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Cost-optimal economic potential of shared rooftop PV in energy communities: Evidence from Austria

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ABSTRACT

In this study, a model is developed to estimate the cost-optimal large-scale economic potential of shared rooftop PV systems based on neighbourhood energy communities (ECs). In a first step, an optimisation model determines the cost-optimal rooftop PV capacities for representative neighbourhood ECs in characteristic settlement patterns (SPs). Next, the number of ECs in the large-scale area of investigation is determined by allocating buildings to SPs and ECs. Finally, the optimal large-scale, EC-based rooftop PV potential is determined by upscaling. A case study is provided for Austria, identifying a cost-optimal economic rooftop PV potential of approximately 10GW$_p$. This PV capacity would already be sufficient (in terms of expected PV deployment) to meet the Austrian 2030 policy goal of a 100% renewable electricity generation. However, results also indicate that accommodating the cost-optimal rooftop PV capacity is difficult in cities/towns in contrast to rural areas. Thus, future ECs should be implemented not only on neighbourhood level, but across the boundaries of different SPs. Different sensitivity analyses are conducted, notably in terms of varying retail electricity prices, including a variation of distribution grid tariff structures, and PV system cost. The trade-off between these sensitivity parameters is critically discussed and provides recommendations for future work.

1. Introduction

The original 2030 climate goal of reaching a renewable energy share of at least 27% in Europe was revised upwards to 32% in 2018 [7]. Currently, wind and hydro power predominantly contribute to renewable electricity generation in the European Union, followed by solar photovoltaics (PV) [8]. For the purpose of further increasing the share of renewable electricity generation on a short-term basis until 2030, PV systems are, besides wind, the most promising solution. PV systems can be installed attached to or integrated in buildings within a short time frame and are expected to receive wide social acceptance in contrast to wind and hydro power plants, which occupy public space.

Over the past years, PV systems have evolved from a technology reserved for wealthy single-family homeowners to a cost-efficient solution for people in different housing situations. In Europe, the legislative background in an increasing number of countries allows for PV sharing concepts and energy communities[2] (ECs) to be established among residents in multi-apartment buildings (MABs). In some countries, ECs can already be established across multiple buildings. Recent studies provide strong evidence for the profitability of PV sharing concepts between residents of individual MABs [10,12,13,34] and ECs between multiple buildings [11,23,41]. Therefore, the motivation of this work is to go one step further and assess the cost-optimal economic potential of shared rooftop PV on a large-scale based on ECs formed in residential neighbourhoods.[3] Empirically, the country assessed is Austria. Moreover, this study shall provide an answer to the policy question whether it is possible to meet the estimated 2030 goal for Austria of achieving solar PV capacities between 9.7GW$_p$ [9] and 11.9GW$_p$ [33] in an economically viable manner by installing PV building-attached only without

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[2] Energy communities are concepts that allow participants to share any kind of energy. Participation is voluntary.

[3] The buildings considered in this study are residential buildings. However, for the purpose of a realistic representation, some multi-apartment buildings are assumed to accommodate small businesses (e.g. bakeries, grocery stores) on the ground floor.

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sealing further green space.

For a realistic mapping of representative neighbourhoods, four different settlement patterns (SPs) that are characteristic not only for Austria but at least for Europe are identified. Based on these SPs, four model ECs are set up, containing a specified number of buildings that are characteristic for each SP. In a next step, the profitability of implementing shared rooftop PV in the four model ECs is determined by using a mixed-integer linear optimisation model. The according optimal PV system capacities are determined as well. As the cost-optimal economic potential is assessed on a large scale, an algorithm is developed to assign buildings of different types per political district (or any other geographical granularity of the large-scale area of investigation) to the four SPs. On this basis, the feasible number of ECs within these SPs is determined. Once the number of ECs per SP as well as the cost-optimal rooftop PV system sizes for the four model ECs is determined, the optimal large-scale economic PV potential can be assessed by upscaling. The empirical results represent the country of Austria, based on local building types, structures and settlement patterns.

The remainder of this paper is structured as follows: Section 2 provides an overview of the state of the art in the scientific literature. The model and the method are introduced in Section 3. The results are provided in Section 4. Section 5 provides the conclusion and elaborates on suggestions for potential future research topics in this field.

2. State of the art

The allocation of emissions from electricity consumption to the different sectors reveals that buildings are the second largest emitter with a share of 27% [17]. Despite the increasing demand for electricity, CO_2 emissions increase at a slower pace nowadays due to enhanced implementation of renewables. A prolongation of this positive trend requires further significant efforts, studies and work to better understand and assess the potential of various renewable energy sources in consideration of different aspects such as administrative and physical limitations [35], technical and environmental constraints [21] and the future development of the electricity [33] and the heating sectors [22].

At present, wind and hydro power predominantly contribute to renewable electricity generation in the European Union, followed by solar PV [8]. However, electricity generation from PV systems is increasing in importance to meet future policy targets. The additional potential of hydropower plants is constrained due to environmental factors, and further wind integration on a significant scale might lack social acceptance. Therefore, studies assessing the potential of solar PV plants [15,28,32] increase in numbers in the scientific literature. An alternative to implement PV besides large centralised PV plants sealing the ground is to install small decentralised PV systems on available building surfaces. This study focuses on the latter. Therefore, the following literature review focuses, on the one hand, on literature concerned with assessing PV implementation potentials in buildings (Section 2.1) and, on the other hand, on the profitability of PV sharing in ECs (Section 2.2).

2.1. PV potential in buildings

The potential of building-attached and/or building-integrated PV systems can be subdivided fourfold[4] [24]:

1. Physical potential: Solar irradiation on the roofs/facades
2. Geographical potential: Available rooftop/facade area in consideration of limitations such as shadowing and structural restrictions
3. Technical potential (Section 2.1.1): Electricity generation in consideration of module efficiency
4. Economic potential (Section 2.1.2): The share of technical potential economically useable from an investor's point of view

2.1.1. Technical PV potential

Studies that only focus on the physical or geographical potential are rare, as these assessments are already required to estimate the technical potential. This applies to residential roof-mounted PV systems in cities or municipalities in studies such as [5,30]. The spectrum of studies estimating the technical potential is broad, focusing on different aspects such as matching supply and demand locally [24,27], proposing techniques to combine geographic information systems (GIS) with object-based image recognition to estimate available rooftop areas [20,40], and quantifying the margin of error [18].

2.1.2. Economic PV potential

The economic potential of PV on the building skin is hardly ever assessed in literature. Only a limited number of articles, which are mainly concerned with other aspects of PV potentials, touch on economic aspects. For example [4], calculates the solar potential of roofs and facades in cities and [16] elaborates on the physical and socio-economic potential of rooftop PV. The economic aspect in both studies is mentioned in the context of estimating the payback time. The goal of [25,31] is to assess the technical PV potential of cities; the economic aspect is limited to the levelised costs of electricity (LCOEs). Only [23] focuses on assessing the economic potential of PV for individual buildings within a city. Economic aspects of PV systems are more likely to be explored in studies that focus on PV sharing in ECs rather than in potential assessing studies. Therefore, a selection of the most recent research concerned with the profitability aspects of PV is provided in Section 2.2.

2.2. Profitability of PV sharing in energy communities

EC cost-minimisation is addressed in Ref. [41], where an algorithm tackling cost-aware electricity sharing among residents is designed. In Ref. [1], an approach for PV electricity sharing by optimising energy sharing tasks of different residential building types is presented. Other topics concerning a (cost-)optimal community development such as proposing community pricing schemes [13,26], an approach to prioritise customers for PV electricity sharing [29] and a model to coordinate electricity sharing of PV at neighbourhood level [6] are covered in the literature. However, only a small number of studies address the profitability of PV sharing concepts in small-scale ECs established within MABs. focuses, amongst others, on the value of shared PV generation for customers. Optimal PV system sizes are determined for residents in MABs [34], considering different customer objectives [12] and focusing on financial aspects [10]. [11] goes one step further and assesses the profitability of PV sharing concepts in neighbourhood ECs between a limited number of buildings in different SPs.

2.3. Progress beyond the state of the art

The literature review indicates a lack of studies assessing the economic potential of building-attached/integrated PV systems in buildings in a wider geographical context. PV potential assessments go as far as to assess the technical potential but at best only hint at

[4] In theory, a fifth category would need to be defined which takes into account the limitations of PV installations caused by the grid (asymmetry, voltage deviation).

economic aspects. The few studies touching on economic PV potential assessments solely base their analyses on the technical potential. This study differs significantly from the existing literature since the cost-optimal economic rooftop PV potential is assessed on a large scale based on neighbourhood ECs. Therefore, this study's innovation can be summarised as follows:

- An optimisation model is further developed to determine the profitability of PV systems and according optimal PV system sizes for representative ECs (called 'model ECs' in the following) formed at neighbourhood level in characteristic SPs.
- An algorithm for assigning buildings of different types to the different SPs and then to individual ECs within a political district (or any other geographical granularity of the large-scale area of investigation) is developed. Thereupon, the number of ECs formed within the large-scale area of investigation can be determined.
- Upscaling to a large scale is performed based on the number of ECs and the cost-optimal PV system sizes for the model ECs of each SP.
- The determined optimal economic rooftop PV potential on a large scale is put in relation to the maximum rooftop PV capacity that can be installed in the investigated area.

3. Method, model and data

Based on the contributions explained in Section 2.3, the entire modelling process is visualised in Fig. 1. It can be divided into four parts:

1. An optimisation model determines the PV system profitability and optimal PV capacity for four model ECs, one for each of the four predefined SPs. (Detailed description: Section 3.1).
2. An algorithm allocates buildings to SPs and subsequently to individual ECs. Furthermore, the number of ECs per SP is determined for the large-scale area of investigation. (Detailed description: Section 3.2).
3. Combining steps 1 and 2, the cost-optimal economic rooftop PV potential on a large scale is estimated by upscaling. (Detailed description: Section 3.3).
4. For comparison, the actually available rooftop PV potential (geographical potential) of the large-scale area of investigation is estimated. (Detailed description: Section 3.4).

3.1. Calculating the optimal rooftop PV system sizes for ECs in different settlement patterns

The calculation of cost-optimal PV system sizes for model ECs in different SPs provides the basis for estimating the optimal economic potential of rooftop PV systems in the residential sector.[3] To that end, four different SPs that are considered characteristic for both Austria and Europe are identified.

3.1.1. Settlement patterns

- City area: The city area is characterised by large multi-apartment buildings (LMABs), which are on average five-storey and mostly residential (sometimes small businesses are located on the ground floor). The population and building density is high.
- Town area: Town areas consist of smaller multi-apartment buildings (SMABs) and can often be found in the extended surroundings of city centres or in the centres of towns/villages. Frequently, small businesses are located on the ground floor.
- Mixed areas: Mixed areas are found in city outskirts, in small villages or towns that do not have a pure city area. They consist of a mix of LMABs and single-family houses (SFHs).
- Rural areas: Geographically widespread SFHs are characteristic for rural areas. The population and building density is low.

3.1.2. Model energy communities

Four model ECs (one for each SP) need to be defined in order to perform the upscaling later on. It is assumed that individual ECs are

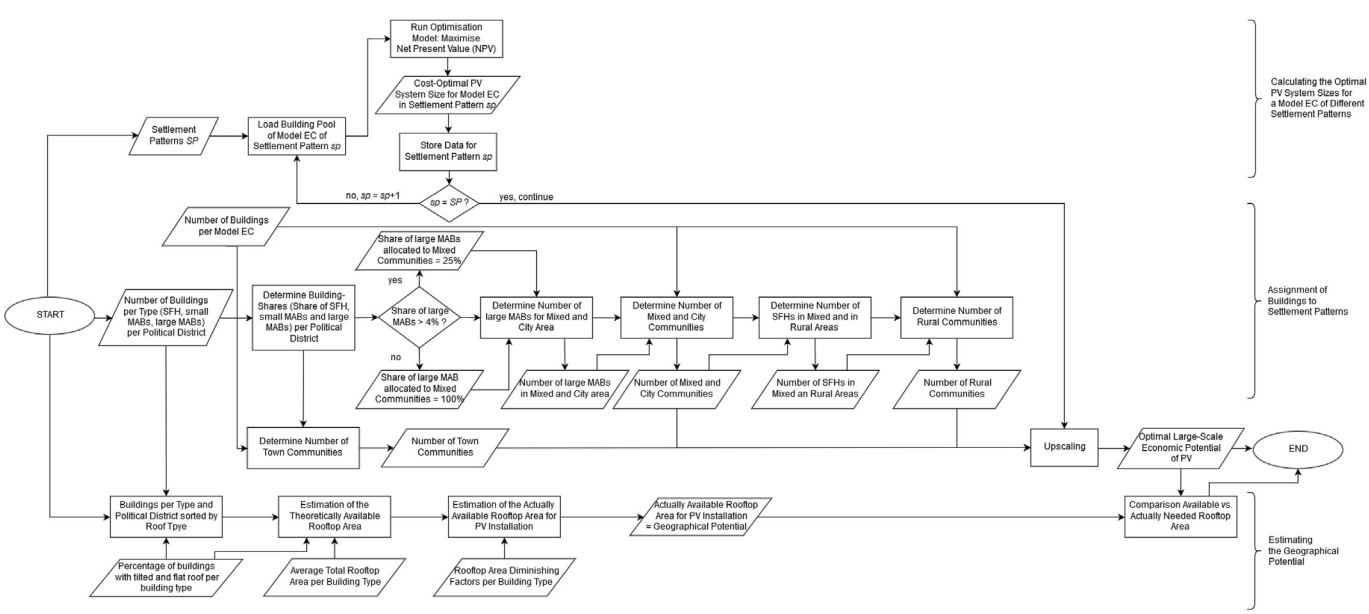

Fig. 1. Flow chart; SFHs - single-family houses, MABs - multi-apartment buildings; The reasoning behind the percentages used in the flow chart are based on statistical data and are explained in more detail in Section 3.2.

Table 1
Default setting of individual buildings considered, based on Austrian statistics [36,38].

Building[a]	Specific heat load[b] in kWh/m^2/yr	Orientation[c]	Business included	Heating system[d]
Large multi-apartment building (LMAB) area				
LMAB 1	145	North-South	–	Gas
LMAB 2	125	North-South	Store	Gas
LMAB 3	145	North-South	–	District Heat
LMAB 4	60	North-South	–	District Heat
LMAB 5	145	North-South	–	Gas
LMAB 6	125	East-West	Bakery	Gas
LMAB 7	80	East-West	Grocery	District Heat
LMAB 8	60	East-West	–	District Heat
LMAB 9	115	East-West	–	District Heat
LMAB 10	60	East-West	Store	District Heat
Small multi-apartment building (SMAB) area				
SMAB 1	115	East-West	Grocery	Gas
SMAB 2	145	East-West	Store	Gas
SMAB 3	145	North-South	Restaurant	Gas
SMAB 4	80	North-South	Restaurant	District Heat
SMAB 5	60	North-South	–	District Heat
SMAB 6	60	North-South	Bakery	District Heat
SMAB 7	145	East-West	–	Gas
SMAB 8	145	East-West	–	Gas
SMAB 9	125	East-West	Restaurant	District Heat
SMAB 10	160	North-South	Bakery	Gas
Rural Area				
SFH 1	145	North-South	–	Oil
SFH 2	115	East-West	–	Oil
SFH 3	80	North-South	–	Wood Pellets
SFH 4	60	East-West	–	Heat Pump
SFH 5	60	North-South	–	Wood Pellets
SFH 6	145	East-West	–	Oil
SFH 7	80	North-South	–	Wood Pellets
SFH 8	60	East-West	–	Heat Pump
SFH 9	145	North-South	–	Oil
SFH 10	115	East-West	–	Wood Pellets

[a] The buildings are considered to have saddle-roofs with a pitch of 30°.
[b] The specific heat loads represent the diversity in building standard in the residential sector in Austria, based on the year of construction [3].
[c] Orientation refers to the orientation of the buildings' saddle roofs. The buildings' orientation can be assumed to be statistically equally distributed across all directions [19], i.e. the same number of buildings are oriented North-South and East-West.
[d] The selection of the different heating systems is based on statistical data from Austria, provided by Statistic Austria [38]. It can be derived from the data that buildings in cities/towns are primarily equipped with gas heating and district heat, whereas the heating system diversity is greater in rural areas. Further details are provided in Ref. [11].

formed at a neighbourhood level between a limited number of buildings[5]:

- A city EC consists of 10 LMABs.
- Town ECs include 10 SMABs each.
- A mixed EC comprises 2 LMABs and 10 SFHs.
- Rural ECs consists of 10 SFHs.

The model ECs are assigned characteristic buildings with real-measured electricity load profiles according to the number of apartments accommodated. Building characteristics concern specifications such as heat load, heating system, orientation and, whether businesses are included in the otherwise residential buildings. Table 1 shows the building pool for city, town and rural model ECs. The model EC for the mixed area consists of a mix of SFHs and LMABs. The building specifications provided in Table 1 are based on statistical data for Austria [38]. Standard load profiles [2] are used for businesses.

3.1.3. Optimisation model

An optimisation model – with the objective of maximising the NPV (net present value) over a time horizon of 20 years – is developed to determine whether PV system implementation is profitable for the previously described model ECs. If profitable, the optimal PV system capacities are also determined.[6] The optimisation model is described in more detail in Refs. [10,11] [7]. However, the cornerstones are summarised in the following. A visual overview is additionally provided in Fig. 2.

- The objective of the optimisation model is to maximise the NPV of the EC's participants over a time horizon of 20 years. The NPV calculation contains investment costs for newly installed technologies, operation and maintenance costs, costs for electricity and heat[8] as well as revenues gained by surplus PV feed-in (if a PV system is installed). A mixed-integer linear optimisation model is established since binary variables are used to determine whether different technologies (in this case PV systems) are profitable.

[5] A manageable number of 10 buildings is assumed for city, town and rural model ECs. The mixed area is composed of 12 buildings: The building load profiles of multi-apartment buildings are dominating compared to the SFH load profiles, wherefore it was decided to comprise 10 SFHs and 2 LMABs in the mixed area model EC.

[6] Generally, the optimisation model considers PV system implementation on roofs and facades. However, in this study, the optimisation determines that only roofs are to be used for PV installation due to the best solar irradiation and thus highest profitability.

[7] These studies were conducted by the same authors.

[8] The heating costs are not relevant for the results concerning cost-optimal PV system installation. However, they are considered for the purpose of completeness in the NPV optimisation. Heat pumps (assumed to be implemented in two SFHs) are the only heating system having synergy effects with PV.

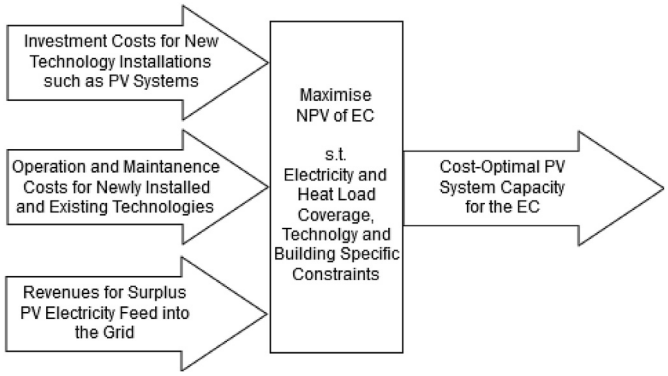

Fig. 2. NPV optimisation.

- The electricity and heat load must be covered at every point in time by the available electricity and heating technologies, respectively. Theoretically, the model allows for the electric load to be covered by electricity from PV systems, the battery storage[9] or the grid. Whether PV systems are available to contribute to load coverage is determined by the optimisation model as PV is only installed if determined profitable by the optimisation.
- The PV systems are modelled such that the generated electricity can be (i) directly used for covering the electric load, (ii) stored,[9] (iii) used for feeding the heat pump or (iv) fed into the grid.

The cost assumptions concerning the technologies considered in the analyses are listed in Appendix A.

3.2. Assignment of buildings to settlement patterns and energy communities

This section describes the algorithm that allocates buildings of different types to SPs and further to ECs within a political district. In this study, the large scale area of investigation is Austria. A map of Austria with the according political districts is provided by Statistik Austria in Fig. 3.

Moreover, Statistic Austria [36] also provides data for the number of residential buildings per type and political district. The distinguished building types are:

- Single-family houses (SFHs)
- Small multi-apartment buildings (SMABs) with 3–6 units
- Large multi-apartment buildings (LMABs) with 10 or more units

Based on the number of buildings ($N(bt, pd)$) of each building type (bt) per political district (pd), the share of each building type ($S(bt,pd)$) on the total building stock ($N\_tot(pd) = \sum_{bt} N(bt,pd)$) per political district can be determined (Equation (1)).

$$S(bt, pd) = \frac{N(bt, pd)}{N\_tot(pd)} \tag{1}$$

SFHs hold the largest share of the total building stock in every political district. The shares held by LMABs are generally the smallest and only range between 4% and 7% in small-to medium-sized cities.[10] Based thereon, it is determined that a city area exists when the share of LMABs exceeds 4% within a political district. If the share of LMABs within a political district is below 4%, it is assumed that this political district has no city area, but the LMABs are part of mixed areas. Nevertheless, when a city area exists, mixed areas also exist (e.g. in the city outskirts). In this case it is assumed that 75% of all LMABs ($N_{LMAB}(pd)$) are allocated to city areas (number of LMABs in city area per political district: $N_{LMAB\_city}(pd)$). The remaining 25% are assigned to mixed areas (number of LMABs in mixed area per political district: $N_{LMAB\_mixed}(pd)$). The mathematical formulation is provided in Equation (2).

$$\begin{aligned} &\text{if the 4\% LMAB threshold is exceeded} \\ &N_{LMAB\_city}(pd) = N_{LMAB}(pd) \cdot 0.75 \\ &N_{LMAB\_mixed}(pd) = N_{LMAB}(pd) - N_{LMAB\_city}(pd) \\ &\text{if the 4\% LMAB threshold is not exceeded} \\ &N_{LMAB\_city}(pd) = 0 \\ &N_{LMAB\_mixed}(pd) = N_{LMAB}(pd) \end{aligned} \tag{2}$$

After the number of LMABs allocated to city areas and mixed areas is determined, it is possible to calculate the number of ECs that can be formed within these two SPs. To that end, it is necessary to specify how many buildings are considered per neighbourhood EC.[5] This information is provided in Table 2.

The number of LMABs allocated to city areas ($N_{LMAB\_city}(pd)$) is divided by the number of buildings considered per model EC of a city. The result is the number of city ECs ($N_{EC\_city}(pd)$) per political district (Equation (3)).

$$N_{EC\_city}(pd) = \frac{N_{LMAB\_city}(pd)}{n_{LMAB\_city}} \tag{3}$$

The number of mixed ECs ($N_{EC\_mixed}(pd)$) is determined analogously (Equation (4)).

$$N_{EC\_mixed}(pd) = \frac{N_{LMAB\_mixed}(pd)}{n_{LMAB\_mixed}}. \tag{4}$$

After the number of mixed ECs ($N_{EC\_mixed}(pd)$) is determined, the number of SFHs allocated to mixed areas ($N_{SFH\_mixed}(pd)$) can be determined by multiplying the number of mixed ECs by the number of SFHs considered per model EC of the mixed area (Equation (5)):

$$N_{SFH\_mixed}(pd) = N_{EC\_mixed}(pd) \cdot n_{SFH\_mixed} \tag{5}$$

In Equation (6), the remaining SFHs are allocated to the rural areas ($N_{SFH\_rural}(pd)$).

$$N_{SFH\_rural}(pd) = N_{SFH}(pd) - N_{SFH\_mixed}(pd), \tag{6}$$

with $N_{SFH}(pd)$ being the total number of SFHs per political district.

The number of rural communities ($N_{EC\_rural}(pd)$) is determined by dividing the number of SFHs allocated to rural areas ($N_{SFH\_rural}(pd)$) by the number SFHs considered per rural model EC (Equation (7)).

$$N_{EC\_rural}(pd) = \frac{N_{SFH\_rural}(pd)}{n_{SFH\_rural}} \tag{7}$$

The number of town communities ($N_{EC\_town}(pd)$) is determined analogously in Equation (8), with $N_{SMAB}(pd)$ being the number of SMABs per political district.

$$N_{EC\_town}(pd) = \frac{N_{SMAB}(pd)}{n_{SMAB\_town}} \tag{8}$$

Discussion of the Allocation of Buildings to Settlement Patterns. There are also other options for assigning buildings to SPs and ECs.

[9] The battery storage is not considered in this analysis as previous research [10,11], showed the lack of profitability.

[10] e.g. Villach, Eisenstadt and Klagenfurt, with population _gures above 40 000 and below 100 000.

Fig. 3. This map is provided by Statistik Austria [39]. The 3-digit code number of the political districts consists of one digit for the federal state (1 for Burgenland, 2 for Carinthia, 3 for Lower Austria, 4 for Upper Austria, 5 for Salzburg, 6 for Styria, 7 for Tyrol, 8 for Vorarlberg and 9 for Vienna) plus a 2-digit serial number.

Table 2
Number of buildings and building types per model EC.

Number of …	LMABs (10–20 units)	SMABs (3–6 units)	SFHs
City EC	$n_{LMAB\_city} = 10$	–	–
Town EC	–	$n_{SMAB\_town} = 10$	–
Mixed EC	$n_{LMAB\_mixed} = 2$	–	$n_{SFH\_mixed} = 10$
Rural EC	–	–	$n_{SFH\_rural} = 10$

In this case, the shares of the different building types per SP are considered to be the significant indicator of how the algorithm to allocate buildings is designed. Another way would be to use the building and population density as an indicator and a basis for an assignment algorithm: The lower the building and population density, the more rural areas with widely distributed SFHs exist. By contrast, a higher population and building density indicates the existence of a city area.

3.3. Upscaling

After cost-optimal rooftop PV system sizes are determined for the four model ECs (Section 3.1) and the number of ECs per SP is calculated (Section 3.2), the upscaling to a large scale can be performed. This is done by multiplying the determined PV system sizes for the four model ECs by the determined number of ECs per settlement pattern.

3.4. Estimating the maximum installable rooftop PV capacities (geographical potential)

The geographical rooftop potential is defined as the available rooftop area for PV installation, accounting for diminishing factors such as shading and structural restrictions. In order to estimate the geographical potential, the following steps are taken:

1. The total number of buildings per type (SFHs, SMABs, LMABs) needs to be subdivided into buildings with tilted and flat roofs. According to Ref. [19], the percentage of building types that are equipped with tilted roofs is as follows[11]:
   - 95%–98% of SFHs
   - 92% of SMABs
   - 75% of LMABs
2. Next, the theoretical rooftop area is determined. SFHs are assumed to have an average rooftop area of 130 m^2, SMABs 150 m^2 and LMABs 330 m^2, which is in line with [19].[12] The rooftop area of flat-roofed buildings is roughly 13% smaller compared to buildings of the same dimensions but with 30°-tilted roofs. On this basis, the theoretical rooftop area can be estimated by multiplying the average rooftop area per building type by the according number of buildings.
3. The rooftop area actually available for PV system installation is then determined by taking into account diminishing factors (Table 3).
4. At this point, the available rooftop area for PV installation is known for SFHs, SMABs and LMABs. Lastly, the available rooftop area of these three building types needs to be allocated to the four different SPs. In Section 3.2, the allocation of the different buildings to the four SPs is described. On that basis, the share of buildings per type that are allocated to the different SPs can be derived. These shares can then be used to transfer the total

[11] The cited literature provides data from Germany. Although this study provides results for Austria speci_cally, the data that is valid for the German building stock is, in this speci_c case, valid for Austria as well. The reasons are as follows. The German and the Austrian building stock are very similar, since the culture and architecture can be considered equal. (Additionally, both countries su_ered equally from World War II). Moreover, cities in both countries are of equal structure: city centre, multi-apartment building living areas, mixed areas in the periphery. Considering rural areas, the circumstances are comparable as well, since both countries have mountain areas (Germany in the South, Austria in the West) as well as at areas (Germany in the North, Austria in the East).

[12] This is an empirical study from Germany. There are hardly any differences between Austria and Germany in this field, which is why the data may also be applied to Austria.

Table 3
Determining the technical rooftop potential.

Reduction of theoretical rooftop potential of tilted roof areas		
20%	η_1	structural restrictions (chimneys, ventilation shafts, skylights, antenna systems, access hatches)
15%	η_2	increased roof development (of industrial buildings)
10%	η_3	shading effects in densely built-up areas
5%	η_4	historical buildings
Reduction of theoretical rooftop potential of flat roof areas		
66%	η_1	one third useable for PV installation due to self-shading
25%	η_2	structural restrictions (chimneys, ventilation shafts, skylights, antenna systems, access hatches)
15%	η_3	increased roof development (of industrial buildings)
10%	η_4	shading effects

rooftop area per building type to the different SPs (= geographical rooftop PV potential for the four SPs).

4. Results

The model developed in this paper is applicable to any large-scale area. However, the results are calculated for the country of Austria. Section 4.1 provides results for the cost-optimal rooftop PV system capacities for the four model ECs in the different SPs in comparison to the calculated large-scale rooftop PV potential. These results are then compared to the estimated geographical potential in Section 4.2. To evaluate the impact of the model EC size, the retail electricity price as well as the specific PV system costs, sensitivity analyses are conducted in Sections 4.3 and 4.4.

4.1. Large-scale cost-optimal potential of rooftop PV in Austria

The large-scale economic rooftop PV potential for Austria is estimated based on model ECs at a neighbourhood level between a limited number of buildings in four different SPs. The optimal PV system capacities that are determined by optimisation for the four model ECs are shown in Fig. 4. The results for individual model ECs are then contrasted with the results received after upscaling to country level (optimal economic large-scale potential), depicted in Fig. 5.

- Regarding cost-optimal rooftop PV system implementation in the individual model ECs (Fig. 4), the largest system capacities are installed in the city EC, the smallest in the rural EC. The electricity demand of LMABs in city areas containing multiple households and occasionally small businesses is significantly higher than in SFHs with only one load profile per building. However, the cost-optimal large-scale economic potential of rooftop PV (Fig. 5) is highest for rural areas with more than 4GW$_p$ and lowest for city areas with about 1.2GW$_p$, since SFHs by far account for the largest share of the total building stock. Therefore, rural areas are the dominating SP in Austria, and subsequently, the economic potential of PV is highest in these areas.
- It is also noteworthy that as soon as SFHs are considered to be part of ECs (as in rural and mixed ECs), PV systems are only installed towards the Southern direction. In this study the rooftops' orientation is assumed to be equally distributed: 50% of the buildings' roofs are assumed to be oriented North-South, the other 50% are oriented East-West (compliant with [19]). Since the rooftop areas of SFHs are large compared to the space required for cost-optimal PV installation for one individual building, the rooftop areas with the best solar irradiation (South) are chosen for PV installation via optimisation. In city and town areas, by contrast, the Eastern and Western parts of the roofs need to be used in order to achieve cost-optimality due to the limited availability of roof space.
- In total, the estimated cost-optimal economic rooftop PV potential for Austria is approximately 10GW$_p$. At first sight, this number might seem low. However, two factors need to be taken into account:
  - First, this analysis estimates the cost-optimal economic rooftop PV potential, which differs from the total economic PV potential[13] in residential buildings[3]. This analysis is based

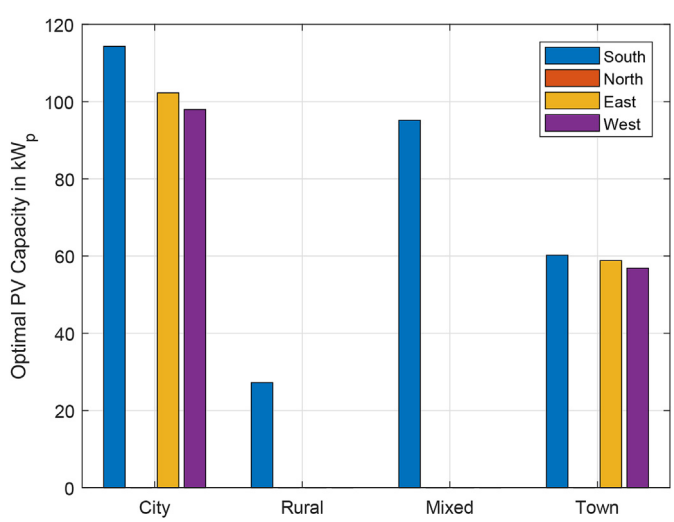

Fig. 4. Cost-optimal rooftop PV system sizes for individual model ECs.

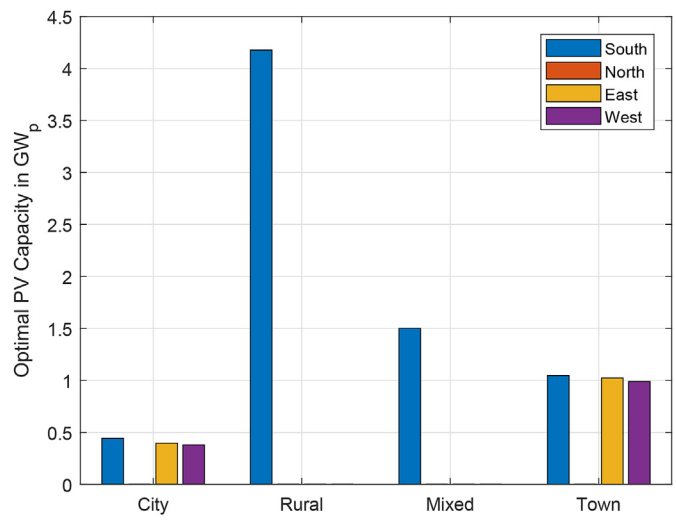

Fig. 5. Cost-optimal rooftop PV system sizes for whole Austria.

[13] The difference is that installing PV on all roof areas and also other parts of the building skin such as the facade might also be economically viable (This would then be the total economic rooftop PV potential). However, this study determines the cost-optimal rooftop PV potential. (The total economic PV potential in buildings is expected to be significantly higher.)

on an optimisation model that determines the cost-optimal PV capacities for four model ECs; these results are then used for upscaling.
– Second, only residential buildings are taken into account. Industrial, commercial and office buildings are not considered.

4.2. Geographical potential in Austria

In Fig. 6, the calculated cost-optimal economic rooftop PV potential is compared to the estimated maximum of PV that may be installed on Austria's residential rooftops (geographical potential).

A significant geographical overpotential can be found in rural areas. This means that significantly more roof space is available for PV installation than is actually required for installation of the cost-optimal amount of PV as determined by upscaling. In densely built areas, such as cities or towns with buildings containing multiple individual households as well as small businesses that increase the buildings' total load significantly, the geographical rooftop PV potential is limited. Fig. 6 even indicates that the rooftop area available for installing the cost-optimal amount of PV is too small in city and town areas, especially considering that the geographical potential also comprises rooftop areas facing North. As determined by the optimisation, north-facing rooftop areas are not suitable for cost-optimal PV installation.

As the availability of roof space is high in rural areas, while the need for roof space is high in city/town areas, future EC development should focus on forming ECs not only at neighbourhood level and thus within one specific SP, but beyond the borders of different SPs. The positive effects of mixing buildings of different types in ECs is already indicated by the results of the mixed area analysis, where the best balance between the availability of and the need for roof space is achieved compared to any other SP, see Fig. 6. However, the technical realisation of ECs beyond the borders of individual distribution grid sections is not straightforward. For this purpose, the grid and according costs for electricity transfer over longer distances would need to be considered in the modelling process. This, however, lies beyond the scope of this paper.

4.3. Varying the energy community size

In the default setting of this study, the mixed area model EC is assumed to consist of 12 buildings, while the other model ECs consist of 10 buildings each[5]. The size of ECs in terms of the number of buildings considered per EC is expected to have a significant impact on the results. Therefore, a sensitivity analysis is conducted to show the effects of changing the EC size. The number of buildings considered per model EC is reduced by half. According results are shown in comparison to the default setting in Fig. 7. Results indicate that the higher the number of buildings per model EC, the more efficiently the generated PV electricity can be used due to synergy effects between load profiles. This increases the profitability of PV sharing concepts and reduces cost-optimal rooftop PV system installation. Another reason is that if the number of participating buildings increases, the optimisation model has more available roof space for cost-optimal PV installation.

It is to be expected that by further increasing the number of buildings per EC, optimal PV system sizes are further reduced, as is the cost-optimal economic PV potential. In Fig. 7, this is indicated by the dashed bars (values not actually calculated). However, the reduction in optimal PV system sizes is expected to diminish if the EC size is further increased. This means that there is no linear development. The reason is that with few buildings per EC, the positive impact of synergy effects on the profitability of PV is most noticeable. As soon as the optimal EC size[14] is reached, the positive influence of synergy effects between load profiles is still present but no longer increases. As for the results of Section 4.2 which clearly show the limited availability of roof space in densely built areas, larger individual communities that require less PV capacity to achieve cost-optimality could resolve the issue of limited roof space.

Results are not only sensitive to variations in the EC size but also to variations in the composition of load profiles. In this study, a representative sample of real-measured load profiles is used to provide a realistic representation of households in different ECs. Due to the large number of individual households and thus load profiles (e.g. 10 to 20 individual household load profiles in a single multi-apartment building), no such sensitivity analysis is conducted within this study.

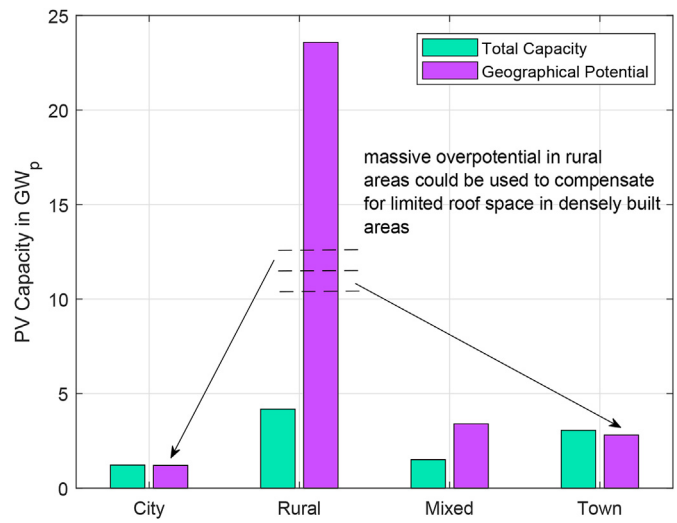

Fig. 6. Cost-optimal, EC-based rooftop PV capacity vs. geographical potential.

4.4. Varying the retail electricity price and specific PV system costs

Retail electricity prices and specific PV system costs are two major factors impacting the profitability of PV systems and PV sharing concepts. In this respect, the effect of varying these parameters is investigated by calculating three case studies as introduced in Table 4. In general, the retail electricity price consists of three parts – (1) energy costs, (2) grid costs, which can be subdivided in a per unit charge and a fixed charge, as well as (3) taxes and levies. The charge per unit (Euro/kWh) across all three categories is assumed to be 0.22Euro/kWh in the default setting. Within the framework of this sensitivity analysis, it is assumed that the structure of the grid costs is altered, in order to mitigate the increasing revenue challanges of distribution system operators (DSOs). Said challanges are intensified by increasing PV penetration on distribution grid level. The charge per unit is expected to decrease while the fixed charge increases. Therefore, the overall charge per unit is assumed to decrease. In the following sensitivity analysis it is assumed to be 0.18Euro/kWh.[15]

[14] Determining the optimal EC size lies beyond the scope of this study.

[15] The initial retail electricity price is assumed to be 0.22EUR/kWh which is on the upper end of the retail electricity price range in Austria. Since the average retail price is rounded 0.20EUR/kWh, this sensitivity analysis aims to investigate the impact of a retail electricity price on the lower end of the price range (0.18Euro/kWh) on the cost-optimal large-scale rooftop PV potential.

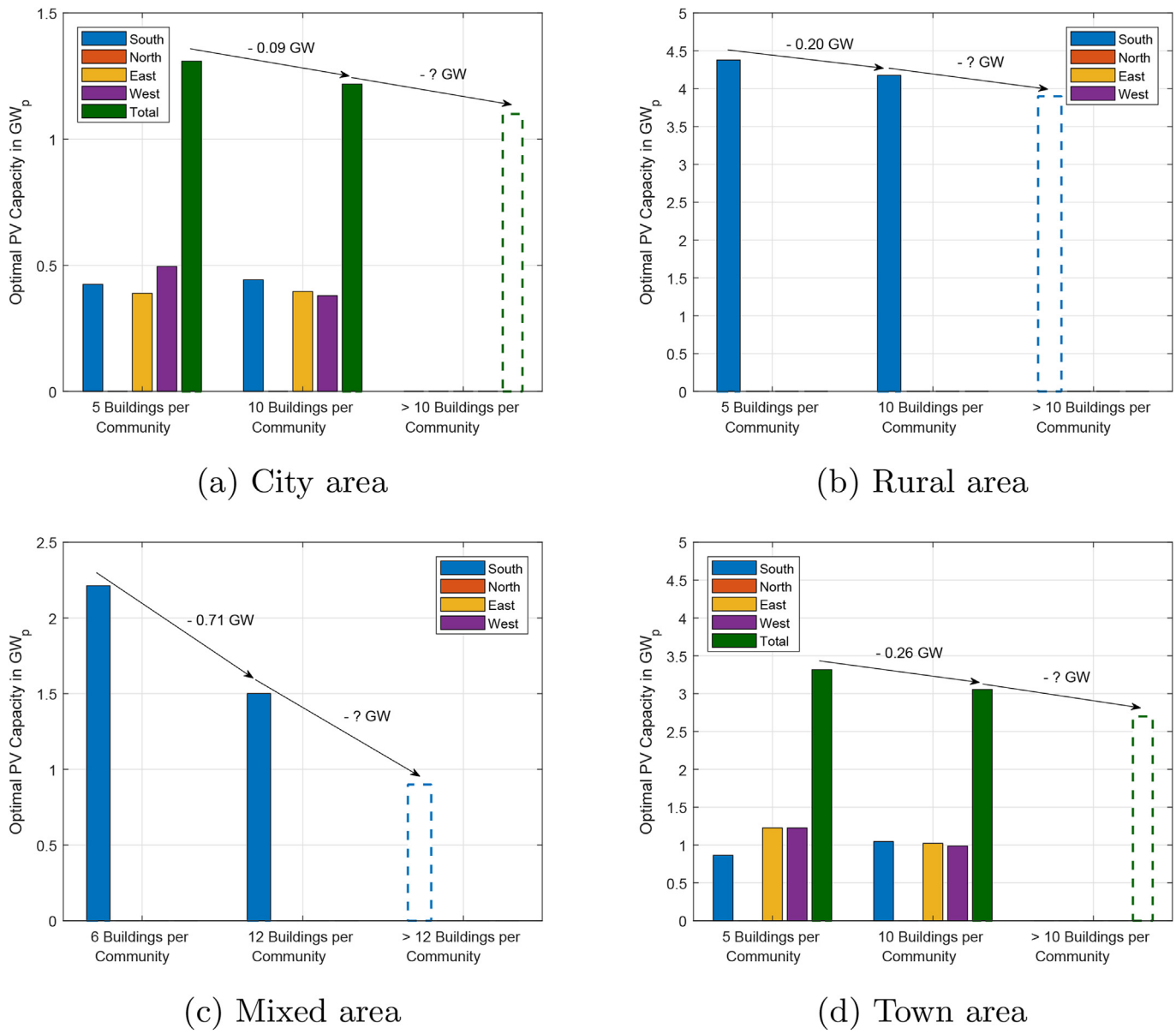

Fig. 7. Effects of changing the EC size on the cost-optimal economic large-scale rooftop PV potential.

Table 4
Case study definition for varying the retail electricity price and PV system costs.

Case studies	(i) Default setting	(ii) Varying the retail electricity price	(iii) Varying retail electricity price and PV system cost
Retail electricity price	0.22Euro/kWh	0.18Euro/kWh	0.18Euro/kWh
PV system cost	1050Euro/kW$_p$	1050Euro/kW$_p$	840Euro/kW$_p$

Corresponding results of the cost-optimal economic large-scale potential are shown in Fig. 8. The green bars indicate the results achieved for the default setting (i) as introduced in Table 4. The assumption of a decrease in retail electricity prices per unit (0.22Euro/kWh → 0.18Euro/kWh) in case study (ii) leads to a reduction of the estimated optimal rooftop PV potential (blue bars in Fig. 8). The reason is that since grid electricity is cheaper, the cost saving potential by installing PV is reduced, as is the economic potential. However, if the assumption of the lower per-unit retail electricity price is preserved, while a reduction of PV system costs by 20%[16] (1050Euro/kW$_p$ → 840Euro/kW$_p$, use case (iii)) is presumed at the same time, the red bars in Fig. 8 show that the cost-optimal economic rooftop PV potential even exceeds the results of the default setting (case study (i)). Therefore, it can be derived

[16] The initial PV system cost assumption of 1050Euro/kW$_p$ is in line with. The same study declared an average decrease of PV system costs by 8% per year. Therefore, with the assumption of a PV system cost decrease of 20%, a realistic scenario in the near future is investigated.

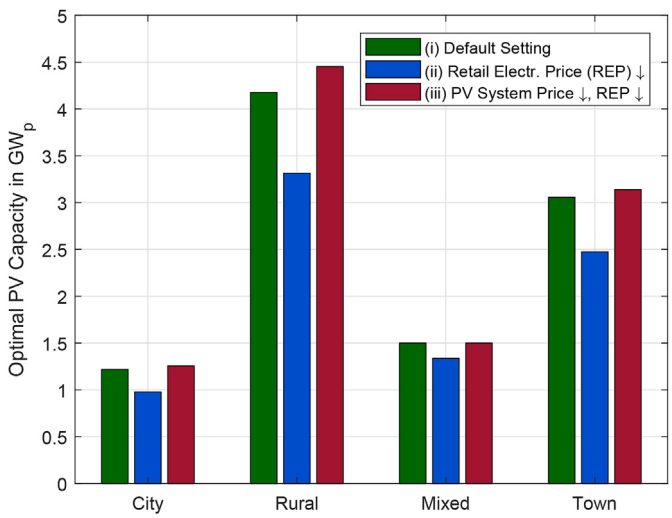

Fig. 8. Cost-optimal economic rooftop PV potential for the default setting, retail price and PV system price variations.

that PV system costs have a significant impact on the results, to a remarkably larger extent than the retail electricity prices.

5. Conclusion and outlook

In order to reach the European 2030 climate goals, the share of installed PV capacities needs to increase significantly in several of the European countries. In Austria, the policy goals are ambitious, since a 100% renewable energy supply shall be realised until 2030. This expects at least 9.7GW_p of PV according to Ref. [9], and 11.9GW_p according to Ref. [33]. In general, there are two alternatives for implementing PV, either as ground-mounted PV plants or as building-attached/integrated generation units which are predominantly used for self-consumption. The latter option prevents a further sealing of surfaces. The results in this paper show that the PV-related part of the 2030 policy goal for Austria can be achieved, indeed in a cost-optimal way, by only using residential rooftops[3] for PV system installation. A realisation as proposed in this study with an optimal PV capacity of approximately 10GW_p leads to cost-optimality for all participants in the ECs.

The applied method of upscaling the optimal results for individual model ECs to larger scale has proven to be suitable. Moreover, the results provide guidance for policy makers concerned with the future development of ECs. In a first step, ECs should be implemented at neighbourhood level, as proposed in this study, in order to build trust in the novel concept of ECs. Next, a relocation of the system boundaries of ECs across different SPs is recommended. This proposed step-wise distribution of PV systems is also recommendable concerning the probably necessary amendments of the electricity grid. Implementing PV capacities of approximately 10 GW_p would pose a huge burden for the electricity grid and is only rationally feasible if most of the generated PV electricity is consumed directly (which is also the most economic solution). Nevertheless, grid reinforcement with increased PV distribution might be unavoidable, even if only the surplus PV electricity generation is fed into the grid.

Although the realisation of ECs with PV sharing concepts has proven to be technically and economically feasible on a small as well as on a large scale, the implementation of such novel concepts will depend heavily on the legislation and the regulatory framework in different countries. In addition, how and if PV sharing concepts in ECs are realised in the future will significantly be affected by the distribution grid tariff structure. The higher the share of the per-unit charge (compared to the fixed component) the better for the profitability of EC-based load coverage based on PV generation. In this study, additional grid costs for PV electricity sharing between different buildings are neglected since ECs are only formed at neighbourhood level within close geographical boundaries. In practice, however, this assumption needs some kind of 'regulatory sandboxes' in order to realise these kinds of ECs within pilot projects. PV electricity sharing in ECs across longer distances would require that additional grid costs are taken into account, while losses would negatively impact the results.

Other key parameters that need to be taken into consideration for estimating the future deployment of EC-based PV sharing concepts are the retail electricity price and the specific PV system costs. If retail electricity prices increase, for example as a result of rising CO_2 prices, the PV system profitability would increase. An additional decrease of PV system costs would significantly enhance this effect. However, the per-unit component of the grid tariff might also decrease in the future while the fixed component simultaneously increases in order to guarantee revenue sufficiency for the distribution grid operator. Such tariff structure amendement would then decrease PV system profitability and thus the upscaled cost-optimal economic PV potential. However, learning effects that decrease PV system costs at the same time could counteract this effect in turn.

Based on this study, the following suggestions for future work can be made:

- A comprehensive analysis of determining the optimal number and composition of buildings and prosumer types (in addition to the residential segment) within an EC needs to be conducted in future studies. This can further increase the accuracy of determining optimal results.
- As already indicated in this work, future ECs should be formed beyond the borders of distribution grid sections. Such analyses, which are at present missing in scientific literature, need to specifically focus on the various related grid aspects, corresponding grid costs and grid tariff structures.
- Building upon the consideration of several grid-related aspects, studies that focus on finding an equilibrium where retail electricity prices, PV system cost and grid tariffs deliver robust results (and thus sustainable business cases in practice) apart from any specific regulatory treatment, are expected to be of interest.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Bernadette Fina: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Hans Auer:** Conceptualization, Validation, Writing - review & editing, Supervision. **Werner Friedl:** Validation, Supervision.

Appendix A. Cost assumptions

The costs and technology data are listed in Tables A.5 and A.6. More detailed explanations regarding the cost assumptions can be found in Ref. [10].

Table A5
Cost assumptions

Specification	Type of Costs	Costs
Rooftop PV, building-attached	Specific investment costs	1050Euro/kW$_p$
	Cleaning costs	15Euro/kW$_p$/yr
	Operational costs	60Euro/yr
Heat pump	Specific investment costs	1000Euro/kW
	Maintenance costs	300Euro/yr
District heating	Connection costs	5000Euro
	Annual fixed costs	3.0516Euro/m^2/yr
	Costs for heat cost allocator	130Euro/yr
	Costs for district heat	0.047Euro/kWh
Pellets heating	Specific investment costs	600Euro/kW
	Maintenance costs	300Euro/yr
	Pellet costs	0.28Euro/kg
Electricity	Variable costs	0.22Euro/kWh
	Fixed Costs	65Euro/yr
	Surplus PV feed-in revenues	0.03Euro/kWh
Gas heating	Variable costs	0.05Euro/kWh
	Fixed costs	150Euro/yr
Oil heating	Variable costs	0.0912Euro/kWh
	Fixed costs	150Euro/yr

Table A6
Further relevant empirical assumptions

PV systems	
Module efficiency	17%
Additional losses	20%
Module size	1.5m^2
Module capacity	0.25 kW
Pellets heating	
Pellet heating value	5 kWh/kg
Efficiency	90%
Interest rate	3%

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