Research article

A framework to estimate the large-scale impacts of energy community roll-out

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ABSTRACT

The gradual enactment of legislation for energy communities in individual European countries has increased the public awareness of these novel concepts. While the establishment of individual, isolated energy communities is unlikely to have any far-reaching effects, it is presumed that the large-scale roll-out will indeed significantly impact different stakeholders. Since the diffusion of energy communities is expected to gain momentum within the next years, this study aims to provide a framework to assess the impact of a large-scale roll-out of solar-PV based energy communities. This nine-step framework provides guidance for determining the number of buildings per type and roof tilt, assessing the usable rooftop area for PV installation and realistically installed PV capacities, estimating the number of future residential PV systems based on renewable expansion plans, determining the shares of buildings to be equipped with PV systems, setting up model energy communities, and upscaling. The nine-step framework is not only described theoretically but also applied to Austria as a case study. Thereby, specific focus is put on Austria's rural areas and thus the single-family building stock. Results indicate the impact of a large-scale roll-out of renewable energy communities on participants' electricity bills, electricity suppliers' sales, and grid operators revenues due to reduced grid tariffs for inner-community electricity transfer. The ability to determine the future impacts of energy community roll-out supports stakeholders in their proper planning towards an energy landscape that includes energy communities.

1. Introduction

The *Clean Energy for All Europeans Package* [1], specifically the *Renewable Energy Directive* [2] and the *Electricity Market Directive* [3], provides guidelines for the legislative basis of *Renewable Energy Communities* (RECs) and *Citizen Energy Communities* (CECs) (all abbreviations are listed in Table 1). European Union (EU) member states are given a timeframe of 1-2 years to transpose these directives into national law. To date, only Austria has successfully completed the transposition process. Some countries, such as Italy and Belgium, have already enacted parts of the legislation for RECs and CECs, while other EU countries have yet to provide a legislative draft. Nevertheless, a legislative basis to establish energy communities will in due time be available in all EU countries and possibly beyond the EU as well.

As of now, there is little (from pilot projects within regulatory sandboxes) to no empirical data available on the impact of energy communities. While the sporadic implementation of individual energy communities may not affect the existing infrastructure and/or different stakeholders, a large-scale roll-out of energy communities may very well have a significant impact, not only on the participants' finances, but also on grid operators' and energy suppliers' revenues. Energy communities are expected to reduce the revenues of conventional suppliers, since part of the electricity demand of energy community participants is covered by the community itself (by community peers). And, since a reduction of grid tariffs – at least for local/regional energy communities – is under discussion in some countries,[1] it can also expected that grid operators' income might be reduced. However, the impact of energy communities will heavily depend on the reception of the idea of founding or participating in energy communities among citizens. Thus, the willingness to participate in community projects and the willingness to pay for renewable energy are key factors in estimating the potential of energy community roll-out. While the scientific literature primarily offers studies on the technical potential of solar photovoltaic (PV) systems (an important factor for energy communities, which are expected

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[1] In Austria, reduced grid tariffs are already applied for renewable energy communities.

Table 1. Abbreviations.

CEC	Citizen Energy Community
CEP	Clean Energy Package
EC	Energy Community
PV	Photovoltaic
REC	Renewable Energy Community

to be largely based on residential PV generation), studies that provide insights into the impacts of large-scale energy community roll-out are largely missing.

Since energy community deployment is expected to gain momentum in the near future, this study aims to provide a framework to assess the impacts of energy community roll-out. This framework provides guidance on necessary data and describes nine detailed steps for assessing the large-scale impacts of energy communities at a future point in time. These steps comprise determining the number of buildings per type and roof tilt, assessing the usable rooftop area for PV installation and the realistically installed PV capacities, estimating the future number of residential PV systems based on renewable expansion plans, determining the shares of buildings that will be equipped with PV systems, setting up model energy communities, and upscaling. The developed framework is not constrained to specific geographic regions but applicable to any region or country worldwide, provided that the required data is available. In addition to describing these nine steps theoretically, calculations are conducted for the case of Austria in order to enhance the comprehensibility of the described method.[2] Thereby – for a specific setting of rolling out renewable energy communities over one-third of the building stock in Austria's rural areas – the total financial benefits that energy communities could achieve are determined along with the reduction in income for energy suppliers and grid operators.

The remainder of this paper is structured as follows: Section 2 introduces a selection of relevant literature related to this study's topic. Section 3 introduces the nine-step framework for assessing the impact of a large-scale roll-out of energy communities. Exemplary results are provided for rural areas in Austria in Section 4, while the work is concluded with Section 5.

2. State-of-the-art

In light of the topics covered in this work, the literature review provides a selection of studies on the willingness to participate in energy communities and also the willingness to pay for renewable energy (Section 2.1), as well as current works on assessing the PV potential and the potential of energy communities (Section 2.2). Moreover, since the large-scale impact of energy communities can be assessed using results gained from simulation/optimisation of individual energy communities, a selection of studies in this field of research is introduced in Section 2.3. Finally, this study's contribution is highlighted in Section 2.4.

2.1. Willingness to participate

Kalkbrenner et al. [4] elaborate on citizens' willingness to engage in community-based renewable energy projects and find that both the ownership of a renewable energy system and living in a rural rather than an urban area increase the likelihood of participating in an energy community. In [5], the willingness to participate in community-based renewable energy projects is investigated using the contingent valuation method. There, the respondents' willingness is measured by the expected return on investment. Investigating the willingness to participate in renewable energy cooperatives, [6] find that the lack of familiarity with energy cooperatives is a major limiting factor to participation.

Another important factor concerning participation in community-based renewable energy projects is that the desire for active involvement is low among potential participants despite widespread support for local renewable generation [7]. In [8], insights into decisive factors for citizens to participate in a prosumer community, based on socio-demographic characteristics are provided. Another recent study finds that the citizens most interested in participating in peer-to-peer electricity trading are those who are already environmentally aware and technically interested [9]. In [10], the impact of demographic, socio-economic, socio-institutional as well as environmental factors on the willingness to participate in community energy systems is analysed. Results obtained in [11] show that participation in collaborative consumption is motivated by different factors such as sustainability, the activity of participating *per se*, as well as economic benefits. In order to predict consumer interest in participating in energy sharing, [12] aim to compare the usage of two behavioural theories, namely 'Value-Belief-Norm' and 'Diffusion of Innovation'.

The actual willingness to participate in community energy projects also correlates with the willingness to pay for renewable energy. Specifically focusing on community solar, [13] investigates the consumers' willingness to pay based on attributes such as proximity, reduction of fossil fuel usage, environmental quality, and energy cost savings. In order to derive lessons-learned, [14] examine the development of shared solar initiatives in the recent history of US energy policy. [15] investigate the role of civil society groups in accelerating the adoption of green technologies, such as renewable energy systems in urban areas. The willingness to pay is also an important topic in relation to optimisation or simulation models. As the first study of its kind, Perger et al. [16] investigate PV sharing in local energy communities under the consideration of the participants' willingness to pay.

Concluding, the willingness to participate in energy community or energy sharing initiatives comes mostly down to energy savings, both from a financial and an environmental point of view. Citizens who are environmentally aware and/or live in rural areas seem to have an increased willingness to participate. Still, however, passive participation is highly appreciated, while the need for active participation is viewed critically. Based on these findings in literature, this study provides results for the example of a rural energy community, and, amongst others, sets the focus on financial benefits for community participants.

2.2. PV potential assessment

The potential of PV systems can be subdivided into four categories: (i) physical potential, (ii) geographical potential, (iii) technical potential, and (iv) economic potential. Studies that focus solely on the physical or the geographical potential are rare since assessing these potentials is a prerequisite to determining the technical or the economic potential of solar PV. Most studies in current literature focus on the technical potential of PV systems. Procedures and methodologies to estimate the technical building PV potential are described in [17, 18], while [19] additionally focuses on the error of such estimations. In [20] and [21], techniques to combine geographic information systems and object-based image recognition to identify available rooftops for PV installation and further determine the technical potential are proposed. Similarly, [22] proposes a new method to assess the rooftop PV potential using publicly available geodata in combination with image recognition. In [23], a combination of support vector machines and geographic information systems is used. The potential of rooftops for PV installation as well as the potential of facades is investigated in [24]. [25] specifically sets the technical potential of residential roof-mounted PV systems in comparison to the estimated local demand. Studies on the economic potential are rare. A bottom-up approach for estimating the economic potential of rooftop solar PV systems that takes market dynamics into consideration is proposed by [26]. Going one step further, [27] estimate the cost-optimal economic potential of shared rooftop PV in energy communities. A framework to integrate geographical, tech-

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[2] It needs to be highlighted that the core-objective of this study is the method, the multi-step framework to assess the large-scale impact of EC roll-out and that the actual results provided in this study depend significantly on the respective assumptions.

nological, and economic parameters for a holistic potential analysis of solar energy is introduced in [28].

In the current literature, studies that assess the potential of PV systems alone are manifold. However, with regard to PV systems in the context of energy communities, enabling a more efficient usage of the generated electricity, the potential of PV systems reaches another dimension. Therefore, assessing the impact of PV-based energy communities is the next step towards gaining a holistic picture.

2.3. Simulation and optimisation of energy communities

Fernandez et al. [29] propose a bi-level optimisation-based community energy management system for the purpose of optimal energy sharing and trading among peers. Fina et al. [30] use an optimisation model to determine the profitability of PV sharing in energy communities in different settlement patterns from a system perspective. Focusing on cost minimisation in energy communities as well, [31] propose an optimisation model that considers a local electricity market between prosumers and electric vehicles. [32] develop a novel methodology for the design and management of energy communities, which includes solving a design and operation optimisation problem to determine optimal capacities of energy assets. Portfolio optimisation of energy communities is applied by [33] to achieve the targets of reducing costs and emissions. In [34], an optimisation model for planning and designing a neighbourhood-scale distributed energy system is proposed. Specifically focusing on energy storage sharing in residential communities, [35] develop an optimisation model that finds the optimal control policy. Focusing on energy storage sharing as well, [36] introduce an energy-credit-based optimisation strategy that aims to increase energy cost savings for consumers in a dynamic pricing environment. In order to simultaneously optimise building envelope retrofit and energy systems in a residential community, [37] introduces a multi-objective optimisation model.

Studies regarding a simulation or optimisation of energy communities are mostly developed in an isolated context. In the current study, the output of an optimisation model is used to further determine the impact of energy community roll-out on a large scale. Therefore, the method elaborated in this study leads to a useful framework for an impactful usage of energy-flow optimisation models' outputs.

2.4. Progress beyond – the impact of large-scale energy community roll-out

Studies assessing the potential of PV systems are numerous; by contrast, literature that elaborates on the assessment of the potential or impact of energy communities is rare. While, for example, the impact of policy changes on energy communities is being assessed in some studies, such as [38, 39], studies that assess the impact of communities on different stakeholders are missing, besides such that are concerned with the impact on the grid ([40, 41, 42]). Moreover, in addition to studies that evaluate the impact of individual energy communities, studies specifically focused on the impact of energy communities on a larger scale would be of significant value. In this research niche, only [27] assess the cost-optimal economic potential of shared rooftop PV for individual model energy communities as well as on a large scale. Additionally, [43] explore the transition potential of renewable energy communities.

Therefore, this study's contribution can be summarised as follows: A framework that allows to assess the impact of large-scale energy community deployment is provided. This framework is not limited geographically and is thus applicable to regions or countries worldwide as long as the required data basis is available. The proposed framework consists of nine steps in total and contains, among others, guidelines to

- determine the number of buildings per type and roof tilt,
- estimate the usable rooftop areas for PV system installation,
- derive the maximum and realistically installable PV capacity per building type and type of rooftop,

- estimate the future number of PV systems and the shares of buildings equipped with rooftop PV,
- set up model energy communities for different settlement patterns, and
- determine the large-scale impact of energy community roll-out via upscaling.

For increased comprehensibility, these guidelines are not only described theoretically but are supported with concrete numerical values for the case of Austria.

3. Method, model and data

Nine steps are required to estimate the future impact of energy community roll-out in different countries or regions. In order to understand the necessity of the individually described steps in the total context, the process is visualised in Fig. 1.

3.1. Step 1 - determine the number of buildings per type at a future point in time

Determining the number of buildings at a certain point in time in the future requires data about the current building stock (Section 3.1.1) and knowledge about probable developments (Section 3.1.2).

3.1.1. Step 1a – current building stock

Firstly, information about the building stock of the region of investigation needs to be acquired. There is no further specification concerning the granularity of this information, which is expected to be available to varying extents in different countries/regions. Independent of the data available, the procedure that is described in the following is applicable. In order to achieve a realistic estimation of the impacts of energy community roll-out, it is recommended to acquire building stock information containing a certain amount of detail such as the number of different buildings per type (which are then allocated to different settlement patterns as explained in a subsequent chapter).

In Austria, the national statistical institute *Statistik Austria* provides the number of buildings per type [44]. Three residential building types are distinguished: Single-family houses (SFH), small multi-apartment buildings (sMAB) with 3-10 units, and large multi-apartment buildings (lMAB) with 11 or more units.

3.1.2. Step 1b – future building stock

Since legislation for energy communities is currently evolving in EU member states, energy community roll-out is expected to gain momentum within the next years. Therefore, the impact of a large-scale roll-out of energy communities shall be evaluated for a future point in time. To that end, it is necessary to estimate developments in the building stock – whether the numbers of buildings will increase, decrease, or stagnate. Future building numbers can be determined based on current building numbers and knowledge about expected future developments/trends.

Within a time period of 10 years (from 2001 until 2011), Austria recorded an increase of 7.1% in the number of buildings [44]. This percentage is also assumed as the growth rate in building numbers within the next ten years (until 2030).[3]

3.2. Step 2 - determine the number of buildings categorised by roof-tilts

Buildings – independent of the building type – are sub-classified into buildings with tilted and flat roofs. Therefore, information about the

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[3] The percentage of 7.1% also contains non-residential buildings and would therefore need to be reduced. However, the fact that the need for living space is likely to increase in future years counteracts this intended decrease. Therefore, the percentage is kept as it is.
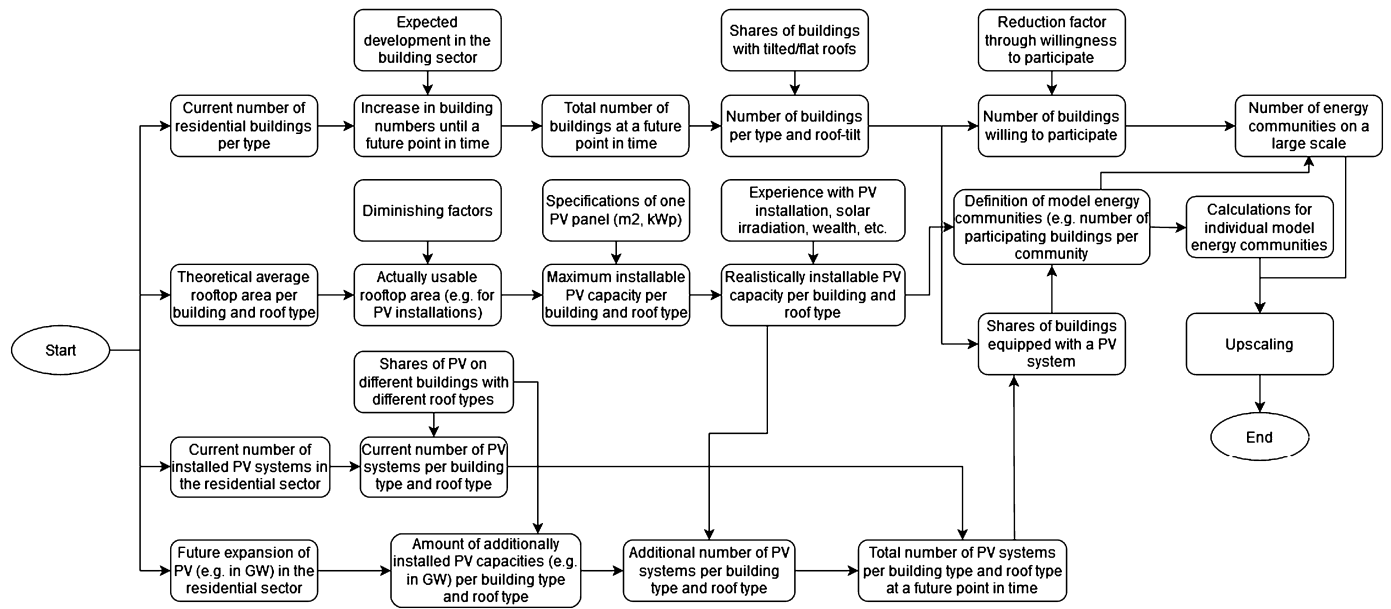
Fig. 1. Visualiation of the nine-step framework: process and interdependencies.

shares of buildings with tilted and flat roofs needs to be obtained.[4] Such information is often difficult to find. In Austria, for example, such information is not directly available. However, information about shares of tilted- and flat-roofed buildings can be found for Germany in [45]. Since Austria and Germany are neighbouring countries in central Europe with a shared history, the building stock and its characteristics can be considered fairly similar. Therefore, if some pieces of information are not available for a specific region or country, it is recommended to search for the same pieces of information in other comparable regions/countries.

With the information about the total number of buildings (independent from the granularity of such information) in combination with the knowledge about the shares of buildings with tilted and flat roofs, the number of buildings with tilted and flat roofs can be calculated. Table 2 summarises (i) the shares of buildings with tilted and flat roofs per type, (ii) the current and (iii) the future number of buildings per type and roof tilt for the example of Austria.

3.3. Step 3 - determining the theoretical and usable rooftop area

For further calculations, information about the buildings' theoretical average rooftop area is required. The average rooftop area of representative buildings in Austria is provided in Table 3.[5]

In order to determine the actually usable rooftop area, the theoretical rooftop area needs to be adjusted for diminishing factors that may hinder the installation of PV panels to some extent. Such diminishing factors (Table 4) in the residential building sector are (i) structural restrictions (such as chimneys, ventilation shafts, skylights, access hatches etc.), (ii) shading from other buildings or trees, and (iii) restrictions due to historic preservation. Diminishing factors differ in a few aspects for buildings with tilted and flat roofs. Structural restrictions and shading effects need to be taken into account for both roof-types, whereas historical restrictions only apply to buildings with tilted roofs. The most important aspect for buildings with flat roofs is that PV modules tend to

Table 2. Total number of residential buildings, shares of buildings with tilted and flat roofs [45] and therefrom derived number of buildings per building type and roof type.

Building type	SFHs	Small MABs	Large MABs
Building number (to date)	1,727,129	175,910	70,940
Share TR	95%	92%	75%
Share FR	5%	8%	25%
Number buildings with TR (to date)	1,640,773	161,837	53,205
Number buildings with FR (to date)	86,356	14,073	17,735
Building number (future)	1,849,755	188,399	75,977
Number buildings with TR (future)	1,757,268	173,327	56,983
Number buildings with FR (future)	92,487	15,072	18,994
Total number of buildings (future)		2,114,131	

Table 3. Average theoretical rooftop area of residential buildings with tilted and flat roofs [45].

Building type	Tilted roofs	Flat roofs
Single-family buildings	129 m^2	112 m^2
Small multi-apartment buildings	210 m^2	158 m^2
Large multi-apartment buildings	272 m^2	206 m^2

Table 4. Diminishing factors in the calculation of the actually available rooftop area for PV installation [45].

Buildings with tilted roofs (TR)		
Restriction type	Abbreviation	Usable rooftop area reduced by...
Structural restrictions	η_{1_TR}	20%
Shading	η_{2_TR}	10%
Historical restrictions	η_{3_TR}	5%

Buildings with flat roofs (FR)		
Restriction type	Abbreviation	Usable rooftop area reduced by...
Module self-shading	η_{1_FR}	66%
Structural restrictions	η_{2_FR}	25%
Shading	η_{3_FR}	10%

shade themselves since they are implemented with a certain tilt in most cases. Self-shading must therefore be taken into account for buildings with flat roofs as another diminishing factor.

The actually usable rooftop area can then be calculated as given in Equations (1) and (2).

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[4] This information will be required to determine the usable rooftop area and further the maximum possible PV installation capacity as described in Section 3.3.

[5] Similar to the shares of tilted- and flat-roofed buildings, information about the average rooftop area per building type is derived from Germany and applied to Austria.

$$A_{SFH\_TR\_usable} = A_{SFH\_TR\_theor} \cdot (1 - \eta_{1\_TR}) \cdot (1 - \eta_{2\_TR}) \cdot (1 - \eta_{3\_TR})$$

$$A_{sMAB\_TR\_usable} = A_{sMAB\_TR\_theor} \cdot (1 - \eta_{1\_TR}) \cdot (1 - \eta_{2\_TR}) \cdot (1 - \eta_{3\_TR}) \quad (1)$$

$$A_{lMAB\_TR\_usable} = A_{lMAB\_TR\_theor} \cdot (1 - \eta_{1\_TR}) \cdot (1 - \eta_{2\_TR}) \cdot (1 - \eta_{3\_TR})$$

$$A_{SFH\_FR\_usable} = A_{SFH\_FR\_theor} \cdot (1 - \eta_{1\_FR}) \cdot (1 - \eta_{2\_FR}) \cdot (1 - \eta_{3\_FR})$$

$$A_{sMAB\_FR\_usable} = A_{sMAB\_FR\_theor} \cdot (1 - \eta_{1\_FR}) \cdot (1 - \eta_{2\_FR}) \cdot (1 - \eta_{3\_FR}) \quad (2)$$

$$A_{lMAB\_FR\_usable} = A_{lMAB\_FR\_theor} \cdot (1 - \eta_{1\_FR}) \cdot (1 - \eta_{2\_FR}) \cdot (1 - \eta_{3\_FR})$$

Based on these calculations, concrete numbers of the actually usable rooftop area for the example of Austria are provided in Table 5.

Table 5. Usable rooftop area of residential buildings with tilted and flat roofs.

Building type	Tilted roofs	Flat roofs
Single-family buildings	88.2 m^2	25.7 m^2
Small multi-apartment buildings	143.6 m^2	36.3 m^2
Large multi-apartment buildings	186.0 m^2	47.3 m^2

3.4. Step 4 - determining the theoretical maximum and realistically installable PV capacity

In order to determine the PV capacity that may be installed on the rooftops of individual buildings, the theoretical maximum PV capacity is determined in Section 3.4.1, and argumentation concerning the realistically installable PV capacity is provided in Section 3.4.2.

3.4.1. Maximum PV capacity
Based on Step 3 (the actually usable rooftop area), the maximum installable PV capacity is calculated. This requires the specification of assumptions on the characteristics of a single PV panel. Characteristics of PV panels differ. In this study, a PV panel is assumed with a size of 1.5 m^2 and an installation capacity of 0.3 kW$_p$.[6] Thus, the maximum installable PV capacity can be calculated based on the actually usable rooftop areas given in Table 5. The results of this calculation for the case of Austria are provided in Table 6.

Table 6. Maximum PV capacity for residential buildings with tilted and flat roofs.

Building type	Tilted roofs	Flat roofs
Single-family buildings	17.6 kW$_p$	5.1 kW$_p$
Small multi-apartment buildings	28.7 kW$_p$	7.3 kW$_p$
Large multi-apartment buildings	37.2 kW$_p$	9.5 kW$_p$

3.4.2. Realistically installable PV capacity
Based on the knowledge of the maximum installable PV capacity in individual buildings, the next step is to determine the capacity that can realistically be expected to be installed in the individual buildings. This varies in all countries and regions, significantly depending on the solar irradiation and other factors such as the regions' financial strength. In Austria, a wealthy country with moderate solar irradiation, it can be assumed that single-family households install on average 4 kW of PV, while for multi-apartment buildings, the entire rooftop area is used for PV installation. The reasoning behind these assumptions is as follows: In single-family buildings, rather small PV installation capacities are common (due to the relatively small building load in comparison to the PV

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[6] It needs to be noted that size and capacity of PV modules can vary significantly, depending on the manufacturer, the number of solar cells used for one module, the quality of the solar cells, and else. For instance, the assumed PV details are in line with [46]. Here, it needs to be taken into account that the PV module capacity has increased over-proportional to its size over the years, wherefore, for an estimation of the future roll-out of ECs, a module size of 1.5 m^2 and an installation capacity of 0.3 kW$_p$ are assumed.

Table 7. Realistically installable PV system capacity for buildings with tilted and flat roofs.

Building type	Tilted roofs	Flat roofs
Single-family buildings	4 kW$_p$	4 kW$_p$
Small multi-apartment buildings	28 kW$_p$	7 kW$_p$
Large multi-apartment buildings	37 kW$_p$	9 kW$_p$

system capacities that could theoretically be installed on the rooftops). In multi-apartment buildings, by contrast, the maximum possible PV capacity is likely to be installed since the PV generation is low compared to the total building load (due to the restricted rooftop area in relation to the living space). In this study, assumptions are summarised in Table 7.[7]

3.5. Step 5 – determining the number of PV systems and distribution among building types

Determining the number of PV systems at a certain point in time in the future requires data about current PV system numbers (Section 3.5.1) and knowledge about probable developments in the residential PV sector (Section 3.5.2).

3.5.1. Current number of PV systems
In Austria, the current number of PV systems is again provided by the national statistical institute *Statistik Austria* [47]. The dataset contains PV systems that are subsidised (since these are registered upon attainment of funding). Since the vast majority of PV systems is likely to be subsidised, the small number of PV systems that did not receive funding are considered negligible.

Next, the total number of PV systems needs to be distributed among single-family buildings and small/large multi-apartment buildings (unless PV system numbers are already provided per building type or any other granularity that matches a region's or country's building data). For the case of Austria, this is done using the knowledge that approximately 4/5 of the total building stock is single-family buildings. Therefore, small and large multi-apartment residential buildings are assumed with 1/10 each [44]. The total number of PV systems is assumed to be distributed in line with the shares of the three building types on the total residential building stock (this means that 4/5 of all PV systems are installed on the rooftops of single-family houses, and 1/10 each are located on the rooftops of small and large multi-apartment buildings).

Subsequently, the PV systems that are allocated to the three building types need to be further subdivided depending on whether they are implemented on buildings with tilted or flat roofs. This further distinction can be achieved with the information in Table 2 (shares of buildings with tilted and flat roofs). These shares can be applied to allocate PV systems per building type according to roof type.

3.5.2. Future number of PV systems
Next, the future number of PV systems needs to be determined. This requires consulting information on renewables expansion plans within the region or country of investigation. Most countries provide such data in annual reports, classified according to expansion plans per renewable generation technology.

For the specific case of Austria, it is stated in [48] that within 10 years, an additional PV potential of 4 TWh could be realised. This value corresponds to an additional PV installation capacity of approximately 4 GW until 2030. In order to derive the future number of PV systems, these 4 GW firstly need to be distributed among single-family buildings and small/large multi-apartment buildings (similar to the procedure described above): Based on the shares of individual building types on the residential building stock (4/5 single-family buildings, 1/10 small and large multi-apartment buildings each [44]), it is assumed that 4/5 of the

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[7] The values are derived from the ones provided in Table 6 and rounded.

4 GW will be installed on single-family buildings, whereas the remainder is equally distributed between the two types of multi-apartment buildings. Then, these gigawatts that are allocated to the different building types need to be further allocated to tilted- and flat-roofed buildings per type. For that purpose, as described above, the knowledge about shares of tilted- and flat-roofed buildings among the three building types can be directly applied.

At this stage, the PV capacity that is likely to be additionally installed (until 2030 in Austria) per building type and roof type is known. Based on this knowledge, in combination with the previously determined realistic PV installation capacity per building and roof type (Table 7), the number of PV systems can be determined. This is achieved by dividing the PV capacity (that may be additionally installed in the future) by the realistically assumed installation capacity per building type and roof type (given in Table 7).

In order to obtain the total number of PV systems at the specified future point in time, the current number of PV systems and the additional number of PV systems need to be summed up. Results for Austria are provided in Table 8.

Table 8. Number of building-attached/integrated PV systems to date and in 2030.

Building type	Tilted roofs	Flat roofs
Current status		
Single-family buildings	91,666	4,825
Small multi-apartment buildings	11,096	965
Large multi-apartment buildings	9,046	3,015
Additions until 2030		
Single-family buildings	760,000	40,000
Small multi-apartment buildings	13,143	4,571
Large multi-apartment buildings	8,108	11,111
Total in 2030 (current status plus additions until 2030)		
Single-family buildings	851,666	44,825
Small multi-apartment buildings	24,239	5,536
Large multi-apartment buildings	17,154	14,126

3.6. Step 6 – determining the shares of buildings equipped with PV systems

Based on the knowledge about the future number of PV systems per building type and roof type (given in Table 8 for the case of Austria), the share of buildings that are equipped with a PV system can be determined. This is achieved by dividing the number of buildings that are equipped with PV systems (Table 8; the number of PV systems equals the number of buildings → one PV system – one building) by the total number of buildings per type (Table 2). The thus determined shares for the specific case of Austria are provided in Table 9.

Table 9. Shares of buildings per type that are equipped with PV systems.

Building type	Tilted roofs	Flat roofs
In 2030		
Single-family buildings	48%	48%
Small multi-apartment buildings	14%	37%
Large multi-apartment buildings	30%	74%

3.7. Step 7 – setting up model energy communities

At the next step, a set of model energy communities needs to be specified. The characteristics of such model energy communities are to be chosen in accordance with the settlement patterns, the building stock and building types, and the citizens' willingness to participate (if this information is available). In many European countries, three characteristic settlement patterns are common: (i) rural areas with geographically wide-spread single-family buildings, (ii) suburban areas with small multi-apartment buildings, and (iii) densely built city areas

with large multi-storey buildings. For an estimation, it is sufficient to assume that energy communities are established within individual settlement patterns. In other words, one model energy community can be defined for single-family buildings in rural areas, the second model energy community can be defined for small multi-apartment buildings in suburban areas, and the third model energy community can be defined for large multi-apartment buildings in city areas.[8]

Having determined which building types participate in which model energy community, the number of buildings participating in each community needs to be defined. This is – since energy communities are a novel concept – no trivial matter. Indications can be found in studies elaborating on the willingness to participate or in pilot projects implemented within regulatory sandboxes.

At the last step of setting up the model energy communities, the diffusion of PV systems within the borders of each model energy community needs to be determined. To that end, information about the shares of buildings per type that are equipped with PV systems (as determined in Section 3.6) can be directly applied to determine the number of buildings that are equipped with PV systems within the borders of the model energy communities. For clarification purposes, the process is demonstrated for three Austrian model energy communities:

- Assuming that a rural model energy community consists of 15 single-family buildings, approx. 14 (95%, Table 2) will have tilted roofs, whereas only one will have a flat roof. Of the 14 tilted-roofed buildings, 7 (48%, Table 9) will be equipped with PV systems. Of the flat-roofed buildings, 48% (Table 9) will be equipped with PV systems. Therefore, the one flat-roofed building will not be equipped with a PV system.[9]
- Assuming that a suburban model energy community consists of 15 small multi-apartment buildings, approx. 14 buildings (92%, Table 2) will be buildings with tilted roofs. Derived therefrom, the remaining one will be flat-roofed. Of the 14 tilted-roofed buildings, 2 (14%, see Table 9) will be equipped with PV systems. The one flat-roofed building will not be equipped with PV (37% of flat-roofed buildings will be equipped with PV, and due to rounding, the one building will not be equipped with PV.)
- Assuming that a city model energy community consists of 15 large multi-apartment buildings, approx. 11 (75%, Table 2) will have tilted roofs, and 4 flat roofs. Of the 11 tilted-roofed buildings, 3 (30%, Table 9) will be equipped with PV. Of 4 flat-roofed buildings, 3 (74%) will be equipped with PV.

3.8. Step 8 – conducting calculations with the model energy communities

Having defined the model energy communities, calculations for these model energy communities can now be conducted. Calculations for individual model energy communities provide the basis for the actual estimation of the impact of large-scale energy community roll-out.

Calculations for individual model energy communities could for example determine a community's minimal costs and the according energy flows (how much of the self-generated electricity is used within the borders of the community, how much is fed into the grid, and how much electricity needs to be purchased conventionally).

In this paper, an optimisation model[10] is used to optimise a renewable energy community towards minimising total costs (for the whole

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[8] N.B.: For each country or region, an arbitrary number of model energy communities can be defined as needed. However, for an estimation, it is useful to define the model energy communities based on the available building type information.

[9] The number of buildings that may be equipped with a PV system are rounded.

[10] The optimisation model is not introduced in detail since this would go beyond the scope of this study. However, a brief description of the general functionality is provided as follows: The optimisation model used in this study

community rather than for individual participants). For the purpose of this paper, the relevant outputs of said optimisation model are the total costs for the energy community and the energy flows (trading between participants, feed into the grid, purchase from the grid). The optimisation model takes into account Austria[11]-specific conditions for the implementation of renewable energy communities, such as a reduction of grid tariffs and an omission of certain levies, such as the renewable energies levy and the electricity levy. Moreover, since this study assesses PV-based energy communities, also climatic conditions for the specific case of Austria need to be mentioned. The solar potential in Austria can be considered moderate, with up to 1130 full-load hours per year for PV systems oriented south, while full-load hours in the eastern and western direction can be up to 940 - 970 per year. The northern direction is not recommendable for the installation of PV systems due to the least possible solar harvest.

3.9. Step 9 – estimating the large-scale impact of energy community roll-out

The estimation of the large-scale impact of energy community roll-out is divided into three sub-steps, namely determining (i) the participating building stock (Section 3.9.1) and based thereon (ii) the number of energy communities (Section 3.9.2) in order to (iii) perform upscaling (Section 3.9.3).

3.9.1. Determining the participating building stock

In order to estimate the impact of energy community roll-out, the participating building stock needs to be determined, since it is unlikely that 100% of the buildings will participate in energy communities (at least at the earlier stages of deployment). Since experiences with energy communities are almost exclusively limited to pilot projects in regulatory sandboxes, it is necessary to estimate the share of buildings, whose inhabitants might be willing to participate in energy communities. Then, the total number of buildings (Table 2) can be diminished by a reduction factor that depends on the willingness to participate. Thus, the number of potentially participating buildings is determined.

For Austria, specific information on how many buildings may be willing to participate in energy communities is unavailable. However, a German study assesses the willingness to participate in community energy projects at one third [4]. Therefore, due to a high degree of

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is based on linear programming. The objective is to minimise a community's total electricity costs under the framework of peer-to-peer electricity trading. This means that electricity is traded such that a global optimum (rather than individual optima for individual participants) is achieved. As for technologies, only PV systems are considered since the objective is to provide results for PV-based energy communities. The considered participants either own PV systems that are assumed to be installed on their buildings' rooftops (prosumers) or do not own a PV system of their own (sole consumers). Individual participants can cover their load by (i) self-consuming PV electricity (if the respective participant owns a PV system), (ii) purchasing electricity from community peers, and (iii) purchasing electricity conventionally from the grid. If a participant owns a PV system, the generated electricity may be (i) used for self-consumption, (ii) sold to community peers, or (iii) fed into the grid. Based on the different options for load coverage or PV electricity usage, the costs for individual participants, and the total costs for the community are determined by optimisation. An article describing the used optimisation model in more detail is published in [49].

[11] Some general information regarding the area of study: Austria is a German-speaking country in Central Europe with almost 9 million inhabitants. Neighbouring countries are the Czech Republic and Germany in the north, Slovakia and Hungary in the east, Slovenia and Italy in the south, and Switzerland and Liechtenstein in the west. Austria has a size of 83.878 km^2 and is subdivided into 9 federal states. The climate can be considered temperate and alpine, not least due to a mountainous geography due to the presence of the Alps. Austria records an average of 1100 mm of precipitation per year. Hours of sunshine per year range between 1656 and 2280 hours [50, 51].

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similarity between Germany and Austria, this number is also assumed for Austria.

3.9.2. Determining the number of energy communities

Based on the assumptions concerning the number of buildings that may actually participate in energy communities (No_{part_build}) and the number of buildings per model energy community (No_{build_perEC}), the number of resulting energy communities (No_{ECs}) can be determined as given in Equation (3).

$$No_{ECs} = No_{part\_build} / No_{build\_perEC} \tag{3}$$

Table 10 summarises the total building number, the number of participating buildings based on a reduction by two thirds of the total building stock [4], and the therefrom derived number of energy communities on a large scale, on the assumption that one model EC consists of 15 buildings each.

Table 10. Total number of buildings, reduced number of buildings per settlement pattern, and derived number of energy communities.

	Rural area (SFHs)	Suburban area (sMABs)	City area (lMABs)
Total number	1,849,755	188,399	75,977
Reduced number	616,585	62,800	25,326
Number of ECs	41,106	4,187	1,688

3.9.3. Upscaling

Based on the knowledge about (i) the number of resulting energy communities per settlement pattern for the area or country of investigation and (ii) the results calculated for the individual model energy communities, upscaling can be performed. Upscaling – after conducting the previously described steps – is the easiest part, since it only requires a simple multiplication. If, for example, cost savings due to energy community participation are determined for an individual model energy community, these cost savings can be multiplied by the expected number of energy communities on a large scale. The result would then be the total cost savings for all energy communities of this particular type. Detailed results concerning the impact of an energy community roll-out for a specific case study are provided in Section 4.

4. Results

In this section, exemplary results are provided for the case of rural areas in Austria. The key features of a rural model energy community are summarised in Section 4.1. The impact of a large-scale roll-out of energy communities in Austria's rural areas is then provided in Section 4.2.

4.1. Case study

The key features of a rural model energy community are summarised as follows:

- The rural model energy community consists of 15 single-family buildings.
- 7 out of the 15 buildings are equipped with residential rooftop PV systems with a capacity of 4 kW$_p$ each.
- The 15 households establish a renewable energy community.
- The participants are located within the medium-voltage grid; therefore, the renewable energy community is regional.[12]

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[12] In Austria, local and regional RECs are distinguished. A local REC requires the participants to be located within the same feeder of the low-voltage grid and has the benefit of significantly reduced grid tariffs. A regional REC requires its participants to be located within the same feeder of the medium-voltage grid. In this case, grid tariffs are still reduced, albeit to a lower extent.
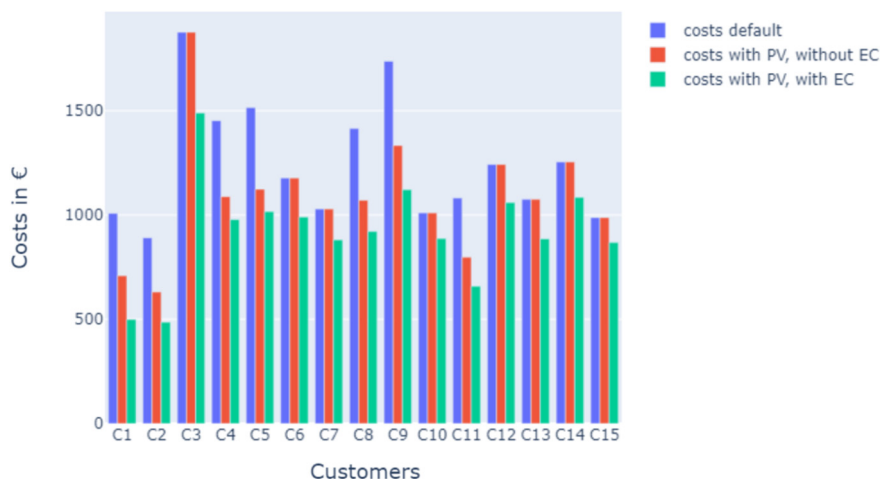
Fig. 2. Cost comparison: Electricity costs with no PV systems, electricity costs with PV systems but without participation in the REC, electricity costs with REC participation.
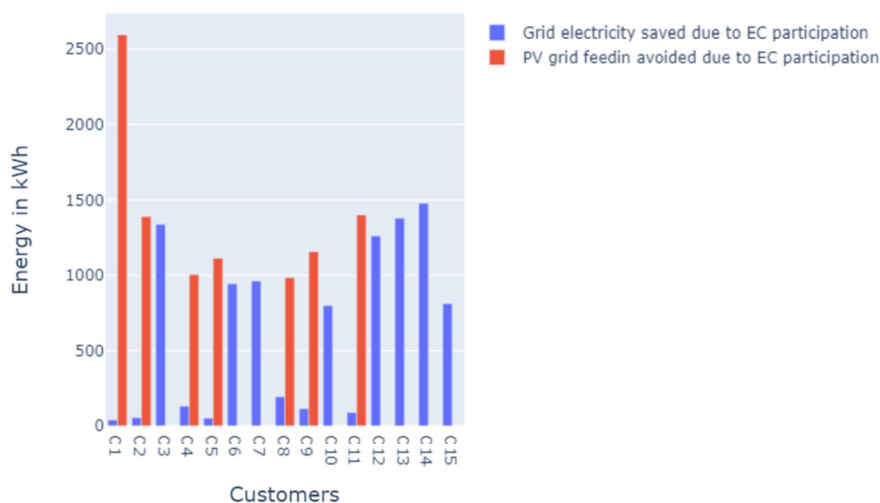

Fig. 3. Electricity traded within the community and avoided PV grid feed-in due to sales within the community.

- Real-measured load profiles in a 15-minute resolution are allocated to the 15 households. The load profiles range between 3500 kWh and 7200 kWh.
- It is assumed that the PV systems are approximately equally distributed over the directions south, east and west. Therefore, it is assumed that 2 PV systems are installed in the direction of east, 2 PV systems are oriented to the west, and 3 PV systems are installed facing south.
- The solar irradiation profiles are derived from *renewables.ninja* [52]. The following full-load hours are determined: south – 1131 h, east – 943 h and west – 974 h.

4.2. The impact of renewable energy community roll-out in Austria's rural areas

Based on the results achieved for the rural model energy community, a variety of large-scale impacts can be assessed. Since the results in this study are exemplary,[13] three different impacts on three different stakeholders are assessed: (i) the energy community participants themselves (Section 4.2.1), (ii) energy suppliers (Section 4.2.2), and (iii) grid operators (Section 4.2.3). It is assumed that one third of the total building stock participates in energy communities.

When optimising the specified rural model energy community with the objective of minimising total costs, the following results are obtained (N.B.: Those results are for one individual model energy community. The impact of energy community roll-out on a large-scale is addressed in Sections 4.2.1, 4.2.2 and 4.2.3.):

- Annual cost savings due to energy community participation[14]: 2578.96 EUR (The results for individual community participants are visualised in Fig. 2: Fig. 2 shows (i) the individual participants' default costs (no PV installed, no energy community participation) in comparison to (ii) the costs if PV is installed without energy community participation, and (iii) the costs with PV installed and an energy community established. For those customers who are not assumed to be equipped with a PV system, the (i) default costs and (ii) costs with PV systems but without EC participation are equal.)
- Total amount of annually shared/traded electricity within the borders of the energy community: 9659.08 kWh. (The results for individual community participants are visualised in Fig. 3. Fig. 3 shows

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[13] 'Exemplary' is used to emphasise that energy communities may have multiple potential impacts. In this study, three significant impacts on different stakeholders are assessed.

[14] In the optimisation model, it is assumed that purchasing electricity from the grid conventionally costs 15.85 c/kWh, purchasing electricity from other community members costs 10.36 c/kWh, and selling electricity within the community generates revenues of 6 c/kWh.

how much PV electricity is used within the borders of the REC and thus does not need to be fed into the grid (red bars). The blue bars show the amounts of electricity that are purchased from the community peers and do not need to be purchased from the grid.)

- Monetary losses for the grid operator due to reduced grid tariffs (equals the amount of annually saved payments for grid usage due to reduced grid tariffs): 108.95 EUR

4.2.1. Impact on the participants' electricity bill

The knowledge that a rural model energy community (as specified in Section 4.1) is able to achieve cost savings of 2578.96 EUR per year combined with the information about the estimated number of energy communities (41,106 energy communities, Table 10) in rural areas is used to determine the large-scale impact of rural energy communities by simple multiplication.

Thus, if rural energy communities were rolled out as assumed, cost savings of approximately 106 million euro could be achieved. While the annual savings for individual energy community participants would be moderate with an average of 171.9 EUR (the total savings of 2578.96 EUR divided by the number of participants), the total amount of savings in case of a wide-spread adoption of rural renewable energy communities would be significant.

Knowledge about the cost-saving potential in energy communities is not only important for the participants themselves but especially for potential third-party service providers. When energy communities join the energy landscape as new players, other novel actors or at least new roles for established market players, are likely to originate. Potential third-party services for energy communities include planning, set-up, operation, and billing. Such work can also be carried out by community members themselves, but it is more likely that communities outsource such tasks. Although profit generation must not be the primary objective of energy communities, a certain financial viability will be necessary in order to achieve broad participation. Therefore, information about the revenue margin of energy communities is important for third-party service providers in two respects: (1) knowing the potential profit margin in case of a large-scale roll-out of energy communities and (2) knowing the maximum costs of third-party services (so that the energy communities can still break even).

4.2.2. Impact on electricity suppliers' sales

Another important stakeholder that is affected by energy communities is electricity suppliers. Since energy communities share/trade electricity within their borders, part of the core business of electricity suppliers is taken away. An estimation of the large-scale impact of energy community roll-out gives electricity suppliers an opportunity to plan accordingly.

In case of a large-scale roll-out of rural energy communities in Austria as defined in Section 4.1, electricity suppliers would sell approximately 397 GWh less than if no energy communities were implemented. This number implies a reduction of the energy suppliers' future income due to reduced household demand. The loss in income caused by smaller amounts of electricity sales could be compensated by offering third-party services to energy communities. However, the reduced need for electricity in case of a large-scale energy community roll-out requires thorough planning of the necessary power plant capacities.

4.2.3. Impact on grid operators' revenues

In addition to the organisational efforts grid operators face due to the increased diffusion of energy communities – in Austria, grid operators are legally required to conduct the measurements, allocate electricity based on predefined distribution keys, and provide data to the energy communities and/or the third-party operators responsible for billing – the roll-out of renewable energy communities will also have a

financial impact on grid operators. In Austria, reduced grid tariffs[15] are applicable for electricity trades within renewable energy communities.

In this specific case study (Section 4.1) of rural energy communities and their roll-out throughout Austria, grid tariff reductions would lead to monetary losses in the range of 4.5 million euro for grid operators. Simultaneously, it is yet unproven that RECs actually have the potential to reduce the grid burden (which would justify grid tariff reductions). From the current point of view, it is more likely that the electricity grid is increasingly burdened by higher shares of distributed renewable generation units. Therefore, grid operators may potentially shift monetary losses caused by grid tariff reductions towards higher power-dependent components of the grid tariffs, which would increase the financial burden on citizens who do not participate in energy communities.

5. Conclusion and outlook

The developed framework to assess the impacts of large-scale energy community roll-out has proven suitable. Using calculations for individual model energy communities in different settlement patterns as a basis to assess the effects of large-scale roll-out are a promising way to achieve realistic results. The strength of the developed framework is its applicability to regions and countries worldwide. While the data used in this study for the example of Austria may not be available at the same level of detail in other countries, the framework can easily be adapted to a certain extent, thus ensuring wide applicability.

The results show that the impact of energy community roll-out can be far-reaching, even if only one third of the total building stock is assumed to participate. Energy community roll-out is expected to significantly impact different stakeholders, such as grid operators, energy suppliers, and third-party service providers. Therefore, realistic estimations of the potential impact of energy communities are crucial for stakeholders. However, besides the impact on different stakeholders as discussed and evaluated in this work, energy communities can also have a significant positive impact on society as a whole. With energy communities as new players in the energy landscape, previously passive end-customers can become active, and contribute in an active way to the energy transition. This is, not least due to the fact that energy communities stimulate increased investments into renewable generation units – especially PV systems in the private sector – and thus aid the penetration of renewables in the energy system and further reduce CO_2 emissions. Moreover, energy communities have the potential to create increased awareness in the population regarding energy in general, energy consumption and energy supply. Specifically in these politically difficult times, the awareness regarding dependency on other countries for energy supply should be used in a positive way to mitigate this dependency, and for that, energy communities could also be one important piece of the puzzle.

This work is to a large extent concerned with assessing certain techno-economic aspects of energy communities regarding their large-scale roll out. Technical, because of the need perform assessments regarding the number of buildings, building types, rooftop areas, PV installation potential and else. Economic, because the large-scale impact is assessed based on an optimisation model with the objective of cost minimization. Social aspects are only considered marginally, e.g. when estimating the citizens willingness-to-participate in EC concepts. It is impossible to reach a general conclusion regarding the willingness-to-participate, since it is different for every country, and can even be different for regions of the same country. A major factor influencing the willingness-to-participate is the social background of the respective

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[15] Renewable energy communities with generation and consumption units within the low voltage grid (local RECs) are subject to higher grid tariff reductions; renewable energy communities that additionally use the medium-voltage grid (regional RECs) for electricity transfer also benefit from grid tariff reductions, albeit smaller ones. The exact numbers have not yet been ascertained.

citizens, as well as their economic interests. Typically, people with difficulties to access proper education or lower levels of education are reluctant towards novel concepts such as energy communities. By contrast, the higher the level of education, the easier to convince people in taking part in such novel concepts, not least due to these people's increased awareness regarding the need to contribute to achieving energy transition. However, specifically for people with lower levels of education, a fact that mostly comes hand in hand with limited financial means, it would be most beneficial to participate in concepts such as energy communities, since these concepts also have a strong social focus. Not only shall people of all backgrounds be included, but especially people suffering from energy poverty. For these people it would be highly beneficial to benefit from lower energy prices within the community in comparison to purchasing from the conventional supplier. Therefore, it can be noted that it is the duty of politicians and officials to promote the concept of energy communities such that knowledge regarding related opportunities is spread among all citizens, and especially those facing energy poverty.

However, it should be pointed out that energy community roll-out *per se* and its impact are difficult to predict, since so far, there have been almost no practical experiences with energy community establishment under the CEP. Studies that are concerned with raising data concerning the willingness-to-participate in community concepts are not directly transferable to energy communities under the CEP. From the current point of view, establishing RECs and CECs is a significant effort that will be different for each country. Moreover, financial aspects are expected to play an important role when it comes to the roll-out of RECs and CECs. To date, costs for third-party services such as energy community planning and set-up, operation, and billing are still a matter of uncertainty. Therefore, it is also likely that countries with a strong economy will show higher adoption rates. However, regardless of the situation in different countries, the proposed framework is always applicable; nonetheless, users of this framework must be aware of the importance of realistic assumptions.

An issue that needs to be discussed for rounding up this work is that within the calculations for the rural model energy community using an optimisation model, increased technical standards in people's homes, such as energy management systems (EMS) or demand response (DR) possibilities are not taken into account. This is justifiable, since EMS and DR options are rather exceptional, due to the necessity of significant additional investments and the fact that the vast majority of citizens has to deal with limited financial means. However, it is important to note that installing PV systems on a large scale in the private sector is likely to cause grid instability due to highly fluctuating generation. Therefore, with the large-scale roll-out of energy communities, also the grid infrastructure will need to be adapted, strengthened and further developed, and not least supplemented by conventional battery storages, or more innovative approaches such as absorbing fluctuations with the battery of electric vehicles, producing hydrogen to store energy, or else. Moreover, increased demand side management, for example incentivised by dynamic pricing, could also be part of the solution.

A limitation of this work is that at certain points – for example when determining the share of buildings likely to participate in energy communities – assumptions can hardly be validated due to missing experience with the adoption of energy communities. Another limitation is that entire buildings are considered 'participants' rather than individual residents in individual buildings. However, this assumption is necessary since the impact assessment is conducted with residential building numbers rather than residential unit numbers. Future work could aim at increasing this framework's precision by conducting calculations based on units rather than buildings. Moreover, future studies should address the issue of estimating the willingness to participate in energy communities under the CEP (renewable energy communities and citizen energy communities). Thus, estimations about the impact of energy community roll-out could be further increased in their precision

when differentiating between renewable energy communities and citizen energy communities.

Declarations

Author contribution statement

Bernadette Fina: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Carolin Monsberger: Performed the experiments.

Hans Auer: Contributed reagents, materials, analysis tools or data.

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Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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