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Profitability of PV sharing in energy communities: Use cases for different settlement patterns

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ABSTRACT

Many countries are changing their legislation to enable photovoltaic (PV) sharing beyond building boundaries. This work aims to investigate the profitability and optimal installation capacities of PV systems for energy communities (ECs) in comparison to individual buildings. To gain a wide spectrum of results, four characteristic settlement patterns with different building types are defined, ranging from urban to suburban and historical to rural areas. Analytically, a mixed-integer linear optimisation model is developed to maximise the net present value over a time horizon of 20 years. The results show that the profitability of implementing optimally-sized PV systems increases when forming ECs compared to the situation of considering buildings individually. The more different the load profiles, the more synergy effects, and the higher the cost saving potential. Consequently, a sensitivity analysis shows that taking into account large customers can increase the profitability of PV installation for the community significantly because large roof/facade areas are provided for optimal PV installation. In addition to a broad participant portfolio, a change in the technology set-up can have a positive influence. Battery- and hot water storage which complement PV systems and heat pumps can contribute to saving energy costs, if only marginally.

1. Introduction

With the increased diffusion of renewable energy – especially photovoltaic (PV) systems – the energy system undergoes a transformation from centralised to decentralised structures. In regions with a less reliable electricity grid infrastructure, the microgrid concept is a common solution for integrating decentralised electricity generation units. However, microgrids are purely technical concepts, with two limitations: (i) obligatory participation of individuals which (ii) live within close geographical range. These limitations are overcome by a novel concept known as the energy community (EC). ECs are market-based concepts that neither enforce participation nor is geographical proximity a binding constraint.

Until recently, the implementation of ECs was prevented in most countries by the missing legislative background and regulatory obstacles. Nevertheless, many countries have managed to adapt the legislation and PV sharing concepts can be realised at least at a building level. Recent studies such as [23,24] provide strong evidence for the financial benefits of shared PV within multi-apartment buildings. Thus, it is to be assumed that the cost-saving potential of shared PV can be further increased for ECs between multiple buildings. The market diffusion of ECs and PV sharing concepts will not only depend on the legal and regulatory framework, but especially on the profitability of such concepts. Therefore, the motivation of this paper is to quantify the economic viability of PV sharing in ECs on the basis of realistic settlement patterns (SPs).

To that end, a mixed-integer linear optimisation model is developed to determine the maximum net present value (NPV) and optimal system capacities of PV and/or heating systems for individual buildings and varying aggregates of buildings that form an EC. To represent a realistic arrangement and dispersion of buildings

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and building types, four characteristic SPs are identified, which are considered representative for many regions: (i) multi-apartment building area, (ii) historical area[2], (iii) rural area and (iv) mixed area[3].

This paper is structured as follows. Section 2 provides an overview of the state of the art in the research and scientific literature. The SPs are introduced in Section 3, followed by a description of the model and the case studies, relevant for the results provided in Section 4. Sensitivity analyses are discussed in Section 5. Section 6 concludes and makes some suggestions for potential future research topics.

2. State of the art

Efforts to increase the share of renewable energy in the still predominantly centralised supply structure require decentralised alternatives. The microgrid [6] is a framework that enables the integration of distributed energy resources [41,51,58] using local energy management systems [2,60,69,76]. Although microgrid concepts have existed for more than a decade, their application is still rare [65], due to limited incentives for implementation and multiple barriers [3,4,31]. The novel concept of local ECs can not only overcome some of these barriers but is also founded on an economic basis trying to maximise the synergy effects between different participants' load profiles and local renewable generation.

Scientific literature that focuses on local energy sharing can be classified as follows based on the methodological approach to modelling:

- Game theory
  - Cooperative games
  - Non-cooperative games
- Explicit agent-based modelling[4]
- System analysis

The game theoretical (Section 2.1) and the agent-based (Section 2.2) approaches have a strong practical relevance due to the modelling of detailed interrelations between agents, whereas system analysis (Section 2.3) provides a global view on the specified problem. As this paper relies on a system analysis approach, the literature review primarily focuses thereon; however, a selection of most important studies addressing game theory and agent-based modelling are also provided in the following.

2.1. Game theory

Game theory is one approach to modelling energy sharing, both at microgrid and EC level, and can be subcategorised in cooperative and non-cooperative games.

2.1.1. Energy sharing with cooperative games

[45] proposes a local power exchange algorithm to help microgrids trade power amongst each other. To coordinate multi-microgrid operation [19], simulates the potential cooperative behaviours of such [21]. studies energy trading among the demand and response side. Focusing solely on the demand-side [49], formulates an energy consumption scheduling game among users and [15] uses cooperative game theory to model system problems that may occur in case of storage sharing.

2.1.2. Energy sharing with non-cooperative games

Usually, every entity is primarily concerned with maximising its own benefit which can be modelled by non-cooperative games [40]. proposes a Stackelberg game between the generation and demand sides. In Ref. [1], households try to optimise their individual utility, which is modelled via Nash equilibrium game. Moreover, non-cooperative games can be used to model energy trading like in Refs. [16,44]. A framework to coordinate energy sharing between neighboring prosumers is introduced by Ref. [27], while [38] proposes an energy-sharing provider to facilitate this task. Energy sharing according to different consumer preferences is modelled in Ref. [25] by a Stackelberg game.

2.2. Explicit agent-based modelling

Agent-based architecture for coordinating locally connected microgrids is proposed by Ref. [73]. As microgrids enable the integration of distributed energy resources [39], presents an application for multi-agent coordination thereof. The economic dispatch problem of a community microgrid is studied in Ref. [63], under the assumption that the agents are capable of trading electricity. Said agents can be modelled to cooperate to reach an optimal operating strategy within an energy system [5]. [56] tries to optimise the balancing of community energy resources while taking into account energy- and cost-aware decision-making [12]. formulates an agent-based game for community energy systems within a group of households.

2.3. System analysis

The scientific literature addressing energy sharing through system analysis is categorised by its geographical scope (Fig. 1):

- Small-scale communities at building level,
- Medium-scale communities comprising multiple buildings in the neighborhood,
- Large-scale communities at district or city level.

In a wider context, ECs also represent the peer-to-peer (PtP) concept, which has no geographical limitation. The PtP concept is realised in various projects as listed in Ref. [75]. Recent projects are BestRES [8] and P2PQ [11].

2.3.1. Small-scale energy communities

By implementing PV in buildings, the amount of electricity purchased from the grid is reduced and thus costs are saved. From an economic point of view, PV system implementation is primarily of interest for commercial and office buildings. The good correlation of load profiles and hours of sunshine [42,46] leads to a high cost saving potential. However, with decreasing PV module costs, investments in PV systems gain increasing attraction in the residential sector [35], also in combination with a battery storage [30,50]. ECs on single-building level are already realised in multi-apartment buildings. Recent literature investigates PV system integration in a small-scale EC of a multi-apartment building in the context of profitability [23,24].

For a sustainable future development in the building sector, a reasonable combination of on-site renewable electricity generation and general building retrofit needs to be found. Passive retrofitting (e.g. insulation, change of windows) in combination with active retrofitting (e.g. renewable energy integration) is therefore addressed in literature, mostly for individual buildings

[2] The term historical area describes a territory with predominantly very old buildings under preservation order.

[3] The mixed area describes regions with a mixture of multi-apartment and single-family buildings as can be found in suburbia or city outskirts

[4] Agent-based modelling is stated as a separate sub-category. However, agent-based modelling has, in principle, a game theoretical set-up, wherefore according literature could also be assigned to game theory.

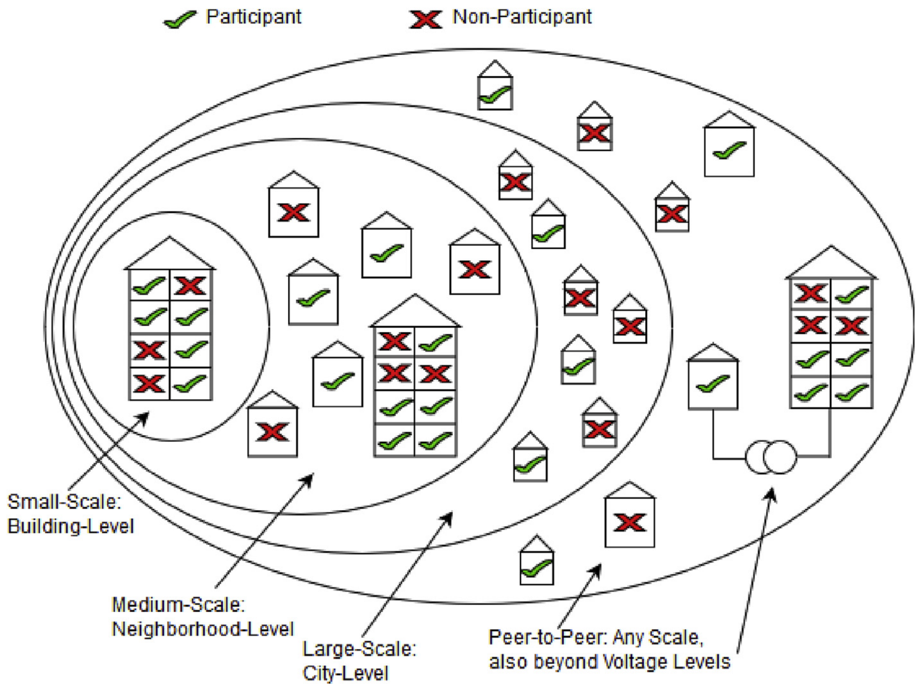

Fig. 1. Scales of EC implementation.

[22,23,43,54] but also for communities [36,53,72].

2.3.2. Medium- and large-scale energy communities

The motivations for individuals to participate at an EC are predominantly economic [17,37]. However, there are also other motivations such as 'green electricity' and a certain degree of self-sufficiency. To achieve individual goals, the public's active participation (e.g. as exemplified in the project [20]) in an EC concept is important [66]. The actual large-scale potential of PV implementation is estimated in Refs. [14,47,64], while [18] evaluates the whole transition potential of renewable ECs. For an optimal community development, the topic of a suitable renewable energy technology portfolio is addressed in Refs. [33,34,74], and the optimal building mix and energy technologies on the neighborhood level are determined by Ref. [71]. [59] focuses on energy resource sharing, such as PV systems and storage, among prosumers. The economic and operational benefits of the latter are addressed in Ref. [70].

2.4. Progress beyond the state of the art

Many studies focus on optimal EC development [34] planning and design [71] along with the identification of the best energy technologies for usage [33]. This study rather focuses on the existing building stock. Moreover, many EC studies provide results for a particular building or place [36,53]. Because such results lack transferability to other situations, the studies' added value is reduced. Some other studies define representative building types [43,72] or whole municipal archetypes [74]. So far, there is a lack of studies that include a grouping of buildings to different SPs (larger scale than individual buildings but smaller than a whole municipality). Moreover, to support policy decisions, optimal renewable system capacities should be determined in the course of EC optimisation. Therefore, based on the shortcomings of the existing literature, the scope of this paper is to provide a system analysis, that determines optimal PV system sizes and that is based on representative SPs and characteristic buildings. The novelties of this study are as follows:

- An optimisation model, with the goal of maximising the NPV (time horizon of 20 years) is developed to assess the profitability of different PV systems in ECs.
- The profitability and optimal size of PV systems is calculated for individual buildings as well as aggregates of buildings (forming an EC). Based thereon, the actual added value of ECs among multiple buildings compared to individual buildings can be determined.
- To reflect realistic set-ups of different ECs, four characteristic SPs (multi-apartment building area, historical area, rural area and mixed area) are considered.
- The modular approach of individualising buildings by various parameters (orientation, tenant profile, specific heat load, technology portfolio etc.) and considering them individually or combined to ECs allows for multiple sensitivity analyses and a wide spectrum of results.
- This study provides a basis for upscaling and thus a solid background for policy decisions concerning the matter of enforcing PV system implementation and incentivising the formation of ECs.

3. Methods and model

The four different SPs are introduced in Section 3.1. Subsequently, a general overview of the whole modelling process using a flow chart is provided in Section 3.2. Section 3.3 gives further details of the optimisation model, Section 3.4 provides the empirical scaling. Section 3.5 specifies the case studies relevant for the results, which are presented in Section 4.

3.1. Settlement patterns (SPs)

Four SPs are considered as a basis for the analyses, whose characteristics are provided in the following subsections.

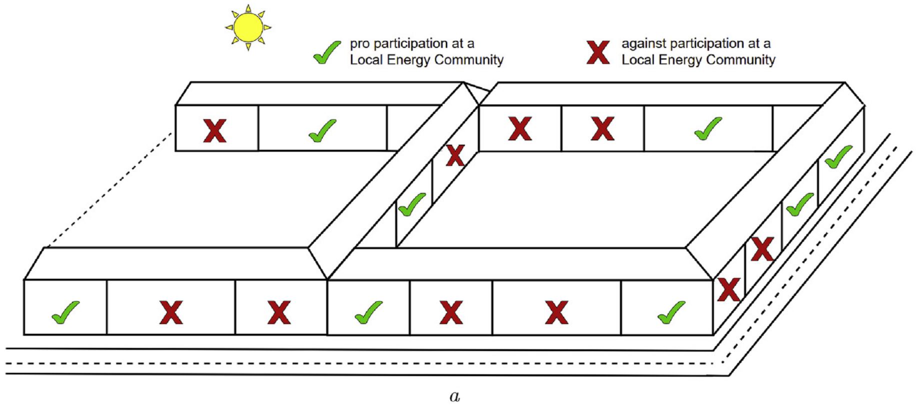

Fig. 2. Multi-apartment building area. [a]People cannot be obliged to participate in an EC. This is depicted by green ticks (pro-participation) and red x's (against participation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1.1. *Multi-apartment building area*

Multi-apartment buildings can be primarily found in city living areas. They are adjoint to one another and arranged more or less as rectangles, as shown in Fig. 2. They are predominantly purely residential and on average five-storey, individual buildings can also accommodate small businesses in the ground floor. In cities, most multi-apartment buildings can be assumed to be heated by district heat or gas[5] [68].

3.1.2. *Historical area*

Buildings in the so-called 'historical areas' can be recognised by their special appearance such as ornamented facades. In most cases these buildings are under a preservation order, making any changes on the building skin costly and laborious, or simply impossible. These buildings are three-storey on average and often contain restaurants, shops, bakeries, grocery stores and other small businesses due to their proximity to pedestrian areas. Historical buildings are mostly heated by gas or district heat[5] and are typically adjoint. However, the structure of a historical area (Fig. 3) shows less density compared to the multi-apartment building area.

3.1.3. *Rural area*

A typical rural area can be characterised by geographically widespread stand-alone buildings, as can be seen in Fig. 4. These buildings are typically single-family houses with two storeys. The heating systems are mainly oil or biomass. Individual new constructed or retrofitted buildings are often equipped with heat pumps. Large consumers, such as diverse agricultural businesses, are often located in close range to living areas.

3.1.4. *Mixed area*

Fig. 5 shows the well-structured arrangement of single-family buildings and multi-apartment buildings within close geographical range in suburbia. This area is for the most part purely residential. The heating systems show greater diversity compared to the inner parts of cities: oil and biomass heating are the most common heating systems, whereas new constructed or retrofitted buildings are often equipped with heat pumps.

3.2. *Modelling process and flow chart*

The flow chart presented in Fig. 6 has three parts: identification of *Settlement Pattern*, setting-up and conducting the optimisation for *Individual Buildings* and setting-up and conducting the optimisation of an *Energy Community*. A detailed description follows.

Settlement Pattern. As introduced in Section 3.1, there are four different SPs predefined for this study. Each SP is assigned a number of different buildings, which are introduced in Section 3.5, Table 1. Thus, a building pool is provided, depending on the SP chosen for analysis.

Individual Buildings. The buildings of this pool can then be individualised by selecting parameters such as orientation, specific heat load, installed heating system, floor area, number of storeys. Based on the number and size of the apartments and whether the building is purely residential or a business is considered, the building's total electricity demand is generated by using real measured load profiles (see Appendix B). The building's heat load profile is based on the specific heat load and its location[6]. Moreover, the building energy technologies, which will later be considered for the optimisation, need to be selected: building-attached and building-integrated PV systems on different parts of the building skin can be selected for profitability investigation. Additionally, a battery storage facility can be considered, as can a heating system change. After a building is completely configured, the optimisation process starts. This optimisation process evaluates, whether the previously selected building energy technologies are profitable. Therefore, the main output of the optimisation model is

- The maximum net present value (NPV) over a time horizon of 20 years,
- Whether the selected building energy technologies are profitable, and
- The optimal technology capacities.

Energy Community. The optimisation process can then be repeated for multiple buildings out of the building pool. Therefore, the model provides the possibility of combining individual buildings to an EC. However, not all buildings of a pool have to be taken into account for the EC. There is also the possibility of only investigating a selection of buildings. Furthermore, it needs to be determined whether parts of the individual buildings' skin are available for PV installation (active participation) or whether a

[5] The reasoning behind the heating system specifications for individual buildings in the different SPs is further explained in Appendix D.

[6] Based on a building's specific heat load, a constant indoor temperature of 20°C, an outdoor temperature profile in 15-min resolution and a heating degree day correction factor, a heat load profile is generated. For more detailed information see Ref. [23]-Appendix B3

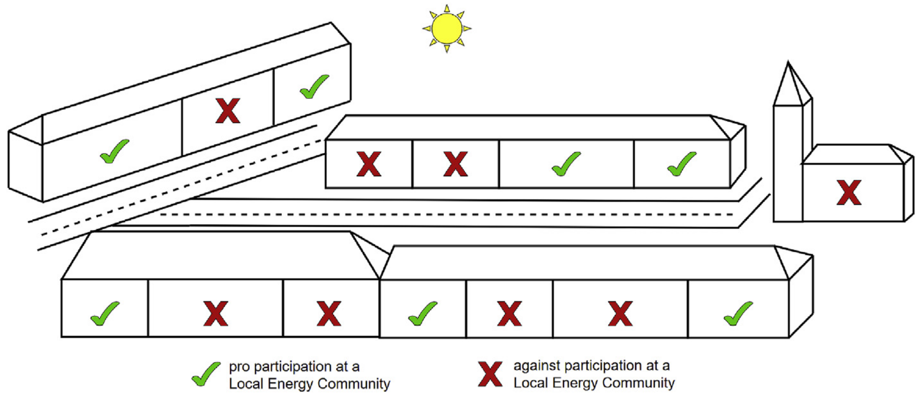

Fig. 3. Historical area[a]. [a]People cannot be obliged to participate in an EC. This is depicted by green ticks (pro-participation) and red x's (against participation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

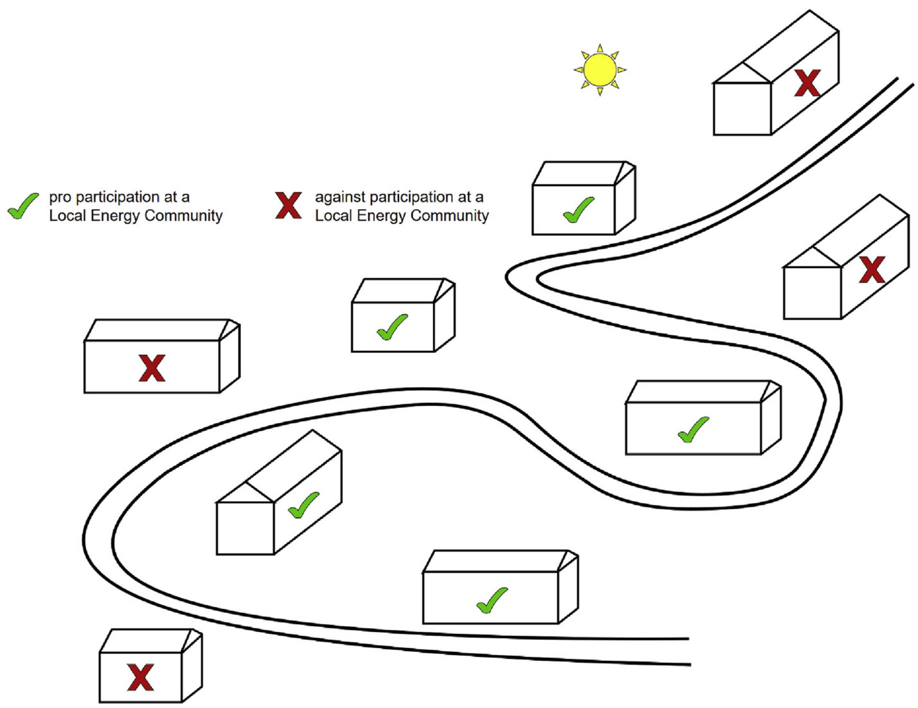

Fig. 4. Rural area[a]. [a]People cannot be obliged to participate in an EC. This is depicted by green ticks (pro-participation) and red x's (against participation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

building is considered as load only. Thus, the process of merging individual buildings to an EC brings the need to determine parameters such as the total roof and facade areas available for the EC and the electricity load profiles need to be combined to a community load profile, for example. The optimisation is then started again for the EC and optimal PV system sizes are again determined. The described two-step process to first conduct optimisation for individual buildings before evaluating optimal results for an EC provides the possibility of comparing results and thus evaluate the actual value of an EC.

3.3. Mathematical formulation of the optimisation model

In this study, a mixed-integer linear optimisation model with the goal of maximising the NPV over a time horizon of 20 years is developed to assess the profitability of different PV systems for ECs which can consist of an arbitrary number of different buildings. The basic principles of the NPV optimisation model have been introduced in a previous paper by Fina et al. [23] for a single multi-apartment building. The basic approach that applies to both individual multi-apartment buildings and ECs is shown in Fig. 7.

- *Case study set-up:* The characteristics of individual buildings or a community are determined along with the selection of the energy technologies which shall be considered in the optimisation process.
- *Types of costs:* The profitability of different energy technologies strongly depends on investment and maintenance costs. Electricity and heating fuel costs also need to be taken into account when calculating the NPV.
- *Major Constraints:* The electricity and heat load need to be covered at every point in time. Furthermore, every energy technology is modelled by individual, technology specific constraints.

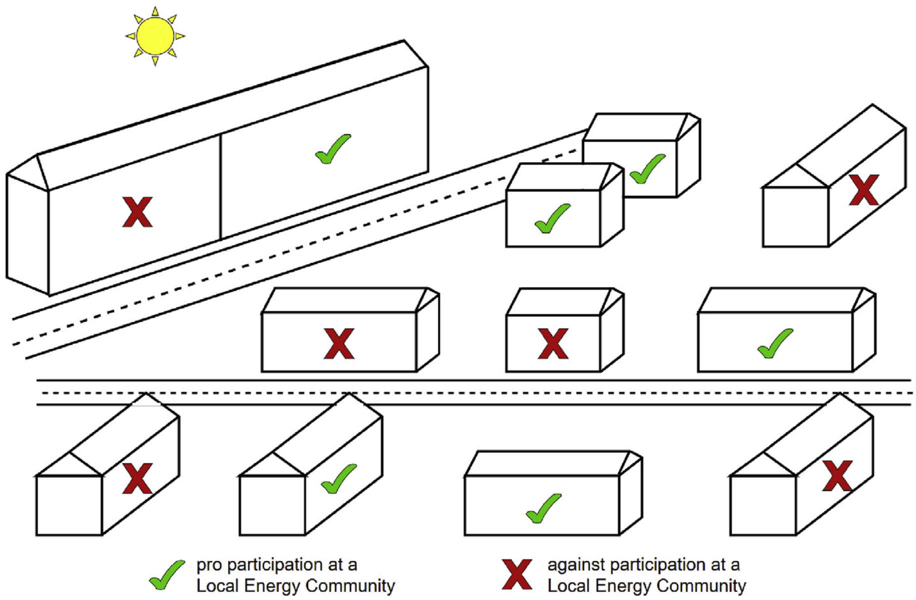

Fig. 5. Mixture of multi-apartment and single-family buildings[a]. [a]People cannot be obliged to participate in an EC. This is depicted by green ticks (pro-participation) and red x's (against participation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

- *Optimisation output:* The optimisation results contain the NPV itself, energy flows, whether individual energy technologies are profitable, and, if they are profitable, their optimal capacities.

Building energy technologies which are modelled are building-attached/integrated PV systems that can be implemented on the roof/facade, battery storage, monovalent/bivalent heat pump, hot water storage, pellet heating, district heat, gas and oil heating. For a more detailed explanation of the modelling of individual technologies, see Fina et al. [23] and Appendix E.

3.3.1. Objective function

The overall objective is to maximise the net present value (NPV) over a time horizon of 20 years. The NPV, given in Equation (1), is composed of:

- Initial technologies' investment costs (I_0), which occur in case a new technology is determined profitable by the optimisation and thus installed.
- Annual revenues $R(y)$ (y – year), which can be gained by feeding surplus PV electricity into the grid in case a PV system is installed.
- Costs $C(y)$, which comprise costs for maintenance, different heating fuels, electricity from the grid and fixed costs, for example for general access to the grid. Technology specific costs incur only if a technology is either already installed or determined profitable for installation by the optimisation.

$$\max_{o \in O} \; NPV = \max_{o \in O} \left(-I_0 + \sum_{y=1}^{Y=20} (R(y) - C(y)) \cdot \left(\frac{1}{(1+z)^y} \right) \right), \tag{1}$$

with o – optimisation variables, O – vector of optimisation variables, y – control variable for each year, Y – observation period, z – interest rate. The optimisation variables are the capacities of newly installed technologies, energy flow vectors and binary decision variables whether or not a technology is profitable. The toolbox Yalmip [32] is used as the optimiser, Gurobi [29] is used as the solver.

3.3.2. Major constraints

The major constraints are the need to cover the electricity and also the heat load at every point in time (load profiles in 15 min resolution t). The electricity load (Equation (2)) can generally be covered by electricity from the grid ($e_{grid\_2eload}(t,y)$), from PV systems (rooftop PV $e_{rpv\_2eload}(d,t,y)$, facade PV $e_{fpv\_2eload}(d,t,y)$ for directions d - North/East/South/West) and the battery storage ($e_{stor\_2eload}(t,y)$):

$$e_{load}(t,y) = e_{grid\_2eload}(t,y) + \sum_d \left(e_{rpv\_2eload}(d,t,y) + e_{fpv\_2eload}(d,t,y) \right) + e_{stor\_2eload}(t,y) \tag{2}$$

The heat load (Equation (3)) can be covered by all of the considered heating technologies: heat pumps ($e_{hp\_2hload}(t,\ y)$), which can be complemented by a heating rod ($e_{grid\_2hload}(t,y)$) or a hot water storage ($e_{hstor\_2hload}(t,y)$), district heat ($e_{dh}(t,y)$), pellet heating ($e_{pe}(t,y)$), gas ($e_{gas}(t,y)$) and oil heating ($e_{oil}(t,y)$):

$$h_{load}(t,y) = e_{hp\_2hload}(t,y) + e_{hstor\_2hload}(t,y) + e_{grid\_2hload}(t,y) + e_{pe}(t,y) + e_{dh}(t,y) + e_{gas}(t,y) + e_{oil}(t,y) \tag{3}$$

The heat pump's output, determined by multiplying a temperature-dependent coefficient of performance (COP)[7] by the heat pump electricity inflow which can consist of electricity from the grid $e_{grid\_2hp}(t,y)$, PV systems (rooftop PV $e_{rpv\_2hp}(d,t,y)$, facade PV $e_{fpv\_2hp}(d,t,y)$) and the battery storage $e_{stor\_2hp}(t,y)$, can either be used directly for covering the heat load or stored in the hot water storage (Equation (4)):

[7] For an outdoor temperature lower or equal to −20°Cs the COP is one, for an outdoor temperature greater than or equal to 35°C the COP is 4.5. The relationship between those boundaries is assumed to be linear.

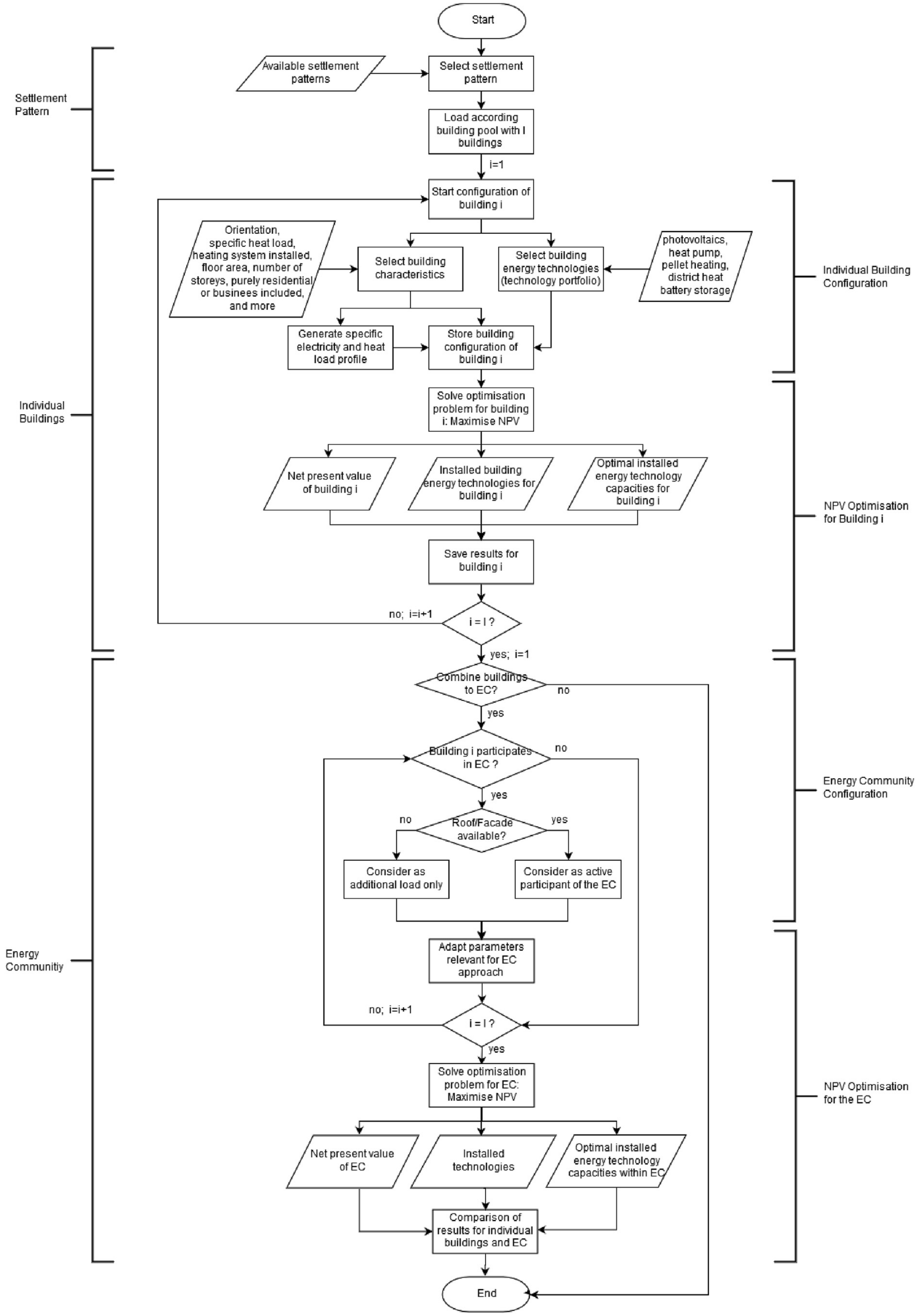

Fig. 6. Flow chart.

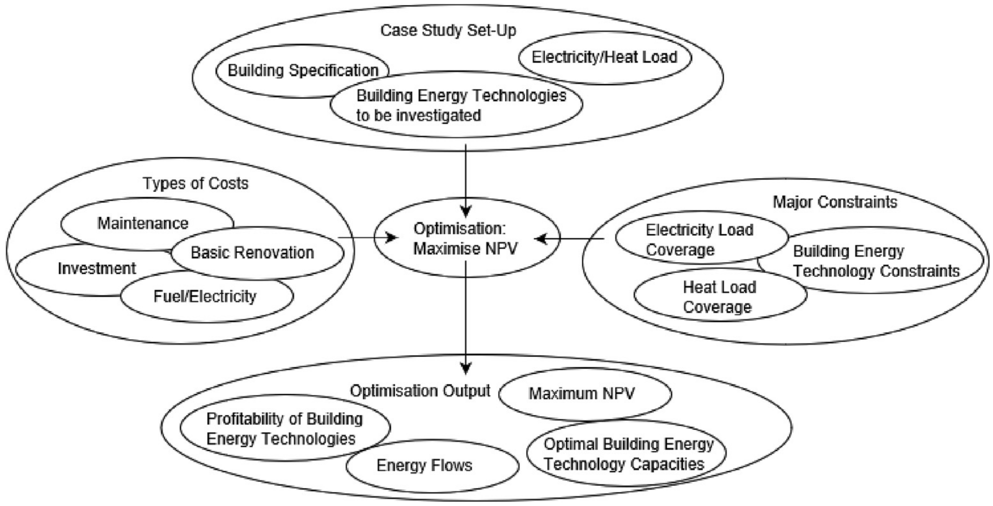

Fig. 7. Model overview.

$$e_{hp\_2hload}(t,y) + e_{hp\_2hstor}\left(t,y\right) = COP\left(t,y\right)\cdot\left[\sum_{d}\left(e_{rpv\_2hp}\left(d,t,y\right) + e_{fpv\_2hp}\left(d,t,y\right)\right)\right. \quad (4)$$

Further details concerning the modelling of individual technologies can be extracted from the authors' previous work [23].

3.4. Empirical scaling

The technical and cost assumptions for the model are provided in Appendix F.

3.5. Case study definition

The previously introduced SPs multi-apartment building area, historical area and rural area are assigned a building pool of 10 different buildings each, which are introduced in Table 1. The mixed area is assumed to be a composition of single family-buildings and multi-apartment buildings. Although the chosen SPs can be found worldwide, the age structures of the buildings and the heating system distribution is representative for Austria. For each SP, three use cases are calculated, which are explained in the following. The according results are shown in Section 4.

(i) 'Building Selection - Individual Approach':
In the first step, it is assumed that just a particular number of buildings out of each building pool have the possibility of being equipped with PV[8,9]. The optimal PV system size and maximum NPV is determined by optimisation for each of these buildings individually. (The remaining buildings of the building pool are not considered at this point.)

(ii) 'Building Selection - EC Approach':
In the second step, the buildings that can be equipped with PV (which are the same as introduced in (i)), decide to establish an EC. Optimal PV system sizes and the total NPV are repeatedly determined for the EC situation. (The remaining buildings of the building pool are still not considered.)

(iii) 'Building pool - EC Approach':
In the third step, an EC is established for the whole building pool. This means that, besides the buildings that are able to implement PV (as introduced in (i) and (ii)), buildings that do not have the possibility of installing PV themselves[8] are also considered. Thus, they are considered as additional loads and based on that, the optimal PV system sizes and the NPV are determined again.

4. Results

This section describes the results of the profitability of PV system installations for individual buildings and ECs. Optimal PV system capacities are determined by the optimisation for each use case. As an overview, the cost reduction potential for each use case is provided at the end of the section.

4.1. Multi-apartment building area

A total of 10 different multi-apartment buildings (MAB) are considered, as specified in Table 1. According to Fig. 2, buildings are adjoint to each other, which means that only two sides of the facade are available for implementing PV, depending on the buildings' orientation. Further assumptions are:

- Out of the MAB building pool, MAB1,2,7,8 and 10 can be equipped with PV systems[9] and are considered in use cases (i) and (ii).
- MAB3,4,5,6 and 9 cannot implement PV systems [8] and are considered in use case (iii) only.

4.1.1. Optimal PV system sizes

(i) Building Selection - Individual Approach

Fig. 8 shows the optimal PV system sizes for the individual buildings, which can be equipped with PV. Despite the available facade areas, only the buildings' roofs are used for PV installation due to the better solar irradiation compared to the facade areas. Of all the roof areas, the Northern roof parts harvest the least solar

[8] Reasons for not equipping buildings with PV are, for example: developed attic, personal reasons, prohibition, and so on.
[9] Whether PV is actually implemented is decided by the optimisation

Table 1
Default setting of individual buildings considered, MAB - multi-apartment building, HIST - historical building, SFH - single-family house. Further building information concerning the buildings' geometry can be found in Appendix C. The individual buildings' load profiles, resolved at 15-min intervals, are shown in compact shape in Appendix B.

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

[a] The buildings are considered having 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 [9].
[c] Orientation refers to the orientation of the buildings' saddle roofs.
[d] By assigning different businesses randomly to some of the buildings the load profile diversity is further enhanced.
[e] Background information concerning the different heating systems is provided in Appendix D.

irradiation. Nevertheless, for MAB2 it is profitable to also use Northern roof parts for PV system implementation due to the store's reasonable correlation to the sunshine hours. Generally, businesses with their high annual load and good correlation to sunshine hours enforce PV system implementation. The sum of individually optimal determined PV capacities for MAB1,2,7,8 and 10 is illustrated in Fig. 9 - (i) 'Building Selection - Individual Approach'.

(ii) Building Selection - EC approach

In this use case, MAB1,2,7,8 and 10 form an EC providing their

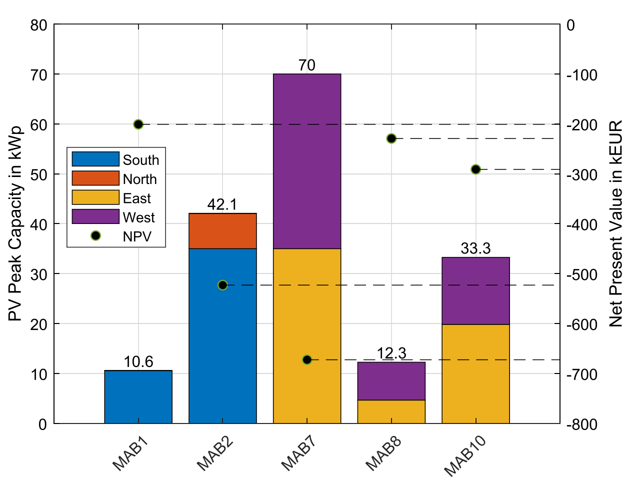

Fig. 8. Building-attached rooftop PV implementation for individual MABs.

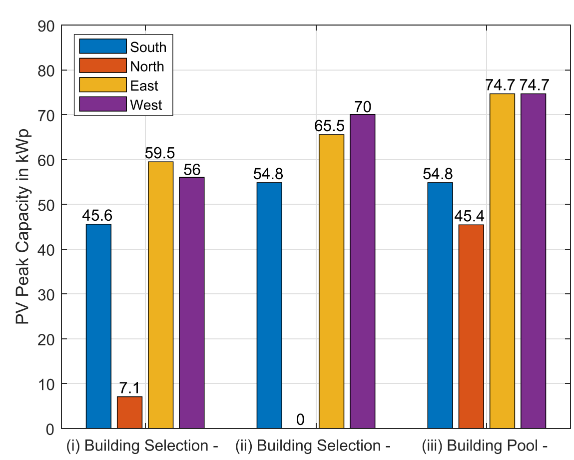

Fig. 9. Optimal building-attached rooftop PV implementation. Theoretical rooftop potential: 54.8 kW North/South and 74.7 kW East/West.

available facade and rooftop areas for community PV installation. It becomes immediately apparent when looking at Fig. 9 - (ii) ‘Building Selection - EC Approach’ that the Northern part of MAB2's roof is no longer used for PV implementation. As a result of the community approach, there are sufficient other rooftop areas with better solar irradiation available. Comparing situations (i) and (ii), the total PV peak capacity rises by more than 22 kW for the EC approach: PV systems' profitability increases due to synergy effects between the loads of individual buildings and also due to the possibility of using a variety of available rooftop areas. This increased amount of optimal PV system installation already indicates the added value of forming ECs.

(iii) Building Pool - EC Approach

In this use case, MAB3,4,5,6 and 9, which do not have the possibility of installing PV systems are taken into account as additional loads. Therefore, the optimal PV system sizes are determined for the whole building pool, whereas roof and facade areas of only five are available. This situation leads to a full usage of available Southern, Eastern and Western roof areas. In addition, the Northern parts of the available roofs are used to a large extent despite their weaker solar irradiation (see Fig. 9 - (iii) ‘Building Pool - EC Approach’). Therefore, the cost saving potential of this enlarged EC could be significantly increased by further buildings providing additional roof space.

4.2. Historical area

A total of 10 historical buildings are considered, as introduced in Table 1. For reasons of urban design and monumental protection PV system installations are difficult to realise in historical areas. Therefore, the following assumptions are made for this analysis:

- Out of the building pool, HIST1,5,7,9 and 10 can be equipped with PV systems [9] and are considered in use cases (i) and (ii), assuming that PV implementation is restricted to building-integrated rooftop PV for HIST5,7 and 9. HIST1 and HIST10 stand alone and have the possibility of also using the facade for building-integrated PV.
- HIST2,3,4,6 and 8 cannot implement PV systems [8] and are considered as additional loads in case study (iii) only.

4.2.1. Optimal PV system sizes

(i) Building Selection - Individual Approach

The modelling constraint of implementing PV systems building-integrated leads to additional basic roof and facade renovation costs. Therefore, the cost saving potential of PV and thus the optimal installed PV capacities are reduced. As basic facade renovation is significantly cheaper than roof renovation [28] [10], facade PV becomes financially more attractive despite the weaker solar irradiation compared to the roofs. The available Southern and Western facade parts of HIST1 and HIST10 are saturated with PV while roof parts are only used to a limited extent (Fig. 10). The sum of individually optimal determined rooftop PV capacities of HIST1,5,7,9 and 10 are illustrated in Fig. 11 - (i) ‘Building Selection - Individual Approach’.

(ii) Building Selection - EC Approach

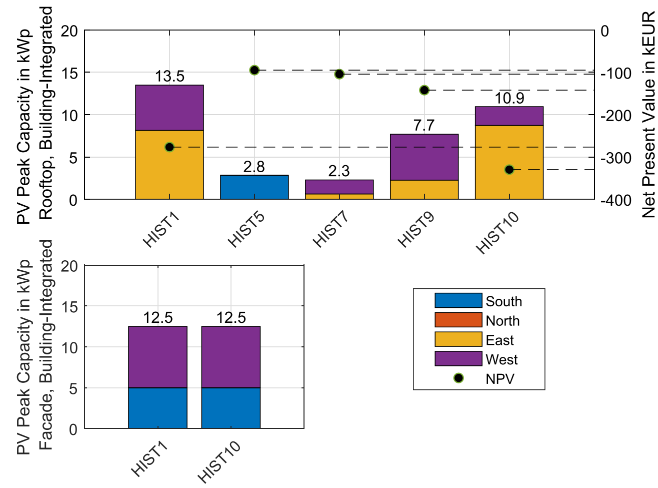

Fig. 10. Building-integrated rooftop/facade PV implementation for individual historical buildings.

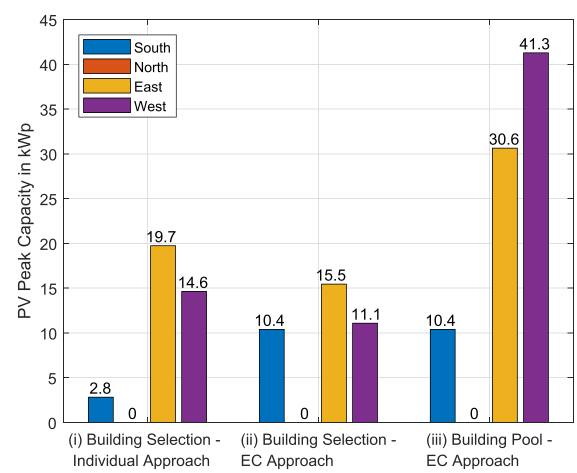

Fig. 11. Optimal building-integrated rooftop PV implementation. Theoretical rooftop potential: 10.4 kW North/South and 53.9 kW East/West.

In this case, HIST1,5,7,9 and 10 form an EC. According results of rooftop building-integrated PV implementation are shown in Fig. 11 - (ii) ‘Building Selection - EC Approach’. The available Southern and Western parts of the facades of HIST1 and HIST10 are again saturated with PV. Compared to the results for individual buildings, the Southern roof part of HIST5 is fully used by the EC as most solar irradiation can be harvested. Therefore, the optimal installed PV system capacities oriented East and West decline (worse solar irradiation compared to South).

(iii) Building Pool - EC Approach

In this use case, HIST2,3,4,6 and 8 also join the EC, wherefore optimal PV system sizes have to be determined for 10 historical buildings (see Fig. 11-(iii) ‘Building Pool - EC Approach’). Thereof, only five can provide building parts for PV installation. Southern roof parts and also Southern and Western facade areas of HIST1 and HIST10 are fully utilised. Compared to the use case (ii), the Eastern and Western PV implementation is more than doubled.

[10] The costs are listed in Table F.11.

4.3. Rural area

A total of 10 single-family houses are considered, as specified in Table 1. If possible, all rooftop and facade areas can be used for PV system implementation. The following assumptions are made:

- Out of the SFH building pool, SFH1,4,5,6 and 8 can be equipped with PV systems[9] and are considered in use cases (i) and (ii).
- SFH2,3,7,9 and 10 cannot implement PV systems [8]. These buildings are just considered in use case (iii).

4.3.1. Optimal PV system sizes

(i). Building Selection - Individual Approach

At first, only five single-family buildings (SFH1,4,5,6 and 8) are examined. The individually optimal determined PV system capacities, shown in Fig. 12, range between 2 kW and 3.3 kW. This result emphasizes how little roof space is needed for the cost-optimal PV system installation on individual single-family buildings. The positive influence of synergy effects, which would lead to higher optimal PV capacities, is clearly missing. The sum of individually optimal determined rooftop PV capacities of SFH1,4,5,6 and 8 is illustrated in Fig. 13 - (i) ‘Building Selection - Individual Approach’.

(ii). Building Selection - EC approach

In the second step, SFH1,4,5,6 and 8 form an EC, where the optimal PV system sizes are repeatedly determined by optimisation. The ratio between the total available rooftop area and the roof space used for optimal PV system implementation is about 10:1, which means that only a small part of the roof is needed for PV installation. In this case, the two Southern oriented roof parts of SFH1 and SFH5 are sufficient for optimal PV capacity implementation of 15.5 kW for five buildings as can be seen in Fig. 13 - (ii) Building Selection - EC Approach.

(iii). Building pool - EC approach

The third use case also takes the remaining single-family buildings into account. The optimal PV capacities are determined again for a load of 10 buildings, where just five can install PV. The results show that the Southern rooftop areas of SFH1 and SFH5 are now completely packed with PV, while a small amount of PV is also built on a Western-oriented roof. This leads to the conclusion that just three buildings are needed to install the cost-optimal amount of PV capacity for 10 single-family buildings (Fig. 13 - (iii) ‘Building Pool - EC Approach’).

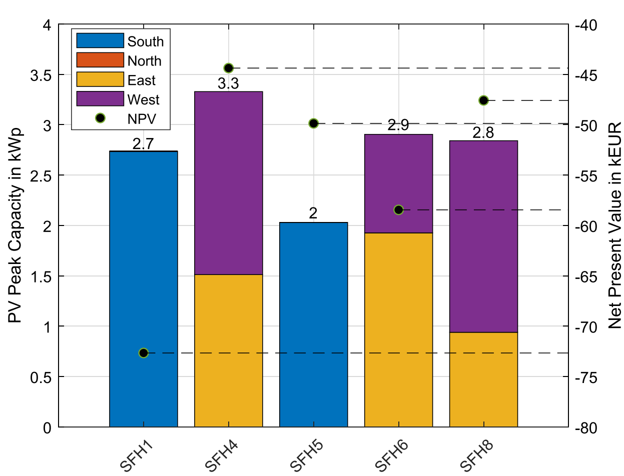

Fig. 12. Building-attached rooftop PV implementation for individual SFHs.

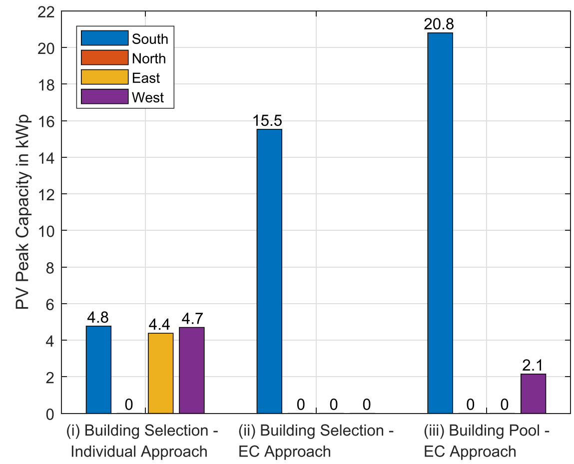

Fig. 13. Optimal building-attached rooftop PV implementation. Theoretical rooftop potential: 20.8 kW North/South and 28.5 kW East/West.

4.4. Mixed area: suburbia, city outskirts

The results for the mixed area, which is composed of single-family and multi-apartment buildings, are clearly dominated by the latter. The impact of forming an EC is especially positive for the multi-apartment buildings because the rooftops of single-family homes can be used for PV installation. These less informative results are provided in Appendix A. The cost saving potential of the mixed area, however, is also addressed in the following for the sake of completeness.

4.5. Cost saving potential for each settlement pattern

Table 2 compares the cost savings achievable by PV implementation for each SP and use case. Generally, the more different load profiles, the more synergy effects, and the more cost saving potential by installing PV. This is emphasised by the results of the multi-apartment building area. Multi-apartment buildings have a high cost saving potential, even when considering them individually (use case (i) where no EC is formed) because the total building load profile is already composed of multiple apartment load profiles. In comparison, the cost savings of individual single-family buildings is insignificant.

The added value of an EC can be determined by comparing use cases (i) ‘Building Selection - Individual Approach’ and (ii) ‘Building Selection - EC Approach’ for each SP. When forming an EC, synergy effects between different building load profiles enhance the cost saving potential of implementing PV. Furthermore, rooftop areas with different directions can be optimally used for PV implementation. The establishment of an EC is of greatest value for single-family buildings in the rural area because the cost savings rise by almost 5% compared to considering the buildings individually. For a multi-apartment building area, where individual buildings already profit from the impact of synergy effects between apartment load profiles, the added value of an EC is less than 1% in this case.

The cost saving potential of use cases (ii) ‘Building Selection - EC Approach’ is always higher compared to those of use cases (iii)

Table 2
Cost reduction.

	Cost savings in %		
Settlement Pattern	(i) Building selection - individual approach	(ii) Building selection - EC approach	(iii) Building Pool - EC approach
Multi-apartment building area	8.3%	9.2%	7.4%
Historical area	2.3%	3.3%	3.0%
Rural area	1.9%	6.8%	5.4%
Mixed area	7.7%	8.9%	8.5%

'Building Pool - EC Approach'. Taking into account the whole building pool with the restriction that only some of the considered buildings can implement PV, the limited rooftop/facade areas reduce the theoretically achievable cost saving potential significantly because more roof/facade space with reduced solar irradiation needs to be used to install PV. This effect becomes specifically obvious for the multi-apartment building area where the cost saving potential of use case (iii) is even lower compared to use case (i) with the buildings considered individually. In this situation forming an EC is only profitable for the buildings which cannot install PV. For the others which can install PV it would be more profitable to install PV individually and refrain from joining an EC with participants that cannot install PV.

4.6. Qualitative comparison of the results

Table 3 gives a concluding, qualitative overview of the results gained for the different SPs.

5. Sensitivity analyses

In addition to the basic results of cost-optimal PV system integration in individual buildings and ECs, sensitivity analyses in terms of installed technologies (Section 5.1) and the set-up of an EC (Section 5.2) are provided:

- Technology portfolio sensitivities comprise the evaluation of the impact of a battery (Section 5.1.1) and a hot water storage (Section 5.1.2).
- The varying set-up of the EC is addressed twofold: The rural area is altered by considering a large consumer in addition to the existing consumers (Section 5.2.1), and the original set-up of the multi-apartment building area is altered in terms of the building standard and heating system (Section 5.2.2).

Given that constant retail energy prices are assumed for the analyses in this study, the sensitivity of the results to retail energy price variations is important, as is the consideration of different interest rates. However, this work deliberately refrains from providing such analyses because they are already provided in Ref. [23] for a single multi-apartment building. These results are also transferable to communities: with rising retail electricity prices, the optimal PV system sizes rise due to the increasing cost saving potential. In contrast, for higher interest rates, optimal PV system sizes drop.

5.1. Technology sensitivities: effects of storage

5.1.1. Battery storage

This sensitivity analysis aims to evaluate whether a battery storage, either implemented for each building individually or for a community, can contribute in a positive way and increase the cost saving potential. Assuming investment costs of 500 EUR/kWh, battery storage is determined to be profitable by the optimisation. Table 4 shows the changes in optimal PV system sizes and NPVs for the multi-apartment building area. Optimal PV system capacities rise (in case additional space for profitable PV installation is available) as soon as a battery storage is installed. However, the cost saving potential is negligible. For example for MAB1, a storage of 10.6 kWh is cost-optimal; however, only 1100 EUR can be saved within 20 years. For an EC of five buildings (MAB1,2,7,8,10), the total cost saving potential is approximately 2900 EUR in 20 years. This value needs to be theoretically divided by the five different buildings, which contain 10 to 20 apartments each. In conclusion, in terms of absolute NPV values, the financial benefit from battery storage is insignificant for individual customers.

5.1.2. Hot water storage

The results for complementing a heat pump with a hot water storage system are shown for an individual building (MAB1) in Fig. 14 and an EC of five multi-apartment buildings (MAB1,2,7,8 and 10) in Fig. 15. Therefore it is assumed that the original heating

Table 3
Comparison of results.

Settlement Pattern	Use Case	No. of buildings considered/can be used for PV implementation	No. of buildings actually used for PV implementation	Roof(R)/Facade(F) used for PV implementation	Building-attached (BA)/ Building-integrated (BI) PV	Orientation of PV[a]	Cost Saving Potential[b]
Multi-apartment building area	(i)	5/5	5	R	BA	N/E/S/W	✓✓✓
	(ii)	5/5	5			E/S/W	✓✓✓✓
	(iii)	10/5	5			N/E/S/W	✓✓✓
Historical area	(i)	5/5	5	R/F	BI	E/S/W	✓
	(ii)	5/5	3			E/S/W	✓✓
	(iii)	10/5	4			E/S/W	✓
Rural area	(i)	5/5	5	R	BA	E/S/W	✓
	(ii)	5/5	2			S	✓✓✓
	(iii)	10/5	3			S/W	✓✓
Mixed area	(i)	6/6	6	R	BA	N/E/S/W	✓✓✓
	(ii)	6/6	6			E/S/W	✓✓✓
	(iii)	12/6	6			E/S/W	✓✓✓

[a] North - N, East - E, South - S, West -W
[b] [25]✓ - insignificant (> 0%–3%), ✓✓- ok (3 > %–6%), -✓✓✓ good (6 > %–9%), -✓✓✓✓ very good (9 > %).

Table 4
Comparison of results for the MAB area - without and with consideration of a battery storage.

	MAB1	MAB2	MAB7	MAB8	MAB10	Building Selection - EC Approach (ii)	Building Pool - EC Approach (iii)
Without storage							
Optimal PV capacity in kW	10.6	42.1	70	12.3	33.3	190.4	249.6
Maximum NPV in kEUR	−201	−523	−672.5	−229.3	−291.2	−1899	−3620.9
With storage							
Optimal PV capacity in kW	13.9	43.6	70	13.2	35.4	198.3	253.8
Maximum NPV in kEUR	−199.9	−522.8	−672.1	−228.8	−290.7	−1896.1	−3620.1
Optimal storage capacity in kWh	10.6	2.1	3.9	3.1	3.9	24.9	8.9

systems (as introduced in Table 1) of the considered multi-apartment buildings are changed to heat pumps. Moreover, it is assumed that building-attached facade PV systems can be installed if determined profitable by the optimisation. The modelling assumptions of the hot water storage are provided in Appendix E.

The implementation of a hot water storage is profitable in both cases: the optimal hot water storage capacity along with corresponding optimal PV and heat pump capacities are marked by the red dot in Figs. 14 and 15 for the single building and the community, respectively. Moreover, these figures contain a sensitivity analysis for different hot water storage capacities. To investigate the impact of increasing hot water storage capacity on the optimal PV system size and heat pump capacity, the capacity of the hot water storage is increased in 200 l steps[11], thus it is no longer an optimisation variable. Both figures show that the optimal installed PV capacities rise with increasing hot water storage capacity, while the necessary heat pump capacity decreases. The advantage of a hot water tank is that the heat demand at peak times does not need to be entirely covered by the heat pump but can additionally be covered by previously stored heat, therefore less heat pump capacity needs to be installed. In case an EC is considered (Fig. 15), optimal PV system sizes show less change compared to the case of an individual building in Fig. 14 because PV electricity can be used more efficiently right away in an EC due to synergy effects between buildings.

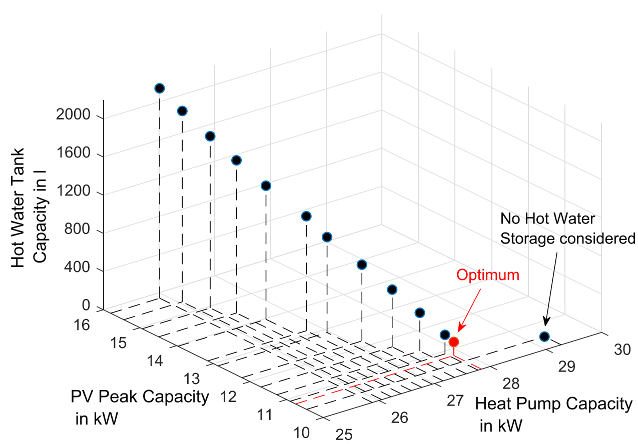

Fig. 14. Impact of different hot water storage sizes on optimal PV and heat pump capacity; Results for MAB1.

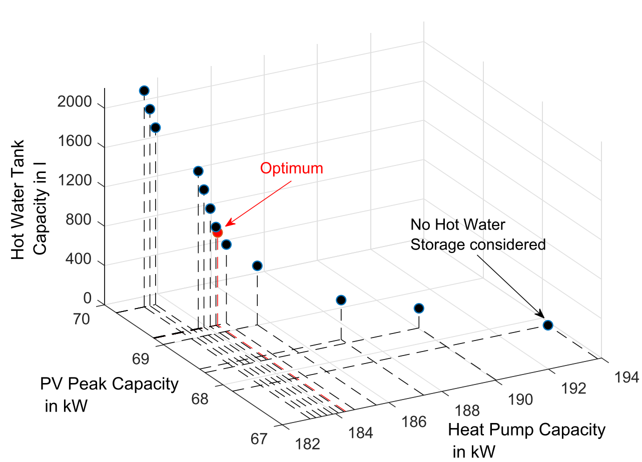

Fig. 15. Impact of different hot water storage sizes on optimal PV and heat pump capacities. The PV peak capacity depicted in this Figure is the one installed on the Western part of the facade. The Southern facade is fully saturated with PV in all cases (78.3 kW).

It has to be mentioned here that the optimal hot water storage capacity rises significantly in case rooftop PV systems are installed. Because of better solar irradiation on the rooftops, higher PV system capacities are installed due to increased profitability and therefore more PV electricity can be used for heat generation and thus be stored in the hot water storage. In the course of the sensitivity analysis provided in Section 5.2.2, optimal hot water tank capacities between 3000 l and more than 5000 l are determined for an EC of MAB1,2,7,8 and 10.

Generally, hot water storage as a supplement for heat pumps proves to be profitable, otherwise the optimisation would determine the optimal hot water storage capacity to be zero. Nevertheless, the cost saving potential is small, which is compatible with the results for a battery storage complementing PV systems.

5.2. Sensitivities of EC set-up

5.2.1. Impact of large consumers

To show the impact of considering large consumers, a dairy farm is taken into account for participation at the EC in the rural area. A standard load profile (Appendix B.21) is used for analysis and is scaled up to an average annual electricity demand of a dairy farm[12] of 22000 kWh.

In the first step, the optimisation is run for the dairy farm alone, to assess the amount of optimal PV implementation for such a large consumer. In case the farming-buildings are oriented North-South, an optimal Southern PV system size of 9.9 kW is determined. When

[11] 200 l steps have proven suitable for visualisation.
[12] This farm is assumed to consist of a large barn with an available rooftop area of 231 m^2 per direction and a farmhouse with an additional available rooftop area of 87 m^2 per direction. The latter is heated by gas, having a specific heat load of 145 kWh/m^2/yr.

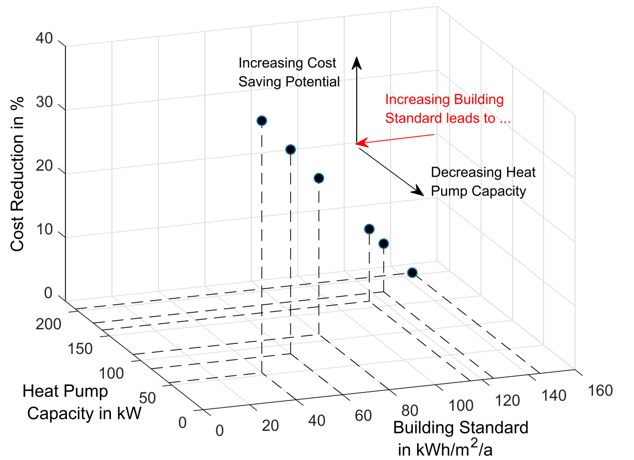

Fig. 16. Impact of improving the building quality of MAB 1,2,7,8 and 10 forming an EC.

they are oriented East-West, optimal PV system sizes of 6.4 kW (East) and 3.7 kW (West) are determined. The impact of considering the dairy farm in addition to the building pool of the rural area leads to the following results:

- Farming business oriented North-South: For the considered EC, it is optimal to install a total PV system capacity of 37.1 kW in the Southern orientation. The Southern part of the farming business's roof provides space for 53 kW, meaning that none of the other single-family buildings need to implement PV on their own rooftops.
- Farming business oriented East-West: In this case, a much smaller Southern rooftop is available, as just SFH1 and SFH5 are oriented North-South and can install PV systems (same assumption as in Section 4.3). Consequently, PV implementation on the most productive direction of South is constrained by the available rooftop area of these two single-family buildings, namely by 20.8 kW. Thus, additional PV capacities of 3.2 kW and 8.2 kW have to be installed in Eastern and Western directions to reach cost-optimality. Thus, three buildings are needed to accommodate the optimal amount of PV panels.

This analysis points out that it is not necessary for every single building to implement PV in order to achieve cost-optimality within an EC.

5.2.2. *Impact of building retrofit*

The sustainable development of the building sector requires a combination of passive retrofitting measures (e.g. insulation upgrades, change of windows) and increased efforts of implementing renewable energy to achieve an overall improved energy balance. To show the effects of improving the building quality, the community of MAB1,2,7,8,10 is assumed to having a specific heat load of 145kWh /m^2/yr initially. This initial heat load is then decreased step-wise[13], to 125kWh /m^2/yr, 115kWh /m^2/yr, 80kWh /m^2/ yr, 60kWh /m^2/yr until a passive house standard of 40kWh /m^2/ yr. It is assumed that the buildings' original heating systems are changed to a heat pump, which can be complemented by a hot water storage and, PV system implementation is possible if determined profitable by the optimisation.

Fig. 16 shows that improving the building standard leads to significantly reduced heat load and thus a smaller heat pump capacity. Consequently, a cost reduction of up to 40% can be achieved in the best case when the building standard is increased to 40kWh /m^2/yr. However [23], showed that passive retrofitting measures are not entirely profitable (without any financial incentives) because the monetary value of energy cost savings by improving the building standard does not compensate for the investment costs. To break even, costs for passive renovation measures must not exceed the NPV difference achieved by increasing the building standard. The maximum passive renovation costs to break even are given in Table 5.

Table 5
Maximum passive renovation costs to break-even.

Increasing the building standard	Maximum passive retrofitting costs to break even	
in kWh /m^2/a	Calculation	Absolute value in kEUR
145→125	$\|NPV_{145} - NPV_{125}\|$	190.5
145→115	$\|NPV_{145} - NPV_{115}\|$	285.6
145→80	$\|NPV_{145} - NPV_{80}\|$	618.5
145→60	$\|NPV_{145} - NPV_{60}\|$	808.3
145→40	$\|NPV_{145} - NPV_{40}\|$	997.6

6. Conclusion and outlook

The applied method of maximising the NPV to assess the profitability of PV sharing in ECs has proven suitable for this study. The definition of four characteristic SPs and the possibility of individualising buildings of different types makes the model widely applicable and leads to eloquent results. A comparison of results for individual buildings and their combination to ECs shows the actual added value of an EC.

The added value of an EC highly depends on the SP, the building types and also the participants. Forming an EC is most valuable for SFHs in rural areas, which can then profit from synergy effects between different load profiles. Generally, PV system implementation is most profitable the more heterogenous load profiles are considered. ECs implemented in MAB areas achieve the highest cost saving potential as a result of the variety of load profiles.

Participants providing large roof/facade areas can significantly contribute to increasing the cost saving potential for the whole community. This aspect is highly important when considering that some buildings might not have the possibility of installing PV. Moreover, results show that a cost-optimal PV system implementation does not require every building in a community to install PV. Thus, an optimal composition of participants for ECs would, besides a large variety of load profiles, also include buildings with large available roof/facade areas.

The results obtained in this study may be especially helpful to policy decision makers concerned with the diffusion of PV systems in the building sector and various building aggregates. In the near future, the quantification of the economic PV potential needs to be performed on a larger scale, and, top-down and bottom-up analyses are required to fully cover the complex case of energy sharing in ECs. Thus, there are various possibilities for future work:

[13] The downgrading of the specific heat load can be led back to an inventory of the existing housing stock in Austria conducted by Ref. [9].

- An upscaling of the cost saving potential of ECs on larger scale can be conducted. This might be of great importance as a future guide for EC development. The introduction of different SPs in this paper provides a solid basis for such an extended research, independent of a particular region.
- An EC might consist of consumers with different objectives, ranging from cost minimisation to self-consumption maximisation. The positive and also the negative aspects of different customer objectives might be worthy to be evaluated.
- The impact of buildings' cooling demand should be the focus of future analyses. It can be expected that the self-consumption rate of PV electricity generation rises significantly because the times of highest cooling demand correlate with the times of PV peak production. In this case, an increase of the optimal PV system sizes can also be expected.
- Finally, an integrated consideration of PV systems, different heating systems and retrofitting options is an important topic for future analysis and can provide guidance for future policy making.

Appendix A. Mixed Area

- SFH2,3,9,10 and MAB2,6 can be equipped with PV[9] and are considered in use cases (i) and (ii).
- SFH1,4,5,6,7,8 cannot implement PV systems[8] and are considered in use case (iii).

Despite the availability of both roof and facade areas, only the roof is used for PV installation (Fig. A.17). Forming an EC (comparing use case (i) and (ii)), leads to increased profitability: A more of 25 kW are installed and the Northern part of the roof doesn't need to be used anymore. Considering the whole building pool (iii) approximately 15 kW of additional PV is cost-optimal.

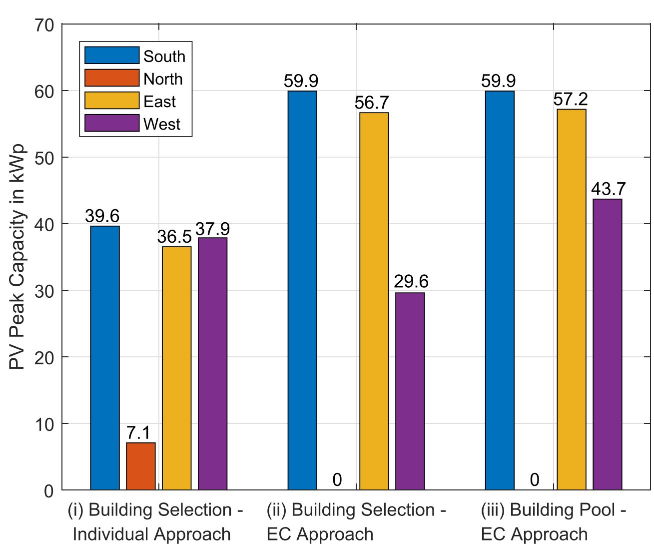

Fig. A.17. Optimal building-attached rooftop PV implementation. Theoretical rooftop potential: 59.9 kW North/South, 57.2 kW East/West.

Appendix B. Load Profiles

The load profiles - measured in 15-min intervals and presented as the average load for every hour of every day within one year - are shown in Figs. B.18, B.19, B.20.

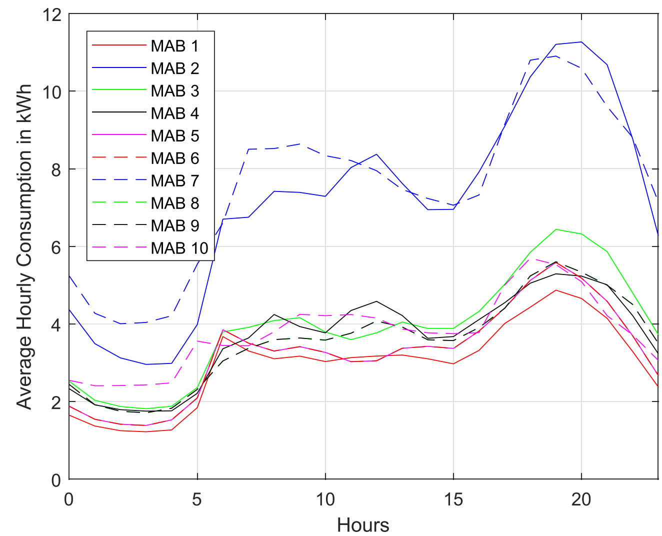

Fig. B.18. MABs

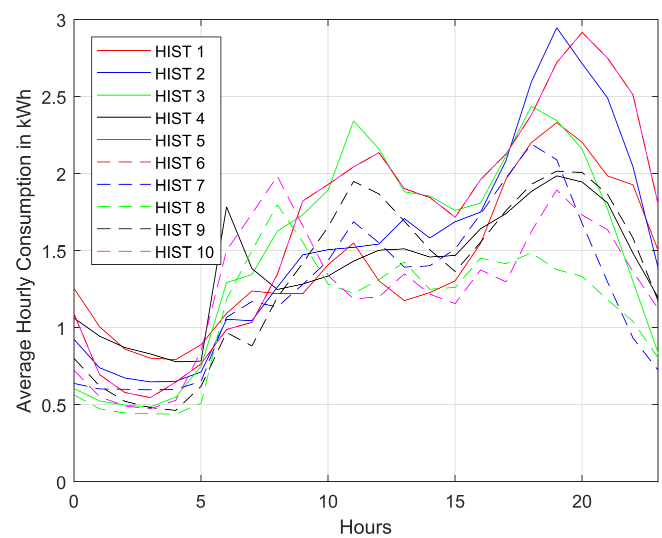

Fig. B.19. Historical buildings

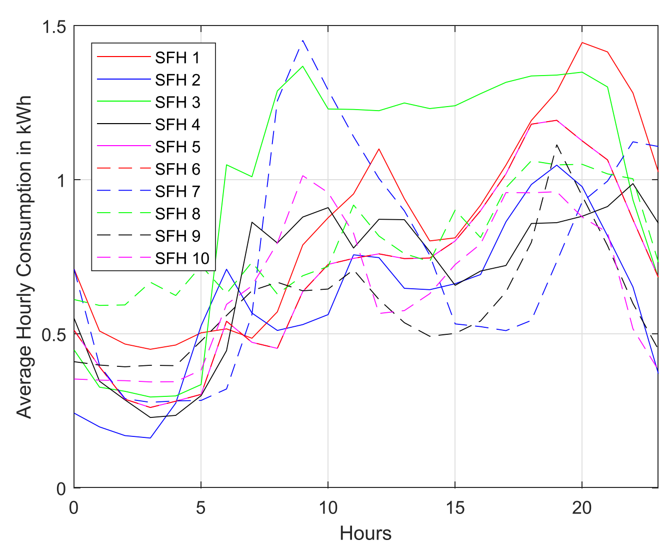

Fig. B.20. SFHs

Businesses (bakery - 500kWh /m² [57], gastronomy - 230 kWh /m² [67], grocery - 413kWh /m² [52], shops - 198kWh /m² [52], agricultural business - 22000 kWh [13]) are represented by standard load profiles [7], shown in Fig. B.21, normed to an annual load of 1000 kWh.

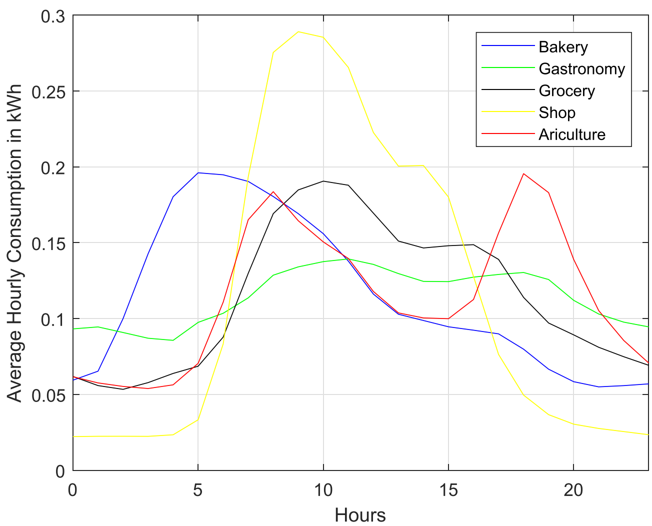

Fig. B.21. Businesses

Appendix C. Building Geometry

The building geometries for the buildings used in the analyses are provided in Tables C.6 C.7 and C.8. The facade areas need to be adapted by a mark-up coefficient of 0.5 to spare windows, doors and the area too close to the ground.

Appendix D. Heating Systems

Table D.9 shows the two most commonly used heating technologies per federal state.

Biomass is widely distributed in rural areas [10]. SFHs are mostly heated with oil, biomass or gas [61]. MABs are mostly heated by district heat and gas.

Table D.9
Heating system ranking [68].

Federal state	No.1 heating technology	No.2 heating technology
Burgenland	Wood	Gas
Vienna	Gas	District heat
Lower Austria	Gas	Wood
Upper Austria	District heat	Wood
Salzburg	District heat	Wood & Oil
Styria	District heat	Oil
Carinthia	District heat	Wood & Oil
Tyrol	Oil	Wood
Vorarlberg	Oil	Wood

Appendix E. Hot Water Storage

Hot water storage can be implemented as a supplement to a heat pump. If storing heat produced by the heat pump is profitable, then the optimisation model determines the optimal hot water storage capacity greater than zero. Then, the according installation costs are considered[14]:

$$I_{0\_hstor} = i_{0\_hstor} \cdot Cap_{hstor\_l}, \tag{E.1}$$

Abbreviations and technical data concerning the hot water storage is given in Table E.10. The hot water storage is modelled such that

Table C.6
SFHs

Building Type	Roof area in m²	Facade areas[a] in m²	Floor space in m²	No. of storeys	Buildings
1	92	60/48	80	2	SFH2, SFH6
2	124.8	72/54	108	2	SFH1, SFH4, SFH5, SFH8, SFH9
3	174	90/60	150	2	SFH3, SFH7, SFH10

[a] Notation: Area of one of the long sides of the building/area of one of the broad sides of the building.

Table C.7
MABs

Building Type	Roof area in m²	Facade areas in m²	Floor space in m²	No. of storeys	Buildings
4	238	340/240	160	5	MAB1, MAB3, MAB4, MAB5, MAB8, MAB9, MAB10
5	420	600/240	277	5	MAB2, MAB6, MAB7

Table C.8
Historical buildings

Building Type	Roof area in m²	Facade areas in m²	Floor space in m²	No. of storeys	Buildings
6	124.8	72/54	108	3	HIST2, HIST3, HIST5, HIST6, HIST8, HIST9
7	174	90/60	150	3	HIST1, HIST4, HIST7, HIST10

[14] 1 Dollar equals 0.88 Euro (February 2019).

- The state of charge (SoC) is determined by the SoC of the previous time step plus heat inflow minus heat outflow of the actual time step. Charging/discharging and stand-by losses are considered as listed in Table E.10.
- The SoC has to be smaller or equal to the hot water storage's capacity.
- The heat discharge at every point in time has to be less than or equal to a quarter of the heat storage's total capacity. So, the hot water storage cannot be discharged at a single time step.

The optimal determined hot water storage capacity in this model has the unit kWh. Usually, hot water storage capacities are specified in the units litre(l) or m^3, therefore the following conversion is applied to approximately determine the size of the hot water storage in litre rather than kWh [62]:

$$Cap_{hstor\_l} = \frac{Q}{\underbrace{(T_{out} - T_{back})}_{\Delta T} \cdot c_w}, \tag{E.2}$$

The outflow temperature is assumed with 50°C. The minimum backflow temperature of water has to be higher than the set-point indoor-temperature of 20°C and is therefore assumed to be 25°C.

Table E.10
Empirical scaling and assumptions for the hot water storage

Specification	Abbreviation	Value/Unit
Charging/Discharging efficiency [a]	η_{load_hstor}	98%
Stand-by efficiency	η_{sb_hstor}	99.9%
Outflow temperature	T_{out}	50°C
Backflow temperature	T_{back}	25°C
Temperature delta	ΔT	25°C
Specific investment costs	i_{0_hstor}	4130$ /m^3[48]
Specific heat capacity of water	c_w	4.182 kJ/kgK
Hot water storage capacity	Cap_{hstor_l}	kg or l [b]
Heating storage capacity	Q	kWh

[a] Compliant with [55] when assuming learning e_ects and further technology development.
[b] 1 kg of water equals 1 l approximately.

Appendix F. Cost Assumptions

The costs and technology data are listed in Tables F.11 and F.12. More detailed explanations regarding the cost assumptions can be found in Ref. [23].

Table F.11
Cost assumptions

Specification	Type of Costs	Costs
Rooftop PV, building-attached	Specific investment costs	1050 EUR /kW_p
	Cleaning costs	15 EUR /kW_p/yr
	Operational costs	60 EUR/yr
Facade PV, building-attached	Specific investment costs	1050 EUR /kW_p
	Cleaning costs	30 EUR /kW_p/yr
	Operational costs	60 EUR/yr
Rooftop PV, building-integrated	Specific investment costs	1110 EUR /kW_p
	Cleaning costs	15 EUR /kW_p/yr
	Operational costs	60 EUR/yr
	Basic roof renovation costs	148 EUR /m^2
	Brick costs	40 EUR /m^2
Facade PV, building-integrated	Specific investment costs	900 EUR /kW_p [a]
	Cleaning costs	30 EUR /kW_p/yr
	Operational costs	60 EUR/yr
	Basic facade costs	18 EUR /m^2
	Costs for the skim	73 EUR /m^2
Battery Storage	Specific investment costs	500 EUR/kWh
Heat pump	Specific investment costs	1000 EUR/kW
	Maintenance costs	300 EUR/yr
District heating	Connection costs	5000 EUR
	Annual fixed costs	3.0516 EUR /m^2/yr
	Costs for heat cost allocator	130 EUR/yr
	Costs for district heat	0.047 EUR/kWh
Pellets heating	Specific investment costs	600 EUR/kW
	Maintenance costs	300 EUR/yr
	Pellet costs	0.28 EUR/kg
Electricity	Variable costs	0.22 EUR/kWh
	Fixed Costs	65 EUR/yr
	Surplus PV feed-in revenues	0.03 EUR/kWh
Gas heating	Variable costs	0.05 EUR/kWh
	Fixed costs	150 EUR/yr
Oil heating	Variable costs	0.0912 EUR/kWh
	Fixed costs	150 EUR/yr

[a] [26] states that prices for BIPV systems vary between 100 EUR /m^2-150 EUR /m^2 for a thin film PV cold facade and 750 EUR /m^2 for a high end PV solar shading system. A price of 150 EUR /m^2at the lower end of the price range is assumed due to learning effects since 2015. With the conversion factor of 6 m^2 /kW (1.5m^2 per 0.25 kW), the specific costs of 900 EUR/kW arise.

Table F.12
Further relevant empirical assumptions

PV systems	
Module efficiency	17%
Additional losses	20%
Module size	$1.5m^2$
Module capacity	0.25 kW
Battery Storage	
Charging and discharging efficiency	98%
Stand-by efficiency	99.9%
Pellets heating	
Pellet heating value	5 kWh/kg
Efficiency	90%
Interest rate	3%

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