

Article

Citizen Participation in Low-Carbon Energy Systems: Energy Communities and Its Impact on the Electricity Demand on Neighborhood and National Level

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Abstract: In this work, the main research question is how a high penetration of energy communities (ECs) affects the national electricity demand in the residential sector. Thus, the existing building stock of three European regions/countries, namely, the Iberian Peninsula, Norway, and Austria, is analyzed and represented by four different model energy communities based on characteristic settlement patterns. A tailor-made, open-source model optimizes the utilization of the local energy technology portfolio, especially small-scale batteries and photovoltaic systems within the ECs. Finally, the results on the national level are achieved by upscaling from the neighborhood level. The findings of different 2030 scenarios (building upon narrative storylines), which consider various socio-economic and techno-economic determinants of possible future energy system development, identify a variety of modification potentials of the electricity demand as a result of EC penetration. The insights achieved in this work highlight the important contributions of ECs to low-carbon energy systems. Future work may focus on the provision of future local energy services, such as increasing cooling demand and/or high shares of electric vehicles, further enhancement of the upscaling to the national level (i.e., considering the distribution network capacities), and further diversification of EC composition beyond the residential sector.

Keywords: energy communities; low-carbon energy systems; local energy technology portfolio; small-scale batteries; local self-consumption; upscaling



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1. Introduction

1.1. Motivation

In the background of the Paris Agreement [1] and the European Green Deal [2], the overriding goal of humanity is to achieve climate neutrality within this century. Hence, fundamental changes are important, which consider different measures and enable a transition toward a low-carbon future society. In this regard, citizen participation and societal engagement play a key role, as it is unquestionable that social and societal elements are capable of making significant contributions and triggering the further penetration of renewable energies in energy systems [3]. The definition of a low-carbon society effort goes far beyond a purely technical or techno-economic consideration. The abovementioned aspect addresses not only sustainable energy systems (which, in turn, would mean a technologically oriented perspective) but also the achievement of holistic *Sustainable Development Goals* (<https://sdgs.un.org/goals>), which comprises a comprehensive strategy, including societal, energy, environmental, climate and policy-related topics.

One approach for taking into account the elements of both societal and techno-economic transformation is energy communities (ECs). In its definition and practical implementation, ECs offer a relatively broad spectrum of applications. The characteristics of application result from the economic, technical, regulatory, and also geographical scope of the respective EC. However, all ECs have one aspect in common: they serve as a social

structure and union of different agents (i.e., consumer, and prosumer) in the energy system. A comprehensive discussion of these and the associated details of citizen and societal participation in energy systems is presented in the Section 1.2. The commitment to further elaborate on local (distributed) energy generation and consumption as well as the recently published major contributions in the scientific literature of ECs is pursued in this work. Thus, the ECs analyzed in this work are very closely related to microgrids and fulfill (i) the physical connection between the different participants and (ii) the geographical limitation to a specific part of the distribution grid.

The core objective of this work is to investigate the qualitative and quantitative effects and implications of an extensive EC implementation at the neighborhood and national levels. Thereby, different socio-economic- and techno-economic-driven future developments of the energy system (storylines) are investigated and considered in the modeling exercise. In particular, the main research question is to what extent the total electricity demand and its temporal profile can be reduced (or modified) by establishing social communities and prosumer participation via ECs. Different operating strategies of local energy technology portfolio utilization in the EC (i.e., operation strategies of small-scale batteries to maximize either the community's profit or the local self-reliance) play a significant role in estimating the electricity demand profile modification potentials. Equally important in the analysis is the identification of the implemented or realized share of ECs according to the different characteristics of the storylines.

The method applied is an extension of an open-source model (OSM) (The model uses the *Python* toolbox *Pyomo* <http://www.pyomo.org/> and is solved using *Gurobi* <https://www.gurobi.com/>.) combined with a spatial clustering algorithm and an upscaling process. In the first step, the existing building stock in different European regions/countries, namely, the Iberian Peninsula, Norway, and Austria, is identified. Based on this building stock, representative settlement patterns are determined. From there, model energy communities (MECs) are formed, which contain for each setup a specific number of various buildings. In the next step, the optimal utilization of the local energy technology portfolio, especially of small-scale batteries, is determined for each MEC. Finally, the empirical results on a country level can be evaluated by upscaling the results from a neighborhood or community to the national level. Thereby, the share of implemented or realized ECs is empirically determined and varies in the different storylines.

The case study analyses include three different European regions/countries, namely, the Iberian Peninsula, Norway, and Austria, as previously mentioned. They are selected in such a way as to achieve a high diversity in terms of the (i) composition of the existing building stock, (ii) distribution of the population density, (iii) regulatory framework enabling EC implementation, and (iv) geographical location and scope. The latter point is particularly important in connection with solar radiation.

1.2. State-of-the-Art

The transition of the current energy system to one dominated by renewable energies and sustainable technologies requires the consideration of different dimensions. It is important to note that several renewable technologies for this sustainable energy transition are already available and mature. Hence, in this context, we are not talking about a technological challenge ahead. Instead, socio-economic and techno-economic aspects significantly determine the rollout of renewable energy technologies on a large-scale and thus CO₂ reduction. Consequently, it is no longer sufficient to examine only the theoretical technological options. These analyses per se provide no further insights. It is important to consider additional dimensions of social acceptance, regulatory frameworks, and the economic efficiency that technology portfolios can possibly provide in future energy systems [4]. As demonstrated by various studies, social commitment and engagement offer magnificent opportunities to trigger renewable energy penetration [5]. Therefore, to obtain a deeper understanding of the early phase of social engagement and citizen participation

in the energy system, the following discussion is provided from a historical perspective, using selected literature references.

Citizen participation in the energy system has a relatively long history. Initially, these bottom-up developments and participation in cooperatives were profit-oriented and thus dominated from a financial perspective (e.g., onshore wind parks in countries like Germany [6] or the Netherlands). Geographically, the participation as a shareholder in a cooperatively or sanized wind farm not necessarily can be denoted to be local onsite generation. Wind turbines are often operated outside or at the edge of populated areas. Contrarily, photovoltaic (PV) systems offer a much closer and onsite citizen participation in the generation of renewable energy. To a certain extent, the operation of PV systems is also entirely economically oriented [7], although the operation can also consider local self-reliance and the ambition to maximize local self-consumption [8]. In any case, a large number of studies in the literature deal with the profitability of decentralized local PV systems of individuals within communities [9], often considering small-scale batteries [10] or peer-to-peer trading within a group of prosumers [11]. However, these kinds of first (profit-oriented) approaches can be perceived as the beginning of a wider citizen participation and social engagement in energy transition.

Further incentives for citizen participation in the energy system concern the group that is collectively referred to as system or grid supporters [12]. This prosumer behavior is no longer driven purely by profit maximization; it contributes to the stability of the grid and thus security of supply for all [13]. As an example, [14] demonstrates how buildings can be optimally integrated into the energy system, taking into account grid stability and the needs for a flexible load control in the modeling framework. In addition, the role of local self-consumption or self-reliance, as mentioned above, is becoming increasingly important [15]. In principle, and as will be shown by the results of this study, local self-consumption can significantly reduce the burden on the grid. An equally important aspect in this context is the supply of areas that are not connected to the public grid (and thus isolated). A related study of a rural off-grid district is presented in [16]. Note that in this study, similar to [17] (Besides, the cited reference also contains a comprehensive discussion of open-source modeling of energy systems. This is only to be understood as an extended note since open-source modeling is not explicitly discussed in detail in this study.), the ECs under consideration correspond to microgrids from a technical perspective [18]. Nevertheless, it is still referred to as ECs to emphasize the social aspect in this respect. Moreover, the intention of self-reliance in the energy supply, and to a certain extent energy autarky, is shown. Hence, the focus is primarily on electricity consumption at the building or unit level rather than the local neighborhood as such.

The third dimension of citizen participation involves an additional dimension of the energy system and can be interpreted as a combination of the first two motivations (profit maximization, grid/system support). It is driven by an idealistic [19] and, to a certain extent, immaterial incentive [20]. Studies in this context exemplarily comprise individual willingness to pay for locally producing renewable energy technologies or CO₂ mitigation [21], energy services and product differentiation [22] and the ambitions for local energy neutrality in [23]. In these studies, profit maximization is not the primary focus of societal engagement [24]. Therefore, these additional incentives represent a socio-economic extension of both techno-economic aspects mentioned in the paragraphs above.

Finally, this section is devoted to the regulatory, environmental, and socio-economic contributions of ECs to the scientific literature. A variety of studies deal with regulations [25] and corresponding business model opportunities of ECs [26], especially in terms of detailed regulatory framework design in different countries [27]. In addition to the comprehensive regulatory consideration (see also in [28]) further aspects, such as environmental [29] and socio-economic [30] objectives, are becoming increasingly important. These and further studies (i.e., exploring the transition potentials of ECs in [31], the renewable energy-based strategies for ECs in [32], or low-carbon pathways for energy systems in [33])

highlight the proposed holistic approach for the implementation of ECs. Furthermore, the work in [32,34] describe ECs that have a compensated energy balance, so called net zero.

1.3. Progress beyond State-of-the-Art

The abovementioned explanations show several studies on ECs dealing with different foci. However, there is no comprehensive work in the literature dealing with the integration of ECs into the existing building stock and taking into account socio-economic transformation. In this work, the bottom-up approach evaluating the building-integrated EC concepts and potentials as well as their effects and implications on the national level makes a novel contribution to scientific research. The literature review reveals a lack of EC potentials at the national or country level.

Therefore, the novelties of this study can be summarized as follows:

- Assessment and quantification of the theoretical potential of ECs at different levels based on the existing building stock and population density distribution. The presented algorithm offers the possibility of categorizing buildings on a regional level into three different settlement patterns and, in sequence, into four separate MECs.
- Development of an analytical method for quantifying the impact of MECs on the basis of load profile modification at the neighborhood level. Thus, it can be demonstrated how different settlement patterns or corresponding ECs maintain energy self-reliance and affect its electricity exchange (supply and feed-in) from superior grids.
- Upscaling of the modified electricity load profiles per MEC on a national level on the basis of four different possible future developments of the energy system (storylines) considering different techno-economic, socio-economic and policy-related ambitions. The storylines significantly determine the share of realized MECs in the countries concerned. Thus, the findings at the neighborhood level have become transferable to the country level.

1.4. Outline

The paper is organized as follows: Section 2 describes the applied methodology, the algorithm to form the MECs on the basis of the existing building stock and settlement patterns (SPs), as well as the optimization model. The results of the different use-cases are presented and discussed in Section 3, followed by the conclusions and outlook in Section 4.

2. Materials and Methods

This section outlines the methodology applied in this paper. Figure 1 presents the overall modeling approach using the spatial and temporal dimensions of MECs in the energy system. Here, the focus is on the four different storylines crucial to the penetration of ECs and reflecting different societal and techno-economic developments (For instance, consumer behavior and lifestyle adaptation as well as technology maturity and efficiency vary in the different storylines. A detailed description can be found in Section 2.4.). Section 2.1 introduces the algorithm for the formation of different SPs and MECs. The description of the applied OSM is provided in Section 2.2. Section 2.3 presents the upscaling of the results to the national level. The description of the storylines, the key performance indicators (KPIs), and the case studies follow in Section 2.4.

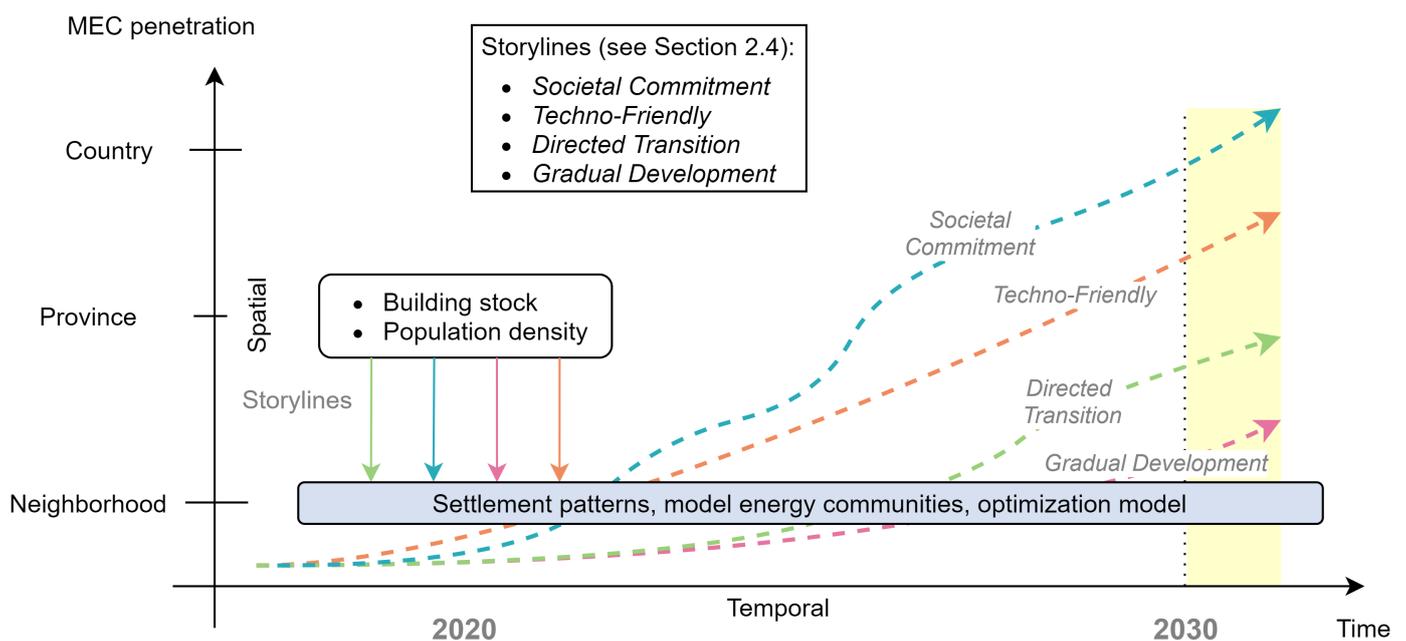


Figure 1. Sketch of the methodology applied.

2.1. Settlement Patterns and Model Energy Communities

To set up the MECs, the first step is to identify the total building stock per spatial unit. In this work, the spatial or geographical granularity corresponds to the provincial level or NUTS2 (*Nomenclature des Unités territoriales statistiques*—NUTS describes a systematic identification and classification of regions in the European Union. It is closely oriented to the administrative structure of the individual countries.) regions in a country. The corresponding building stock per region is then split into three different SPs or building types:

- (i) Single-family houses (SFHs)
- (ii) Small multi-apartment buildings (SMABs) with 3–10 units
- (iii) Large multi-apartment buildings (LMABs) with 10 or more units

The allocation of the buildings to the different SPs is based on the empirically available statistical building stock data or the distribution of the population density in the individual regions. A comprehensive overview of the data and the corresponding references and sources are presented in Appendix A. Figure 2 provides an overview of the process to determine the numbers of the three different SPs per NUTS2 region (highlighted in red in Figure 2). This is done as follows. In the first step, all SFHs of the building stock are collected and summarized. Using statistical data of the dwelling size distribution and the average housing space per person (\overline{HS}), the population living in SFHs (Δ_{SFH}) is calculated as follows:

$$\Delta_{SFH} = SFH \cdot \frac{\overline{DS}_{SFH}}{\overline{HS}} \quad (1)$$

where \overline{DS}_{SFH} denotes the average dwelling space of SFH in the corresponding region (Both values \overline{DS}_{SFH} and \overline{HS} are assessed individually for each region.). In the second step, the share of the population living in highly populated areas or cities (Δ_{city}) is determined as follows:

$$\Delta_{city} = \sum_i \Delta_i \text{ with } \Delta_i = \begin{cases} \Delta_i & \Phi_i \geq \tilde{\Phi}_{city} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where Δ_i denotes the population of an individual municipality; Φ_i , the corresponding population density of the municipality; and Φ_{city} , the minimal required population density of a city. The number of LMABs is determined according to Equation (3) from Δ_{city} and the population density per LMBA Φ_{LMAB} (It is, therefore, assumed that a portion of the population living in densely populated areas Δ_{city} lives exclusively in LMABs. Conversely, the share of LMABs in more rural areas (with a population density below Φ_{city}) is neglected.).

$$LMAB = \frac{\Delta_{city}}{\Phi_{LMAB}} \quad (3)$$

The number of SMABs is determined by using Equation (4), where Δ_{SMAB} denotes the population living in SMABs, and Φ_{SMAB} the population density per SMAB.

$$\Delta_{SMAB} = \Delta_{city} - \Delta_{SFH} \quad SMAB = \frac{\Delta_{SMAB}}{\Phi_{SMAB}} \quad (4)$$

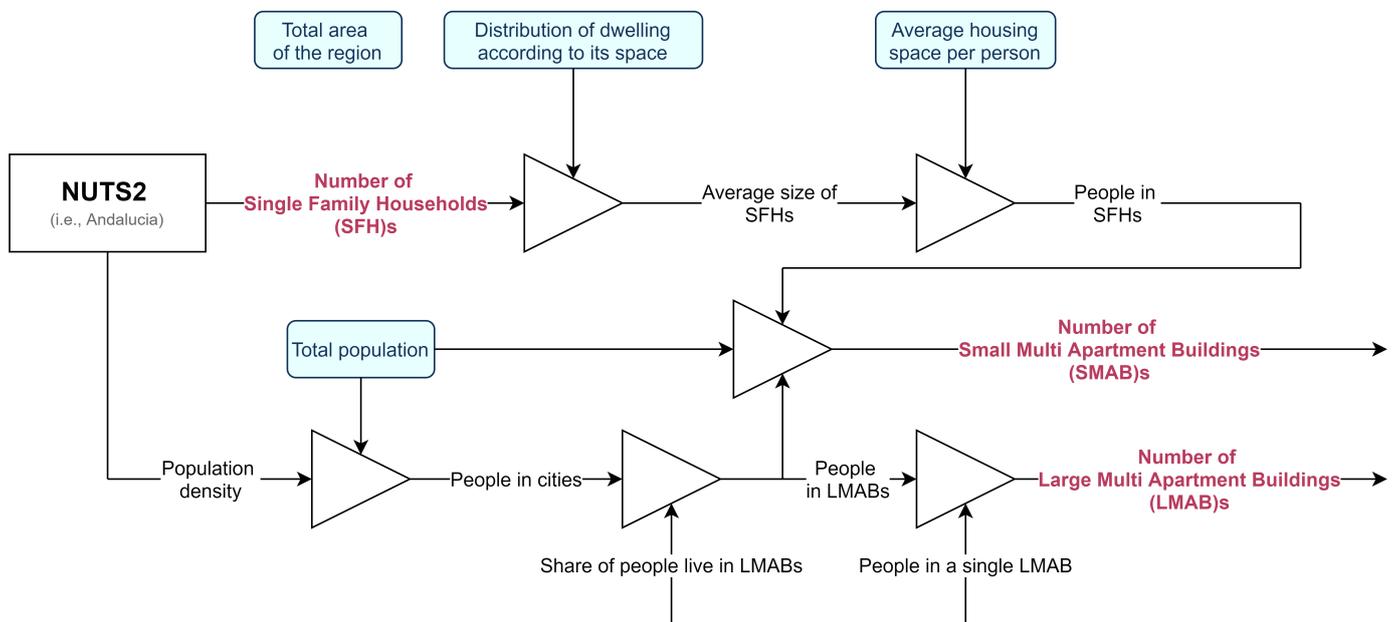


Figure 2. Flow chart of the settlement pattern algorithm.

Based on the specific SPs, the MECs are formed in Table 1 as follows, whereas $\alpha_{j,k}$ (With $j \in \{LMAB, SMAB, SFH\}$ and $k \in \{City, Town, Mixed, Rural\}$) denotes therein the various number of SPs assumed to form the specific MEC. At this point, it is noted that 75% of the LMABs are assigned to *City ECs*. The remaining building stock of LMABs is used to form *Mixed ECs*. Exemplarily, the number of *City MECs* (Λ_{City}) is calculated using Equation (5) (An even more detailed description of the allocation can be found in [9]).

$$LMAB' = 0.75 \cdot LMAB \quad \Lambda_{City} = \frac{LMAB'}{\alpha_{LMAB,city}} \quad (5)$$

Table 1. Formation of model energy communities (MECs) on the basis of different settlement patterns.

MEC	LMABs (10 or more Units)	SMABs (3–6 Units)	SFHs
City	$\alpha_{LMAB,city} = 10$	–	–
Town	–	$\alpha_{SMAB,town} = 10$	–
Mixed	$\alpha_{LMAB,mixed} = 2$	–	$\alpha_{LMAB,town} = 10$
Rural	–	–	$\alpha_{SFH,rural} = 10$

2.2. Optimization Model

The optimization model applied in this work is constructed on the existing OSM *urbs* by Dorfner [35] and its extension in [17] (It is noted that this work also has been conducted by the author of this paper.). It is a mixed-integer linear program and enables a tool for energy technology/infrastructure investment decisions and an optimal energy technology dispatch with a high temporal resolution. Basically, the model allows the consideration of different objective functions. In addition to minimizing the total costs or total emissions, the local self-consumption of the neighborhood can be maximized (Furthermore, the minimization of the deviation between declared and actual feed-in by local renewable energies can also be considered as an objective function. Considering the corresponding storylines in Section 2.4, especially those of *Societal Commitment*, this aspect is mentioned as a footnote.). In this work, both objective functions, total cost minimization and local self-consumption maximization (see Equation (6)), are analyzed.

$$\min \zeta = \zeta_{fix} + \zeta_{var} + \zeta_{ext} \qquad \max \lambda = \lambda_{pv} + \lambda_{bat} \quad (6)$$

whereby ζ denotes the sum of annual fixed (ζ_{fix}), variable (ζ_{var}), and external costs (ζ_{ext}) (Note that external costs can be seen as a representation of CO₂ and other greenhouse gas pollution costs.). This objective function can be seen as an equivalent to the operation strategy of price arbitrage of (small-scale) batteries. In the sense of maximizing local self-consumption of the neighborhood, λ denotes the sum of locally generated and consumed energy from (local) PV systems and small-scale batteries within the EC. However, the electricity demand within the EC needs to be covered at every time step by the available energy technologies, namely, PV systems, small-scale batteries, or via the public grid. As described in the previous section, the MECs specify not only the different prosumers but also the corresponding characteristic energy technology portfolio (see Table A2 in Appendix B). Accordingly, the model is exclusively used in this work as an optimization tool for the energy technology dispatch (Therefore, no (annual) investment costs are considered in the objective function in Equation (6)).

2.3. Upscaling on a Country Level

The optimization model calculates the optimal utilization of batteries and energy technologies available within the neighborhood as well as the corresponding grid supply according to the objective function. Finally, these results can be scaled up to the national level. To achieve this, the modified electricity profiles (equivalent to electricity supply from the grid) of the neighborhood are multiplied by the number of realized ECs and summed over all MEC types. This is expressed by Equation (7) where Ω_t denotes the modified electricity profile for the residential sector on a national level; β_i , the factor of the implemented share; and $\omega_{i,t}$, the electricity profile of the specific MEC type i (*City, Town, Mixed* or *Rural*) (Therefore, the national electricity profile regarding the residential sector is modified as a result of the formation of the ECs.). The index t describes a specific time step and highlights the high temporal resolution of the modeling exercise.

$$\Omega_t = \sum_{\forall EC} \beta_i \cdot \Lambda_i \cdot \omega_{i,t} \quad (7)$$

2.4. Description of Storylines and Case Studies

2.4.1. Storylines—Narrative Description of Possible European Energy System Development

The four different storylines described below are those developed in the openENTRANCE project (<https://openentrance.eu/>). These storylines outline different transition paths to a low-carbon European energy system. In the narrative description, the emphasis is placed on socio-economic and techno-economic aspects as they are particularly relevant to the implementation and realization of ECs. The key drivers of the individual storylines can be very different. Figure 3 presents the fundamental approach of a 3-dimensional space, spanned by the essential key drivers:

- Smart Society: maximizes social engagement and awareness to participate and mitigate climate change, including behavioral change in lifestyle
- Technology Novelty: rapid technological innovations and breakthroughs that are immediately profitable and drive the energy transition
- Policy Exertion: strong policy measures that lead to energy transition and decarbonization (top-down decisions and centralized initiatives)

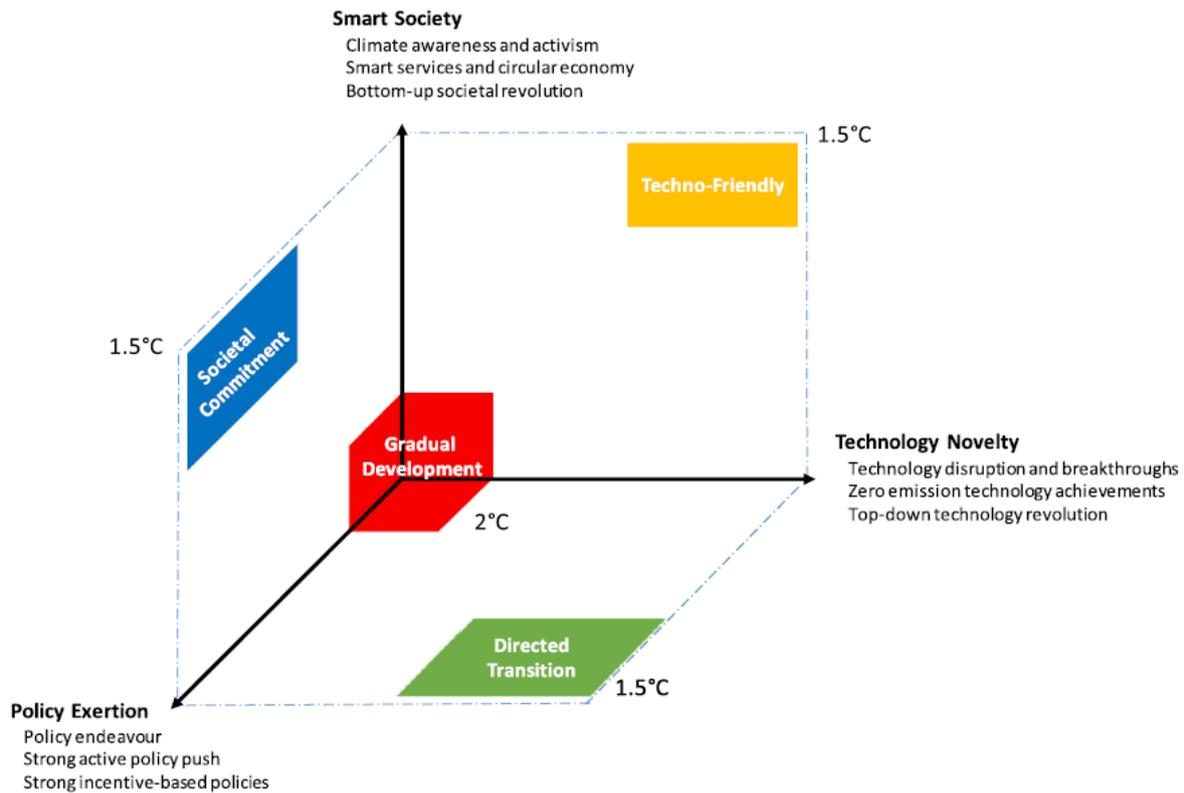


Figure 3. Fundamental approach of the storylines[33].

Each storyline considers two essential key drivers; hence, they are located in the corners of the 3-dimensional space. Note, that this is not the case for *Gradual Development*, since none of the key drivers predominate in this storyline (see origin of coordinates in Figure 3). However, it should be stated that there are indeed similarities in all storylines (i.e., a high share of renewable penetration significant and reduction of final energy demand) (The storylines in the openENTRANCE project lead to the achievement of the 1.5 °C target for the first three candidates and the 2.0 °C target for the less ambitious *Gradual Development*). The fundamental research questions underlying the storylines concern to what extent (i) societal commitment and stronger cooperation can contribute to a low-carbon energy system in case no pioneering technology innovations (i.e., carbon capture and storage (CCS) or large-scale hydrogen) exist; (ii) market forces and technology innovation can deliver, taking into account economies of scale for renewable energy technologies and compensating a lack of policy actions; or (iii) significant policy steering can govern the energy transition process in case of failures in both the remaining dimensions, societal commitment and technology innovation. Note that the storylines are not limited to Europe; they can be understood in a global context (see also [36]). Finally, based on the qualitative description, the values of the KPIs (β_i) per storyline are then defined and ultimately quantified in terms of realized share in ECs.

Societal Commitment: This storyline is characterized by high social responsibility and sensitivity (societal engagement and awareness) to become a low-carbon society. Individuals and communities, as well as the public, strongly support policy measures.

Lifestyle and behavioral changes in energy usage and energy service choice contribute to the penetration of renewable energy. However, no significant breakthrough of new technologies, such as CCS and large-scale hydrogen, occurs. Therefore, the key driver is a social bottom-up (grassroots) one.

Techno-friendly: This storyline is dominated by groundbreaking technology innovation and deployment as well as societal and behavioral changes in the energy choice (grassroots movement). However, societal development and adaptation also demonstrate slight resistance and reservation to large-scale infrastructure projects. Furthermore, there is less need for active policy/regulatory intervention because the technological progress and markets deliver accordingly. Moreover, the key drivers are societal grassroots, innovation, and technologies in the industry.

Directed Transition: The key driver in this storyline is strong policy incentives, which support an uptake from carbon-mitigation energy technologies. Despite policy-driven engagement, grassroots and citizen-led initiatives are minimal. Centralized visions and large-scale infrastructure projects, including novel technologies, as part of policymakers, incentivize to aim for low-carbon energy technologies implementation.

Gradual Development: Hereby, the awareness that the current efforts in energy transition are not sufficient exists. The effort to achieve decarbonization of the energy system is proportionally split among societal, technological, and policy/regulatory actions without a dominating key driver. However, this *little of each* of the remaining storylines is to be understood as an ambitious reference scenario in openENTRANCE, as it attempts to achieve a maximum increase in the global temperature of 2.0 °C.

The abovementioned narrative description of the storylines is quantified in the following, which enables the determination of the implemented share of the theoretical potential per MEC. Various aspects relevant to the assessment of the realized ECs are considered. Table 2 qualitatively demonstrates how the existing pilot projects and already practically implemented ECs, besides the existing or ongoing regulatory framework, influence the share. The strongest influence has both an existing (supporting) regulatory framework and already existing practically implemented ECs in the countries.

Table 2. Qualitative overview of the indicators and their impact on the share of implemented energy communities (ECs) in 2030.

	Existing Regulatory Framework	Ongoing Regulatory Framework	Pilot Projects	Existing ECs
Share of ECs	↑	↗	↗	↑

Figure 4 presents the realized share of the theoretical potential for the different MECs and storylines in 2030. The quantitative values are estimates that are empirically determined using the qualitative criteria described above. With regard to realized ECs, *Societal Commitment* means that all types of MECs are equally implemented. However, this share is the highest in countries with an existing regulatory framework in place (see circular symbol with 50%), lower in those with an emerging regulatory framework (see triangle symbol with 40%), and lowest in those with limited provisions (see diamond symbol 30%). This share assignment is also used in the two storylines, *Techno-Friendly* and *Gradual Development*, even if the shares are more limited there (40% in *Techno-Friendly* and 20% in *Gradual Development*). In *Directed Transition*, more urban ECs, especially *City ECs*, are realized more strongly than *Rural* ones (This should reflect the reluctance of the population, which is particularly relevant with regard to ECs where the building stock is in private ownership. This is mostly the case with SFHs and, thus, predominantly in more rural areas.).

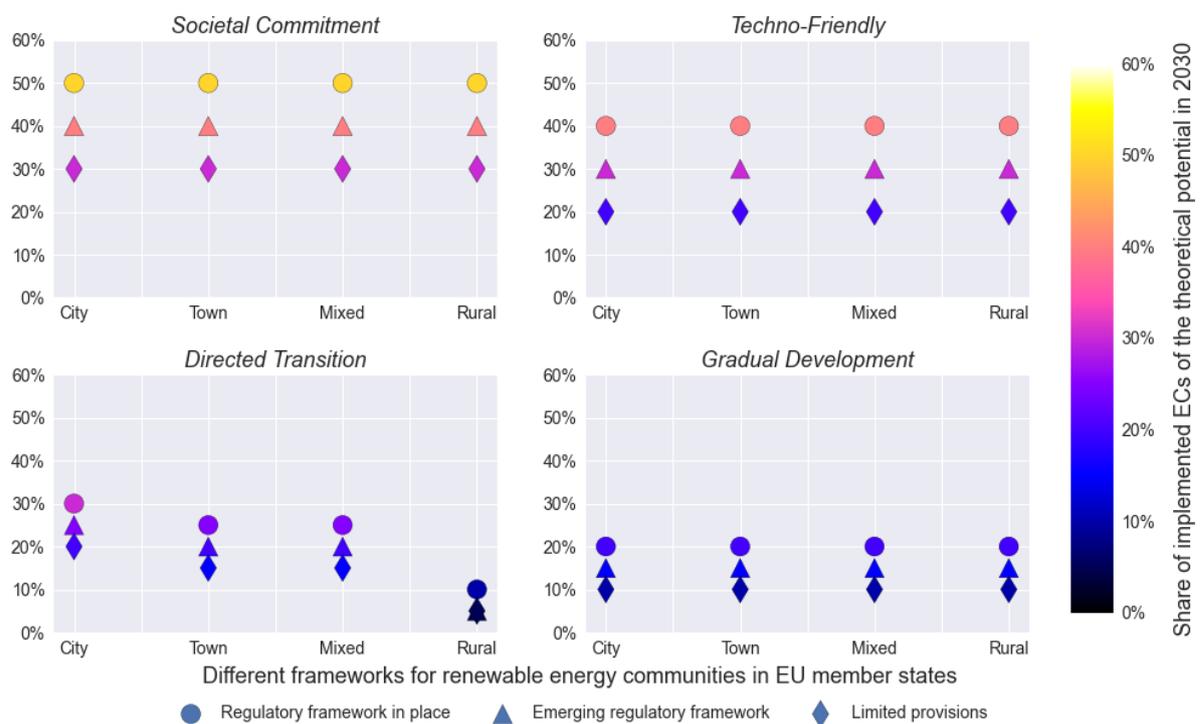


Figure 4. Share of implemented MECs per storyline. **(top-left)** *Societal Commitment*; **(top-right)** *Techno-Friendly*; **(bottom-left)** *Directed Transition*; **(bottom-right)** *Gradual Development*.

Justification of the EC shares: As mentioned above, the different key drivers provide possible space for future developments of a sustainable and decarbonized energy system, as well as a large number of uncertainties. However, the scientific literature offers studies that address the potentials and future developments, especially of renewable energies in the energy system. A fundamental work of renewable energies in this context at a global scale can be found in [37]. The recently published paper in [38] deals with the systematic characterization of key predictors of renewable energy penetration for sustainable and resilient communities.

However, in this study, an empirical approach is employed to evaluate the penetration of ECs in different storylines. The storyline of *Societal Commitment* can be perceived as the upper bound of penetration (see Figure 4). In this context, Figure 5 presents the annual installed PV capacity in Austria required to realize a share of 50% implemented ECs, compared with the historical values (Data available at <https://www.eurobserv-er.org/pdf/barometre-photovoltaique-2020/>, p. 7 (accessed on 10 December 2020).) (between 2013 and 2019 in blue), those of the storyline *Techno-Friendly* (yellow), and the recently announced national target of the *1,000,000 roofs program* (See the governmental program in Austria, available at <https://www.bundeskanzleramt.gv.at/bundeskanzleramt/die-bundesregierung/regierungsdokumente.html>, p. 80 (accessed on 10 December 2020).) (purple). Note that the annual newly installed capacities of the *Techno-Friendly* storyline are comparable to the historical ones between 2013 and 2019. However, in the storyline, they are exclusively for use in ECs and the residential sector.

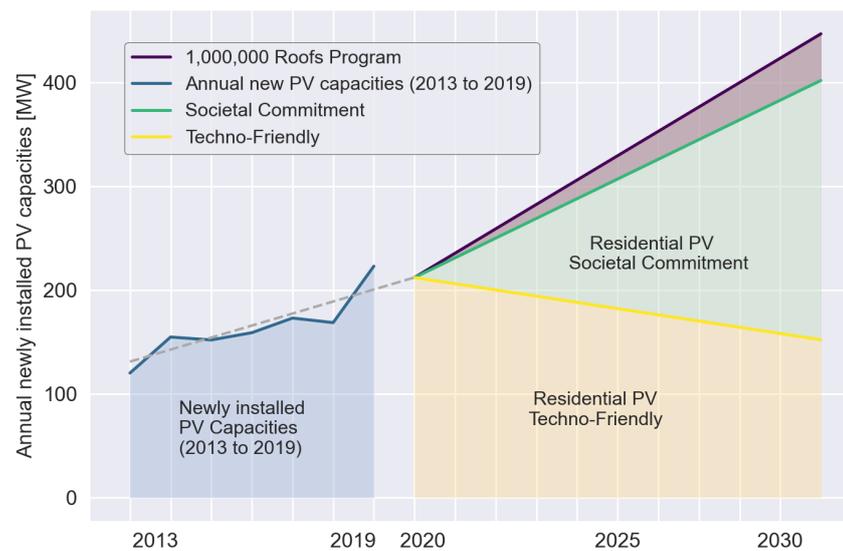


Figure 5. Annual newly installed photovoltaic (PV) capacities between 2013 and 2019 and for storylines *Societal Commitment* and *Techno-Friendly* in Austria.

2.4.2. Case Studies

In the following, the potentials of implemented ECs in three different European regions/countries, namely, the Iberian Peninsula (Spain and Portugal), Norway, and Austria, are analyzed. These four countries (or three regions) are an adequate representation of the European countries and exhibit a high diversity in terms of (i) population density distribution, (ii) share of urban and rural areas, (iii) building stock, and (iv) regulatory framework for the implementation of ECs. At the same time, the four mentioned aspects also indicate that the selected countries are also representative of regions outside Europe.

Norway is a sparsely populated country with a high proportion of electrification of the energy system. The potential for *Rural ECs* is very high (high shares of the population living in SFHs), whereas *Urban ECs* can rarely be formed. The other two types of MECs (*Town* and *Mixed ECs*) also have a relatively low potential. However, currently, there are only limited provisions in the regulatory framework explicitly promoting the implementation of ECs. In Portugal, there is an emerging regulatory framework, whereas in Spain and Austria one already exists (Here, two points are expressly referred to. On the one hand, the authors are aware that the essential aspects of the regulatory framework for ECs can be considered and described in much more detail. However, this study is not intended to deal with regulatory research questions, thus arguing for general regulatory classification. On the other hand, the authors are aware of some regulatory developments that have been observed, particularly in the recent past, which makes the distinction between limited provisions and emerging regulatory framework ambiguous and gives room for interpretation in the classification of countries.). Especially Spain and also parts of Austria offer the potential (in terms of building stock and corresponding (local) population density) for more urban neighborhoods, such as *City* and *Town ECs*. Table 3 provides an overview of the countries in the case studies and their classification in this work with regard to the regulatory framework. In addition, the solar radiation and thus the energy produced by PV systems also significantly differ between the different countries in the case study analyses.

Table 3. Allocation of the regulatory framework in the Iberian Peninsula (Spain and Portugal), Norway, and Austria.

Spain	→	Regulatory framework in place
Portugal	→	Emerging regulatory framework
Norway	→	Limited provisions
Austria	→	Regulatory framework in place

3. Results and Discussion

This section presents and discusses the results of the case studies. Section 3.1 highlights the results for the Iberian Peninsula, Section 3.2 for Norway, and Section 3.3 for Austria, which all take into account the assumptions and achievements of the *Societal Commitment* storyline. Section 3.4 provides a deeper understanding of the different storylines and compares the results for Norway.

3.1. Iberian Peninsula

3.1.1. Theoretical Potentials of Energy Communities

The theoretical potential, derived from the existing building stock in each region, is presented in Figure 6. The pie chart illustrates the corresponding shares of the different MECs per NUTS2 region. The area of the diagram is directly proportional to the total number of ECs. The predominant majority are *Rural* ones, especially in those regions with a low population density. As the population density increases, the number of MECs—*City*, *Town*, and *Mixed*—also increases: compare those regions indicated in dark blue (e.g., Comunidad de Madrid, País Vasco) with a population density of over 230 persons/km². The area of Andalusia (the far southern region on the map) has the highest number of potential ECs (slightly over 150,000). Taking into account that, in comparison with the other two countries (Norway and Austria), the proportion of *City* ECs is the highest, the emphasis is put on them.

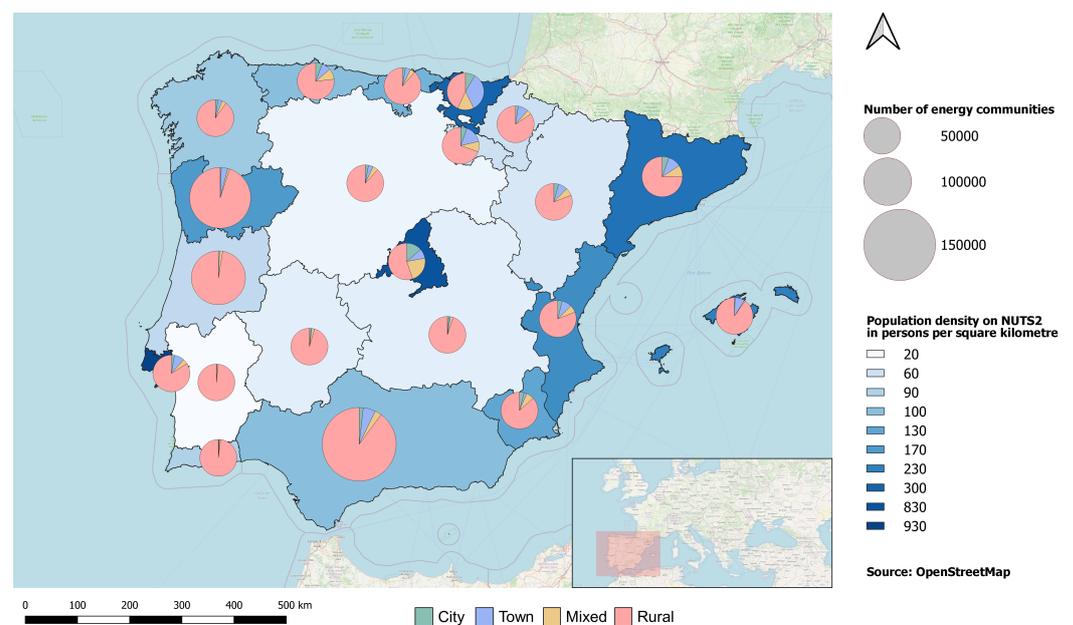


Figure 6. Theoretical potential of the different MECs in the Iberian Peninsula.

3.1.2. Electricity Demand Profile Modification by MECs

Figure 7a,b present the initial electricity demand and the results of the modified ones for a *City EC* for both operational strategies, namely, minimization of cost and maximizing of (local) self-consumption. In both cases, the generation of local PV and the utilization of small-scale batteries reduce the electricity demand. However, if the EC maximizes self-consumption, almost the entire generation can be used locally without feeding into the public grid. Taking minimization cost into account, the share of feed-in increases, although it is relatively small, especially compared with other ECs (compare Figure 7c where the two demand profiles (initial demand and cost-minimizing modified) for a *Rural EC* are shown). The amount of feed-in electricity is significant here, as local generation exceeds the demand within the neighborhood. Note that for *Rural ECs*, this applies to both behaviors (compare Figure 7c,d). In *Rural ECs*, the solar radiation characteristic is crucial for the modified demand profile. Figure 8 presents the annual duration line of the electricity demand profile for the residential sector upscaled to the national level. By comparing the two modified curves with the initial one, the reduction in demand becomes clear. Both modified load profiles to a certain extent have a negative offset. From hour 6000 (for minimizing cost) and almost 7500 (for maximizing self-consumption), the modified load profile for the residential sector is negative and feeds into the public grid. The peak values of the grid supply are almost equal to those of the initial demand with profit maximization. Conversely, local self-consumption, does indeed lead to peak value reduction.

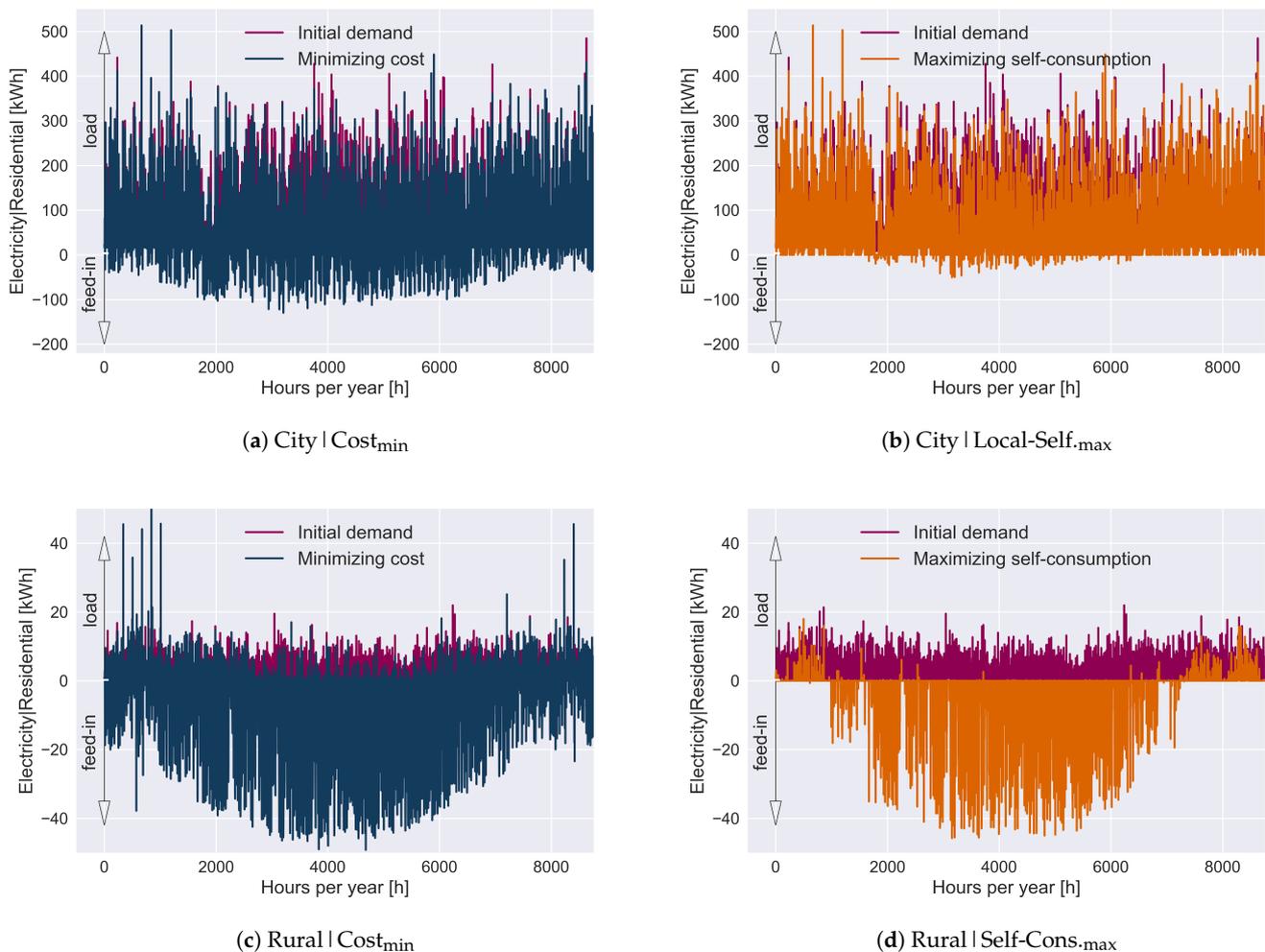


Figure 7. Electricity demand profile in *City* and *Rural ECs* in the Iberian Peninsula. (a) *City EC* minimizing cost; (b) *City EC* maximizing local self-consumption; (c) *Rural EC* minimizing cost; (d) *Rural EC* maximizing local self-consumption.

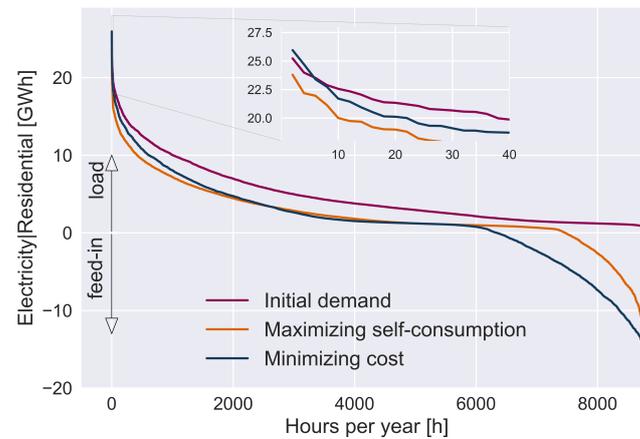


Figure 8. Annual duration line of the electricity demand profile for the residential sector in the Iberian Peninsula.

3.2. Norway

3.2.1. Theoretical Potentials of Energy Communities

Figure 9 presents the theoretical potential for the four different MECs in Norway. Due to the low population density and the existing building stock, *Rural ECs* have the highest share among the MECs. Only in the area indicated in dark blue are there theoretical potentials for *Town ECs* due to the high population density (exemplarily, there is the densely populated capital of Norway, Oslo). The remaining three MECs can be neglected in the further analysis as they have no significant effect on the modification of the electricity profiles. Thus, the different operating strategies of small-scale batteries are investigated in more detail. Note that the regions in Figure 9 correspond to the different Norwegian price zones (i.e., five in total) and not NUTS2 due to a lack of Norwegian region mapping onto NUTS2.

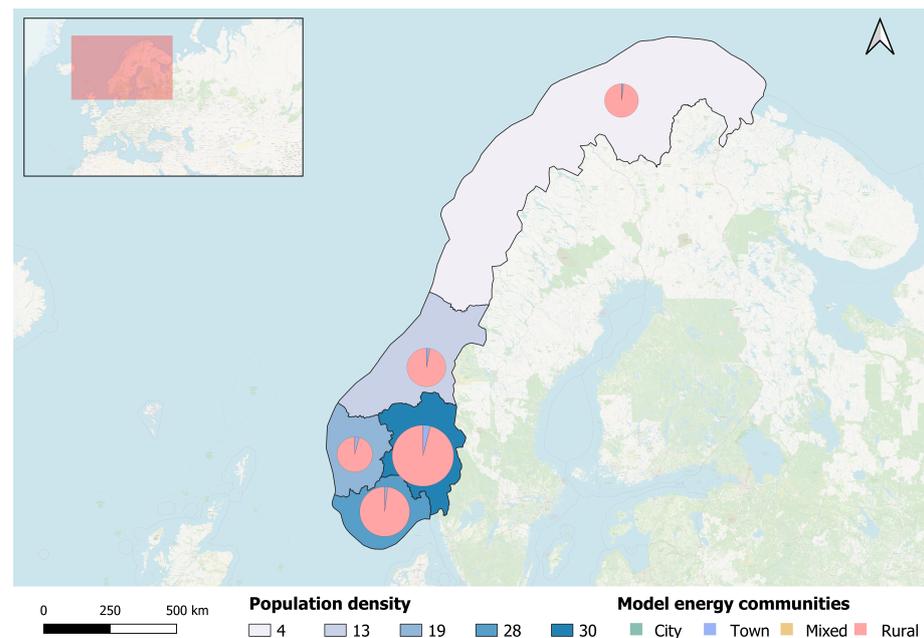
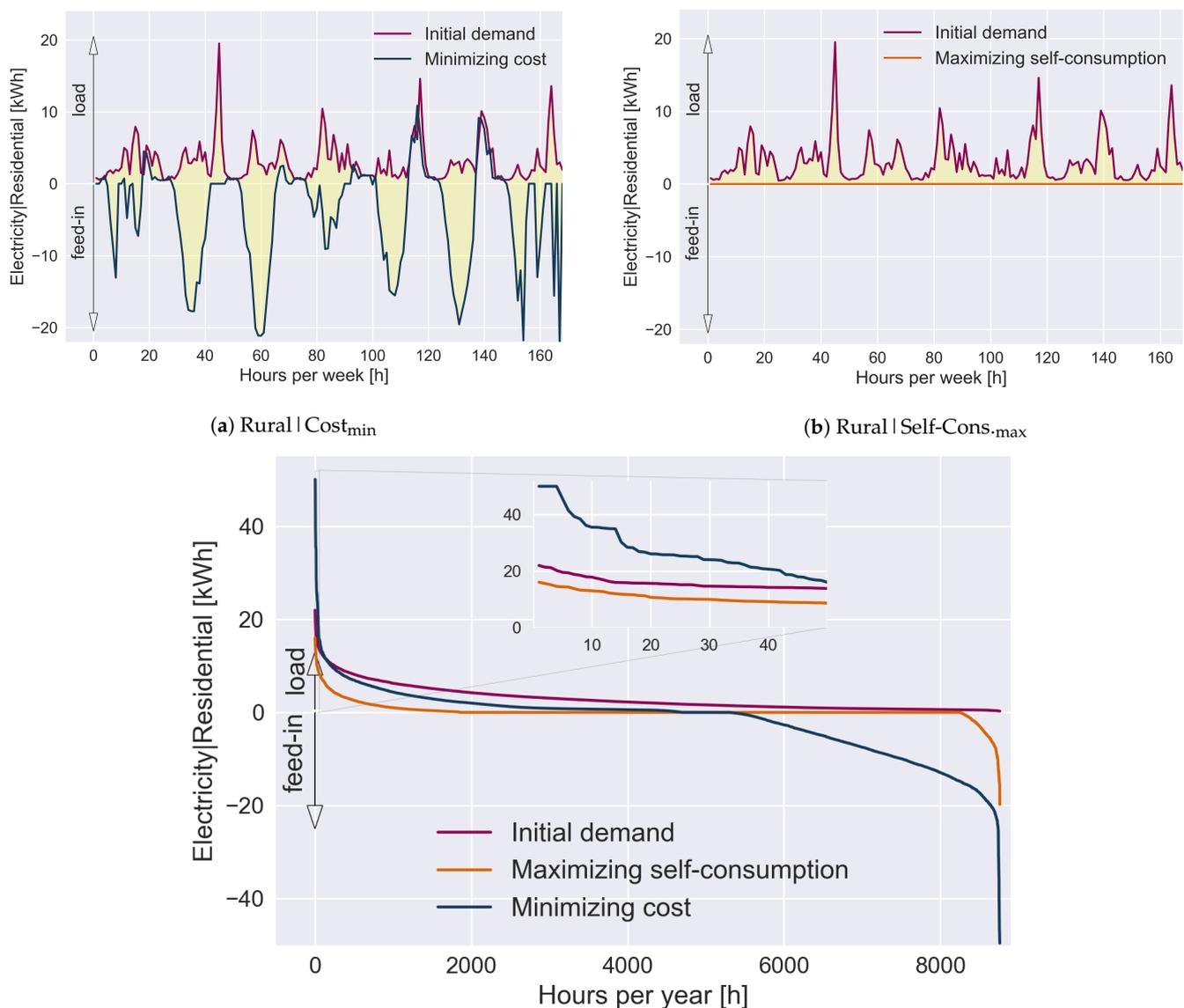


Figure 9. Theoretical potential of the different MECs in Norway.

3.2.2. Electricity Demand Profile Modification by MECs

Figure 10 presents the modeling results with a high temporal resolution for *Rural ECs* in Norway. Figure 10a,b present the load profile of the neighborhood exemplary in a typical summer week, considering the different operation strategies of local small-scale batteries. The initial demand for the entire EC is shown in red. The modified electricity demand profiles for minimizing cost are indicated in blue (left) and for maximizing local self-consumption in orange (right). The difference between the profiles is indicated in yellow. Cost-minimizing utilization of the local small-scale batteries results in a significant increase in the amount of electricity fed into the grid by the neighborhood. Therefore, the load profile is often in the negative range. However, that is not the case for maximizing local self-consumption. The initial load profile is significantly reduced by local generation. In the typical summer week presented, the neighborhood is self-sufficient and purchases no electricity from the public grid and nothing is fed into the grid. Since an analogous presentation of the results per MEC as in Figure 7 for the Norwegian case does not provide any further relevant insights, it is intentionally omitted. This also applies to the Austrian case in the following section.



(c) Annual duration line of the electricity demand profile in Norwegian *Rural ECs*.

Figure 10. Modified electricity demand profile for a characteristic summer week in (a,b) and annual duration line for the entire *Rural ECs* in (c).

The modification of the load profiles is also presented in Figure 10c, where the annual duration lines of the three different load profiles are presented. Local self-consumption by *Rural ECs* essentially acts as a negative offset concerning the annual duration lines compared with the initial load profile. At the same time, however, there are also weeks of the year when the EC feeds-in, and hence, the modified load profile is negative. In comparison, cost-minimization leads to a significant increase in peak values (supply and feed-in from the grid) as well as to significantly more hours per year the EC is feeding in.

3.3. Austria

The existing building stock in Austria offers the theoretical potential of all four MECs, although, as before, the *Rural ECs* have the highest shares (82%) (Due to the high proportion of *Rural ECs*, a detailed illustration of the shares of MECs per NUTS2 region has refrained from an explicit presentation.) among the MECs. *Town* and *Mixed ECs* have a portion of almost 9% each. The results for the latter two MECs are presented in Figure 11a for *Town ECs* and Figure 11b for *Mixed ECs*. However, Figure 11 shows the results again by the annual duration line. In both cases, the excess of the peak demand value is relatively small. It becomes clear that the *Town EC* can be self-sufficient for a large number of hours per year and, therefore, the load profile is zero while still feeding a small number of hours into the grid. At the same time, profit maximization leads to higher peak values for grid supply, feed-in capacity, and feed-in electricity. *Mixed ECs* have similar results, although it should be noted that the neighborhood is significantly less self-sufficient.

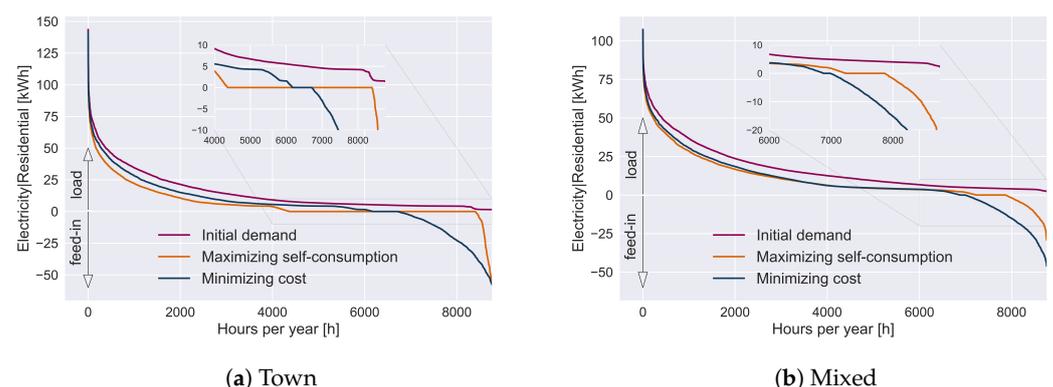


Figure 11. Annual duration line of the electricity demand profile in Austrian ECs. (a) *Town EC* and (b) *Mixed EC*.

The differences between the four MECs regarding their exchange with the public grid is shown in Figure 12a. For each MEC, the supply and feed-in electricity for the two different operational strategies are shown, normalized to the total initial electricity demand of the neighborhood. For the MECs *City* and *Mixed*, there is almost an identical situation in both cases. Local self-consumption is prioritized, and scarcely any electricity is fed into the grid. In *Town ECs*, profit maximization leads to a significant proportion of electricity feed-in. However, the difference is most evident in *Rural ECs*. The feed-in energy reaches 1.5 times the initial demand in case of cost minimization. There is also significant feed-in electricity despite maximizing local self-consumption.

Figure 12b shows the annual duration line for the total national electricity demand for the residential sector. It is shown that the implementation of ECs leads to self-sufficiency (or to a disappearance of the resulting load profile). However, the peak value of the modified electricity profile increases if cost minimization is taken into account. In both cases of the modified load profiles, locally generated electricity is fed into the grid. However, as demonstrated above, this is lower in the case of local self-consumption due to *Rural ECs*.

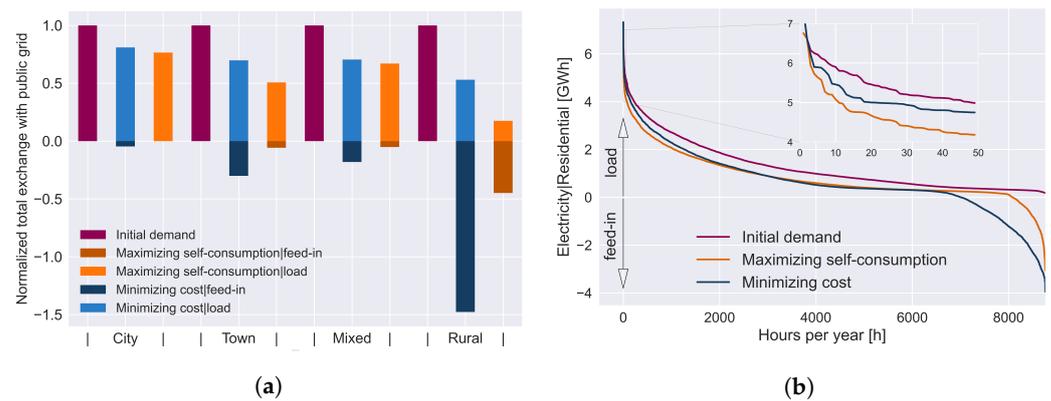


Figure 12. Austrian results for the four different MECs and total electricity demand for the residential sector. (a) Comparison among demand, load, and feed-in. (b) Annual duration line of the electricity demand for the residential sector in Austria.

3.4. Comparison of the Storylines (Norwegian Case)

Figure 13 shows the total electricity demand in Norway for the residential sector in the four different storylines. The initial demand (red) and the demand reflecting the impact of the ECs (minimizing cost (blue) and maximizing local self-consumption (orange)) are shown. Accordingly, the highest impact of ECs on the national electricity demand is due to the following:

- the high implementation of the theoretical potential in the *Societal Commitment* storyline. The installed PV capacities in the ECs enable significant feed-in and thus total energy generation in the ECs can not be entirely used there locally. Note that this is especially the case when minimizing the total costs.
- local self-consumption, which also leads to a reduction in the electricity demand, but to a lesser extent, due to the efficiency (or losses) of small-scale batteries. The small-scale batteries have a high utilization rate especially in *Rural ECs* where the individual prosumer load profiles or PV generation profiles are similar.

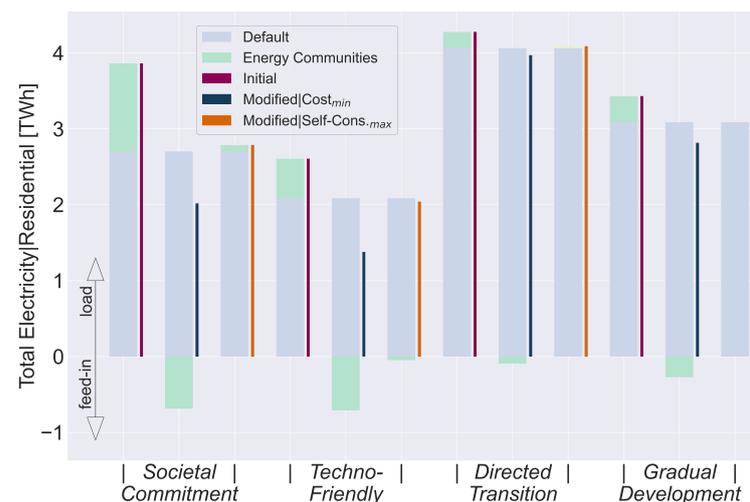


Figure 13. Total electricity demand for the Norwegian residential sector (incl. components) in the different storylines.

4. Conclusions and Outlook

This work examines the impact of high penetration of energy communities (ECs) on the electricity demand for the residential sector on the neighborhood and national levels. In three European regions/countries, namely, the Iberian Peninsula, Norway, and Austria, the modification of the electricity demand and its profile are investigated. In this context,

systematically splitting the existing building stock into different settlement patterns (SPs) and, subsequently, into model energy communities (MECs) has proven to be appropriate.

The different SPs significantly affect the electricity exchange of ECs with the public grid. The individual local electricity demand profiles and operation strategies of small-scale batteries affect both the exchange with the public grid (supply/feed-in) and the total electricity balance of the neighborhoods. *Rural ECs* significantly increase the peak value of the grid capacity while maximizing the profit of the local energy technology portfolio. However, this is essential for further planning of the energy system, especially at the level of distribution grid. A high diversity of the characteristics of individual prosumers within the EC, as is the case in *Town* and *Mixed ECs*, ensures (i) a high local self-consumption, (ii) a low increase in the needed grid connection capacity, and (iii) a high share of local renewable energy generation. Note, that these aspects are independent of the operating strategy of local small-scale batteries. *Town ECs* also exhibit the highest level of local self-reliance among the MECs, indicated by the hours per year when the electricity exchange with the public grid is zero.

Furthermore, the results of this work indicate that ECs also have an impact on the electricity demand in the residential sector at the national level. Thus, in addition to reducing the electricity load profile, they also provide flexibility and contribute to a high share of renewable energy in the energy system. The formation of ECs can be denoted as an important milestone in energy transition as ECs are associated with benevolent qualities, such as careful use of energy, energy efficient technologies, and adopted user behavioral and lifestyle changes. Depending on the different storylines addressed in this work, the weights of the abovementioned determinants are differently pronounced. However, the general trend toward sustainability in the provision of energy services is strong everywhere.

Future work may include at least the following aspects: a comprehensive enhancement of all local energy services (e.g., cooling), and an increasing penetration of electric vehicles (especially in less densely populated areas), a detailed consideration of the local distribution grid capacities, particularly when upscaling the local electricity demand profiles at the neighborhood level, and the quantification of the avoided CO₂ emissions. A more comprehensive perspective on electricity demand, which is therefore not limited to the residential sector, can reveal synergies with other sectors (e.g., commercial, industrial, or public sector). This enables investigation of the possibilities to optimally use excess electricity generation of the energy communities locally or in the surrounding areas.

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Abbreviations

EC	Energy Community
LMAB	Large Multi-apartment Building
MEC	Model Energy Community
NUTS	Nomenclature des Unités territoriales statistiques
PV	Photovoltaic
SFH	Single Family Household
SMAB	Small Multi-apartment Building
SP	Settlement Pattern

Appendix A. Data and Model Validation

Appendix A.1. Input Data

In the following, the input data of the modeling exercise are described in detail. In particular, the annual time series for the (i) electricity demand, (ii) solar radiation, and (iii) electricity buying and selling prices are discussed. The electricity demand profiles of the different SPs or MECs are calculated via a bottom-up approach using standard load profiles [39]. The solar radiation is provided by [40] or by [41] (For Spain [42].), whereby the electricity prices are also obtained from [41]. The statistical data on the building stock for the Iberian Peninsula are taken from [43], for Norway from [40] and for Austria from [44]. In this respect, essential information on empirical reference values (e.g., the average housing space per building type) is also found in [45,46].

Appendix A.2. Model Validation

As mentioned above, the annual time series of the total electricity demand for the residential sector is calculated using standard load profiles via a bottom-up approach. The corresponding total amount of electricity per year can be calculated by summing up all MECs in the NUTS2 regions. These annual values are verified by comparing with the values from [41,47]. The latter also includes essential information obtained from [48]. Table A1 presents the total electricity demand for the residential sector for both, the bottom-up approach and the national modeling results by the GeneSys-MOD model framework [41]. These results are mainly based on the modeling results of [33,47,48].

Table A1. Total energy demand (in GWh) for the residential sector in 2030.

2030	Spain		Norway		Austria	
	GeneSys-MOD	Bottom-Up	GeneSys-MOD	Bottom-Up	GeneSys-MOD	Bottom-Up
<i>Societal Commitment</i>	40,520	40,854	4189	4669	12,661	11,071
<i>Techno-Friendly</i>	34,313	34,004	3137	3633	7934	8725
<i>Directed Transition</i>	47,777	50,949	5083	6094	13,811	13,767
<i>Gradual Development</i>	39,074	41,742	4416	4992	11,431	11,279

Appendix B. Energy Technology Portfolio of the Settlement Patterns

Table A2 presents the local energy technology portfolio of the different MECs. The description does not differ with regard to the different storylines. The MECs are formed from the individual SPs as already presented in Table 1. Regarding the PV system capacities per SP, characteristic rooftop areas are assumed, analogous to the approach in [9]. The grid connection capacity per SP is assumed according to the calculated maximum electricity demand, taking into account a capacity reserve. The small-scale battery storage and related input/output capacities per unit are from the *Danish Energy Agency* (see <https://ens.dk/en>) according to their forecast for the year 2030. The number of corresponding small-scale battery storage units in each SP corresponds to the number of dwelling units.

Table A2. Energy technology portfolio in the different settlement patterns.

Settlement Pattern	Energy Technology	Value
Large multi-apartment building	PV system	15 kW
	Grid connection capacity	55 kW
	Battery storage capacity	65 kWh
	Battery input/output	8 kW
Small multi-apartment building	PV system	8 kW
	Grid connection capacity	20 kW
	Battery storage capacity	20 kWh
	Battery input/output	5 kW
Single-family household	PV system	5 kW
	Grid connection capacity	12 kW
	Battery storage capacity	8 kWh
	Battery input/output	5 kW

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