050. This is mainly because "*Cluster 1*" scenario requires short-term electricity storage (i.e., utility BESS) at a faster rate than the "*BAU*" scenario due to the underinvestment in pumped hydro.

Specifically, in the "*Cluster 1*" scenario, utility BESS reach 13.2 GW by 2045, while pumped hydro reach only 1.7 GW by 2050. In the "*BAU*" scenario, utility BESS reach 9.2 GW by 2045, while pumped hydro reach 3.1 GW by 2050. These differences in storage capacity investments are due to the cost-optimal prioritization of flexibility options by OSeMOSYS-GR. This prioritization changes based on the different electricity demand projections in housing and mobility sectors between the modeled scenarios (**Figure 12**) and the distinct demand profiles between the two (2) sectors.

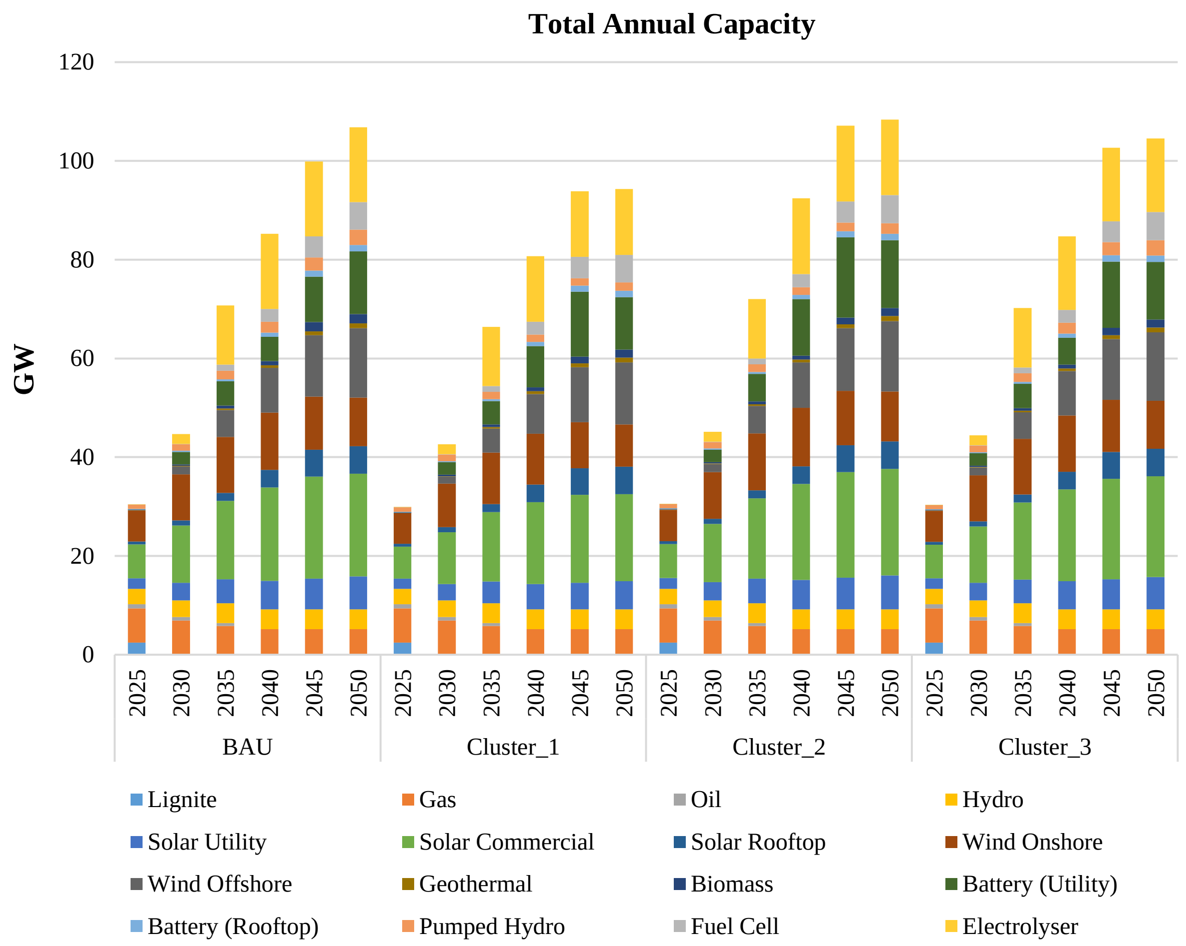

Figure 25. Total capacity mix in the Greek power sector by 2050 for the baseline scenario and the scenarios informed by the clustering analysis.

In contrast, "*Cluster 2*" stands out as the only scenario in which projected capacity additions surpass those of the "*BAU*" scenario. This is due to the fact that the citizens belonging to the second cluster exhibit by far the highest energy consumption in the mobility sector among all three clusters and more neutral climate change perceptions than the other clusters.

In this scenario, total capacity requirements are projected to reach 108.4 GW, reflecting an increase of approximately 78 GW by 2050 compared to 2025. The significant increase in electricity demand results in the largest growth in RES capacity among all scenarios, reaching 65 GW. The most significant capacity additions by 2050 compared to 2025 are anticipated again in solar commercial PV (14.7 GW), offshore wind (14.3 GW), electrolyzers (15.3 GW), and utility-scale BESS (13.8 GW).

In "*Cluster 3*", the total capacity additions fall between those of "*Cluster 1*" and "*Cluster 2*". This is because the corresponding cluster represents individuals with higher energy expenditures on housing and moderate consumption in the mobility sector as well as positive climate change perceptions. Specifically, the total capacity is expected to expand by 74.2 GW between 2025 and 2050, slightly below the "*BAU*" projections. In response to the rising electricity demand, RES installations in *"Cluster 3"* are anticipated to reach a total capacity of approximately 62.7 GW by 2050, reflecting a similar growth to the "*BAU*" scenario.

6.2.2. Capital investments by 2050

As illustrated in **Figure 26**, the energy transition is heavily dependent on wind and solar energy, with offshore wind turbines requiring by far the most substantial capital investments across all four (4) scenarios. Onshore wind turbines and commercial solar PV systems follow behind. Notably, projections indicate that investments in offshore wind energy will be nearly double compared to those in each of the solar and onshore wind technologies.

More specifically, in the "*BAU*" scenario offshore wind average annual investments are expected to reach approximately €1.14 billion. In "*Cluster 1*", where citizens' behaviors are the least energy intensive among all examined scenarios, the corresponding average annual investments in offshore wind technology is the lowest among all scenarios, namely around €1.02 billion. On the other hand, in "*Cluster 2*", the increased electrification in the mobility and housing sectors leads to the higher average annual investments of approximately €1.16 billion. Lastly, "*Cluster 3*" resembles the "*BAU*" scenario as the identified energy consumption patterns for this scenario are closer to the NECP's trends among all scenarios that were informed by the clustering analysis. In this case, expected necessary average annual investments in offshore wind energy reach €1.12 billion.

Similar trends characterize the capital investments for the construction of onshore wind farms. A combined total of €1.65 billion of average annual investments is required for both offshore and onshore wind energy projects in the *"BAU"* scenario, followed closely by the "*Cluster 3*" scenario requiring €1.63 billion. For "*Cluster 1*" and "*Cluster 2*" scenarios, €1.46 and €1.69 billion are needed respectively. These amounts constitute around 39% of total spendings for all the scenarios.

However, when looking at the total average annual capital investments aimed at increasing the capacity of the future Greek power sector, we notice that despite the similarities between the energy consumption patterns in the *"BAU"* scenario and those noticed in the "*Cluster 3*" scenario, we find some discrepancies. More specifically, total average annual capital investments of €4.24 and €4.17 billion are required for the *"BAU"* scenario and the *"Cluster_3"* scenario, respectively.

Total average annual capital investments in "*Cluster 2*" equal to €4.26 billion, thus being closer to the *"BAU"* scenario projection, despite the differences in the electricity demand patterns in the housing and mobility sectors. This difference can largely be attributed to the amount spent for the development of pumped hydro energy storage, which it is the only technology whose expenses in the *"BAU"* scenario surpass those in the *"Cluster_2"* scenario. Similar to the "*Cluster 1*" scenario, this difference is due to the cost-optimal prioritization of the various flexibility options based on the different electricity demand projections in housing and mobility sectors between the modeled scenarios and the distinct demand profiles between the two (2) sectors.

Finally, total average annual capital investments in "*Cluster 1*" are the lowest among all scenarios and equal to €3.71 billion. "*Cluster 1*" saves 12.5% of total average annual capital investments compared to the *"BAU"* scenario. These significant investment savings can be mainly attributed to the cluster's higher population, more energy-conscious behaviors in the housing and mobility sectors, and more positive climate change perceptions when compared to the other two (2) clusters.

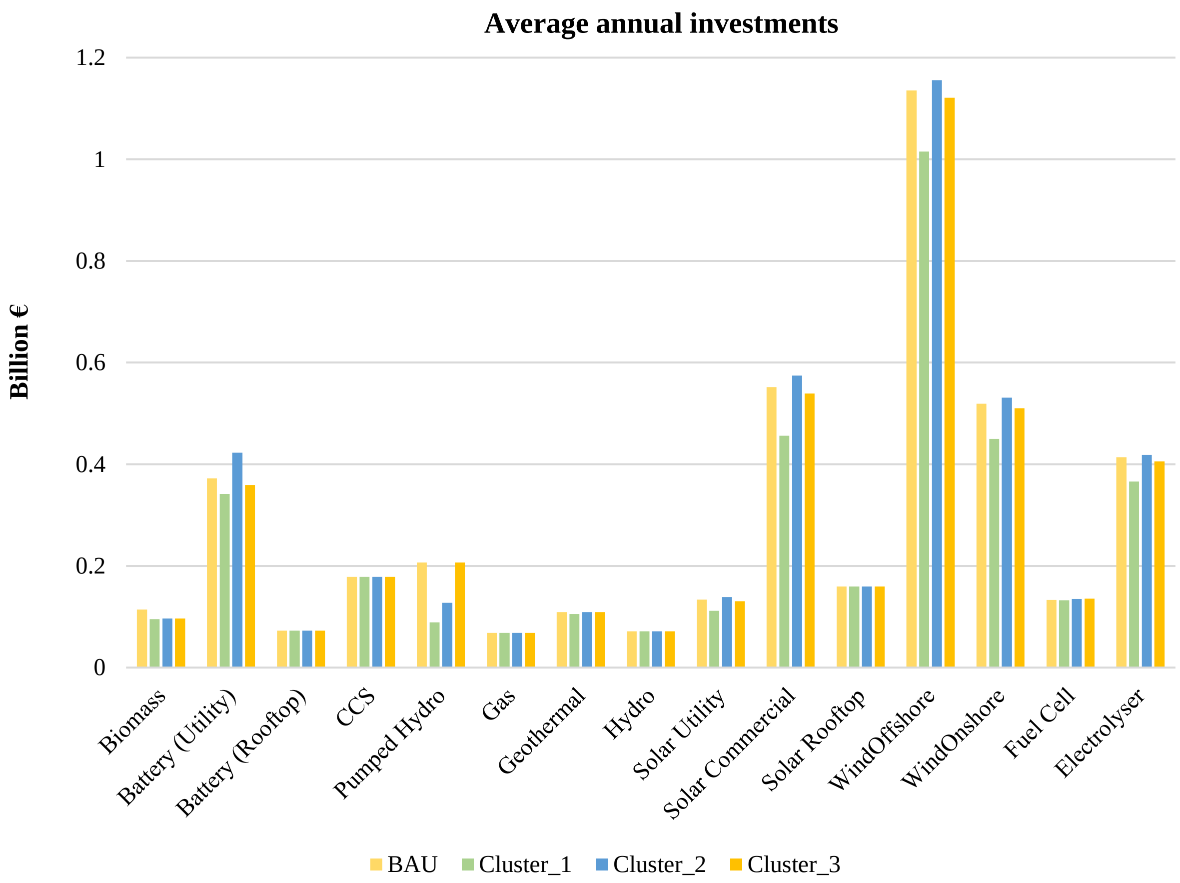

Figure 26. Average annual investments per technology for the baseline scenario and the scenarios informed by the clustering analysis over the period 2024-2050.

6.2.3. Power generation by 2050

As shown in **Figure 27**, the total annual power generation in 2050 will substantially rely on RES, and especially VRE, as well as hydrogen across all the scenarios under study. In the *"BAU"* scenario, RES and hydrogen constitute approximately 89.6% of the total power generation by 2050, with wind energy accounting for the largest share. Specifically, in *"BAU"*, 42.7% of the total electricity generation originates from wind energy, with offshore wind farms contributing approximately 178.2 PJ and onshore wind farms producing around 83.2 PJ. Solar energy also plays a dominant role, with a combined total of 168.9 PJ generated from rooftop, utility-scale, and commercial PV systems. This highlights the growing importance of both wind and solar technologies in shaping the future energy landscape in Greece.

In "*Cluster 1*", total power generation is the lowest among all simulated scenarios in 2050 (i.e., 560.3 PJ), consistent with the more modest energy consumption patterns observed in the first energy citizen cluster. In this scenario, RES and hydrogen constitute approximately 88.7% of the total power generation, with wind energy accounting for the largest share, followed closely by solar energy. On the one hand, this scenario does not achieve the 2050 target for the share of RES penetration to the electricity mix (98.3%) by the largest margin (9.6%) between all examined scenarios. On the other hand, it underscores the potential for significant reductions in electricity supply when citizens adopt more conservative energy usage behaviors.

"*Cluster 2*" results in the greatest total power generation by 2050 due to the scenario's highest electricity demand among all scenarios, particularly in the mobility sector. RES and hydrogen once more dominate the electricity mix, contributing 89.8% of total power generation, the highest proportion of renewable energy among all scenarios. This scenario exemplifies the critical role that renewable energy must play in meeting the demands of a high-consumption society while ensuring sustainable energy production.

"*Cluster 3*" scenario reflects moderate energy consumption patterns for both mobility and housing and thus presents a total power generation in 2050 that closely mirrors the *"BAU"* scenario, reaching 605.1 PJ. In this scenario, 89.5% of the total annual generation by 2050 is generated from RES and hydrogen.

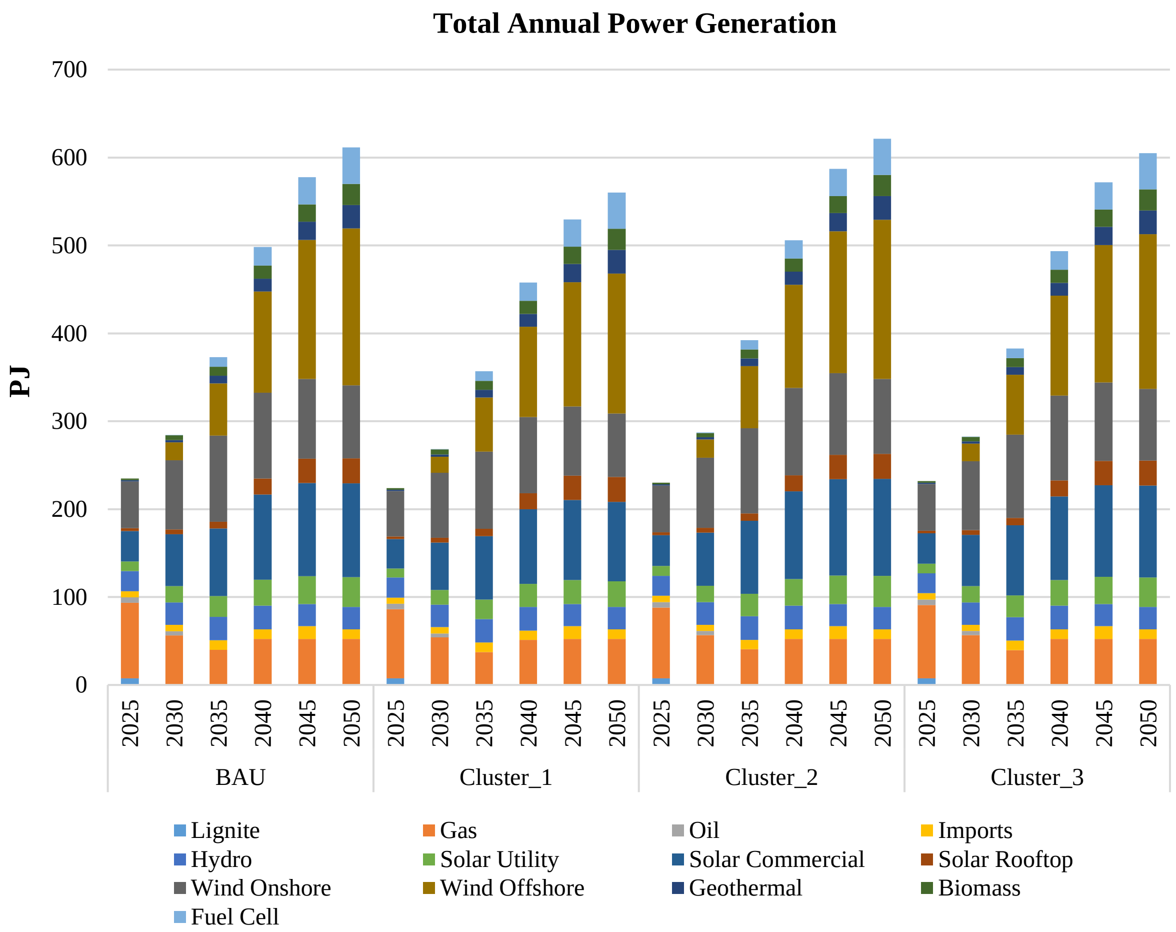

Figure 27. Total annual power generation mix in the Greek power sector by 2050 for the baseline scenario and the scenarios informed by the clustering analysis.

While fossil fuels such as lignite and oil are expected to be phased out by 2028 and 2040, respectively, natural gas remains part of the electricity mix by 2050 due to the deployment of CCS. Specifically, natural gas provides 8.4-9.4% of the total annual power generation in 2050, with the lower value being attributed to the scenario with the highest electricity demand, i.e., "*Cluster 2*", and the higher value being attributed to the scenario with the lowest electricity demand, i.e., "*Cluster 1*".

6.2.4. CO_2 footprint by 2050

Regarding the carbon footprint of the energy transition in the Greek power sector (**Figure 28**), "*Cluster 1*" exhibits the lowest carbon emissions between 2025 and 2050 (0.057 Gton CO_2), driven by the environmentally conscious energy consumption patterns of the citizens within this cluster. The reduced emissions in this scenario reflect the alignment of energy use with sustainable practices, contributing significantly to the faster decarbonization of the energy sector.

Interestingly, despite the higher energy consumption observed in the "*Cluster 2*" scenario, its total cumulative carbon emissions between 2025 and 2050 (0.059 Gton CO_2) are projected to be lower than those in the *"BAU"* scenario. As shown in **Figure 12**, citizens in this cluster tend to consume more electricity in the mobility sector and less electricity in the housing sector. However, in the short term (i.e., 2025-2030) when the power generation from gas is at its peak, the amount of electricity required from the mobility sector is much less than the amount required from the housing sector due to the exponential patterns of mobility demand by 2050 (Figure 11). Thus, this scenario leads to lower short-term consumption of gas in the short-term and thus a lower total carbon footprint in the power sector.

As regards "*Cluster 3*", its total cumulative carbon emissions between 2025 and 2050 (0.06 Gton CO_2) are projected to be the closest to those of the *"BAU"* scenario among all examined scenarios. This is due to the fact that citizens in this cluster tend to consume electricity with very similar patterns with those of the Greek NECP both in the mobility and the housing sector, as shown in Figure 12.

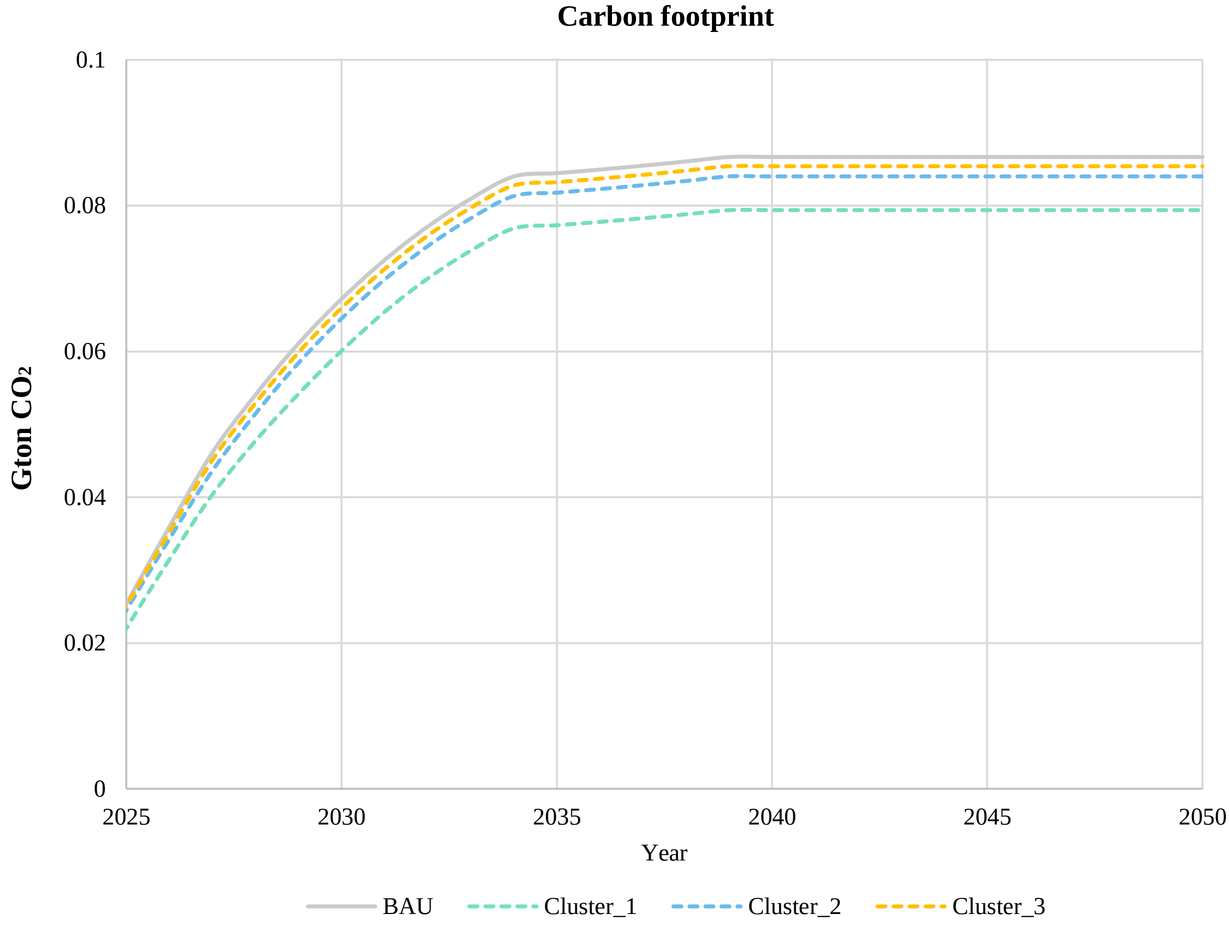

Figure 28. The total annual CO_2 footprint in the Greek power sector by 2050 for the baseline scenario and the scenarios informed by the clustering analysis.

7. Conclusions, recommendations, and further research

This section synthesizes the key findings derived from the model applications presented in this deliverable and aims to provide a comprehensive reflection on the insights gained, addressing the broader implications of the modeling results based on the outcomes of the energy citizen clustering and profiling. Moreover, it explores potential pathways for future research and highlights key areas where targeted actions can drive impactful change. The discussion also considers the limitations of the current analysis and provides recommendations for overcoming challenges in future applications. Ultimately, this section seeks to guide stakeholders and policymakers in leveraging the results in relation to policy and practical implementation to strengthen and scale diverse forms of citizen-led engagement and foster sustainable energy transitions and citizen-led initiatives.

7.1. Bridging energy citizen clusters with energy models to identify the decarbonization potential of energy citizenship at the national level

This deliverable focused on bridging findings from the citizen clustering and profiling analysis (**WP4**) with energy modeling and simulation tools (**WP5**), by translating the semi-quantitative clustering outputs and citizens' energy behaviors and profiles to energy models' inputs.

To do so, we utilized two (2) models to investigate the relationship between different energy citizen clusters and their emission reduction potential in national-scale energy systems. To achieve this goal, we employed a multi-method approach that combined the strengths of semi-quantitative clustering and profiling methods with quantitative energy system modeling.

More specifically, our approach consisted of four (4) main methodological steps. These steps involved understanding the citizen clustering and profiling analysis, as described in **Deliverable 4.2** (Naderian et al. 2024) and **Deliverable 4.3** (Naderian et al., 2024a), adjusting the models to integrate the clustering and the profiling results, selecting the case studies and designing the scenarios, as well as applying the ENCLUDE modeling ensemble to the case studies.

Overall, two (2) different models, i.e., ATOM and OSeMOSYS-GR, were used to simulate the case-specific decarbonization pathways outlined in this deliverable. Using ATOM, we investigated the adoption of rooftop solar PV systems in the housing sector for different energy citizen clusters, in Greece and the Netherlands, by 2030. Utilizing OSeMOSYS-GR, we computed the power sector capacity buildout based on electricity consumption patterns of different energy citizen clusters in the housing and the mobility sectors in Greece by 2050.

7.2. Adoption of rooftop solar PV systems in the housing sector for different energy citizen clusters in Greece and the Netherlands

Building upon the work conducted in **Deliverable 4.2** and **Deliverable 4.3**, we used ATOM to evaluate the adoption potential of small-scale solar PV systems in the residential sector in Greece and the Netherlands by 2030. ATOM was calibrated against historical data and past observations about different technoeconomic factors like the installed capacity, PV and BESS costs, electricity prices, etc.

In this study, we sought to answer the following RQs:

***(i)**. "How could different policy schemes empower prosumerism and further citizen adoption of small-scale PV systems in Greece and the Netherlands by 2030, for the different citizen clusters that have been defined?"*

***(ii)**. "What are the carbon emissions that could be avoided (decarbonization potential) through the further empowering of prosumerism in Greece and the Netherlands by 2030 for the different citizen clusters that have been defined?"*

Forward-looking simulations led to different projections for small-scale solar PV capacity additions by 2030 in both Greece and the Netherlands and showed that projected residential PV capacity additions are considerably higher under a FiT scheme for both Greece and the Netherlands, highlighting the effectiveness of such policy schemes, especially when combined with higher fixed prices for the remuneration of prosumers. Modeling results also pointed out that the adoption of small-scale PV systems in the Greek and the Dutch housing sectors have high decarbonization potential by 2030 due to the respective carbon intensive power sectors.

Furthermore, in the case of the Netherlands, higher uncertainty levels indicate that Dutch citizens (especially those who belong to "*Cluster 3*"), feel less secure about the profitability of investing in solar PV systems despite the higher total PV capacity additions. This is attributed to the lower electricity consumption and the higher population of this cluster.

On the other hand, according to our results, Greece cannot achieve the 2030 target for total small-scale PV capacity, since we found no policy pathway that reaches the target of 1 GW of installed capacity by 2030. The closest to this target (692 MW) was achieved using a FiT scheme with a fixed price equal to 87 €/MWh. We also observed that "*Cluster 1*" contributes with higher capacity additions compared to the other clusters. The case is different in the Netherlands where the target of 14 GW of residential solar PV capacity installed by 2030 seems attainable under the application of a single FiT (with a fixed price equal to 109.7 €/MWh), or net metering scheme. To achieve this target, "*Cluster 3*" contributes with higher capacity additions compared to the other clusters.

Our results can provide valuable insights for Dutch policymakers, considering that there is no need for combination of policy schemes in order to achieve the national targets. Contrastingly, Greek policymakers need to consider a combination of different schemes so as to achieve the 1 GW target. This need becomes even more pressing given the increased ambition of the Greek PV market in terms of capacity additions (i.e., 2 GW by 2030).

With regards to the net metering with BESS scheme (with 80% subsidy on the capital cost of BESS), we saw that it is not capable to achieve the Dutch national target of 14 GW installed capacity by 2030. This indicates the need for even more generous subsidies on BESS costs. It becomes apparent that even with 80% subsidy, Dutch citizens are not so willing-to-invest on BESS. Policymakers need to take this insight into account when designing the supportive framework for small-scale PV systems.

From a cluster analysis perspective, our results showed that policymakers have to target citizen groups that are characterized by lower electricity consumption patterns and positive climate change perceptions. For households with lower electricity demand, the self-consumption ratio is higher which increases profitability since the electricity consumed onsite offsets the cost of electricity that would otherwise be purchased from the grid. In contrast, if excess electricity is exported to the grid, it may be sold at a lower price (depending on the fixed price of FiT), reducing overall profitability. Furthermore, households with lower electricity demand typically require smaller PV systems to meet their needs. Smaller systems have lower initial capital costs, which can make the payback period shorter and the return on investment more attractive (when the price that excess electricity is sold to the grid is lower).

Finally, the profitability of prosumerism is highly sensitive to the policy and regulatory environment. Households with lower electricity demand might benefit more from net metering policies, where they are credited for the electricity, they export to the grid at the same rate they pay for consumption.

Policymakers are able to target such citizen clusters with various schemes like:

- Programs that offer subsidies for installation costs of solar PV systems up to a certain capacity, specifically targeted at households with lower-than-average electricity consumption.
- Policies where low electricity demand households receive a generous premium (for example, 20% over the retail electricity price) on the standard net metering rate for electricity fed into the grid, resulting in higher economic benefits for low electricity demand prosumers.
- FiT schemes that offer a higher fixed price for households with solar PV systems of under 5 kW_p installed capacity, aiming this way low electricity demand households which are more likely to invest in lower capacities.

- Annual rebates on electricity bills for households that maintain their electricity consumption below a specific threshold, while also participating in a solar PV program.

7.3. Power sector capacity buildout based on electricity consumption patterns of different energy citizen clusters in the housing and mobility sectors in Greece

Building upon the work conducted in **Deliverable 4.2** and **Deliverable 4.3**, we used OSeMOSYS-GR to assess the power sector capacity buildout based on electricity consumption patterns of different energy citizen clusters in the housing and the mobility sectors in Greece by 2050.

In this study, we sought to answer the following RQs:

***(i)**. "How do different citizen groups' energy consumption patterns affect the capacity and flexibility requirements as well as the resulting electricity mix of decarbonization pathways in the Greek power sector by 2050?"*

***(ii)**. "How do different citizen groups' energy consumption patterns affect the capital investments and the carbon footprint of decarbonization pathways in the Greek power sector by 2050?"*

We observed that OSeMOSYS-GR prioritized the capital investments in BESS and pumped hydro in a different manner across the examined scenarios. This finding shows that the electricity demand profile significantly affects the prioritization of energy storage capacity investments. On the one hand, the scenarios with sharper seasonal peaks due to higher shares of electricity demand in the mobility sector and lower shares of electricity demand in the housing sector (i.e., *"Cluster 1"* and *"Cluster 2"* scenarios) necessitated more peak demand management and prioritized storage investments on BESS that can respond quickly and discharge electricity over shorter durations to provide short bursts of electricity to meet these peaks. On the other hand, the scenarios with smoother seasonal peaks due to lower shares of electricity demand in the mobility sector and higher shares of electricity demand in the housing sector (i.e., *"BAU"* and *"Cluster 3"* scenarios) necessitated more off-peak storage and prioritized storage investments on pumped hydro, which are favored, in general, for longer-term shifts of excess electricity during off-peak periods to high-demand periods.

We also found that the scenario informed by the first citizen cluster (i.e., *"Cluster 1"* scenarios), representing the citizen group with the lowest energy expenditures in the housing and mobility sectors as well as positive perceptions towards climate change, results in the lowest carbon emissions between 2025 and 2050, total capacity additions by 2050 (12.5 GW less than the baseline scenario), and total average annual capital investments (0.53 billion/year less than the *"BAU"* scenario, thus achieving 12.5% total annual investment savings compared to the *"BAU"* scenario). This highlights that citizens belonging to *"Cluster 2"* and *"Cluster 3"* should be further targeted with tailored policies that could lead to the mitigation of emissions and costs in the Greek power sector.

In addition, modeling results demonstrate that citizens' energy-sufficient behaviors not only reduce housing and mobility costs by consuming less and adapting energy services to citizens' needs (e.g., through appropriately sized products), but also mitigate system costs by avoiding unnecessary infrastructure investments. This, in turn, can mitigate energy price increases and further reduce citizens' energy costs by reducing their bills.

Of course, energy sufficiency requires a level of consciousness on behalf of citizens with regards to their daily choices, and thus tailored policies and infrastructures are required to intrinsically support the need for changes in citizens' behaviors, lifestyles, and collective organization without compromising their life quality.

In this regard, we suggest that policymakers in Greece design an appropriate sufficiency strategy while maintaining human well-being for all citizens. By developing sufficiency policies, Greece can provide a more secure, fair, and less costly transition to carbon neutrality with fewer strategic dependencies. Such policies can help Greece become less dependent on energy imports from neighboring countries and reach full energy independence based on energy efficiency and domestic RES. This avoids or reduces the need for less socially acceptable technologies that bear risks and highly uncertain costs, such as nuclear, or CCS that are currently being mentioned in the current energy and climate policy discourse.

Some examples of sufficiency policies related to the energy transition in the housing and mobility sectors are:

Housing

- Supporting framework for energy suppliers to introduce progressive tariffs favoring low consumption and guaranteeing energy access to vulnerable households.
- Improving sustainability in the building stock through the integration of whole-life carbon requirements.
- Optimizing the use and size of buildings and dwellings by promoting tax regimes, zoning rules, building codes, and other policies that favor renovations, home sharing, and use of vacant buildings over new ones.

Mobility

- Setting frameworks and incentives, including a paradigm shift in infrastructure investments, to support the move away from private car use by making public transportation and cycling more attractive and available, and by promoting short-distance travel and a more localized provision of services and supplies.
- Stringent eco-design criteria limiting excessive and unnecessary characteristics of vehicles placed on the market by addressing weight, dimensions, and carbon and environmental footprint of vehicles.

7.4. Limitations, further research, and exploitation

Our research comes with specific limitations that primarily lie within the databases used to cluster the energy consumption patterns of citizens. While coarse-grained data is useful for broader, high-level assessments and aggregations, the availability of more detailed, fine-grained data, would most likely reveal different and potentially more nuanced clusters of energy behaviors. Another notable limitation stems from the self-reported nature of the data, which makes it difficult to accurately measure the energy consumption of the survey's participants, potentially leading to biases, such as over-, or under-reporting of energy consumption patterns. Furthermore, the lack of sufficient data restricted our process of completely bridging the energy citizen clusters with the energy models, considering that the utilized data were not only fed into the clustering analysis but also subsequently into the assumptions used for the integration of clustering results into the models.

Nevertheless, these limitations highlight the common challenges faced when grouping and modeling energy consumption behaviors. In the context of improving the quality of similar assessments, suggestions for future research would be related to the improvement of survey methodologies to account for various types of citizen-related attributes, enhance the accuracy of self-reported data, and expand data availability and granularity in order to boost the robustness and applicability of such studies.

Our work can be exploited both within and outside of ENCLUDE by policymakers 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. Our results can also be taken up by researchers and other end-users from the field of academia that are interested in the ways that different data-driven energy citizen clusters can be integrated into the design of decarbonization pathways and simulated with computational models.

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[12], while case study results will be made available on the ENCLUDE Interactive Policy Platform[13] (as developed in the context of **WP7**).

[12] https://github.com/TEESlab-UPRC
[13] https://energycitizenship.eu/

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