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On the Profitability of PV Sharing in Residential Energy Communities

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Abstract

The European climate and energy framework requires significant cuts in greenhouse gas emissions, a substantial increase in the shares of renewable energy as well as considerable improvements in energy efficiency until 2030. The increased deployment of renewable energy communities could contribute significantly to achieving these targets. Therefore, this thesis aims to provide a comprehensive assessment of the profitability of photovoltaic (PV) electricity sharing in residential energy communities of different scales. System analysis is used as the approach to modelling energy communities and a mixed-integer linear optimisation model is developed with the objective of maximising the energy community's net present value over a time horizon of 20 years. Thereby, the cost-optimal PV installation capacities are determined. The results demonstrate that PV electricity sharing can in general be considered economically viable for energy community participants, even under circumstances which clearly lead to a reduction in financial benefits, such as third-party financing. The actual added value of adopting PV sharing concepts instead of considering PV implementation in buildings individually does heavily depend on the settlement pattern and the according building stock. Apart from the obvious advantages of installing PV systems, such as an increase in the share of renewable energies and the resulting reduction in CO_2 emissions, investments in classical building renovation measures are expected to be triggered. The positive financial impact of PV systems reduces the monetary gap of thorough building retrofit towards break-even. This effect would be further enhanced by internalising external costs for CO_2 emissions and could eventually peak in an actual break-even of thorough building retrofit in some cases. Thus, it can be concluded that the increased diffusion of PV in buildings and the realisation of energy communities on a large-scale might be a valuable asset for turning the building sector towards sustainability in the future. In Austria, it might even be possible to achieve the 2030 climate goals - in terms of necessary PV installation capacities - in a cost-optimal way in the residential building sector only.

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Kurzfassung

Der europäische Klima- und Energierahmen erfordert bis 2030 eine deutliche Senkung der Treibhausgasemissionen, eine signifikante Erhöhung des Anteils erneuerbarer Energien sowie erhebliche Verbesserungen der Energieeffizienz. Eine verstärkte Realisierung von Energiegemeinschaften könnte wesentlich zum Erreichen dieser Ziele beitragen. Diese Arbeit bietet eine umfassende Wirtschaftlichkeitsbewertung der gemeinsamen Nutzung von PV-Anlagen und des gemeinschaftlich erzeugten PV-Stroms in Energiegemeinschaften. Es werden Energiegemeinschaften unterschiedlicher Größenordnungen beleuchtet. Der gewählte Ansatz zur Modellierung von Energiegemeinschaften ist die Systemanalyse. Es wird ein gemischt-ganzzahliges lineares Optimierungsmodell entwickelt, das zum Ziel hat, den Barwert einer Energiegemeinschaft über einen Zeitraum von 20 Jahren zu maximieren. In diesem Zusammenhang werden die kostenoptimalen PV-Installationskapazitäten bestimmt. Die gemeinsame Nutzung von PV-Strom in Energiegemeinschften hat sich als wirtschaftlich tragfähig herausgestellt, selbst bei Fremdfinanzierung, welche die Wirtschaftlichkeit von Investitionen schmälert. Der tatsächliche Mehrwert der gemeinsamen Nutzung von PV-Anlagen anstelle einer individuellen Implementierung in Gebäuden hängt stark von der betrachteten Besiedlungsstruktur und dem Gebäudebestand ab. Neben den offensichtlichen Vorteilen der Installation von PV-Anlagen, wie der Erhöhung des Anteils erneuerbarer Energien und der damit einhergehenden Reduktion der CO_2-Emissionen, ist zu erwarten, dass Investitionen in klassische Gebäudesanierung beanreizt werden. Die positiven monetären Auswirkungen von PV-Anlagen verringern den gesamtheitlichen finanziellen Aufwand einer umfassenden Gebäudesanierung. Dieser Effekt würde durch die Internalisierung externer Kosten für CO_2-Emissionen noch verstärkt werden und könnte in einigen Fällen sogar im Break-Even einer gesamtheitlichen Gebäudesanierung gipfeln. Daraus kann geschlossen werden, dass die verstärkte Durchdringung von PV-Anlagen und die flächendeckende Realisierung von Energiegemeinschaften wesentliche Aspekte sind, um Nachhaltigkeit im Gebäudesektor zu erreichen. Auf österreichischer Ebene könnten die im Rahmen der Klimaziele bis 2030 notwendigen PV-Kapazitäten unter dem Gesichtspunkt der Kostenminimierung sogar ausschließlich im Wohngebäudesektor realisiert werden.

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1. Introduction

1.1. Motivation

Climate change has evolved to one of the world's most pressing issues that can only be effectively addressed globally. To that end, the first universial and legally binding climate action framework, known as the *Paris Agreement*, was adopted in 2015 and came into force the year after. The goal is to make global emissions peak as soon as possible in order to keep the average global temperature increase well below 2 % above pre-industrial levels [39]. Based on that, individual countries that ratified the agreement undertake to achieve national targets within a specified time frame. Within the European Union, the *Climate and Energy Framework* [37] schedules a cut of 40 % in greenhouse gas emissions, an increase in renewable energy shares to 32 %, and an inprovement in energy efficiency of 32.5 % by 2030.

Currently, wind and hydro power predominantly contribute to renewable electricity generation in the European Union [44], followed by solar photovoltaics (PV). For the purpose of further increasing the share of renewable electricity generation on a short-term basis until 2030, the PV technology might be the most promising solution due to short implementation times and wide social acceptance. Basically, PV systems can either be implemented ground-mounted or attached to or integrated in buildings. The latter option has multiple obvious advantages. On the one hand, the shares of on-site electricity generation and direct consumption are increased, thereby counteracting an increased stressing of the grid which is usually caused by the volatile behaviour of renewables. On the other hand, a further use of land is prevented.

Another reason to enforce PV system integration in buildings directly is the fact that the building sector accounts for approximately 36 % of CO_2 emissions and 40 % of the total energy consumption [38] in Europe. These numbers are not surprising when considering that 75 % of the building stock is energy-inefficient and only 0.4 %-1.2 % is retrofitted every year [38]. Increasing the shares of PV systems in buildings might also trigger investments in thorough

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building retrofit, such as building envelope renovation and changing the heating system. Combining PV system implementation with heating system upgrades and renovation measures to increase the building standard at the same time raises the overall value of building retrofit. Put into practice, the building sector would not only be able to contribute to achieving the European 2030 targets by increasing the shares of renewable energy generation and reducing emissions, but also by enhancing energy efficiency.

Despite the multiple positive effects, the diffusion of PV systems in the building sector can only account for slow progress at a global level. Considering PV integration in single-family builings, only countries with high retail electricity prices and/or above-average solar irradiation such as Australia, or countries with extensive subsidies such as Germany, record significant shares. Moreover, PV system implementation needs to spread beyond the border of single-family houses to have significant influence on climate change. Therefore, recent trends point towards PV sharing concepts in multi-apartment buildings or energy communities between multiple buildings. Until recently, however, the actual implementation of PV sharing concepts was prevented by the missing legislative and regulatory background in many countries.

Meanwhile, many countries have managed to adapt their legislation, and PV sharing concepts can be put into practice, at least to some extent. In Austria for example, amendments of the *Electricity Industry and Organisation Act* [110] that came to force in 2017, allow the shared use of PV systems in buildings with more than one unit. The implementation of energy communities beyond the border of individual buildings on the contrary is not yet legally anchored. In principle, however, the establishment of energy communities between multiple building can be described as a 'grey area'. The *Electricity Industry and Organisation Act* states that the precondition for establishing an energy community is a common grid connection point. And since the legislation does not explicitly limit energy communities to a single property [135], PV sharing concepts could theoretically be also implemented between multiple buildings, in case the public grid is not used for PV electriciy transfer [1]. This excursion into the current situation of the Austrian law shows immediate need

[1] At the same time, however, the implementation of so-called sub-grids is strongly discouraged.

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for action to facilitate the implementation of energy communities by providing a clear regulatory background. Therefore, a set of rules concerned with the implementation of citizen energy communities [41] and renewable energy communities [40] will be provided in the course of 2020 and 2021, respectively.

Besides the ill-conceived or even missing regulations concerning the implementation of energy communities, the reasons for the low implementation rate of building-attached/integrated PV systems are multiple. On the one hand, there is the people's lack of PV system awareness in general. Often, comparably low retail electricity prices do not provide sufficient incentives to look into substitutes to electricity from the public grid. On the other hand, PV system implementation is tied to significant upfront investments. High investment costs in combination with a relatively low retail electricity price and a cimate with non-excessive solar irradiation raises the question of the economic viability of implementing PV in residential buildings. Due to these reasons, the PV system technology has remained a technology reserved for wealthy single-family home owners so far. However, to increase PV system diffusion in the building sector up to significant shares, the majority of the population would be needed to participate in installing PV systems and sharing on-site electricity. At the same time it is reasonnable to not only think about sole PV system implementation, but a combination with thorough building retrofit. Implementing renewable energy in buildings is noble on the one hand, but wasting energy due to low building standards on the other hand at the same time would be contradictory.

Based thereon, the overall goal of this thesis is to examine whether PV system implementation in buildings and PV sharing concepts are profitable for energy community participants. Thereby, a specific focus is laid upon a variety of building and energy community set-ups. In the context of implementing PV sharing concepts in buildings, this thesis additionally builds a bridge to the topic of thorough building retrofit, including building envelope renovation and/or a heating system change. Moreover, the issue of third-party financing options to possibly decrease the financial barrier to investments is tackled.

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1.2. Research questions

This thesis is built upon posing four major research questions and is therefore subdivided into four major parts. Each part addresses one specific aspect within the general topic of the profitability of shared PV systems in energy communities. The answers to all four research questions are published in international scientific journals with peer-review process.

The specific research questions are introduced in detail in the following and are graphically illustrated in Figure 1.1. Moreover, Figure 1.1 shows how the individual follow-up questions have evolved from the initial research question.

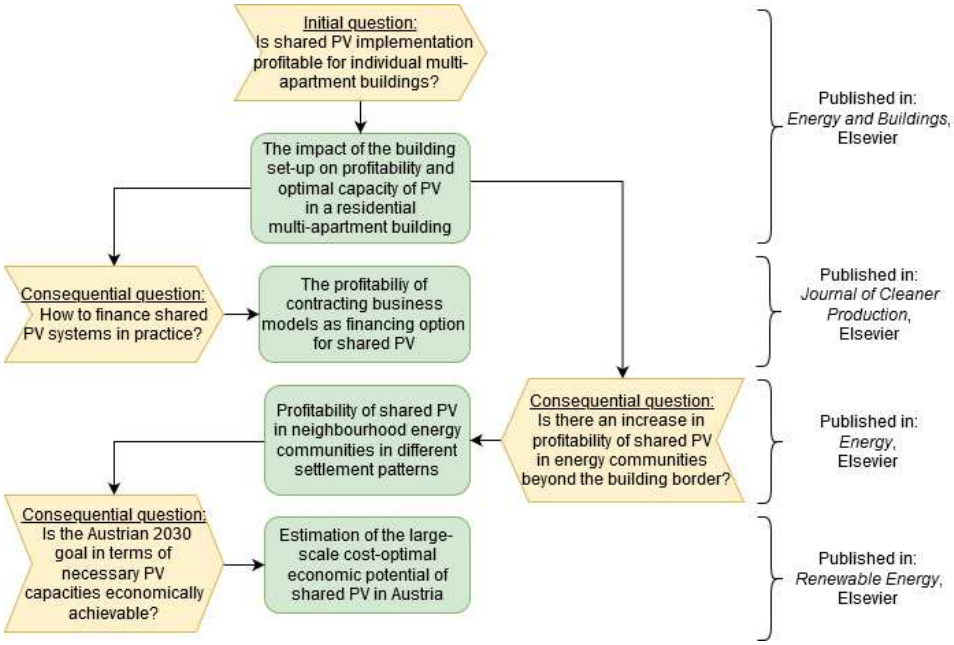

Figure 1.1.: Research questions and corresponding journal articles.

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Initial Core-Research Question

The legislative amendments in some countries, which enable the concept of sharing PV electricity at least in multi-apartment buildings, now raise the core question whether such concepts are profitable for the building's residents. This basic question triggers multiple sub-questions concerning the impact of

- the building set-up (orientation, roof tilt, tenant portfolio, heating system and building standard),
- the PV system itself (building-attached or building integrated on different parts of the building skin), and
- cost-related factors (electricity price developments, additional costs for CO_2 emissions and interest rates).

Therefore, the first part of this thesis tries to provide answers to these questions by determining the maximum net present value and optimal capacity of a shared PV system in a residential multi-apartment building for the use case of Austria. An according journal article is published in *Energy and Buildings* [50], Elsevier.

Based on the inital research question, two consecutive questions occurred. The first central issue regards the topic of PV system financing, the second crucial question concerns energy communities formed beyond the border of an individual multi-apartment building.

Consecutive research question - Financing

Investments in PV systems, and especially combined investments in PV systems and additional renovation measures, are tied to significant upfront investment costs. However, a significant number of building/apartment owners do not have the monetary capacity of bearing significant investments, which is confirmed by the low shares of building retrofits every year [38]. Thus, solutions need to be found to still enable investments in PV systems and upgrades of the building envelope. This raises the question about third-party financing options. Thus, the second part of this thesis elaborates on the profitability of contracting business models for PV system financing, as well as combined investments in PV systems and conventional renovation measures. The corresponding journal article is published in *Journal of Cleaner Production* [53],

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Elsevier.

Consecutive research question - Neighbourhood energy communities

The initial research question concerns the profitability of a small-scale energy community in an individual multi-apartment building. As a logical consequence, the follow-up question whether extending energy communities beyond the building border has a positive impact on the profitability of PV sharing concepts needs to be posed. The third part of this thesis provides an answer to this question by investigating neighbourhood energy communities of four typical Central European settlement patterns. Doing so, the impact of different building types being part of an energy community can be evaluated. A corresponding journal article has been published in *Energy* [51], Elsevier.

Consecutive research question - Country scale

With respect to the country specific climate goals, Austria has defined the ambitious target of achieving a 100 % renewable electricity supply until 2030. A variety of studies such as [49] and [128] estimate the necessary renewable installation capacities to be able to achieve this target. In terms of PV capacities approximately 10 GW are estimated for Austria. This raises the question whether said amount of PV capacity could be achieved in a cost-efficient manner in the residential building sector only. The fourth part of this thesis aims to provide an answer to this question by estimating the large-scale cost-optimal economic PV potential on the basis of neighbourhood energy community optimisation. The effective feasibility is then examined by estimating the geographical potential. The according journal article is published in *Renewable Energy* [52] , Elsevier.

1.3. Structure of the thesis

Based on the research questions outlined above, the remainder of this thesis is structured as follows.

Chapter 2 provides a selection of important scientific literature for all topics tackled in the course of this thesis. The main focus of the literature review lies on work related to the general topic of the profitability of PV sharing

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concepts in buildings and the modelling of energy communities. In addition, literature elaborating on topics such as building retrofitting, contracting as a financing option, and the potential of PV in the building sector is presented. Finally, this thesis' contribution to the current knowledge is presented.

Chapter 3 elaborates on the question of the profitability of a shared PV system and according optimal PV system sizes in a small-scale energy community within an individual multi-apartment building. Thereby, the impact of the building-set up, PV system variations and cost-related factors is quantified.

Being tied to a significant amount of upfront investment costs, Chapter 4 tackles the issue of contracting as a possible financing option for PV system installation. It is elaborated whether such business concepts are economically viable for both parties, the contractor and the building owner/ building residents. In this context, not only PV contracting is addressed, but also renovation contracting to increase the building standard. A special focus is given to the impact of costs for CO_2 emissions.

The aim of Chapter 5 is to investigate the positive impact of expanding energy communities from the border of a single building to multiple buildings. The added value of forming neighbourhood energy communities, compared to implementing PV in individual buildings, is determined. Thereby, energy communities in four typical Central European Settlement Patterns are investigated in order to assess the impact of different building types in different geographical situations.

Chapter 6 finally provides an estimation of the large-scale cost-optimal economic PV potential in the residential sector for the country of Austria, based on neighbourhood energy community optimisation in different settlement patterns. To that end, an algorithm assigning individual buildings within a political district to settlement patterns and further to energy communities is introduced. Based on that, reasonable upscaling can be performed.

The obtained results provided in the course of Chapters 3 to 6 are discussed in Chapter 7. Moreover, Chapter 7 is used to emphasize the strengths of the applied method, as well as to discuss its limitations. Finally, implications for

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future regulation and policy making are derived.

Chapter 8 concludes and provides an outlook upon possible future research topics and consequential questions arising from the research conducted in this thesis.

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2. State of the art and progress beyond

Following the introductory chapter that derives the motivation for this work and the according reasearch questions, this chapter aims at providing the scientific background this thesis is built upon. Since the detailed definition of the reasearch questions shows that the general topic of *PV sharing in energy communities* is tied to a variety of related sub-topics, an overview of all fields of research tackled in the course of this literature review is provided in Figure 2.1.

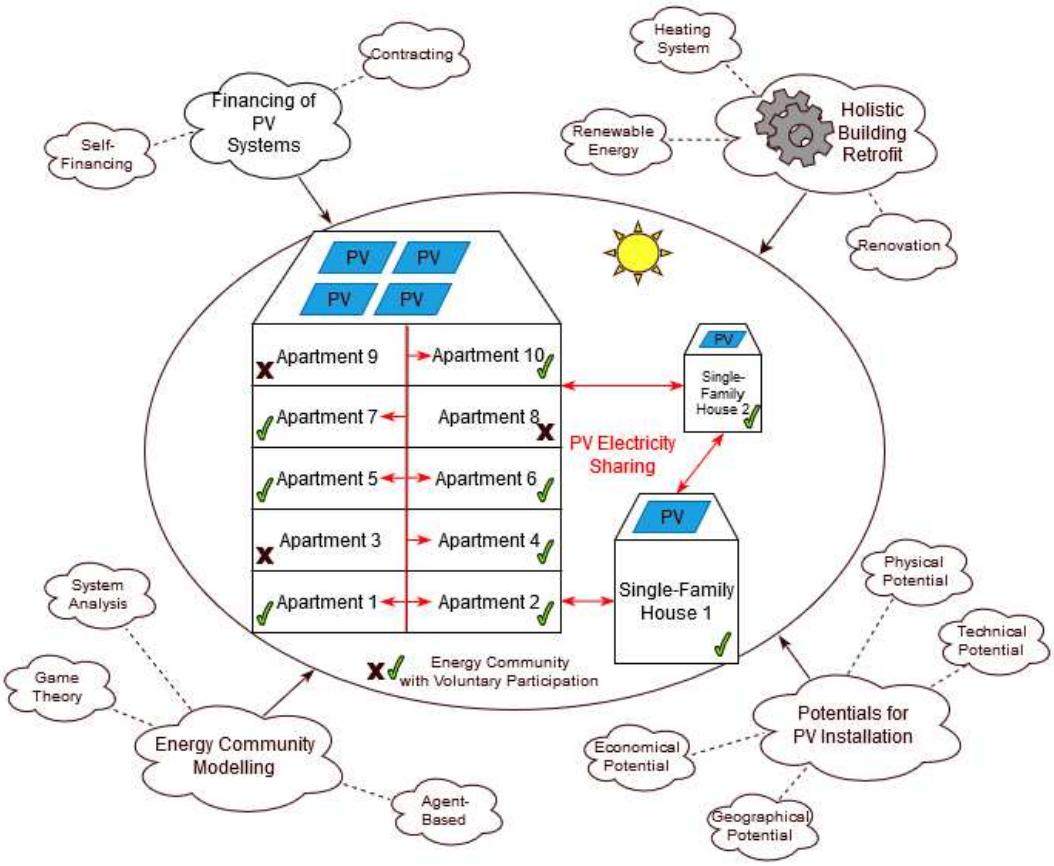

Figure 2.1.: Overview of topics tackled in the course of this thesis.

Based on the fields of research illustrated in Figure 2.1, the following liter-

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ature review is split in subsections with different focus.

- Section 2.1 is dedicated to the topic of PV in single-family buildings which can be described as the starting point of PV deployment on larger scale. Early adopters of the PV technology in the single-family house sector enabled further developments and learning rates, resulting in the actual possibility of implementing PV sharing concepts these days.

- The second part of this literature review elaborates on different aspects concerning PV sharing in energy communites as well as topics related to the actual implementation of such. Section 2.2 can be divided into three major parts.

  1. Section 2.2.1 covers scientific literature that elaborates on energy communites of different scales. Thereby, a special focus lies on literature taking into account various aspects of related costs and profitability.

  2. Since the set-up of energy communities and related investments in renewable technologies pose a financial burden, Section 2.2.2 focuses on thrid-party financing options. A selection of relevant scientific literature concerning the application of contracting business models is provided.

  3. Another important aspect of PV sharing in energy communities is the actual available potential for PV implementation on/in buildings. To that end, Section 2.2.3 discusses literature concerned with the different classifications of PV potentials and their assessment.

- Attaching PV systems to the building, or integrating them in the building envelope, is also known as active building retrofit. In terms of achieving sustainable building performance that goes beyond renewable energy implemenation alone, Section 2.3 elaborates on the different possibilities of retrofitting a building, including building envelope renovation and changing the heating system.

- Since there is more than one possibility to energy community modelling, Section 2.4 focuses on literature that can be found in this specific field of research. Generally, three basic options to modelling an energy commu-

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nity can be defined: (i) game theoretical modelling, (ii) explicit agent-based modelling and (iii) system analysis.

- Most importantly, Section 2.5 elaborates on this thesis' progress beyond the state of the art in scientific literature with respect to the provided literature review.

2.1. Residential PV in single-family buildings - The starting point for PV deployment in the building sector

The photovoltaic technology itself dates back to 1954, with the first solar cell capable of converting a sufficient amount of solar energy into power to supply electrical equipment. In 1973, the world's first photovoltaic powered residence is built by the University of Delaware, and 5 years later, in 1978, the world's first village PV system is installed by a NASA-spinoff for the purpose of remote area electrification. After significant developments in the solar cell technology the following years, encompassing cost decrease along with efficiency increase, the first households decide to invest in a residential PV system around the year 2000 [159]. From this point on, the learning effects and the therefrom further derived cost reductions have increased PV system's affordabiliy in the private sector ever since. Scientific literatre also contributes to this development by publishing studies which tackle different topics concerning PV in single-family buildings, such as potentials [31], energy performance [117], profitability [78,81] and net zero energy aspects [62, 103, 153][1].

With the increased efforts to enhance the shares of renewable energy in the system, a variety of concepts are developed to support PV implementation in residential buildings. The most widely spread support scheme for PV systems is the feed-in-tariff (FiT). At the early stages of PV system deployment FiTs are realised such that the whole amount of generated PV electricity is fed into the grid for a predefined remuneration per kilowatt-hour, whether or not the

[1] Due to the scope of this thesis, a more detailed literature review concerning PV in single-family buildings is not provided.

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PV system is a stand-alone ground-mounted one, attached to or integrated in a building. In case of building-attached/integrated PV systems, this meant a feed of PV electricity into the grid, just to buy the electricity back at the same point in time for load coverage. Especially with increasing shares of renewables in the electricity system, causing significant challenges for maintaining reliable grid operation due to the fluctuations in the generation profiles, the original realisation of full-feed-in PV in buildings would need some afterthought.

Since PV generation in the private sector is becoming more and more cost-efficient due to decreasing PV installation costs, the need for subsidies and high feed-in tariffs is reduced and grid-parity is achievable in many countries already. Based thereon, the topic of implementing PV systems in residential buildings and using the self-generated electricity for load coverage directly comes to the fore. Then, only the surplus PV electricity is fed into the grid and remunerated accordingly. The development described - namely that at some point it is more profitabile to self-consume the generated PV electricity than feeding the entire PV generation into the grid - is another milestone in the direction of today's developments in the energy community sector.

2.2. PV sharing in residential energy communities

2.2.1. Different scales of energy communities

When discussing to enhance the shares of renewable electricity generation in the residential building sector to significant levels, PV installations on single-family buildings only might not be sufficient. However, until recently, PV system installation was restricted to single-family buildings by the means of law. Within the last years, some countries have managed to pass according bills to also enable the realisation of energy community concepts.

So far, however, there is no simple or uniform definition of energy communities. However, what can certainly be said about energy communities is that the goal of on-site renewable energy generation and consumption is pursued

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and that there is a strong focus on the end-user side. Moreover, energy communities are neither limited to a specific geographical scale in theory, nor is participation a binding contraint. These characteristics are probably the most outstanding differences to the well-known microgrid concept. The microgrid approach rather focuses on local generation units which do not need to be renewable and provides the possibility to operate in island mode without active connection to the electricity grid. This enforces participation of all residents within the perimeter of a microgrid.

As mentioned above, the multifarious concept of energy communities (ECs) is not limited to a certain scale. Theoretically, three different scales of ECs can be defined as illustrated in Figure 2.2. Small-scale ECs are characterised

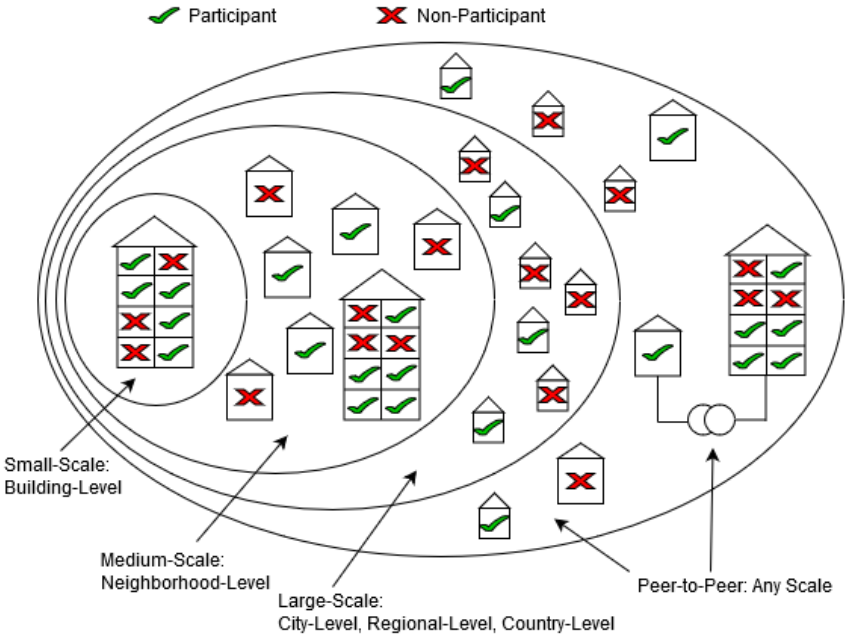

Figure 2.2.: Energy communtiies from small to large scale.

by being formed within the borders of individual buildings. Medium-scale ECs encompass multiple buildings in close geographical proximity, whereas the term 'geographical proximity' is a topic of heated discussions. ECs implemented on a large scale can even be realised across an entire city or region. The following literature review concerning the general topic of PV sharing concepts in energy communities is based on this classification. A selection of scientific articles addressing small-scale ECs is provided Section 2.2.1.1. Literature addressing

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medium and large-scale energy communities is presented mutually in Section 2.2.1.2, since the exact border between these two scales is not yet defined and thus a rather subjective matter so far.

2.2.1.1. Small-scale: PV sharing in multi-apartment buildings

Implementing PV in buildings transforms conventional consumers into prosumers with the goal of maximising PV electricity self-consumption. Consequently, the amount of electricity purchased from the grid is reduced and so is the electricity bill. 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 [98, 104] leads to a high cost saving potential. However, with decreasing PV module costs, investments in PV systems gain increasing attraction in the residential sector [84], also in combination with a battery storage [68, 109]. Energy communities on single-building level in the residential sector are already realised in multi-apartment buildings. Shared PV generation can not only increase self-consumption but also adds customer value [132], while the effect of increased self-consumption and self-sufficiency can be enhanced by implementing battery storage [133,136]. The added value of shared PV systems for customers in terms of cost savings is specifically addressed in [54] and [51]. Drivers of profitability, self-consumption and self-sufficiency are evaluated in [10]. However, there are also still barriers that hamper PV deployment. The scientific literature [131] juxtaposes a variety of opportunities for PV deployment with barriers. [172] focuses on market barriers specifically, while still existing technical challenges are addressed in [74].

Energy communities are predominantly examined concerning the integration of renewable energy, especially PV systems. However, 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 of walls, change of windows) in combination with active retrofitting (e.g. a heating system change and renewable energy integration) is therefore addressed in the literature, mostly for indi-

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vidual buildings [48, 50, 100, 116] but also for communities [85, 115, 165]. More details concerning literature in the context of retrofitting is provided in Section 2.3.

2.2.1.2. Medium- and large-scale: PV sharing between multiple buildings

The motivations for individuals to participate at an energy community are predominantly economic [28,88]. However, there are also other motivations, which are more difficult to quantify, 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 [34]) in an energy community concept is important [145]. The actual large-scale potential of PV implementation is estimated in [20, 105, 144], while [29] 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 [79, 80, 169], and the optimal building mix and energy technologies on the neighborhood level are determined by [164]. [126] focuses on sharing of energy resources, such as PV systems and storage, among prosumers. The economic and operational benefits of the latter are addressed in [155].

2.2.2. Contracting as enabler to implement energy communities in paractice

Not only the regulatory background is a necessary pre-condition for the actual realisation of energy communities and PV sharing concepts in practice, but also the possibility to finance such concepts. Within the last years, three basic options to PV system financing have evolved for multi-apartment energy communities [125].

- The property owner[2] invests in the PV system and provides the residents with electricity according to a mutually agreed distribution key.
- An energy supplier makes the investment and provides the residents with

[2]The term 'owner' refers to an individual person as well as to a community of owners.

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PV and grid electricity.

- An exernal company or a contractor bears the investment, while the building residents 'lease' the right to use the generated electricity.

Significant upfront investment costs can pose a significant burden for individuals with limited financial capabilities, wherefore third-party financing options are valuable solutions. The following literature review focuses on contracting specifically, since contracting is not limited to purely energy-related investments, but can also encompass general building renovation.

To properly display a contracting situation, two different ways can be chosen. On the one hand, there is the theoretical approach of contract theory. Contract theory is an agent-based approach that maps the interrelations of client and contractor and the contract bargaining process in detail. Such approach is suitable for the purpose of analysing very specific situations, which is not the goal within this thesis' framework[3]. On the other hand, a less theoretical system analysis approach can be used. System analysis models rather focus on the practical situation of a contractor offering his services under specific conditions to which the clients agree in case their expectations are met in terms of energy service and building management. Thus, with respect to this thesis's scope, the following literature review focuses specifically on articles elaborating on energy and retrofit contracting, presented in Section 2.2.2.1 and Section 2.2.2.2, respectively.

2.2.2.1. Energy contracting

Due to the increased diffusion of renewable energy, energy market stakeholders may have to adapt their business models to remain competitive in the new energy landscape [130]. Adequate contracting business models could be an option for utilities to stay competitive as well as facilitate residential investments in PV systems. Due to the increased importance of this subject matter, scientific

[3]However, a broad selection of scientific literature can be found that addresses various aspects of contracting in buildings in an agent-based way. To present a few examples, articles such as [89], [70], [90] and [134] focus explicitly on game theoretical and agent-based approaches to address retrofit decision making, energy performance contracting, energy-efficiency retrofit, and economic retrofit aspects, respectively.

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literature that focuses on energy contracting has multiplied within the recent years. Respectively, [130] and [141] provide a review of utilities' business models for renewable energy contracting as well as energy performance contracting (EPC) business models. By contrast, [124] critically questions the viability of business models based on EPC offered by energy service companies. [164] proposes a multi-criteria decision-making approach to investments in distributed PV projects under the EPC business model. The potential of said business model is rated in [56]. [154] focuses on third-party ownership models where solar service firms plan, install and maintain PV systems on the premises of a customer while using financing from a third party.

2.2.2.2. Retrofit contracting

Energy conservation is a challenging issue due to disincentives that inhibit innovation in the building sector. [69] experimented with EPC that aims to replace disincentives with a stimulus for innovation. Similarly, [119] finds that barriers to retrofitting can be addressed by EPC, since outsourcing alleviates financial constraints. An EPC-based framework is proposed in [173] to enhance the profitability of 'green' investments by carefully sharing the existing risks. [45] provides a methodology for decision support of EPC with respect to risk associated with performance guarantee. Thus, EPC is one possible market mechanism to ensure building energy efficiency retrofit [166]. The success factors are addressed in [167], while the risks and uncertainties in EPC projects are considered in [87] and [127]. The contract period of EPC is one major factor influencing the success of such business models. Thus, optimal EPC contract periods are addressed in [25, 94, 142].

2.2.3. PV potentials in buildings

Another imortant factor in the equation of realising PV sharing concepts are the different potentials of PV. The potential of building-attached and/or building-integrated PV systems can be subdivided fourfold[4] [96]:

[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).

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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: Electricity generation in consideration of module efficiency
4. Economic potential: The share of technical potential economically usable from an investor's point of view

The physical and geographical potential are not considered individually within this literature review, since such analysis are automatically included when aiming to estimate the technical and economic potential. A selection of scientific literature concerned with estimating the technical and economic PV potential is provided in the following Section 2.2.3.1 and Section 2.2.3.2, respectively.

2.2.3.1. Technical 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 [19, 114]. The spectrum of studies estimating the technical potential is broad, focusing on different aspects such as matching supply and demand locally [96, 108], proposing techniques to combine geographic information systems (GIS) with object-based image recognition to estimate available rooftop areas [82, 163], and quantifying the margin of error [72].

2.2.3.2. Economic 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, [18] calculates the solar potential of roofs and facades in cities and [63] 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

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time. The goal of [97] and [118] is to assess the technical PV potential of cities; the economic aspect is limited to the levelised costs of electricity. Only [86] focuses specifically on assessing the economic potential of PV for individual buildings within a city.

2.3. PV system implementation in the context of building retrofit

With the extended efforts of increasing the shares of renewable electricity generation in buildings, the importance of thorough building retrofit should also be brought emphasised, since implementing novel PV systems in buildings of low standard can not be considered sustainable. This would imply green electricity generation on the one hand, but a waste of energy when it comes to the building heat on the other hand. The most environmental friendly - but also most expensive - option would be to install PV in the course of thorough building retrofit. Since building retrofit is a topic that can be found several times in the course of this thesis, the literature review also provides a selection of outstanding work in this field of research. Thereby, available literature is clustered into two parts: The first part considers literature concerned with passive retrofitting (renovation measures to the building envelope) in Section 2.3.1. Literature addressing the holistic form of retrofitting, namely a combination of active and passive retrofitting measures, is introduced in Section 2.3.2.

2.3.1. Passive retrofitting

An innovative approach to analysing the potential energy savings of the existing building stock by passive retrofitting measures is developed in [24]. A cost-optimum analysis of a multi-storey residential building by considering energy efficiency measures is presented in [14]. [156] focuses on building envelope renovation and the energy savings potential of individual and combined retrofitting measures. The goal of [120] is to analyse whether different passive state of the art retrofitting solutions are suitable from a life cycle perspec-

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tive. [30] extends the standard passive retrofitting measures by taking into account efficient electric appliances and lighting, glazed enclosed balcony systems, and heat recovery systems. [58] presents research which addresses the effectiveness of passive building renovation measures (thermal insulation, glazing, natural ventilation and more) to reduce energy consumption and thus the environmental footprint.

2.3.2. Combined active and passive retrofitting

Active retrofitting measures include investments in electricity and/or heating technologies, preferrably renewable ones. The most prominant renewable electricity technologies in buildings are building-attached/integrated PV systems, which can be complemented by a battery storage. With investments in heating technologies, a change of conventional fossil heating systems (oil, gas) towards more renewable options of HVAC technologies are meant. Additionally, a particular nieche in the scientific literature contains studies that focus specifically on passive retrofitting in combination with implementing a solar thermal system, such as [3, 7, 21].

The cost-effectiveness of renewable energy, such as PV system building integration, is investigated for four different buildings in [129]. A techno-economic evaluation method is developed in [83], where an optimal set of active retrofitting measures for a public administration building in Germany is determined with the focus on heating technologies. A cluster analysis is applied in [8] to assess the effectiveness of using materials, technologies and renewable energy in educational buildings. [92] conducts a cost-benefit analysis, focusing on heat source replacement and building envelope retrofit. A multi-objective optimisation model with the goal of maximising both the energy savings and the economic benefits is introduced in [160]. Existing building technologies are replaced by feasible alternatives, including heat pumps, chillers, and control systems. [100] presents a cost-optimal analysis by using a multi-stage framework for assessing the influence of energy retrofitting actions. Similarly, the optimal investment in the building envelope is determined in [47] by using a multi-objective op-

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timisation approach focusing on energy savings and economic benefits. The same authors also present a study [48] with the goal of improving the energy efficiency of existing buildings (passive measures in combination with rooftop PV) with a predefined budget. The goal is to maximise occupants' as well as investors' benefits. Staying with the multi-objective approach, [170] evaluates a building's costs and energy savings when implementing a photovoltaic/battery system and [165] presents an energy hub optimisation model which aims at optimally combining a building envelope retrofit with renewable and high efficiency energy supply technologies in order to minimise the life cycle cost and greenhouse gas emissions. [2] indroduces a new methodology for optimal decision making concerning building renovation, whilst keeping a balance between energy consumption, emissions and added value due to renovation in a cost-effective way. Cost optimality is also discussed by [116] concerning the energy refurbishment of a multi-family residential building. [116] and [100] conclude that in order to achieve A-level standards, the integration of active retrofitting measures is unavoidable. This is confirmed by [112]: Investments in renewable electricity and heat generation systems are the most cost-effective for meeting different energy performance target levels. Moreover, [73] states that 'green buildings' which are environmentally sustainable in terms of design, construction and maintenance, are a potential answer to climate change. However, retrofitting a building is often less expensive than demolishing or rebuilding one.

2.4. Modelling approaches to energy sharing concepts

When it comes to the modelling of energy communities, there are three common approaches to be used, depending on the specific purpose of the model and the underlying problem. When the focus lies on the actual game that takes place in the strategic decison making process, game theoretical modelling would be the most suitable approach. Energy modelling with game theory (Section 2.4.1) can be subcategorised in cooperative and non-cooperative games. According literature is discussed in Section 2.4.1.1 and Section 2.4.1.2. Despite game theory being also agent-based, this literature review distinguishes

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explicitly between agent-based modelling and game theory. Scientific articles concerned with agent-based modelling of ECs are introduced in Section 2.4.2. Both approaches come with the positive aspect of elaborating on a very specific problem in depth. However, general conclusions are difficult to be drawn. System analysis, on the contrary, provides a broader perspective of energy community modelling without paying specific attention to detailed interrelations of paricipating parties. More detail is provided in Section 2.4.3.

2.4.1. Game theory

Game theoretical modelling is used to depict the interrelations and the strategic decision making of the participating parties in detail. Basically, game theoretical modelling can be split up in a variety of sub-categories. However, the most common forms are cooperative and non-cooperative games. Cooperative games allow the forming of coalitions between the participating parties and the focus is on how coalitions are formed and how profits are distributed amongst themselves. Non-cooperative games rather focus on the individual players and their strategic decision making since coalitions amongst each other are prohibited.

2.4.1.1. Energy sharing with cooperative games

[102] proposes a local power exchange algorithm to help microgrids trade power locally with neighbouring microgrids. In order to coordinate multi-microgrid operation, [32] simulates the potential cooperative behaviours of such. [46] studies energy trading among flexible demand response aggregators via a cooperative model. Focusing solely on the demand-side, [107] formulates an energy consumption scheduling game among users and [22] uses cooperative game theory to model system problems that may occur in case of storage sharing.

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2.4.1.2. Energy sharing with non-cooperative games

The issue of an entity being primarily concerned with maximising its own benefit can be modelled by non-cooperative games. For example, [95] proposes a Stackelberg game between the generation and demand sides. In [1], households also try to optimise their individual utility, which is modelled via a non-cooperative Nash equilibrium game. Moreover, non-cooperative games can be used to model energy trading like in [23] and [101]. A framework to coordinate energy sharing between neighboring prosumers is introduced by [60], while [92] proposes an energy-sharing provider to facilitate this task. Energy sharing according to different consumer preferences is modelled in [55] by a Stackelberg game.

2.4.2. Explicit agent-based modelling

Agent-based modelling is used to simulate the interrelations between individual agents, which make decisions based on predefined rules. Agent-based architecture for coordinating locally connected microgrids is proposed by [168]. As microgrids enable the integration of distributed energy resources, [93] presents an application for multi-agent coordination thereof. The economic dispatch problem of a community microgrid is studied in [140], under the assumtion 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 [4]. [121] tries to optimise the balancing of community energy resources while taking into account energy- and cost-aware decision-making. [15] formulates an agent-based serious game for community energy systems within a group of households.

2.4.3. System analysis

System analysis as a counterpart to game theory and agent-based modelling refrains from focusing on the detailed interrelations amongst participating parties or individual agents, but provides a system perspective on the specific problem. This modelling approach is applied to research questions that require

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answers to a general problem. The advantage is that more general statements can be provided and since answers to research questions that are addressed with system analysis are widely applicable, generally valid conclusions can be derived.

Scientific studies that are concerned with different aspects of PV sharing in energy communities and provide results by using system analysis are already presented in the course of Section 2.2.1 and are therefore not listed repeatedly in this part of the literature review.

2.5. Contribution to progress beyond the state of the art

The contribution of this thesis is multifold since a variety of thematic fields is tackled and combined in an unprecendented way in the course of this work. Contributions are made in the research fields of profitability and optimal sizing of PV, retrofitting of buildings, the profitability of contracting models, the added value of extending energy communities beyond the building border and cost-optimal PV potential assessments. The major contributions are listed in the following.

- A mixed-integer linear optimisation model is developed to determine the profitability of a shared PV system along with its optimal installation capacity in a multi-apartment building. A major achievement in this context is the general validity of the provided results since a large variety of different building set-ups, PV- and heating systems is investigated, along with exogenous inflencing factors such as retail electricity prices and interest rates. Based on such a broad spectrum of results, generally valid conclusions can be drawn to assist building owners or owner communities in their decision making process whether to implement PV or not.

- Another major contribution beyond the state of the art in scientific literature is the evaluation whether PV implementation in multi-apartment buildings still remains profitable within the framework of contracting

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and how such third-party financing option changes optimal PV system capacities. Moreover, in order to emphasize the importance of combining PV system implementation with building renovation, the profitability of holistic building retrofit is addressed. Thereby it is shown that PV system implementation is able to reduce the profitability gap of purely passive renovation measures towards break-even. Moreover, it is shown that introducing additional costs for CO_2 emissions can - in some specific situations - entirely close this profitability gap.

- By assessing the profitability and optimal PV system capacities for individual buildings as well as for energy communites in the residential neighbourhood, the actual added value of establishing energy communities between multiple buildings can be quantified. The achieved results can be considered generally valid since four typical Central European settlement patterns are identified and representative buildings are chosen for evaluation accordingly.

- Last but not least, an assessment of the potential of PV in residential buildings is performed. This potential assessment differs significantly from preceding work, since the cost-optimal economic PV potential in buildings - unlike the conventional purely economic building PV potential - is assessed for the residential building sector of a whole country, based on the assumption that the concept of neighbourhood energy communities would take hold on a large scale. The proposed algorithm of allocating buildings per political district to settlement patterns and individual energy communities is the very first of its kind.

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3. Building-attached/integrated PV on a multi-apartment building: The impact of the building set-up on profitability

3.1. Introduction

The legislative amendments of the *Electricity Industry and Organisation Act* [110] in 2017, allow the actual realisation of PV sharing concepts in multi-apartment buildings. There are two legally anchored basic possibilities of allocating the self-generated PV electricity to the energy community participants: PV electricity can either be allocated statically or dynamically. These two distribution possibilities are explained in more detail in the following Section 3.1.1 and Section 3.1.2.

3.1.1. Static allocation of PV generation

In case static allocation is applied, the generated PV electricity is allocated to individual energy community participants according to a predefined distribution key. In other words, each household can consume a fixed share of PV electricity at each point in time. In case a household does not consume the entire amount of his share, the surplus is fed into the grid. If a household's load exceeds the amount of allocated PV generation, the residual load needs to be covered by electricity purchase from the grid. The situation of static allocation is illustrated for a simplified example of two households in Figure 3.1.

Using static allocation to distribute PV electricity generation to individual households has the advantage of being transparent, easily understandable and straightforward in terms of implementation. However, the full potential of PV sharing cannot be harvested due to the limitation caused by the fixed

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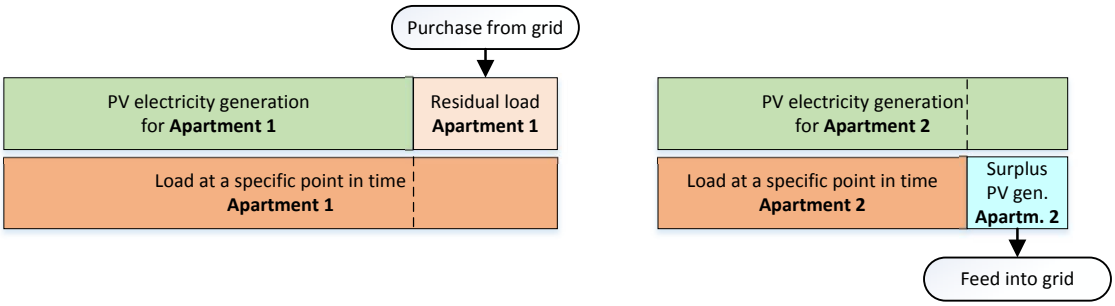

Figure 3.1.: Static allocation of PV generation [54].

distribution key.

3.1.2. Dynamic allocation of PV generation

Dynamic allocation, in comparison to static allocation, does not rely on a predefined distribution key, but instead the generated PV electricity is allocated optimally to the households. Optimally in this context means that PV electricity consumption is not limited for individual households by predefined shares. For example, if at specific times, one household needs less electricity than average, another household can use the PV surplus to cover his load. The situation of dynamic allocation is graphically illustrated in Figure 3.2, again for a simplified example of two households.

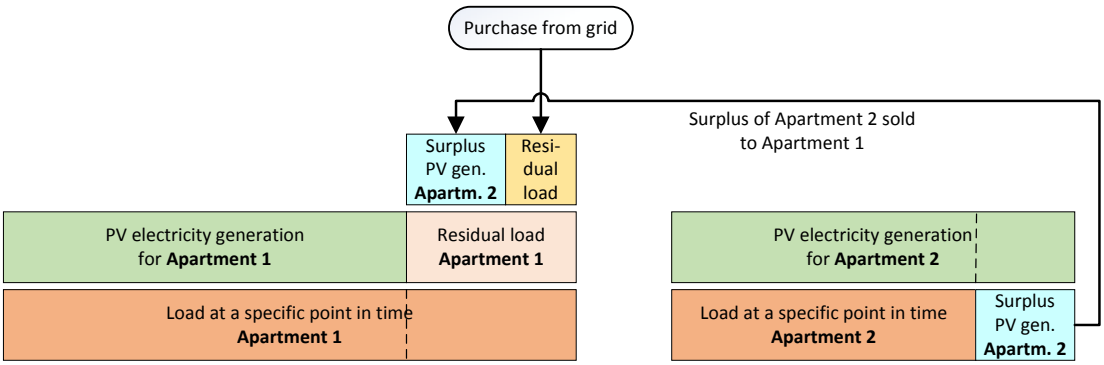

Figure 3.2.: Dynamic allocation of PV generation [54].

Dynamic allocation of PV generation has the advantage of increasing self-

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consumption, wherefore the potential of PV sharing can be fully harvested. This increases the profitability of PV systems in general and reduces the grid burden of increased PV deployment in the electricity system. The drawback of dynamic allocation is its missing transparency. In order to compensate for the missing transparency, business models need to be developed to guarantee an adequate distribution of costs and benefits between households.

3.1.3. Cost advantage of dynamic allocation

Allocating PV electricity dynamically between energy community participants leads to an optimal usage of the generated PV electricity. This entails positive effects on the PV system's profitability at the same time. The significance of applying dynamic PV electricity allocation compared to static allocation is emphasized by results gained in previous research [54]. Figure 3.3 compares optimal PV system capacities for a multi-apartment building with ten residential units for the two situations of static and dynamic PV electricity allocation. In case of dynamic allocation, the building is considered as total load, in case of static allocation each household is considered individually. The optimal PV capacity is calculated via multi-objective optimisation. Thereby, two conflicting objectives are taken into account - maximising self-consumption and minimising costs - and weighted accordingly. The x-axis shows the weight of the cost minimisation objective for each datapoint[1]. In case the objective of cost minimisation is weighted 100 %, the impact of allocating PV electricity dynamically becomes obvious: Taking advantage of synergy effects between load profiles and their collectively improved correlation with the hours of sunshine can be decisive for the profitability of a PV system[2].

[1] A weigth of 1 means, that the objective of minimising costs is weighted 100 %, the objective of self-consumption maximisation is this weighted 0 %. A weight of 0.6 means that the cost-minimisation objective is weighted with 60 % while the objective of self-consumption maximisation is weighted with 40 %.

[2] The leap in the optimal PV peak capacity is caused by taking into account fixed costs for PV system installation.

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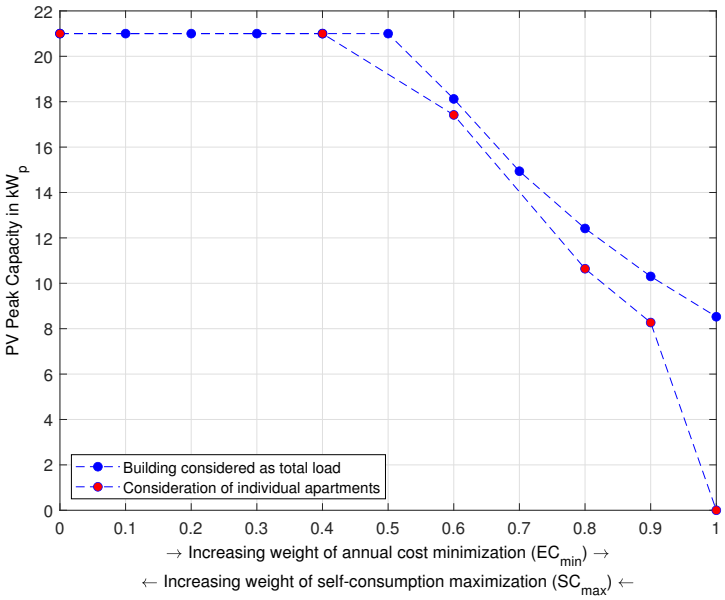

Figure 3.3.: The positive impact of dynamic PV electricity allocation

3.2. Methods and model

With respect to the first research question, the goal of the first part of this thesis is to develop an optimisation model that is capable of determining the profitablity of a shared PV system in a residential multi-apartment building. Thereby, not only the profitabiliy is determined per se, but also the optimal installation capacities necessary to achieve a cost-optimum. The optimisation model is presented in detail in the course of Section 3.2.1 and Section 3.2.2. Based thereon, case studies are defined which are introduced in Section 3.2.3. The whole modelling procedure is illustrated using a flow chart in Section 3.2.4. The nomenclature is provided in Section 3.2.5.

Due to the previously shown obvious financial advantages of allocating PV system electricity dynamically (Section 3.1.3), this thesis' net present value analyses are based on the assumption of dynamic PV electricity alloction within an energy community.

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3.2.1. Maximising the residents' net present value

For the purpose of determining the profitability of a shared PV system and novel heating system technologies within a multi-apartment building, a mixed-integer linear optimisation model is developed[3]. The overall objective of the optimisation model, given in Equation 3.1, is to maximise the building residents' net present value (NPV) over a time horizon of 20 years.

$$\max_{o \in O} \; NPV = \max_{o \in O} \left(-I_0 + \sum_{y=1}^{Y=20} (R(y) - C(y)) \cdot \left(\frac{1}{(1+z)^y} \right) \right), \tag{3.1}$$

whereas, o represents each optimisation variable included in the vector O, which contains all optimisation variables, depending on the case study and the building energy technologies included.

The NPV calculation presented in Equation 3.1 juxtaposes investment costs I_0 and annual costs $C(y)$ with annual revenues $R(y)$, properly discounted, over a time horizon of 20 years.

The investment costs I_0 (Equation 3.2) can be split into technology investment costs ($I_{0_X}(x)$) and additional basic retrofitting costs for the roof and facade ($I_{0_retr_X}(x)$), occuring in the case of installing building-integrated PV[4]. The individual technology investment costs are calculated as the specific costs per kW or kWh multiplied by the installed optimal capacity of the individual technologies; thus a linear relation is assumed. The costs for the investment in a specific technology are incurred only if the technology is considered profitable by the optimisation model and thus installed.

[3]The model is developed in the programming development environment Matlab [99], using the toolbox Yalmip [75] as the optimiser and Gurobi [64] as the solver.

[4]Installing building-integrated PV systems means a violation of the building envelope at the same time, wherefore additional costs for retrofitting need to be taken into account.

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$$I_0 = \sum_x I_{0_X}(x) + I_{0_retr_X}(x) \tag{3.2}$$

The annual costs are composed of tree different cost items, namely maintenance costs $C_{maint}(y)$, variable costs $C_{var}(y)$ (per unit costs for consumed energy) and fixed costs $C_{fix}(y)$ for grid connection (Equation 3.3). Here again, annual costs for specific technologies are incurred only if the technology is considered profitable by the optimisation model and thus installed. In this case, the corresponding binary variables are set to one[5].

$$C(y) = C_{maint}(y) + C_{var}(y) + C_{fix}(y) \tag{3.3}$$

The total amount of maintenace costs is determined by summing up costs occurring for all technologies installed as indicated in Equation 3.4. Maintenance costs are annual cleaning and operational costs for PV systems, as well as annual operational costs for the different heating systems.

$$C_{maint}(y) = \sum_x C_{maint_X}(x, y) \tag{3.4}$$

The cost item of annual variable costs $C_{var}(y)$ (Equation 3.5) considers costs caused by purchasing electricity from the grid to cover the electric load ($e_{grid_2eload}(t, y)$), to supply the heat pump ($e_{grid_2hp}(t, y)$) and the electric device complementing the bivalent heat pump ($e_{grid_2hload}(t, y)$), as well as for purchasing district heat ($e_{dh}(t, y)$) and pellets ($m_{pe}(t, y)$). Obviously, not all technologies can be installed at the same time within one building; Therefore, if a technology is not considered, the according energy flow is zero and thus are the according costs.

[5]The according constraints needed to determine the value of the binary variables are as follows for the different technologies. Rooftop PV: $P_{rpv}(d) \leq bin_{rpv}(d) \cdot P_{rpv_max}(d)$, Facade PV: $P_{fpv}(d) \leq bin_{fpv}(d) \cdot P_{fpv_max}(d)$, Heat pump: $Cap_{hp} \leq bin_{hp} \cdot Cap_{hp_max}$, Pellet heating: $Cap_{pe} \leq bin_{pe} \cdot Cap_{pe_max}$.

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$$C_{var}(y) = \sum_t \left(e_{grid_2eload}(t,y) + e_{grid_2hp}(t,y) + e_{grid_2hload}(t,y)\right) \cdot c_{var_elec}(y) + \sum_t \left(e_{dh}(t,y) \cdot c_{var_dh}(y) + m_{pe}(t,y) \cdot c_{var_pe}(y)\right) \tag{3.5}$$

Lastly, the fixed costs ($C_{fix}(y)$) for the electricty grid connection of each apartment need to be considered as well (Equation 3.6).

$$C_{fix}(y) = c_{fix_elec}(y) \cdot n_{units} \tag{3.6}$$

At this point it needs to be emphasised, that in this optimisation, the least negative NPV is determined. The reason is that the costs for electricity and heat are examined over a period of 20 years. The costs – payments for electricity and heat including initial investments in new technologies – as indicated above, are significantly higher than the revenues. Revenues are only obtained for feeding surplus PV electricity generation into the grid. The revenues gained by surplus PV generation are determined as given in Equation 3.7, depending on the PV system's location on the building envelope.

$$R(y) = \left(\sum_d \sum_t e_{rpv_2grid}(d,t,y) + e_{fpv_2grid}(d,t,y)\right) \cdot c_{feed_in}(y) \tag{3.7}$$

3.2.2. Constraint specification and technology implementation

The optimisation model's major constraints are the necessity to cover the electricity and heat load at every point in time (t) each year (y), shown in Equations 3.8 and 3.9, respectively.

The electricity load can be covered by three different sources: First, there is the option of covering the electricity load with self-generated PV electricity. The model distinguishes between rooftop PV $e_{rpv_2eload}(d,t,y)$ and/or facade PV $e_{fpv_2eload}(d,t,y)$. The generated PV electricity depends on the PV system's

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orientation (d), and, considering facade PV, on whether standard PV elements or salient shading elements are used. Other options to cover the electric load are using electricity provided by a possible battery storage $e_{stor_2eload}(t, y)$ or grid electricity purchase $e_{grid_2eload}(t, y)$. If a technology is not part of the building's default setting or is not determined profitable by the optimisation, the corresponding energy flow vector is zero.

$$\begin{aligned} e_{load}(t, y) = e_{grid_2eload}(t, y) + \sum_{d} \left(e_{rpv_2eload}(d, t, y) + e_{fpv_2eload}(d, t, y) \right) \\ + e_{stor_2eload}(t, y) \end{aligned} \tag{3.8}$$

The heat load can be covered by different heating systems considered within the developed model. Options to heating are pellet heating $e_{pe}(t, y)$, district heat $e_{dh}(t, y)$ or heat pump. The heat pump can be operated in monovalent $e_{hp}(t, y)$ or in bivalent operation mode, supplemented by a heating rod $e_{hp}(t, y) + e_{grid_2hload}(t, y)$. The heat pump itself has multiple options to be supplied, namely by the different PV systems (rooftop $e_{rpv_2hp}(d, t, y)$ or facade PV $e_{fpv_2hp}(d, t, y)$), the battery storage $e_{stor_2hp}(t, y)$ or the public grid $e_{grid_2hp}(t, y)$. The heat pump's total electricity inflow is multiplied by the temperature-dependent coefficient of performance (COP) to determine the heat pump's output (Equation 3.9). Further information regarding the modelling of the COP is provided in Appendix A.3. The capacity of all heating systems is determined such that the peak heat demand can be covered.

$$\begin{aligned} h_{load}(t, y) &= e_{hp}(t, y) + e_{grid_2hload}(t, y) + e_{pe}(t, y) + e_{dh}(t, y) \\ e_{hp}(t, y) &= COP(t, y) \cdot \Big[\sum_{d} \left(e_{rpv_2hp}(d, t, y) + e_{fpv_2hp}(d, t, y) \right) \\ &\quad + e_{grid_2hp}(t, y) + e_{stor_2hp}(t, y) \Big] \end{aligned} \tag{3.9}$$

The total electricity generated by rooftop or facade PV systems is determined by the installed capacity multiplied by the solar irradiation in kWh/kW[6] (Equation 3.10). Said electricity can be used to cover the electricity load

[6] Usually, the solar irradiation is given in kWh/m^2, but by introducing a transformation factor of 6 m^2/kW (a panel of 0.25 kW is assumed to have the size of 1.5 m^2), the irradiation can be converted to the unit kWh/kW.

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$(e_{rpv_2eload}(d,t,y) + e_{fpv_2eload}(d,t,y))$, supply the heat pump $(e_{rpv_2hp}(d,t,y) + e_{fpv_2hp}(d,t,y))$ or charge the battery storage $(e_{rpv_2stor}(d,t,y) + e_{fpv_2stor}(d,t,y))$. Only the surplus is fed into the grid. The optimal PV system capacity is determined endogenously in the optimisation process and is constrained by the maximum available space of roof and/or facade.

$$\begin{aligned} P_{rpv}(d) \cdot I_{rpv}(d,t,y) &= e_{rpv_2eload}(d,t,y) + e_{rpv_2hp}(d,t,y) \\ &\quad + e_{rpv_2grid}(d,t,y) + e_{rpv_2stor}(d,t,y) \\ P_{fpv}(d) \cdot I_{fpv}(d,t,y) &= e_{fpv_2eload}(d,t,y) + e_{fpv_2hp}(d,t,y) \\ &\quad + e_{fpv_2grid}(d,t,y) + e_{fpv_2stor}(d,t,y) \end{aligned} \tag{3.10}$$

All electricity and heat flows as well as the PV and heating technology capacities are optimisation variables; Their values are determined cost-optimal by optimisation. This means that in case PV system implementation would not profitable, the optimal PV capacity would be determined to be zero by optimisation.

The storage's state of charge $SOC(t,y)$ at every point in time t is determined based on the state of charge at the previous timestep $SOC(t-1,y)$, plus the electricity inflow $e_{in}(t,y)$, minus the electricity outflow $e_{out}(t,y)$ at the current time step. Standby losses as well as charging and discharging losses are taken into account as given in Equation 3.11. The storage capacity (Cap_{stor}) is determined such that it is greater than or equal to the storage's state of charge at all times.

$$SOC(t,y) = \eta_{sb} \cdot SOC(t-1,y) + e_{in}(t,y) \cdot \eta_{loss} - e_{out}(t,y)/\eta_{loss} \tag{3.11}$$

$$e_{in}(t,y) = \sum_{d} \left(e_{rpv_2stor}(d,t,y) + e_{fpv_2stor}(d,t,y)\right. \tag{3.12}$$

$$e_{out}(t,y) = e_{out_2el}(t,y) + e_{out_2hp}(t,y) \tag{3.13}$$

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3.2.3. Variants to the building set-up

A particular multi-apartment building with 10 residential units is the basis for all analyses within this chapter. The individual apartments are allocated real measured load profiles with a time resolution of 15 minutes. The building's total load as well as the load profiles of the individual appartments are presented in Appendix A.2. The household profiles range from an annual consumption of 1399 kWh to 3683 kWh. Due to the lack of real measured heat load profiles, an algorithm is developed to self-generate the building's heat load according to the building standard. This algorithm is explained in detail in Appendix A.4.

The building set-up, namely its orientation, whether it stands alone or is adjoined to other buildings, its roof pitch and building standard, can be altered in order to cover a variety of different situations. Figure 3.4 presents several possible building set-ups, together with the available building energy technologies (BAPV and BIPV panels on roof, facade, or implemented as salient shading elements, monovalent or bivalent heat pump, pellet heating, district heating, and battery storage device).

Another option to altering the building set-up that can not be illustrated within Figure 3.4 is the option of varying the tenant portfolio, for example by introducting a business as tenant in the ground floor instead of two households. Since no real measured business load profiles are available, a standard load profile of a grocery store, also depicted in Appendix A.2, is used for according analysis.

3.2.4. Illustration of procedure

Based on the detailed explanations concerning the developed optimisation model and the different building set-ups considered, the implemented procedure can be illustrated as shown in Figure 3.5.

Based on the building's location, having different outdoor temperature profiles, and building standards in terms of the specific heat demand, the heat load profile of a specific building is generated at a 15-minute resolution[7]. Based

[7]Buildings can be categorised by their specific heat demand (heat load) (see, e.g. Table 3.9,

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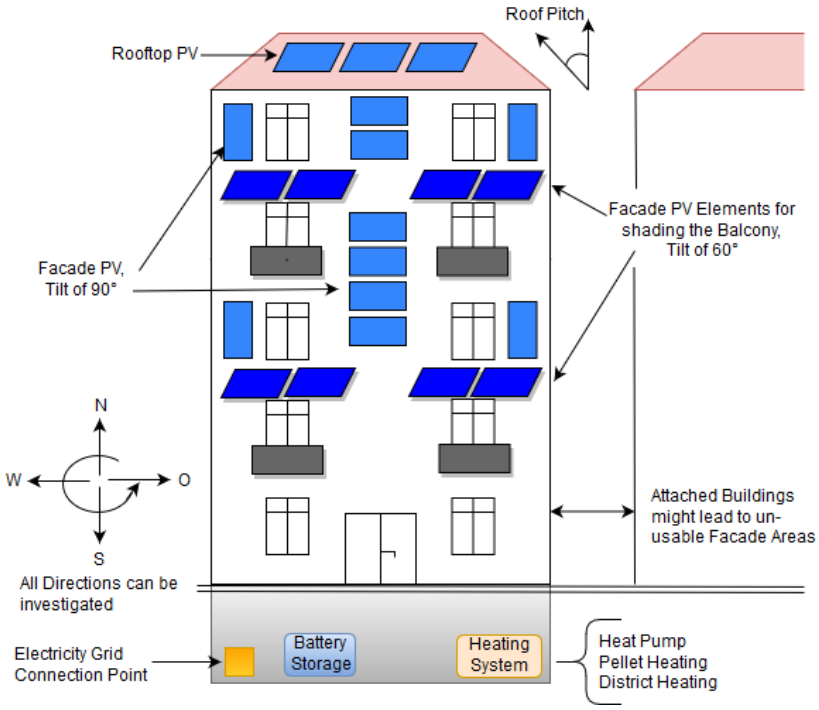

Figure 3.4.: Building energy technologies and possible variations of the building characteristics.

on the number and size of the apartments, the building's total electricity demand is generated by using real measured load profiles ([111], see Figure A.2). These load profiles are resolved at 15-minute intervals and hold measured data of one year. Therefore, calendar effects are implicitly taken into account. Then, the total number of technology portfolios J (the number of use cases) has to be selected. An energy technology vector specifies an individual use case based on the selected building energy technologies. This vector, however, does not determine whether the selected building energy technologies are actually installed. (This decision, together with the determination of the optimal technology capacities, is made during the optimisation process.)

Section 3.2.5, where the Austrian residential building stock is presented), which represents the quality of the building and, in general, depends on the date of the construction. The heat load profile, which correlates with the outdoor temperature at a particular site, at a fine time resolution of 15 minutes, is generated as specified in A.4. For the sake of simplicity, the hot water demand is assumed to be 15 % in addition to the heat demand. This is in line with [66].

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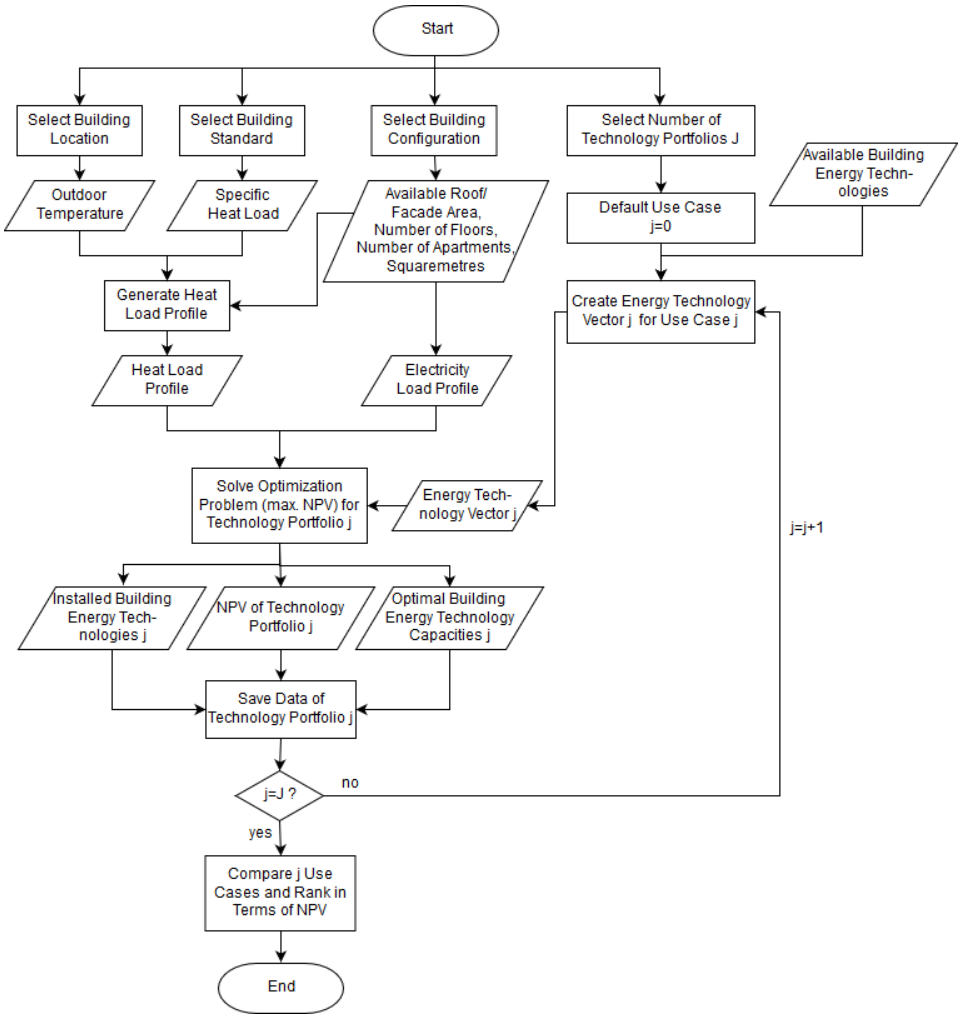

Figure 3.5.: Flow Chart.

At this point, the actual optimisation process starts. The optimisation model's major output is the maximum NPV of the selected technology portfolios. This in turn determines the profitability of the intended retrofitting measures. In addition, the corresponding optimal technology capacities are determined.

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3.2.5. Nomenclature, empirical scaling and coding

The nomenclature is provided in Tables 3.1, 3.2 and 3.3.

Cost assumptions for the calculations are provided in Tables 3.4 and 3.5[8]. Table 3.6 presents further relevant technology and building related assumptions. Last but not least, for an efficient and comprehensive presentation of the results in the following Section 3.3, a coding is provided in Tables 3.7, 3.8 and 3.9 to be able to better specify the individual use cases.

[8]Investment costs for PV systems are in compliance with those used in [26, 59], under the assumption of a further cost decrease due to learning effects. Expenses for pellet heating and heat pump installation are in compliance with [27,67,112]. Roof and facade renovation costs are provided by [61]. Assumptions concerning retail electricity, gas, pellet and district heating tariffs, along with their respective development within the following years are commented in detail in Appendix A.5.

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Name	Explanation	Unit
bin_{fpv}	Binary variable vector: Existence of facade PV, one binary variable per direction	-
bin_{hp}	Binary variable: Existence of heat pump	-
bin_{pe}	Binary variable: Existence of pellet heating	-
bin_{rpv}	Binary variable vector: Existence of rooftop PV, one binary variable per direction	-
c_{feed_in}	Remuneration for surplus PV electricity infeed	EUR/kWh
c_{fix_elec}	Fixed costs for electric grid connection	EUR/yr
c_{var_pe}	Specific pellet costs	EUR/kg
c_{var_dh}	Specific district heating costs	EUR/kWh
c_{var_elec}	Specific cost for electricity purchase from the grid	EUR/kWh
d	Direction	-
e_{dh}	Heat from district heating grid	kWh
e_{fpv_2eload}	Electricity produced by facade PV to cover electric load	kWh
e_{fpv_2grid}	Surplus electrictiy feed from facade PV to the grid	kWh
e_{fpv_2hp}	Electricity from facade PV to supply heat pump	kWh
e_{fpv_2stor}	Electricity from facade PV to charge the battery storage	kWh
e_{grid_2eload}	Electricity from the grid to cover the electric load	kWh
e_{grid_2hp}	Electricity from the grid for supplying heat pump	kWh
e_{grid_2hload}	Electricity from the grid to supply electrical device complementing the bivalent heat pump	kWh
e_{hp}	Heat provided by heat pump	kWh
e_{in}	Electricity to charge the battery storage	kWh
e_{load}	Electric load	kWh
e_{out}	Electricity discharged from the battery	kWh
e_{out_2el}	Electricity discharged from the battery to cover the electricity load	kWh
e_{out_2hp}	Electricity discharged from the battery to feed the heat pump	kWh
e_{pe}	Heat provided by the pellet heating	kWh
e_{rpv_2eload}	Electricity from rooftop PV to cover electric load	kWh
e_{rpv_2grid}	Surplus electricity feed from rooftop PV to the grid	kWh

Table 3.1.: Nomenclature.

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Name	Explanation	Unit
e_{rpv_2hp}	Electricity from rooftop PV to supply the heat pump	kWh
e_{rpv_2stor}	Electricity from rooftop PV to charge the battery storage	kWh
e_{stor_2eload}	Electricity from storage facility to cover electric load	kWh
e_{stor_2hp}	Electricity from storage facility to supply heat pump	kWh
h_{load}	Heat load	kWh
m_{pe}	Weight of pellets	kg
n_{units}	Number of apartments	-
o	Optimisation variable	-
t	Control variable time	-
x	Control variable technology	-
y	Control variable year	-
z	Interest rate (3 %)[9]	%
C	Total annual cost	EUR/yr
C_{fix}	Fixed amount of annual cost	EUR/yr
C_{maint}	Total annual maintenance costs	EUR/yr
C_{maint_X}	Annual maintenance costs for each technology	EUR/yr
C_{var}	Variable amount of annual cost	EUR/yr
Cap_{hp}	Optimal heat pump capacity	kW
Cap_{hp_max}	Maximum heat pump capacity	kW
Cap_{pe}	Optimal pellet heating capacity	kW
Cap_{pe_max}	Maximum pellet heating capacity	kW
COP	Coefficient of Performance (heat pump)	-
HL	Specific heat load	kWh/m^2/yr

Table 3.2.: Nomenclature.

[9] A conservative interest rate is chosen as a basis for the analyses, covering at least the inflation which is currently around 2.2 % [71]. Generally, the rate of return consists of a base interest rate plus a risk add-on. When considering risk-free investments in building energy technologies, 3 % is a reasonable assumption for a lower boundary for interest rates.

[10] [59] 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^2 at the lower end of the price range is assumed due to learning effects since 2015.

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Name	Explanation	Unit
I_0	Total initial investment costs	EUR
I_{0_X}	Investment costs of different technologies	EUR
$I_{0_retr_X}$	Additional retrofitting costs of the building envelope	EUR
I_{fpv}	Generation of facade PV	kWh/kW
I_{rpv}	Generation of rooftop PV	kWh/kW
NPV	Net present value	EUR
O	Vector of optimisation variables	-
P_{fpv}	Optimal facade PV capacity	kW
P_{fpv_max}	Maximum facade PV capacity	kW
P_{rpv}	Optimal rooftop PV capacity	kW
P_{rpv_max}	Maximum rooftop PV capacity	kW
R	Annual revenues (by PV surplus feed-in)	EUR/yr
SOC	Battery storage's state of charge	kWh
Y	Number of years	-
η_{loss}	Battery storage charging and discharging efficiency	-
η_{sb}	Battery storage stand-by efficiency	-

Table 3.3.: Nomenclature.

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Specification	Type of Costs	Costs
Rooftop PV, building-attached	Specific investment costs	$i_{0_rpv} = 1050\,\mathrm{EUR/kW_p}$
	Cleaning costs	$c_{clean_rpv} = 15\,\mathrm{EUR/kW_p/yr}$
	Operational costs	$c_{op_rpv} = 60\,\mathrm{EUR/yr}$
Facade PV, building-attached	Specific investment costs	$i_{0_fpv} = 1050\,\mathrm{EUR/kW_p}$
	Cleaning costs	$c_{clean_fpv} = 30\,\mathrm{EUR/kW_p/yr}$
	Operational costs	$c_{op_fpv} = 60\,\mathrm{EUR/yr}$
Rooftop PV, building-integrated	Specific investment costs	$i_{0_rpv} = 1110\,\mathrm{EUR/kW_p}$
	Cleaning costs	$c_{clean_rpv} = 15\,\mathrm{EUR/kW_p/yr}$
	Operational costs	$c_{op_rpv} = 60\,\mathrm{EUR/yr}$
	Basic roof renovation costs	$c_{roof_basic} = 148\,\mathrm{EUR/m^2}$
	Brick costs	$c_{brick} = 40\,\mathrm{EUR/m^2}$
Facade PV, building-integrated	Specific investment costs	$i_{0_fpv} = 900\,\mathrm{EUR/kW_p}$[10]
	Cleaning costs	$c_{clean_fpv} = 30\,\mathrm{EUR/kW_p/yr}$
	Operational costs	$c_{op_fpv} = 60\,\mathrm{EUR/yr}$
	Basic facade costs	$c_{facade_basic} = 18\,\mathrm{EUR/m^2}$
	Costs for the skim	$c_{skim} = 73\,\mathrm{EUR/m^2}$
Battery Storage	Specific investment costs	$i_{0_stor} = 1000\,\mathrm{EUR/kWh}$
Heat pump	Specific investment costs	$i_{0_hp} = 1000\,\mathrm{EUR/kW}$
	Maintenance costs	$c_{maint_hp} = 300\,\mathrm{EUR/yr}$
District heating	Connection costs	$i_{0_dh} = 5000\,\mathrm{EUR}$
	Annual fixed costs	$c_{basic_dh} = 3.0516\,\mathrm{EUR/m^2/yr}$
	Costs for heat cost allocator	$c_{add_dh} = 130\,\mathrm{EUR/yr}$
	Costs for district heat	$c_{var_dh} = 0.047\,\mathrm{EUR/kWh}$

Table 3.4.: Cost assumptions, see also Appendix A.5.

Specification	Type of Costs	Costs
Pellets heating	Specific investment costs	$i_{0_pe} = 600\,\mathrm{EUR/kW}$
	Maintenance costs	$c_{maint_pe} = 300\,\mathrm{EUR/yr}$
	Pellet costs	$c_{var_pe} = 0.28\,\mathrm{EUR/kg}$
Electricity	Variable costs	$c_{var_elec} = 0.22\,\mathrm{EUR/kWh}$
	Fixed Costs	$c_{fix_elec} = 65\,\mathrm{EUR/yr}$
	Surplus PV feed-in revenues	$c_{feedin} = 0.03\,\mathrm{EUR/kWh}$
Gas heating	Variable costs	$c_{var_gas} = 0.05\,\mathrm{EUR/kWh}$
	Fixed costs	$c_{fix_gas} = 150\,\mathrm{EUR/yr}$

Table 3.5.: Cost assumptions, see also Appendix A.5.

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PV systems	
Module efficiency	17 %
Additional losses	20 %
Module size	1.5 m^2
Module capacity	0.25 kW
Storage	
Charging and discharging efficiency	0.98 %
Self-discharging losses	0.001 %
Pellets heating	
Pellet heating value	5 kWh/kg
Efficiency	90 %
Building envelope	
Usable saddle roof area for PV (per direction)	100 m^2
Usable facade area for PV (per direction)	210 m^2

Table 3.6.: Further relevant empirical assumptions.

Electricity technologies	Coding
Rooftop building-attached PV	PV_{RBA}
Rooftop building-integrated PV	PV_{RBI}
Facade building-attached PV	PV_{FBA}
Facade building-integrated PV	PV_{FBI}
Battery storage	BS
Heating technologies	
Heat pump – monovalent	HP_M
Heat pump – bivalent	HP_B
Pellet heating	PE
District heating	DH
Gas heating	GH

Table 3.7.: Coding of electricity and heating technologies.

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Specification	Coding
Orientation saddle roof North-South	NS
Orientation saddle roof East-West	EW
PV panel pitch (degrees):	
Roof PV pitch	20, 30, 40
Pitch of salient shading elements on facade	60
Facade PV pitch	90
Stand-alone building (all facades available)	SA
Built-in building: free facade North-South	F_{NS}
Built-in building: free facade East-West	F_{EW}

Table 3.8.: Coding of building specification and roof/PV panel pitch.

Construction period	Specific heat load in kWh/m^2/yr	Coding
before 1919	145	HL_{145}
1919–1944	160	HL_{160}
1945–1960	145	HL_{145}
1961–1970	125	HL_{125}
1971–1980	115	HL_{115}
1981–1990	80	HL_{80}
after 1990	60	HL_{60}

Table 3.9.: Heating energy consumption in the residential sector (in Austria; used in this study) based on the year of construction [11] and coding.

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3.3. Results

Starting from the default setting – stand-alone multi-apartment building with 10 residential units, 30 °-pitched saddle roof, specific heat demand of 145 kWh/m^2/yr, heated by gas – different use cases are investigated.

- Section 3.3.1 points out the differences between BAPV and BIPV systems implemented on different parts of the building skin, as the optimal PV capacities are highly dependent on the solar irradiation and the implementation details.
- Section 3.3.2 takes into consideration a variety of changes in the building-set up to be able to quantify the individual effects on the profitability and optimal size of PV.
    1. Section 3.3.2.1 aims at investigating the changes of a combination of standard building-attached rooftop PV and different heating systems in terms of their NPVs, compared to the default setting. In addition, the impact of a change of the heating system in terms of CO_2 emissions is analysed.
    2. Section 3.3.2.2 emphasizes the effect on the profitability and optimal size of the PV system of varying the tenant portfolio, and thus changing the building electricity load profile.
    3. Section 3.3.2.3 studies the effect on the profitability and optimal size of the PV system of varying the roof pitches.
    4. The effect of higher building standards on the optimal technology portfolio and profitability is addressed in Section 3.3.2.4.

3.3.1. Building-attached/integrated PV on different parts of the building envelope

In many cases, buildings do not provide optimal conditions for implementing PV systems. For example, inconvenient loft constructions often prevent a PV system from being installed. Especially in cities with buildings located side-by-side, at least two facades out of four are not usable, in contrast to a

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stand-alone building. Therefore, the most lucrative southerly direction might not be available for PV installations. Regardless of the available surface, there is the opportunity to implement PV systems either building-attached (BAPV) or building-integrated (BIPV). These different building conditions and ways of PV implementation are presented in Figure 3.6.

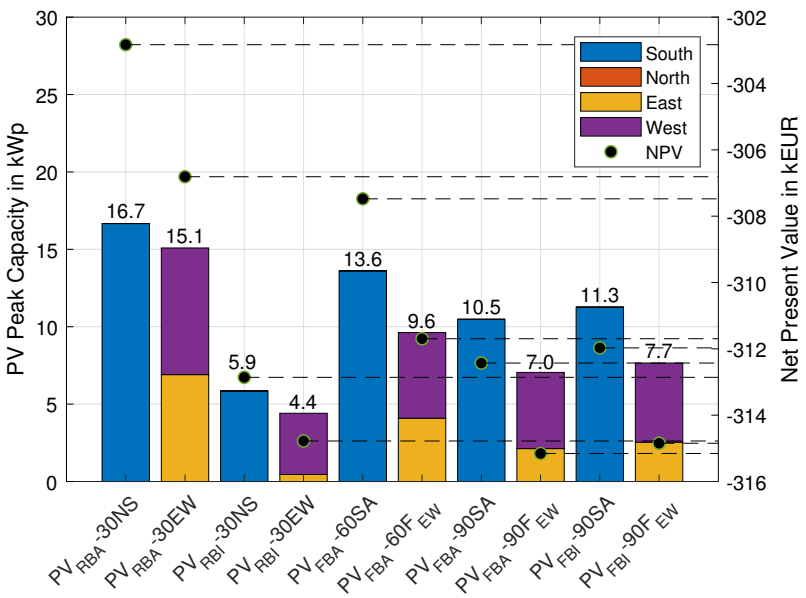

Figure 3.6.: Impact of the building configuration and the location of a PV system on the optimal system size and NPV. Building heat load: 145 kWh/m^2/yr. Heating system: monovalent heat pump.

- Rooftop PV, roof pitch of 30° (PV_{RBA}-30NS, PV_{RBA}-30EW, PV_{RBI}-30NS, PV_{RBI}-30EW): As expected, a BAPV system (on the southern side) on a roof oriented North-South is the most profitable, due to the fact that the best solar irradiation is in the southern direction. The PV capacity on the northern side of the roof is determined to be zero. Surprisingly, in case the roof has an East-West orientation, the optimal size for a collectively installed PV system is only slightly smaller. As soon as rooftop PV systems are implemented in a building-integrated fashion, instead of as building-attached, the costs rise (the NPV drops) significantly, leading to smaller optimal PV system sizes. In addition to the higher costs for rooftop BIPV elements (compared to BAPV), additional basic roof renovation

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costs have to be taken into account, as a building-integration of a PV means an intervention in the existing building envelope. This reduces the profitability.

- Shading PV elements on the facade, pitch of 60° (PV_{FBA}-60SA, PV_{FBA}-60F_{EW}): Due to the salient character of shading elements, the only way to implement them is by attaching them to the building. In case the building stands alone, the optimisation favours implementing shading elements on the South facade, proving this direction to be the most profitable. However, in case the South facade is not available due to adjoining dwellings, shading elements on the East and West facade are also profitable – otherwise the optimal PV capacities would be set to zero by the optimisation.

- Facade PV, pitch of 90° (PV_{FBA}-90SA, PV_{FBA}-90F_{EW}, PV_{FBI}-90SA, PV_{FBI}-90F_{EW}): For facade PV implementation, the building-integrated solution (despite the additionally occurring basic facade renovation costs) proves to be more profitable than implementing building-attached facade PV panels. The cost range for building-integrated facade elements is basically large, but when assuming a cold facade[11] with standard PV elements it is a less expensive option [59][12]. This results in significant PV implementation, despite the non-optimal solar irradiation. If a warm facade[13] is assumed, the higher costs lead to a decrease of the optimal PV system size. Moreover, at the upper end of the cost range of a warm facade, no PV system is implemented at all, due to its lack of profitability.

The analyses above have shown that in the case of a PV roof solution, the building-attached implementation is the most profitable, whereas building-integrated solutions are preferrable for cold facades. For reasons of urban design, the results of building-integrated solutions being more profitable for cold facades than building-attached ones is doubly pleasing. PV panels used as shading elements are not only profitable and contribute to reducing the electricity and heating costs, but they also enhance the residents' living comfort.

[11] A cold facade is characterized by the following structure from outside to inside: (i) external surface, (ii) air space, (iii) insulation (iv) construction/wall.
[12] For further explanations see Table 3.4.
[13] The main structural distinction of the warm facade in comparison to the cold facade is that it lacks an air space.

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3.3.2. The impact of varying the building set-up

3.3.2.1. Heating system change

Starting from the default setting, a rooftop BAPV system is studied. In addition, different heating systems are tested to complement the PV system. Figure 3.7 presents the long-term profitability results for the different use cases in terms of NPVs.

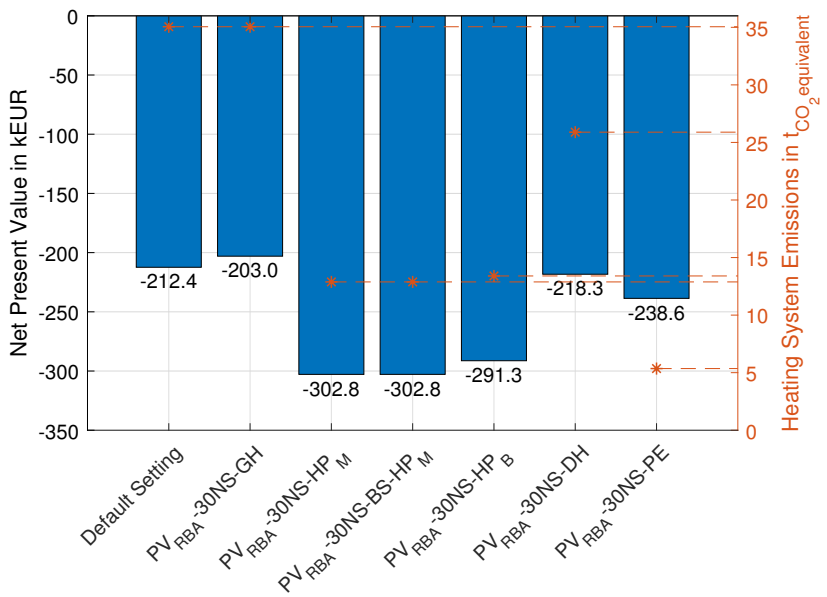

Figure 3.7.: Influence of different heating systems on NPV and corresponding CO_2 emissions. Building heat load: 145 kWh/m^2/yr.

Small cost savings can be achieved by implementing a rooftop BAPV system in addition to the default setting. When expanding the analysis to an additional change of the heating system, the NPV drops in comparison to the default setting, making the gas heating the cheapest alternative. The cost ranking from lowest to highest cost for the different heating systems is: (i) gas heating, (ii) district heating, (iii) pellet heating, (iv) bivalent heat pump, (v) monovalent heat pump (plus battery storage). The equality of the NPV of a monovalent heat pump with and without battery storage indicates that a stor-

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age can not yet contribute to energy cost savings: no storage is implemented according to the optimal solution of the optimisation. Therefore, battery storage devices are not considered in the further analyses of this chapter.

However, when retrofitting a building, besides the costs, also the CO_2-footprint is of interest. Therefore, the CO_2 emissions of the heating systems are roughly quantified [158][14] in addition, see Figure 3.7. Pellet heating achieves the best results, followed by the monovalently operated heat pump. The heat pump – in contrast to pellet heating – interacts with the PV system, meaning that the heat pump has a positive influence on the profitability of the combined technology portfolio. As this part of the thesis focuses on different PV systems on/in the building skin in particular, the monovalently operated heat pump is the heating system of choice for further use cases.

3.3.2.2. Tenant portfolio

Often, the ground floor of a multi-apartment building is used to accomodate small businesses instead of being used for residential purposes only. It can be assumed that their presence has a significant impact on the optimal installed PV system size, as businesses use most of their electricity during the day. In order to assess such a situation, the load profiles of two ground floor apartments are now replaced with a standard load profile for a grocery store (45 000 kWh/yr)[15]. To make the results comparable, the remaining settings are the same as in the case studies in Section 3.3.1. Figure 3.8 presents the results of the tenant changes.

In direct comparison to Figure 3.6, the PV system sizes rise significantly. This can be explained, on the one hand, by the significantly higher total electricity demand of the building. On the other hand, the business load profile has a better correlation with the hours of sunshine than the households. Most interestingly, the implementation of a BAPV system, located on a roof oriented North-South, is also profitable for the northern direction – the first and only time in this study. This means that the size of the building's total load and the improved correlation with the sunshine hours has a significant impact,

[14] Estimates of the CO_2-equivalent by the Austrian Federal Environmental Agency also include the upstream greenhouse gas emissions.

[15] The load profile can be found in Figure A.2.

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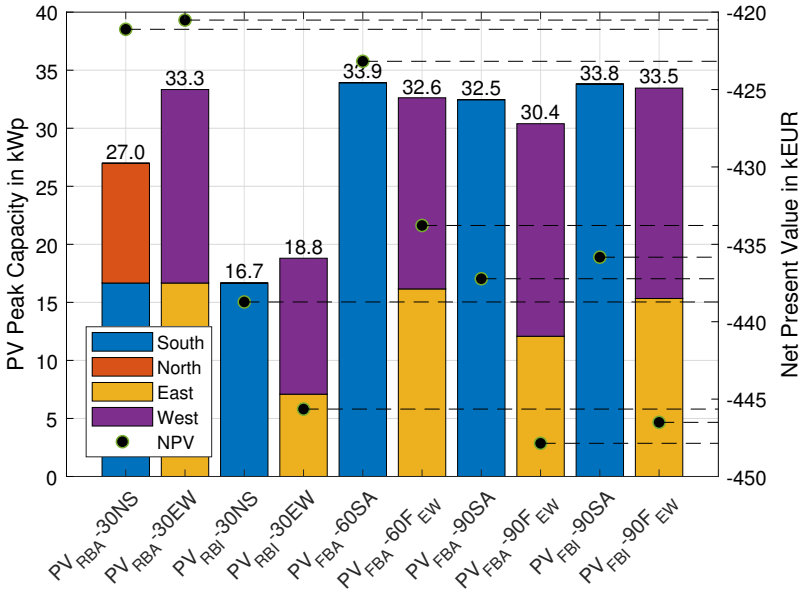

Figure 3.8.: Impact of building configuration and PV implementation concept on optimal system size and NPV. Building heat load: 145 kWh/m^2/yr. Heating system: monovalent heat pump.

and triggers the installation of a PV system in the northern direction despite the moderate solar irradiation.

3.3.2.3. Roof pitch

Until now, the multi-apartment building's roof pitch has been assumed to be 30 °. As saddle roofs with pitches between 20 ° and 40 ° are also common, the impact of variations in the pitch are now analysed. For a rooftop BAPV system with the roof oriented North-South, the maximum PV peak capacity of 16.7 kWp (limited by the available roof area) is built South for all use cases. In the case of a roof with an East-West orientation, the ideal pitch is 20 ° whereas a pitch of 40 ° proves to be least profitable (smallest PV system size) for BAPV as well as BIPV systems (see Figure 3.9). In addition, it can be seen that in all cases, the western oriented part of the PV systems is larger than the eastern part. The higher the electric load in the afternoon hours, the more profitable a western-oriented PV system becomes. However, the steeper the pitch, the more the PV is built on the eastern part of the roof, as the morning

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sun can be harvested more easily.

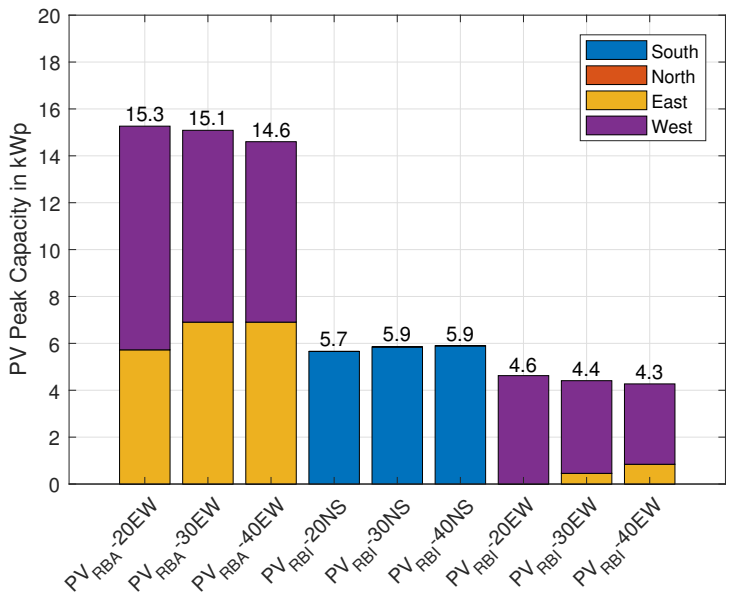

Figure 3.9.: Comparison of different roof pitches and their impact on the optimal PV system size. Building heat load: 145 kWh/m^2/yr. Heating system: monovalent heat pump.

When looking into the set-up of a BIPV solution for a roof with a North-South orientation, pitches of 30 ° and 40 ° yield PV system sizes that are almost equal. It can be concluded that the profitability of a PV system is just insignificantly dependent on the roof pitches' varying within a small range.

3.3.2.4. Building standard

In Table 3.9 (Section 3.2.5), the representative example of Austria shows that the average building quality of the housing stock is correlated with the year of construction. For sensitivity analyses of the building quality, six different building standards are considered in the following use case analyses.

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3.3.2.5. Without consideration of retrofitting costs for heat load reduction

Six identically equipped stand-alone multi-apartment buildings, whose only difference is the heat load, are investigated. As the buildings with different heat loads are assumed to exist already, there is no need to take additional passive retrofitting costs for heat load reduction into account. In each of the studied use cases, the building can be equipped with an optimally sized facade BAPV system. Figure 3.10 shows the optimal system capacities of PV and heat pump for each case. The optimal heat pump capacity decreases significantly along with the heat load, whereas the PV system size declines insignificantly. The reason is that the main part of the generated PV electricity is used to cover the electric load. The red line in Figure 3.10 shows the cost reduction for covering electricity and heating services with increasing building standards compared to the heat load of 160 kWh/m^2/yr. The calculation of this relative cost reduction is presented in Equation 3.14.

$$c_{red} = \frac{(NPV_{HL_{160}} - NPV_{HL_{else}})}{NPV_{HL_{160}}}, \tag{3.14}$$

whereas $NPV_{HL_{160}}$ is the NPV of the building with the worst heat load of 160 kWh/m^2/yr and $NPV_{HL_{else}}$ represents the NPV of each case with a smaller heat load.

3.3.2.6. With consideration of retrofitting costs for heat load reduction

In the following, the passive retrofitting costs for improving the building envelope are taken into account, starting from the initial value of 160 kWh/m^2/yr. The heat load reduction achieved by different renovation measures and corresponding costs are listed in Table 3.10[16].

[16] It is assumed that besides the listed renovation measures, an insulation upgrade of the top floor ceiling and the ground floor ceiling is done in all cases, at a cost of 30 EUR/m^2. Costs provided by [61]. Facade improvement is used as the primary renovation measure, since facade insulation can be easily combined with necessary building maintenance measures. Furthermore, specific costs for a window change are higher compared to those of a facade insulation.

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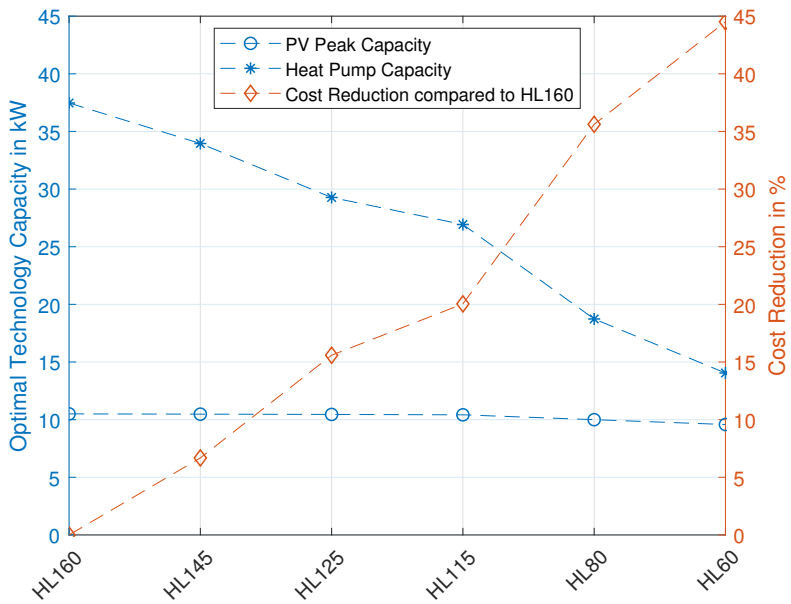

Figure 3.10.: Optimal installed heat pump- and PV peak capacity for different building qualities (heat loads). Heating system: monovalent heat pump.

Heat load reduction in kWh/m^2/yr], from → to	Thickness of insulation in cm	Costs for insulation in EUR/m^2	Window change	Costs for windows in EUR/pc
160 → 145	9	70	no	-
160 → 125	13	82	no	-
160 → 115	16	91	no	-
160 → 80	18	97	yes	1000
160 → 60	20	103	yes	1000

Table 3.10.: Improvement of building quality (heat load reduction) by facade insulation and change of windows.

Figure 3.11 presents the cost reduction results of Figure 3.10 in absolute terms (red line) in comparison to the renovation costs of Table 3.10 (blue line), coming with increasing improvement of building quality. From the comparison (renovation cost versus cost reductions) shown in Figure 3.11, it can be seen that passive building renovation is not profitable in these use cases without

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any financial incentive (e.g. governmental subsidies, etc.). The cost reduction achieved by better building quality (red line), is not even close to compensating for the renovation costs (blue line). This profitability gap is further analysed and discussed in Section 3.4.4.

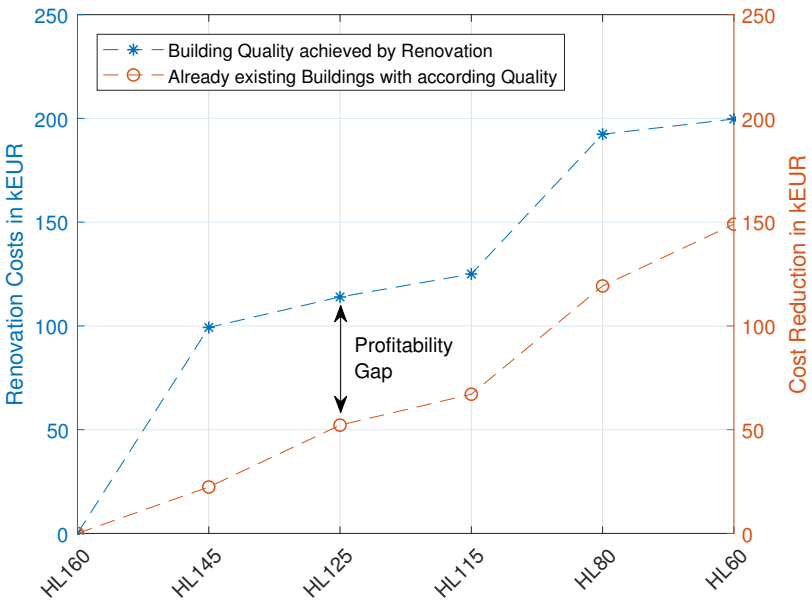

Figure 3.11.: Renovation costs (blue line) are shown in contrast to cost reductions (red line), which can be achieved by an improved building quality. Starting from a heat load of 160 kWh/m^2/yr, passive renovation costs and energy cost savings are determined for improvements of the specific heat load as listed in Table 3.10. Heating system: monovalent heat pump.

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3.4. Sensitivity analyses

So far in this study, retail energy prices for electricity, gas, district heat and pellets are assumed to be constant. However, there is no guarantee for these prices to remain constant over the next 20 years. Therefore, sensitivity analyses are conducted to address the impact of price changes (Section 3.4.1 and Section 3.4.2). The reasoning behind the assumed prices and price developments is further explained in Appendix A.5. Moreover, the impact of different interest rates (Section 3.4.3) and CO_2 price variations (Section 3.4.4) is evaluated.

3.4.1. Retail electricity price

Due to the assumption of monovalent heat pumps in the majority of the case studies, the retail electricity prices are most important for this work. Therefore, three additional electricity price developments are investigated: According to [42], an annual average retail electricity price increase of 2.37 % can be assumed based on historical data. Additionally, a double price increase of 4.74 % and a decrease of 2.37 % per year is investigated for result diversity. Figure 3.12 presents the results of named price variations in comparison to the setting with 22 c/kWh which remain constant for 20 years. It can be observed that the NPV decreases with increasing retail electricity prices as expected. Furthermore, the influence of different retail electricity prices on the profitability of PV systems becomes obvious: Optimal PV capacities rise significantly with increasing prices. In the case of a retail electricity price increase of 4.74 % per year, the optimal PV system size is more than doubled (+117.8 %). This is especially surprising when considering that in this case a rooftop building-integrated PV system is assumed, which is the most costly PV option in this study due to additional basic roof renovation costs. This fact emphasizes the cost saving potential of PV systems, especially for high retail electricity prices.

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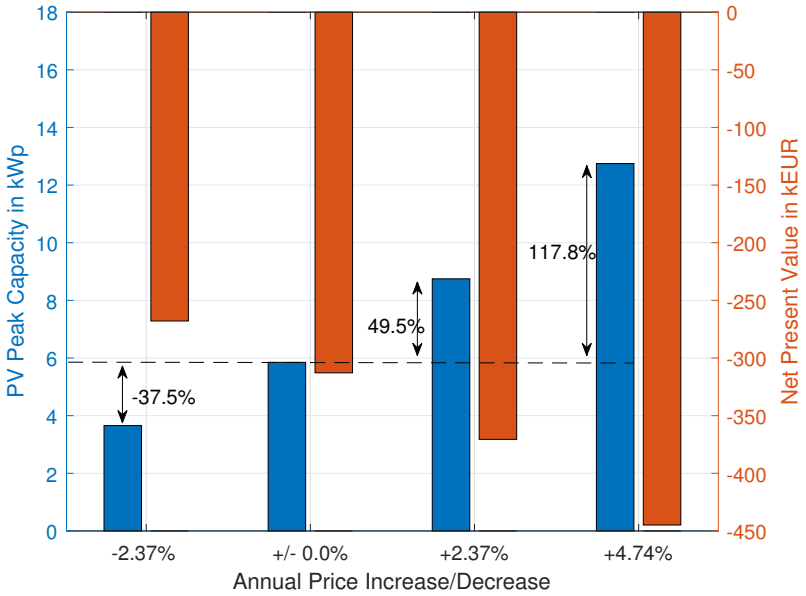

Figure 3.12.: Varying retail electricity prices. Starting point for the price variations is a price of 0.22 EUR/kWh as originally specified in Table 3.5. The use case analysed is PV_{RBI}-30NS-HP_M.

3.4.2. Retail heating fuel price

In order to also address price variations for heating technologies, an average annual retail price increase of 1.15 % is assumed for gas [43], 1.4 % for wood pellets [122] and 5 % for district heat [162]. More detailed information is provided in Appendix A.5.

Table 3.11 shows the results for retail price variations of the different heating fuels. The case study of a rooftop building-attached PV system (North-South orientation, tilted 30 °) is analysed in order to compare the results with those presented in Section 3.3.2.1. The results show that a slight increase in retail fuel prices leads to a moderate NPV decrease in the single-digit percentage area within 20 years. When looking at the results for district heat when assuming a 5 % price increase per year, the NPV changes significantly by 23.55 %. In that case, the pellet heating would overtake district heat in the profitability ranking. However, district heat would still be cheaper than the bivalent or monovalent heat pump (compare to Figure 3.7).

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	Gas heating	Pellet heating	District heat
Initial situation (Section 3.3.2.1)			
Constant fuel price in EUR/kWh[17] or EUR/kg[18]	0.05	0.28	0.047
NPV in kEUR	-203	-239	-218
New situation			
Fuel price increase per year in %	1.15	1.4	5
NPV in kEUR	-213	-254	-270
NPV decrease in %	4.89	6.4	23.55

Table 3.11.: NPV change due to a fuel price increase. Comparison of the results of Section 3.3.2.1, referred to as initial situation, and the new situation with a fuel price increase. The use case analysed is PV_{RBA}-30NS-GH/PE/DH.

3.4.3. Interest rate

As a basis for all analyses so far, a conservative interest rate of 3 % is assumed. A private investor might just expect a minimum return on investment, which should cover at least the inflation. In order to also illustrate the impact of higher interest rates (which could be expected by housing companies for example), which can also be related to the risk of investment, a sensitivity analysis is conducted for higher interest rates of 5 % and 7 %.

Figure 3.13 shows the results for higher interest rates in comparison to the results for the default interest rate of 3 %. It can be seen that the optimal PV system capacities drop with increasing interest rates. This means a decreasing profitability of PV, and at the same time an increasing NPV. With increasing interest rates, future cash flows shrink, reducing the positive impact of PV systems (their cost saving potential is reduced). At the same time, however, there is the phenomenon of an increasing NPV. As higher interest rates make future cash flows shrink, the negative contribution of future payments for energy to the NPV is reduced, leading to a less negative NPV. The NPV for the use case with an interest rate of 5 % increases by 13.5 %, while the optimal PV

[17] Gas heating and district heat
[18] Pellet heating

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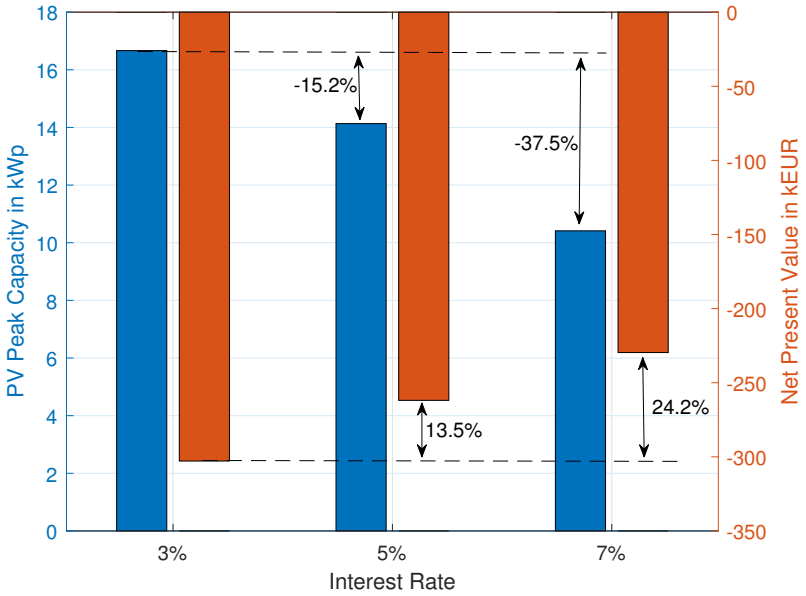

Figure 3.13.: Varying interest rates. The use case analysed is $PV_{RBA} - 30NS - HP_M$.

system size drops by 15.2 % compared to the use case of a 3 % interest rate. Assuming an interest rate of 7 % leads to an NPV increase by 24.2 % and a decrease in the optimal PV system size of 37.5 %.

3.4.4. Costs for emissions

The pass-through of CO_2 allowance prices to wholesale and retail electricity prices depends on different factors, e.g. the generation technology portfolio in the market area of investigation, regulations, and other factors [76]. According to [91], in the European Union on average, wholesale electricity prices rise by 10-13 EUR/MWh when assuming CO_2 costs of 20 EUR/t_{CO_2}. These numbers are in line with [143]. A report from 2016 confirms these results, by stating that an increase in EU ETS prices by 1 EUR/t_{CO_2} results in an increase of average wholesale electricity prices by 0.2–0.8 EUR/MWh [17].

This section aims at examining a complete pass-through of rising CO_2 costs to the retail electricity price. The alteration of the size of the profitability gap,

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introduced in Section 3.3.2.6 for a retail electricity price of 0.22 EUR/kWh, is addressed in this context. Therefore, an increase of the retail electricity price by 0.04 EUR/kWh and 0.08 EUR/kWh, triggered by a rise in CO_2 costs, is assumed. This corresponds to CO_2 costs of 80 EUR/t_{CO_2} (when assuming an average increase in the wholesale electricity price of 0.5 EUR/MWh per increase of EU ETS prices by 1 EUR/t_{CO_2}) and 160 EUR/t_{CO_2} for the 0.04 EUR/kWh and 0.08 EUR/kWh retail price increase, respectively [17]. This finally leads to increased retail electricity prices of 0.26 EUR/kWh and 0.30 EUR/kWh. Furthermore, it is assumed that PV systems do not receive remuneration for feeding surplus PV electricity generation into the grid anymore (0.03 EUR/kWh $\rightarrow$ 0 EUR/kWh). The rationale behind this assumption is that incentives are anticipated to entirely consume PV generation on-site in the multi-apartment building.

Figure 3.14 shows the impact of altered CO_2 prices (thus altered retail electricity prices) on the profitability gap. The size of the profitability gap decreases significantly with increasing CO_2– and thus retail electricity prices. The highest CO_2 prices almost lead to a monetary compensation for the initial passive renovation costs through the resulting energy cost savings in the case of the highest building standard of 60 kWh/m^2/yr.

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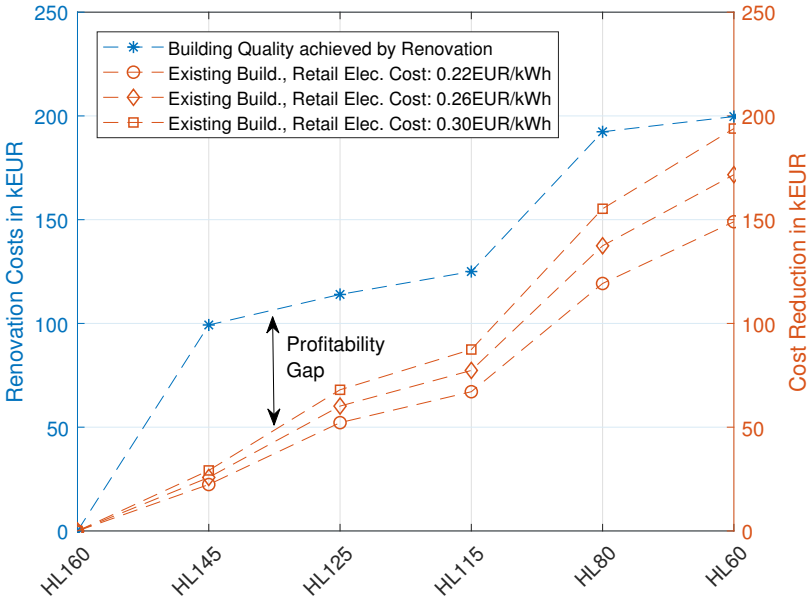

Figure 3.14.: Changes of profitability gap between renovation costs and cost reductions with increasing CO_2 prices. Heating system: monovalent heat pump.

3.5. Resume

To answer the question about the profitability of implementing shared PV systems in multi-apartment buildings, the developed optimisation model which determines the maximum NPV for the building residents along with optimal technology capacities, has proven to be suitable. The modularity of the approach (detailed selection of the multi-apartment building set-up) has proven to be helpful for providing a variety of meaningful results which help do derive general conclusions.

The results indicate that optimally-sized BIPV and BAPV systems on roof and facade are promising investments for an active multi-apartment building retrofit. Cost savings can be achieved, even with BIPV systems causing additional basic renovation costs and with facade PV installations despite reduced solar irradiation. A change in the heating system does not contribute to cost savings: The default gas heating remains the cheapest option. A heat pump

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installation, however, supports PV implementation due to synergy effects and thus triggers higher optimal capacities of the BAPV and BIPV systems. Results concerning the profitability of PV system installation can be considered robust, since sensitivity analyses are conducted for retail electricity price developments and varying interest rates. Even with decreasing per-unit retail electricity prices over the next 20 years, PV system installation breaks even - even for the most costly option of implementing a rooftop PV system building-integrated (additional costs for renovation due to violation of the building envelope).

However, despite the proven profitability of different kinds of PV systems implemented on various parts of the building skin, the increased diffusion of PV systems is still hampered by financial obstacles. Indeed, PV systems break even after multiple years of operation. This fact, however, does not alleviate the significant financial burden of upfront investment costs. The majority of people have limited financial means, especially when it comes to significant investments that are payable in full. With the increasing demand for PV installation in dwellings with multiple residents, new business models for third-party financing emerge.

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4. Contracting as enabler to PV sharing and thorough retrofit in multi-apartment buildings

4.1. Introduction - Financing of PV sharing concepts in practice

Despite the fact that implementing PV sharing concepts in multi-apartment buildings breaks even, the practical realisation of such still faces financial obstacles. The specifics of these monetary hurdles do significantly depend on the different kinds of building ownership, but can all be traced back to significant upfront investment costs and uncertainty caused by missing expertice of building owners / residents in the field of PV sharing. When going one step further and considering PV system implementation as only one part in the process of holistic building retrofit, the monetary difficulties become even more drastic since insulation upgrades of different parts of the building skin along with a replacement of old and energy-inefficient windows, require immense investments.

These issues are reflected in reality by insignificant shares of PV sharing concepts in multi-apartment buildings and insignificant shares of holistically retrofitted buildings. This again causes stagnation of (i) the deployment of renewable energy in the building sector and (ii) the reduction of the building sector's total energy consumption and thus CO_2 emissions.

A possible solution to break this downward spiral is contracting. Contracting enables building owners or owner communities with limited financial means to realise building projects, be it PV implementation only or a holistic building retrofit. With respect to the results gained in the course of Chapter 3, the current chapter aims to determine whether the implementation of PV sharing concepts remains profitable within the framework of contracting. Moreover, with respect to the previous analysis that showed a rough estimation of the

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profitability gap of passive renovation measures towards break-even, this chapter aims to investigate the (non-)profitability of applying renovation measures in detail, also within the framework of contracting.

4.2. Methods and model

In order to properly map the situation between a contractor and a building owner[1], the optimisation model introduced in Chapter 3 needs to be adapted. The part of the optimisation model that concerns the modelling of different technologies (Chapter 3.2.2) is not affected by a contracting framework, but the part that concerns the costs (Chapter 3.2.1) and the NPV calculation itelf is. Therefore, after introducing the different contracting options in Section 4.2.1, Sections 4.2.2 and 4.2.3 explain how the contractor-client relationship is modelled and how costs are allocated between these two parties.

4.2.1. Specification of contracting options

The primary purpose of contracting is that the initial investment is made by a contractor, potentially offering financial relief to the building owner. In return, the building owner undertakes to make annual payments to cover the contractor's total expenditures (plus a certain profit) at the end of the contracting period. The contractor's expenditures comprise the investment as well as possible operation and maintenance costs. The annual payments by the building owner to the contractor are also referred to as 'contracting rate' (CR).

In the course of this work, three different contracting models are examined.

- *Contracting option 1:* PV contracting
- *Contracting option 2:* Renovation contracting
- *Contracting option 3:* PV and renovation contracting including a heating system change

[1]The term 'building owner' is used to represent any kind of building ownership. In the course of this chapter, the building owner will also be referred to as 'client'.

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The first contracting option considers active building retrofit by implementing a rooftop PV system. The second option focuses on a variety of passive building retrofitting options such as building envelope insulation. The third and holistic contracting option combines active and passive retrofitting measures including a heating system change.

In order to realistically determine the profitability of building retrofitting measures within the framework of contracting, the original optimisation model is adapted such that it illustrates the interrelations between the client (the building owner or a community of owners) and the contractor on a practical level. This means, that it is explicitly refrained from using game theoretical or agent-based approaches, but the system analysis approach is pursued. System analysis models concerned with contracting issues focus on the practical situation of a contractor offering his services under specific conditions to which the clients agree in case their expectations are met in terms of energy service and building management. The practical approach is explained in detail in Sections 4.2.2 and 4.2.3. Since a part of this chapter addresses the implementation of different passive retrofitting (renovation) options, the impact of said renovation measures on the building heat load needs to be modelled in detail (Section 4.2.4). Since the whole model is applied to a realistic building, the building and its specifictaions is introduced in Section 4.2.5. The nomenclature is provided in Section 4.2.7.

4.2.2. A practical approach to modelling the interrelations of client and contractor

When investigating the business case of building retrofit contracting, two major parties can be identified. First, there is the client who aims at improving the building's standard but has trouble affording the high upfront payment. Second, there is the contractor, who agrees to make the investment instead and in turn receives annual payments from the client to cover the expenditures (plus an additional profit). Therefore, the contractor and the client have similar objectives, namely to maximise their own financial positions.

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Since the focus of this study lies on the profitability for the client, the optimisation problems' objective remains to maximise the client NPV (Equation 4.1). The nomenclature for this section is provided in Section 4.2.7.

$$NPV_{clients} = -I_{0_clients} + \sum_{y=1}^{Y} \frac{R_{clients}(y) - C_{clients}(y)}{(1 + r_{clients})^y} \tag{4.1}$$

However, in order to be able to guarantee the reimbursement of the contractor's expenditures including a certain profit, an according constraint needs to be set. To that end, the contractor NPV is calculated as well and is constrained to be greater than or equal to zero (Equation 4.2). The contractor's profit is determined by the chosen interest rate. Since the optimisation objective is to maximise the client NPV, the contractor NPV is kept as close to zero as possible (with respect to the contractor's expected interest rate) in the optimisation process, because the greater the contractor NPV, the worse the client NPV becomes.

$$\begin{aligned} NPV_{contractor} &= -I_{0_contractor} + \sum_{y=1}^{Y} \frac{R_{contractor}(y) - C_{contractor}(y)}{(1 + r_{contractor})^y} \\ NPV_{contractor} &\overset{!}{\geq} 0 \end{aligned} \tag{4.2}$$

Since this approach calculates the NPV's of both the contractor and the client, all costs occurring within the time horizon of 20 years need to be allocated to either of those two parties. The cost allocation is presented in detail in Section 4.2.3.

4.2.3. Cost allocation between client and contractor

A listing of all occurring costs, along with their calculations is provided in detail in Table 4.1. Compared to Chapter 3 it needs to be noted that in the current chapter, the number of technologies considered in the optimisation process is reduced. Since contracting is expected to decrease the profitablity of investements, only the most profitable option of a building-attached rooftop

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PV system is considered. In terms of holistic building retrofit that includes a heating system change, a heat pump is considered due to its synergy effects with the PV system. Moreover in this part of the thesis, an additional cost term for CO_2 emissions is introduced. Explicitly considering costs for emissions is important to realistically determine the profitabliliy of renovation measures.

Based on the contracting option chosen, costs are allocated appropriately to either the client or the contractor. The allocation of costs according to the chosen contracting option is given in Table 4.2[2]. The nomenclature is provided in Section 4.2.7, Tables 4.6 and 4.7.

[2]When PV contracting is analysed, all costs associated with PV (investment as well as operation and maintenance costs) are allocated to the contractor. The remaining costs are allocated to the client. However, cost terms such as investment costs for a heating system change or passive retrofitting would be zero in this example.

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Cost item	Explanation	Calculation	Indication
Investment costs			
I_{0_rpv}	RPV investment costs	$i_{0_rpv} \cdot \sum_d P_{rpv}(d)$	I_1
I_{0_hp}	Heat pump investment costs	$i_{0_hp} \cdot Cap_{hp}$	I_2
I_{0_renov}	Investment in passive renovation measures	$i_{0_win} \cdot n_{win} + i_{0_insul_out} \cdot A_{OW} + i_{0_insul_in} \cdot (A_{CFC} + A_{TFC} + A_{NW})$	I_3
Annual revenues			
$R_{rpv}(y)$	Revenues by surplus RPV feed-in into the grid	$\sum_t \sum_d e_{rpv2grid}(d,t,y) \cdot p_{feedin}(y)$	R_1
CR	Contracting rate (revenue from contractor view)	determined by optimisation	R_2
Annual costs			
$C_{Anno_rpv}(y)$	Annual costs for RPV (operational cost, cleaning costs)	$c_{op_rpv}(y) + c_{clean_rpv}(y) \cdot \sum_d P_{rpv}(d)$	C_1
$C_{gridcons}(y)$	Costs for grid electricity purchase (electricity load coverage, feeding heat pump and heating rod)	$\sum_t (e_{grid_2eload}(t,y) + e_{grid_2hp}(t,y) + e_{grid_2hload}(t,y)) \cdot p_{grid}(y)$	C_2
$C_{CO2}(y)$	Additional costs for CO_2 emissions	$\left(\sum_t h_{load}(t,y) \cdot f_{CO_2_heat} + \sum_t (e_{grid_2eload}(t,y) + e_{grid_2hp}(t,y) + e_{grid_2hload}(t,y)) \cdot f_{CO_2_elec}\right) \cdot p_{CO_2}(y)$	C_3
$C_{anno_heatsys}(y)$	Fixed/maintenance cost of heating system	gas/oil: $c_{maint_heat}(y) \cdot n_{units}$, heat pump: $c_{maint_heat}(y)$	C_4
$C_{Anno_else}(y)$	Additional annual costs - fixed costs for grid connection	$c_{fix_elec}(y) \cdot n_{units}$	C_5
$C_{var_heatsys}(y)$	Heating 'fuel' costs	$\sum_t h_{load}(t,y) \cdot p_{fuel}(y)$	C_6
CR	Contracting rate (costs from client view)	by optimisation	C_7

Table 4.1.: Different cost items.

		Contractor	Client
Contracting Option 1	Investment	I_1	I_2,I_3
	Annual revenues	R_1,R_2	-
	Annual costs	C_1	C_2,C_3,C_4,C_5,C_6,C_7
Contracting Option 2	Investment	I_3	I_1,I_2
	Revenues	R_2	R_1
	Annual costs	-	C_1,C_2,C_3,C_4,C_5,C_6,C_7
Contracting Option 3	Investment	I_1,I_2,I_3	-
	Revenues	R_1,R_2	-
	Annual costs	C_1,C_4	C_2,C_3,C_5,C_6,C_7

Table 4.2.: Cost item allocation according to contracting model.

4.2.4. Algorithm for detailed heat load calculation

As previously mentioned, the building's heat load and thus the impact of renovation measures on the heat load are modelled in detail, based on the specifications of the materials used. The nomenclature for this section is given in Table 4.8, Section 4.2.7. In general, the heat load (P_H in kW) of a building is composed of transmission P_T and ventilation P_V heat load (Equation 4.3).

$$P_H = P_T + P_V \tag{4.3}$$

The transmission heat load can be calculated as demonstrated in Equation 4.4[3]. The total transmission heat load is composed of the individual transmission heat loads of the individual building parts (x). The thermal conductivity (U_x) of each building part depends on the materials (specifications and thickness).

[3]The factor $10^{(-3)}$ adjusts the unit W to kW.

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$$P_T = \sum_x U_x \cdot A_x \cdot (t_i - t_a) \cdot 10^{(-3)}, \text{ with } t_a \in t_{aN},\, t_{aB},$$
$$\text{with} \quad U_x = 1/\big(\alpha_x + \sum_j b_j/\lambda_j\big) \tag{4.4}$$

The calculation of the ventilation heat load is shown in Equation 4.5[4].

$$P_V = (0.75 \cdot n_{air} \cdot \rho_{air} \cdot c_{hc} \cdot V_{MAB} \cdot (t_i - t_{aN}))/3600 \tag{4.5}$$

After calculating the building heat load P_H, the theoretical net energy demand can be determined as shown in Equation 4.6[5].

$$E_{net} = P_H/(t_i - t_{aN}) \cdot HDD \cdot 24 \tag{4.6}$$

The heating degree days (HDD) are defined as the sum of the differences between the indoor temperature (assumed to be 20 °C) and the daily outdoor temperature average across all heating days of a year. A day is considered a heating day if the average outdoor temperature falls below the heating limit, which is usually assumed to be 12 °C. Thus, the HDD calculation can be formulated as demonstrated in Equation 4.7.

$$HDD = \sum t_{diff} \quad \forall t_{diff} \leq 8$$
$$\text{with} \quad t_{diff} = t_i - t_{daily_av} \tag{4.7}$$

In order to achieve a realistic value of a specific heat load (in kWh/m^2/yr), the net energy demand needs to be adjusted for two factors – solar gains and inside thermal gains. Depending on the orientation of the building (d - direction), solar gains through windows need to be considered (Equation 4.8[6]). Inside thermal gains[7] can be considered to be 3 W/m^2. The total thermal gains

[4]The factor 0.75 is the heat recovery factor. The factor 3600 implies the conversion from Joule, which equals Watt-Seconds, to Watt-Hours.
[5]The factor 24 implies the conversion of days (heating degree days (HDD)) to hours.
[6]The factor $10^{(-3)}$ adjusts the unit of the solar irradiation from Wh/m^2 to kWh/m^2.
[7]The inside thermal gains depend on the building utilisation (household, businesses or else) as well as on the number of people and electric appliances giving off heat. Since in this case a residential building is assumed, where the inhabitants are likely to work during

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are calculated as demonstrated in Equation 4.9[8].

$$E_S = \sum_{d} \sum_{t=1}^{35040} (E_{in}(d,t) \cdot 10^{(-3)}) \cdot f_{corr} \cdot A_{windows}/2 \tag{4.8}$$

$$E_I = (G_I \cdot 10^{(-3)} \cdot n_{HD} \cdot 24) \cdot A_{MAB} \tag{4.9}$$

After the net energy demand is adjusted for solar and internal thermal gains, the building's specific heat load in kWh/m^2/yr can be calculated as demonstrated in Equation 4.10.

$$E_{HL_spec} = (E_{net} - E_S - E_I)/A_{MAB} \tag{4.10}$$

Based on the specific heat load, the building's heat load profile, resolved at 15-minute intervals, is determined as described in [50].

4.2.5. Physical building structure and building set-up

In this study, the object of investigation is a five-storey multi-apartment building with ten residential units. This building is located in the city of Vienna, Austria, being directly adjoint to two neighbouring buildings. The building's roof is tilted at 30 ° and is oriented North-South. The building characteristics such as dimensions and construction materials, are specified in Table 4.3. The total building electricity load profile is equal to the one introduced in Chapter 3. In the default setting[9], the building is heated by gas[10], and the specific heat load is determined to be approximately 140 kWh/m^2/yr. The heat load calculation[11] is based on the building's construction materials and their dimensions,

the day, the internal gains are assumed to be on the lower end of the spectrum with 3 W/m^2, which is in line with [65] and [137].

[8] The factor 24 implies the conversion to hours; $10^{(-3)}$ converts the original unit of the internal gains to kW/m^2.

[9] Default setting means that neither active nor passive retrofitting measures are implemented.

[10] Gas heating is typical for old multi-apartment buildings in city areas.

[11] The detailed calculation of a building's heat load is explained in Section 4.2.4.

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which are listed in Tables 4.4 and 4.5.

Element	Description	Value[12]/Unit
Long building side	Yard and street side	17 m
Short building side	Adjoint to neighbouring buildings	12 m
Height of the building	Approx. 4 m per storey	20 m
Number of storeys	-	5
Number of windows	16 per storey (8 yard-, 8 street-side)	80

Table 4.3.: Building specifications, default setting.

Element	Material	Dimension[13]
Outer walls (yard and street side)	Limestone	0.02 m
	Brick	0.45 m
Outer walls (to neighbouring buildings)	Limestone	0.01 m
	Brick	0.3 m
Basement upper ceiling	Brick	0.45 m
Attic upper ceiling	Brick	0.45 m
Windows	Double windows, wood	1.1 m × 1.8 m
Door	Wood	1.5 m × 2.5 m

Table 4.4.: Building specifications, default setting.

Characteristic	Material	Value
Thermal conductivity (U-Value)	Brick	0.85 W/(mK)
	Limestone	0.87 W/(mK)
Heat transfer coefficient (α)	Outer walls	0.17 m^2K/W
	Intermediate floor (upwards)	0.25 m^2K/W
	Intermediate floor (downwards)	0.34 m^2K/W

Table 4.5.: Material characteristics [65], default setting.

[12]The building dimensions are typical for multi-apartment buildings in the inner districts of Vienna, Austria.

[13]The individual material dimensions are typical for central European buildings constructed around 1900.

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4.2.6. Illustration of procedure

Finally, a flow chart is given in Figure 4.1 to graphically show the linkages between the different parts of the proposed methodology and algorithms of Sections 4.2.2, 4.2.3, 4.2.4 and 4.2.5.

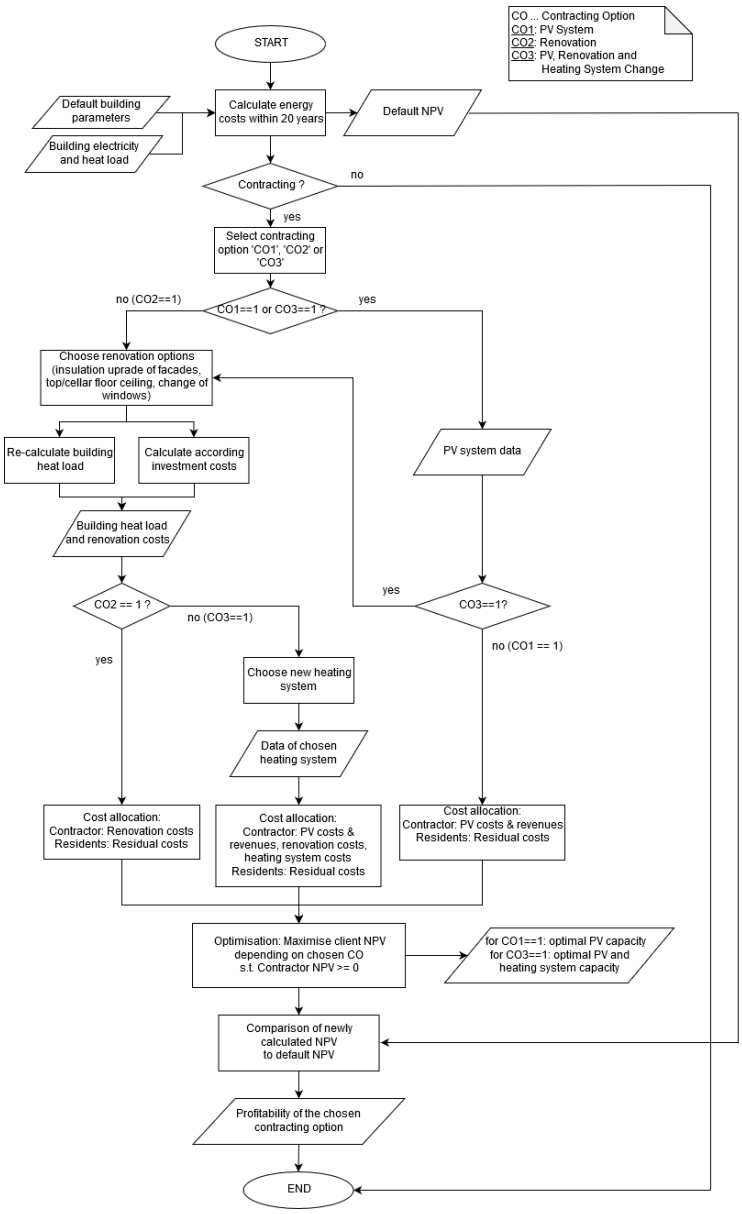

Figure 4.1.: Flow chart.

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4.2.7. Nomenclature and empirical scaling

Name	Explanation	Value/Unit
c_{clean_rpv}	Cleaning costs for rooftop PV	15 EUR/kW
c_{fix_elec}	Fixed costs for grid connection	65 EUR/yr
c_{maint_heat}	Fixed heating costs	gas: 150 EUR/yr/unit, oil: 150 EUR/yr/unit, heat pump: 300 EUR/yr
c_{op_rpv}	Annual operational costs for rooftop PV	60 EUR/yr
d	Direction	-
e_{grid_2eload}	Electricity from RPV to grid	kWh
e_{grid_2hload}	Electricity flow from grid to heating rod	kWh
e_{grid_2hp}	Electricity flow from grid to heat pump	kWh
e_{rpv_2grid}	Rooftop PV electricity fed to grid	kWh
$f_{CO_2_elec}$	Transformation factor kg_{CO_2} per kWh [14]	0.25 kg/kWh
$f_{CO_2_heat}$	Transformation factor kg_{CO_2} per kWh[15]	Gas: 0.44 kg/kWh, Oil: 0.645 kg/kWh
h_{load}	Building heat load	kWh
i_{0_hp}	Specific investment costs for heat pump	1000 EUR/kWh
$i_{0_insul_in}$	Specific costs for internal insulation with mineral wool[16]	83 EUR/m^2
$i_{0_insul_out}$	Specific costs for external insulation with mineral wool	106 EUR/m^2
i_{0_rpv}	Specific investment costs rooftop PV systems	1050 EUR/kW
i_{0_win}	Costs for one window	488 EUR/piece
n_{units}	Number of apartments	10

Table 4.6.: Nomenclature and costs.

[14] The assumed CO_2 factor is valid for the Austrian electricity mix [158].
[15] The assumed CO_2 factors are in line with [33].
[16] Costs for renovation measures are confirmed by [61].

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Name	Explanation	Value/Unit
n_{win}	Number of windows	-
p_{CO_2}	Price for CO_2 emissions[17]	84.3 EUR/t
p_{feedin}	Price for surplus PV feed-in	0.03 EUR/kWh
p_{fuel}	Heating fuel costs[18]	Gas: 0.05 EUR/kWh, Oil: 0.08 EUR/kWh
p_{grid}	Price for electricity purchase from the grid[19]	0.22 EUR/kWh
$r_{clients}$	Client's interest rate	3 %
$r_{contractor}$	Contractor's interest rate	5 %-15 %
t	Time steps (35040 quarter hours per year)	-
y	Year	-
A_{CFC}	Cellar floor ceiling area	m^2
A_{NW}	Area of wall to neighbouring buildings	m^2
A_{OW}	Outer wall area	m^2
A_{TFC}	Top floor ceiling area	m^2
Cap_{hp}	Optimal heat pump capacity (optimisation variable)	kW
$C_{clients}$	Client's annual costs	EUR/yr
$C_{contractor}$	Contractor's annual costs	EUR/yr
$I_{0_clients}$	Investment costs borne by clients	EUR
$I_{0_contractor}$	Investment costs borne by contractor	EUR
$NPV_{clients}$	Client's net present value	EUR
$NPV_{contractor}$	Contractor's net present value	EUR
P_{rpv}	Optimal rooftop PV capacity (optimisation variable)	kW
$R_{clients}$	Client's annual revenues	EUR/yr
$R_{contractor}$	Contractor's annual revenues	EUR/yr
Y	Period of investigation, in years	20

Table 4.7.: Nomenclature and costs.

[17] Future CO_2 prices are uncertain in general, for reasons of citability the assumed price is taken from [36].

[18] Costs for fossil fuels are in line with [35].

[19] The Austrian retail energy prices depend on the supplier and the region. The chosen retail electricity price in this study is in line with data from the Austrian statistics institute 'Statistik Austria' [151].

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Abbreviation	Specification	Value/Unit
α_x	Heat transmission coefficient of building part x	m^2K/W
λ_j	Heat conductivitiy of material j	W/(mK)
ρ_{air}	Air density	$1.3\,kg/m^3$
b_j	Thickness of material j	m
c_{hc}	Specific heat capacity	1.009 kJ/(kgK)
d	Direction (North/South/East/West)	-
f_{corr}	Solar irradiation reduction factor (shading by other buildings, trees, etc.)	5 %
j	Material	-
n_{air}	Air exchange rate	0.2 1/h
n_{HD}	Heating days	
t_a	Outdoor temperature	°C
t_{aB}	Buffer room temperature	10 °C
t_{aN}	Norm/standard outdoor temperature	−12 °C
t_{diff}	Temperature difference	°C
t_{daily_av}	Average daily temperature	°C
t_i	Indoor temperature	°C
x	Building part (e.g. outer wall, cellar floor ceiling etc.)	-
A_{MAB}	Multi-apartment building living area	m^2
$A_{windows}$	Total window surface	m^2
A_x	Surface of building part x	m^2
HDD	Heating degree days	Kd
E_{HL_spec}	Specific heat load	$kWh/m^2/yr$
E_I	Internal gains	kWh
E_{in}	Solar irradiation	Wh/m^2
E_{net}	Theoretical net energy demand	kWh
E_S	Solar energy gains	kWh
G_I	Internal thermal gains	$3\,W/m^2$
P_H	Total heat load	kW
P_V	Ventilation heat load	kW
P_T	Transmission heat load	kW
U_x	Thermal conductivity of building part x	$W/(m^2K)$
V_{MAB}	Building volume	m^3

Table 4.8.: Nomenclature and values specifically for the heat load calculation algorithm.

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4.3. Results and sensitivities

This section provides results for the previously introduced contracting options (i) PV contracting, (ii) renovation contracting and (iii) PV and renovation contracting including a heating system change.

- Section 4.3.1 addresses PV contracting. The results aim to provide an answer to the question whether PV systems are still profitable within the framework of a contracting business model where a third party – the contractor – expects to make a profit as well, which reduces the profitability of the installed technology for the building residents.
- Section 4.3.2 addresses the question whether building renovation, such as installing higher quality windows and upgrading the insulation, is actually not profitable or whether there are certain circumstances that help building renovation measures to break even.
- Section 4.3.3 addresses a holistic form of retrofit contracting, taking into account the possibility of PV system implementation, renovation and a heating system change. It is discussed under which circumstances a holistic building retrofit could be economically viable, even after changing the heating system from fairly cheap fossil fuels to a heat pump.

4.3.1. Profitability of PV contracting

4.3.1.1. The impact of the contractor's interest rate

This section aims at determining whether installing a rooftop PV system within the framework of contracting is profitable for the client[20]. The cost-optimal PV system capacity is determined by optimisation. Therefore, the installed PV system capacity is an indicator for profitability. The more PV is installed, the higher the monetary value is. If PV system installation is not profitable, the optimal PV system capacity is set to zero in the optimisation process.

[20] The term 'client' refers to an individual building owner as well as a community of owners or residents.

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The profitability of PV systems within the framework of contracting is highly dependent on the contractor's expected return on investment. The contractor's expectations are reflected in the interest rate used to calculate the contractor's NPV.

Figure 4.2 shows the impact of the contractor's interest rate on the optimal PV system size and the according client NPV[21]. The higher the contractor's interest rate, the less profitable PV installation becomes for the client, and consequently, the less PV is installed. At the same time, the client NPV decreases (worsens). Comparing the two extreme cases of a contractor's interest rate of 5 % and 15 %, it can be determined that the cost-optimal PV system capacities differ by 5.46 kW. This means that a 10 % increase in the contractor's interest rate (from 5 % to 15 %) leads to a 63 % reduction in the optimal PV system size. At the same time, however, the client NPV only worsens by 3.35 %. This decrease might seem small at first; However, the positive financial impact of PV in this case study is limited to reducing the electricity grid consumption, while the client NPV considers all occurring costs within a time period of 20 years, including the cost for heating. Moreover, the monetary benefits of a PV system with an installation capacity well below 10 kW for an entire multi-apartment building remain modest, as a matter of course.

The positive monetary impact of installing a PV system is higher without contracting. In this case, there is no third party, who also expects to make a profit from installing PV. In order to understand the monetary difference between these two situations (optimal PV installation with and without contractor), the client's NPV without contracting is visualised as a plane in Figure 4.2. The according optimal PV system size rises to 10.57 kW.

4.3.1.2. The impact of CO_2 emission costs

This sensitivity analysis examines the effect of introducing additional CO_2 costs for electricity and heat to the results of PV contracting. A CO_2 price

[21] It needs to be remarked that the client NPV is always negative, since the NPV calculation considers all costs within a time horizon of 20 years. If retrofitting measures are profitable, the client NPV increases (or in other words, the NPV 'becomes less negative'), but still remains negative as a matter of course.

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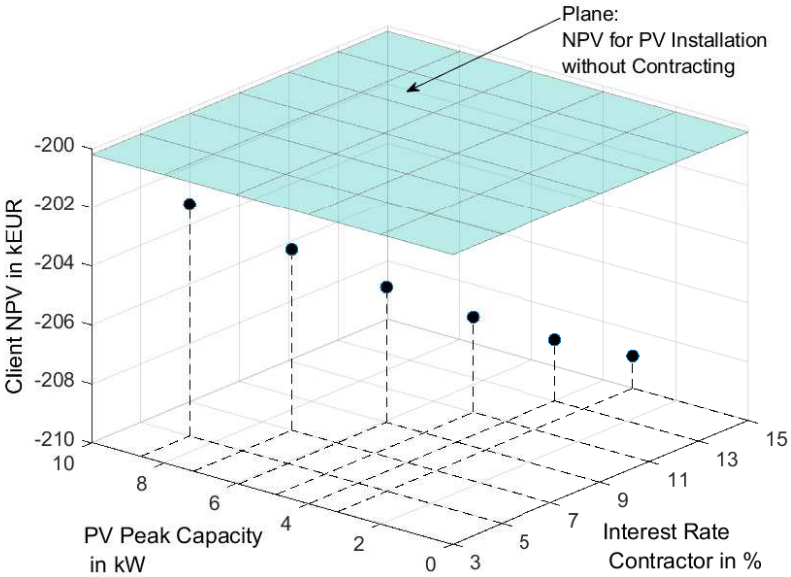

Figure 4.2.: Optimal PV capacity and client's NPV for a variety of contractor's interest rates.

of 84.3 EUR/t [36] is assumed[22]. Besides CO_2 costs, CO_2 factors of electricity and heat generation are needed as well. Since the multi-apartment building of investigation is located in Vienna, Austria, data is collected accordingly: The Austrian electricity generation mix causes CO_2 emissions of 0.25 kg/kWh, according to the federal environment agency [158]. The CO_2 factor of the building's default gas heating is assumed to be 0.44 kg/kWh, which is in line with [33].

The impact of CO_2 costs on the results for PV contracting is summarised in Table 4.9. The determined optimal PV system sizes increase, since purchasing electricity from the grid is more expensive if external costs, such as costs caused by CO_2 emissions, are internalised. However, the increase is modest and stays below 1 kW. By contrast, the client NPV difference is significant, since not only do the increased costs for purchasing grid electricity influence the client NPV, but especially the increased costs for heating with gas.

[22]This exact number is assumed due to reasons of citability.

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Contractor's interest rate	Without CO_2 costs PV Capacity in kW	NPV in kEUR	With CO_2 costs PV Capacity in kW	NPV in kEUR	Differences PV Capacity in kW	NPV in kEUR
5 %	8.65	-202.13	9.46	-276.67	0.81	74.54
7 %	7.19	-203.87	7.97	-278.59	0.78	74.71
9 %	5.93	-205.42	6.69	-280.32	0.76	74.90
11 %	4.90	-206.77	5.61	-281.85	0.71	75.07
13 %	3.99	-207.93	4.65	-283.19	0.66	75.25
15 %	3.19	-208.91	3.86	-284.34	0.67	75.43

Table 4.9.: Result comparison of PV contracting with and without CO_2 costs.

4.3.2. Profitability of renovation contracting

The second contracting option of investigation is renovation contracting. Renovation contracting can also be referred to as pure 'savings contracting', since it is not concerned with producing and self-consuming energy in contrast to PV contracting; It is solely focused on increasing the building standard and reducing the heat load. The most commonly implemented building renovation measures are installing higher quality windows and upgrading the insulation of the outer walls, the cellar floor ceiling, the top floor ceiling, and sometimes also the walls to the neighbouring buildings. Therefore, in this study, these five renovation measures are considered in the analyses and introduced in more detail in Table 4.10[23].

In order to properly assess the impact of building renovation measures, nine renovation options – including individual renovation measures as well as various combinations thereof – are introduced in Table 4.11. Depending on the renovation measures implemented, the building's heat load is reduced. If all renovation measures considered are implemented at once, the building quality increases to almost passive house standards with a heat load of only 21 kWh/m^2/yr[24].

The more significantly the heat load is reduced by the implementation of renovation measures, the better the impact on the environment (decreased

[23]Realistic costs for individual renovation measures are provided by [61].
[24]For passive house standards, the heat load must not exceed 15 kWh/m^2/yr.

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Renovation measure	Abbrev.	Specification	Costs
Window change	WD	triple glazing, thermal-insul. frame, U-value = 0.6 W/m^{2}K	488 EUR/piece
Insulation of top floor ceiling	TFC	16 cm of mineral wool, λ-value = 0.04 W/mK	83 EUR/m^2
Insulation of cellar floor ceiling	CFC	16 cm of mineral wool, λ-value = 0.04 W/mK	83 EUR/m^2
Insulation of outer wall	OW	16 cm of mineral wool, λ-value = 0.04 W/mK	106 EUR/m^2
Insulation of wall to neighbouring building	NW	16 cm of mineral wool, λ-value = 0.04 W/mK	83 EUR/m^2

Table 4.10.: Renovation measures specifications.

Renovation Measure	Heat load kWh/m^2/yr	Heat load reduction kWh/m^2/yr	Code
No Renovation (default)	140.69	-	Default
$TFC + CFC$	119.35	21.33	RC1
WD	108.02	32.66	RC2
OW	94.31	46.37	RC3
$WD + TFC$	91.29	49.39	RC4
$WD + TFC + CFC$	86.69	53.99	RC5
$WD + OW$	61.65	79.04	RC6
$WD + OW + TFC$	44.92	95.77	RC7
$WD + OW + TFC + CFC$	40.32	100.37	RC8
$WD + OW + NW + TFC + CFC$	21.41	119.28	RC9

Table 4.11.: Renovation measure combinations and their impact on the heat load.

CO_2 emissions, since the usage of the default gas heating is reduced). However, this also leads to higher investment costs. Whether the monetary value of annual energy cost savings (due to the reduced heat load) can compensate for the annual payments to the contractor is examined in the following.

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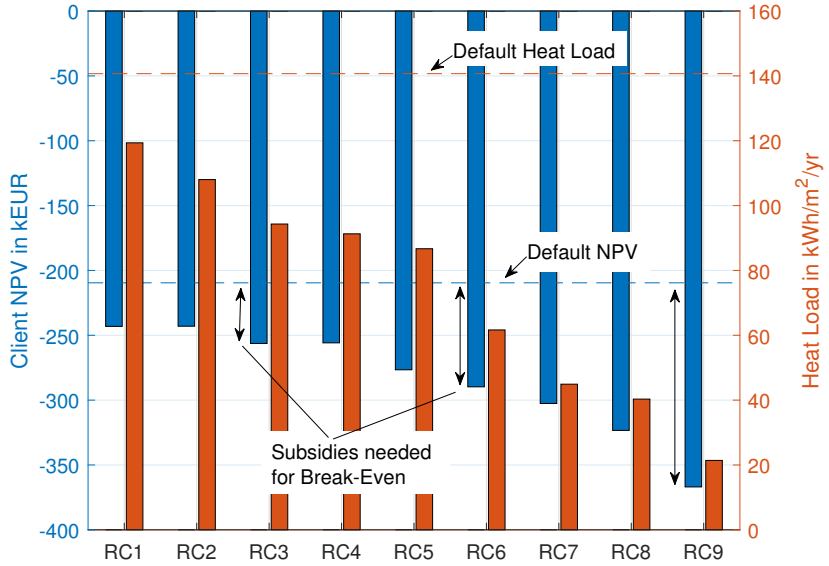

Figure 4.3.: Impact of renovation measures on the client NPV and the heat load. The contractor's interest rate is assumed to be 7 %.

In Figure 4.3[25], the impact of different renovation options on the client NPV is illustrated. Along with the decreasing heat load, the client NPV decreases as well (NPV worsens). It can be seen that the client NPVs calculated for the individual renovation possibilities (RC1 to RC9) are clearly below the default NPV that is calculated when no renovation measures are installed. The higher the monetary gap to the default NPV, the less profitable it is to implement the according renovation measures. This gap is indicated as 'subsidies needed for break-even' in Figure 4.3, since governmental financial compensation would be necessary to incentivise the implementation of renovation measures.

The non-profitability of renovation contracting poses a big problem, since building owners have no incentive to increase the building standard if the monetary value of energy cost savings does not compensate for the annual

[25] The contractor's interest rate is assumed to be 7 %, since the results in Section 4.3.1 have already shown that a high interest rate leads to a significant reduction in the profitability of retrofitting measures.

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payments to the contractor. However, there are three major factors that impact the monetary value of building renovation in general.

1. The introduction of costs for CO_2 emissions affects the results. The significance of said impact is analysed in Section 4.3.2.1.

2. Another influencing factor, which is analysed in Section 4.3.2.2, is the framework of contracting itself, since not only do the building owner seeks a profit, but also the contractor as a third party.

3. Last but not least, the default setting of the building plays an important role. Depending on the default heating system installed and the according costs for heating, the positive impact of renovation measures varies. This is analysed in Section 4.3.2.3.

4.3.2.1. The impact of emission costs

Fossil heating systems account for a significant amount of CO_2 emissions in the building sector. This section analyses the impact of introducing CO_2 costs of 84.3 EUR/t on the economic viability of renovation measures.[26] Since the default heating system of the building is gas, emissions of 0.44 kg/kWh [33] are assumed.

Figure 4.4 compares the client NPVs when implementing different renovation options for the two cases with and without additional CO_2 costs. On the one hand, introducing costs for emissions reduces the client NPV in total, since the costs for heat and electricity rise significantly. On the other hand, it therefore becomes more valuable to reduce the building's heat load by implementing renovation measures. In other words, saving one kWh of heat load is significantly more valuable in the CO_2 costs scenario than it is in the case study without additional CO_2 costs. Therefore, when taking CO_2 costs into account,

[26] Previous analyses showed that passive retrofitting measures per se do not break even within the assumed time horizon of 20 years. This means that the monetary value of energy savings achieved by implementing passive retrofitting measues does not compensate for the initial investment. However, when starting to internalise external costs, such as costs for CO_2 emissions, passive retrofitting measures might break even or, at least, the profitability gap towards the break-even point can be reduced.

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the monetary gap to the default NPV[27] is reduced and thus the number of subsidies that would be needed for renovation measures to break even shrinks. The number of subsidies needed to compensate for implementing renovation measures is depicted in Figure 4.4, in percent of the default NPV ($NPV_{default}$ – client NPV before the implementation of any renovation measures) as given in Equation 4.11.

$$Subsidy = \left| \frac{(NPV_{default} - NPV_{renov})}{NPV_{default}} \right|, \tag{4.11}$$

with NPV_{renov} being the client NPV after the implementation of renovation measures.

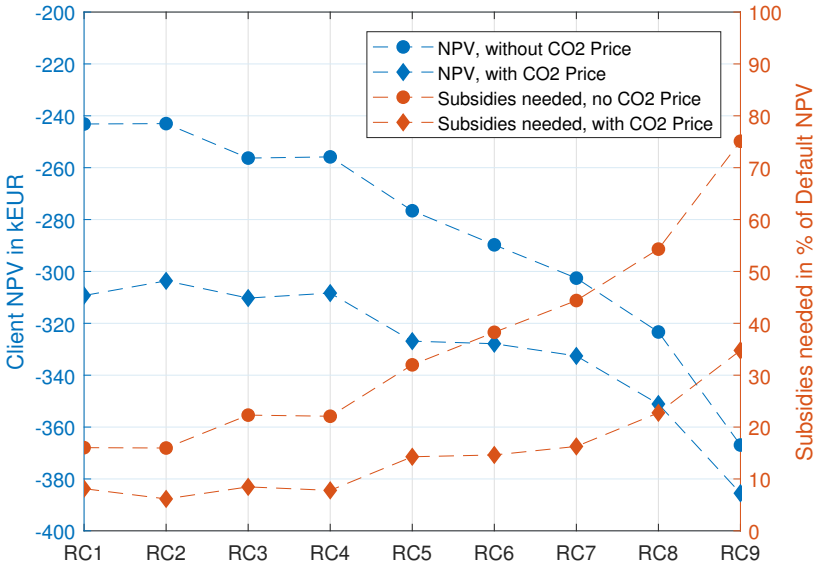

Figure 4.4.: Client NPV and subsidies needed in % of the default NPV. Heating system: Gas. Contractor interest rate: 7 %.

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Interestingly, it can also be observed that the gap between the curves of the client NPV decreases with increasing building standards (RC1 towards RC9). This phenomenon can be explained as follows: Due to the high CO_2 costs, heat load reduction by renovation measures becomes more profitable: The positive

[27]Depending on the case study, the default NPV differs whether additional CO_2 prices are taken into consideration or not.

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monetary effect of avoiding CO_2 costs comes closer to compensating for the negative monetary effect of the annual payments to the contractor. This effect is the more pronounced, the more renovation measures are implemented, and consequently the more significantly the heat load is reduced.

4.3.2.2. The impact of the contracting business model itself

Besides additional costs for CO_2 emissions, the contracting business model itself has an impact on the profitability of renovation measures, since the contractor expects a certain return on investment. These expectations are represented by the contractor's interest rate. Therefore, the profitability of renovation measures is expected to increase if the building owner/ owner community refrains from assigning a contractor.

The blue and green bars in Figure 4.5 indicate whether different renovation measures are economically viable if no contracting is applied by calculating the NPV difference[28] as given in Equation 4.12. These results are contrasted with the red bars, which show the client NPV difference if renovation measures are implemented within the framework of contracting (7 % interest rate of the contractor.)

$$NPV_{diff} = NPV_{renov} - NPV_{default} \tag{4.12}$$

If the client NPV in the default setting[29] ($NPV_{default}$) is less negative than the client NPV after implementing renovation measures (NPV_{renov}), it would be more profitable to refrain from implementing renovation measures, since the monetary value of annual energy savings does not compensate for the initial investment. In such cases, the determined NPV difference NPV_{diff} is negative.

The actual impact of the contracting framework, with a contractor's interest rate of 7 %, can be derived from the significant difference between the red and blue bars. The profitability gap when no contracting is applied (blue bars)

[28] The NPV difference can also be seen as the profitability gap towards break-even.

[29] Default setting of the blue-bar scenario: gas heating, no additional CO_2 costs. Default setting of the green-bar scenario: gas heating, additional CO_2 costs. Default setting of the red-bar scenario: gas heating, no additional CO_2 costs.

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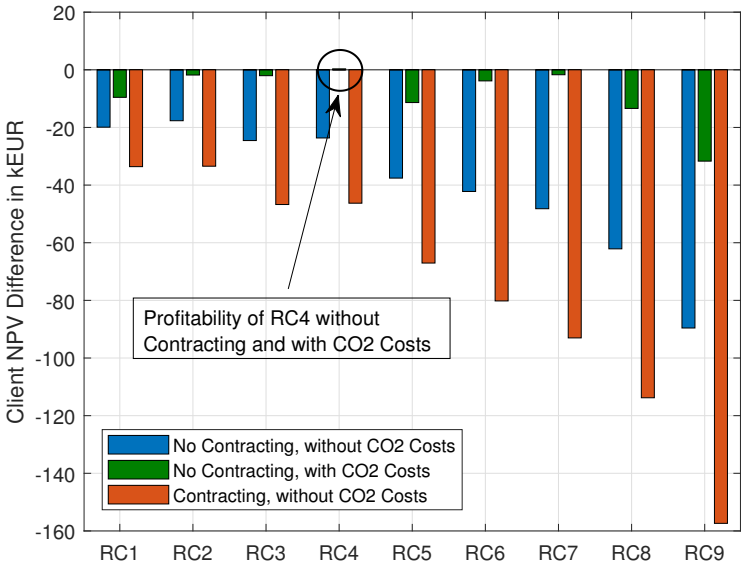

Figure 4.5.: Client NPV differences in case studies with and without contracting. In the case of contracting, the contracting interest rate is assumed with 7 %.

is almost half as big compared to when contracting is applied (red bars). If additional costs for CO_2 emissions are introduced, renovation options such as RC2, RC3 and RC7 do almost break-even, while RC4 even achieves a positive NPV difference. This means that investing in higher quality windows and top floor ceiling insulation is actually profitable if additional costs for CO_2 emissions are introduced and the building owners do not assign a contractor.

4.3.2.3. The impact of high emission heating systems

Up to this point, the multi-apartment building has been assumed to be heated with gas as the default setting. In this section, the default heating system is changed to oil. This assumption is justified because at present there are still many oil heating systems implemented in Austria, which have to be replaced as soon as possible[30]. Oil is an energy carrier that is more

[30] In some parts of Austria, the installation of oil boilers is not only prohibited in new buildings, but also oil heating systems in the existing building stock may not be renewed anymore and need to be replaced with other heating options.

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expensive (0.08 EUR/kWh [35]) than gas and causes higher CO_2 emissions (0.645 kg/kWh [33]).

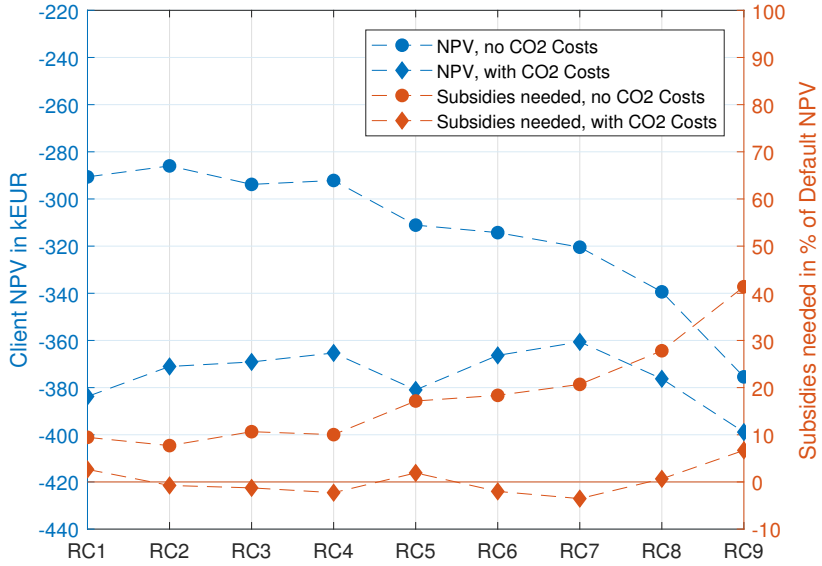

Figure 4.6.: Client NPV and subsidies needed in % of the default NPV. Heating system: Oil. Contractor interest rate: 7 %.

Figure 4.6 shows results that are equivalent to those in Section 4.3.2.1, with oil heating instead of gas heating as the only difference. This supposedly small change in the default setting has a significant impact. Renovation measures break even more easily since heat load reduction is more valuable, from an economic point of view, the higher the costs for the energy carrier and emissions. In the case of oil heating as the default heating system and additional costs for CO_2 emissions, five out of nine renovation measures break even.

4.3.3. Profitability of PV, renovation and heating system contracting

The most holistic approach to contracting takes into account PV system installation, passive retrofitting measures as well as a heating system change. The latter investigates a change from the default gas heating to a bivalent heat pump that is supplemented by a heating rod. The cost-optimal heat pump

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capacity is determined by optimisation.

Since the heat pump can not only be supplied by electricity from the grid but also by electricity generated by the PV system, the optimal PV system size changes with the implementation of a heat pump. Going back to pure PV contracting, Table 4.9 shows an optimal PV system size of 7.19 kW (no additional CO_2 costs; contractor interest rate of 7 %). In the event that all specifications are left unchanged, while the gas heating is replaced with a bivalent heat pump, the determined optimal PV system size rises to 10.34 kW.

Figure 4.7 shows results of the holistic contracting approach for three different versions of the contractor's interest rate. The following observations can be made:

- The higher the improvement of the building quality, the smaller the optimal heat pump size becomes. If the heat load is reduced to 21.41 kW (RC9), a heat pump capacity below 3 kW is cost-optimal[31].
- Since optimal PV system sizes correlate with the optimal heat pump capacities, the PV system capacities also shrink with the installed heat pump capacity.
- The decrease in optimal PV system sizes, however, is far less significant than the decrease in heat pump capacities with improved building quality. The reason is that the majority of PV electricity generation is still used for covering the electric load rather than feeding the heat pump, since heat demand and PV electricity generation are anti-correlated[32].
- The contracting rates (annual payments to the contractor) increase from RC1 to RC9, despite the shrinking capacities of PV and heat pump. This emphasises the comparably small impact of the investment costs for PV and a heat pump in comparison to the investment costs for passive retrofitting measures, which clearly dominate the total investment costs and thus the contracting rate.

[31] The residual load is covered by the heating rod.

[32] In times of high PV generation (summer), the heat demand is low or even zero. In times of low PV generation (winter), the heat demand is high.

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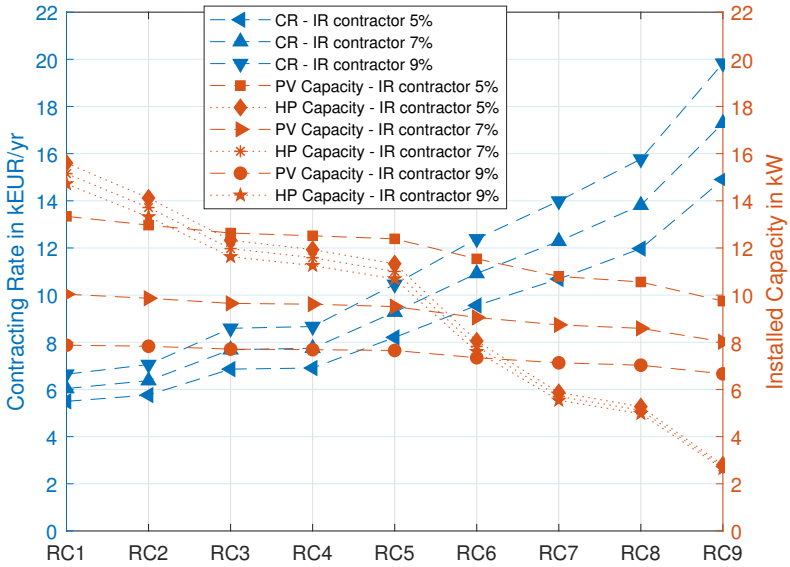

Figure 4.7.: Amount of contracting rate and optimal PV/heat pump capacities for different contractor interest rates.

The results in this chapter have so far shown that the profitability of retrofitting measures in general significantly depends on the contractor's interest rate and the costs of CO_2 emissions. The smallest possible interest rate of 5 % is used for the final analysis as illustrated in Figure 4.8. Additional costs for CO_2 emissions are also considered. On the one hand, the client NPVs are calculated for a holistic building retrofit (PV system, renovation measures and a heating system change). These NPVs are contrasted with two different default settings: (i) gas heating plus CO_2 costs and (ii) oil heating plus CO_2 costs. The client NPV of the default setting with an oil heating system lies significantly below (or in other words: is significantly more negative than) the client NPVs after holistic retrofitting. This means that holistic retrofitting is profitable if additional costs for CO_2 emissions are taken into account and oil heating is assumed to be the default heating system. Therefore, the NPV difference that is also shown in Figure 4.8 is positive in this case (light blue bars). If the default heating system is gas, holistic retrofitting does not break even. This is illustrated by the dark blue bars, which show a negative NPV difference ($NPV_{diff} = NPV_{renov} - NPV_{default}$).

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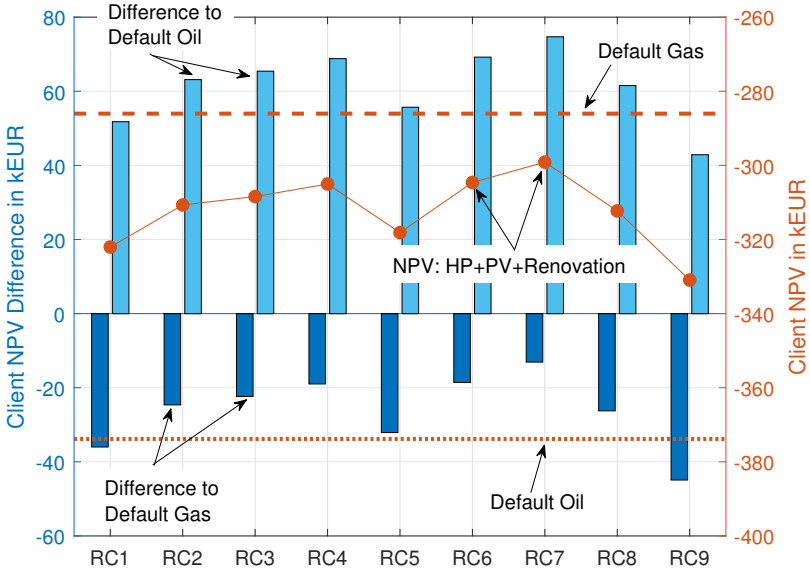

Figure 4.8.: Profitability of holistic retrofitting in the context of two different default settings (gas/oil heating). Contracting rate: 5 %. Additional costs for CO_2 emissions included.

4.4. Resume

Building retrofit offers multiple options to positively influence the climate change: Active retrofitting measures such as PV system implementation lead to an increased deployment of renewables in the building sector and thus mitigate the need for conventional electricity. Replacing fossil heating systems or implementing passive renovation measures such as insulation upgrades and installing higher quality windows leads to significant improvements of a building's CO_2 balance. However, at present, the rate of building retrofits is insignificant, not least due to the high upfront costs. Contracting indeed solves the problem of bearing high upfront costs, but the profitability of implementing active and/or passive retrofitting measures is reduced at the same time, since the contractor expects a certain return on investment. The results have shown that the more conservative the contractor's profit expectations (the lower the assumed interest rate), the smaller the negative effect on the retrofitting measures' profitability.

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Using system analysis as an alternative to contract theory in general and game theoretical modelling specifically, has proven to be suitable for determining the profitability of different retrofitting options within the framework of contracting. The focus is on the clients, since it is primarily their monetary expectations that need to be fulfilled. At the same time, a certain profit is guaranteed for the contractor to reflect a realistic market situation. The system analysis modelling approach provides results that are valid for a variety of different situations, which can be of help in the decision making process for building owners whether hiring a contractor is economically viable.

The contracting model of pure renovation contracting has not taken hold yet due to a lack of profitability, which is also confirmed by the results achieved in this study. However, the new developments in PV electricity generation in buildings lead to an increase in profitability of holistic building retrofit, since PV implementation is actually profitable. Moreover, a regulatory implementation of additional costs for CO_2 emissions can be expected in the near future, at least in Europe. The results show that this step would have a significant impact on the profitability of building retrofitting. By introducing CO_2 costs, even originally highly non-profitable options such as pure renovation contracting would eventually break even without additional subsidies, or, at least the knock-on financing could be reduced. Moreover, not only additional costs for CO_2 emissions are expected in the future, but also changes in the general structure of energy prices and PV system costs. Due to increased technological learning triggered by increasing PV installation shares, PV system costs are expected to decrease. Therefore, the economic viability of PV system installation itself and holistic building retrofit is expected to increase. On the contrary, a possible adaptation of future retail electricity prices could bring a reduction of per-unit prices while simultaneously increasing the fixed part of the electricity bill. Such development might hamper the implementation of building retrofit, since the savings in the electricity bill decrease due to reduced per-unit costs for grid electricity purchase. In case of a simultaneous decrease in PV system costs and per-unit retail electricity prices, the individual effects on profitability of retrofitting could, more or less, cancel each other out.

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5. Profitability of PV sharing in the residential neighbourhood - Energy communities beyond the building border

5.1. Introduction - Going beyond the building border

So far in this thesis, PV system implementation and sharing is addressed for an energy community formed within the borders of an individual multi-apartment building. The major findings allow to conclude that PV systems are economically viable under a variety of different, and not always optimal, circumstances. Despite the proofen profitability, the implementation of PV sharing concepts still remains an investment with significant upfront costs. Based thereon the question that is posed in this part of the thesis is whether the profitability of implementing PV sharing concepts in energy communities can be further increased. Chapter 3 already pointed out the importance of synergy effects between the individual apartment load profiles when assuming a dynamic allocation of the generated PV electricity. The positive impact of such synergy effects could be enhanced even more, if the borders of the energy community are extended beyond individual buildings.

Therefore, this part of the thesis aims at quantifying the profitability increase in case energy communities are formed between a limited number of buildings in the neighbourhood. Thereby, the specifics of energy communities can vary significantly based on their geographical location. This means that establishing energy communities within a city neighbourhood might not have the same effects as establishing an energy community in a rural neighbourhood, since the building stock is enirely different. In regions of historic growth, PV implementation might even be prohibited in some buildings due to historic preservation

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orders. In order to provide meaningful results that allow to draw generally valid conclusions concerning the profitability of PV sharing in neighbourhood energy communities, different settlement patterns (SPs) are introduced and energy communities are formed according to the respective building stock.

5.2. Methods and model

Since the analyses are conducted for representative neighbourhood energy communities in different locations, the according settlement patterns are introduced in Section 5.2.1. Moreover, in order to gain results that quantify the increased profitability of implementing PV sharing concepts between multiple buildings in comparison to PV installation in individual buildings, the optimisation model introduced in Chapter 3 needs to be extended. The necessary adaptations are explained in Section 5.2.2. The building stock sample for the individual settlement patterns is introduced in Section 5.2.3. Moreover, three basic case studies of investigation are introduced. The procedure of this part of the thesis is illustrated and described in Section 5.2.4.

5.2.1. Specification of different settlement patterns

Four different settlement patterns (SPs) are considered as a basis for the analyses: Multi-apartment building area, rural area, historical area and mixed area. The individual characteristics of these four settlement structures along with specifications of the respective building stocks are provided in the following Sections 5.2.1.1 to 5.2.1.4.

5.2.1.1. 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 Figure 5.1. They are predominantly purely residential and on average five-storey, individual buildings can also accommodate small businesses in the ground

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floor. In cities, most multi-apartment buildings can be assumed to be heated by district heat or gas[1] [147].

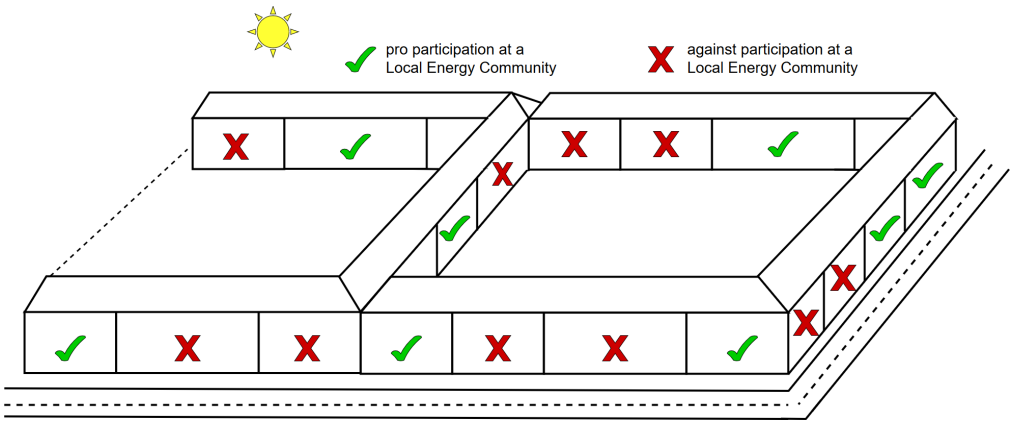

Figure 5.1.: Multi-apartment building area.

5.2.1.2. 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 and are typically adjoint. However, the structure of a historical area (Figure 5.2) shows less density compared to the multi-apartment building area.

5.2.1.3. Rural area

A typical rural area can be characterised by geographically widespread stand-alone buildings, as can be seen in Figure 5.3. 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

[1]The reasoning behind the heating system specifications for individual buildings in the different SPs is further explained in B.4.

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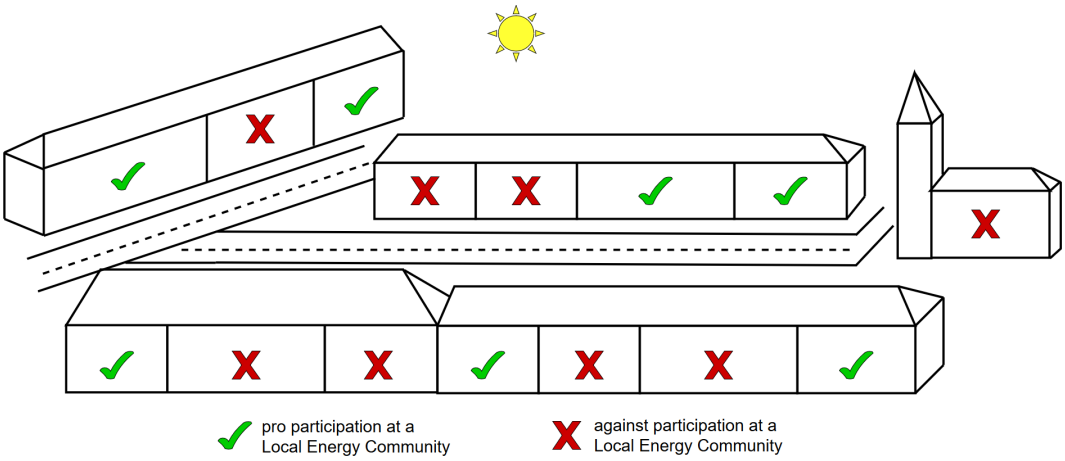

Figure 5.2.: Historical area.

with heat pumps. Large consumers, such as diverse agricultural businesses, are often located in close range to living areas.

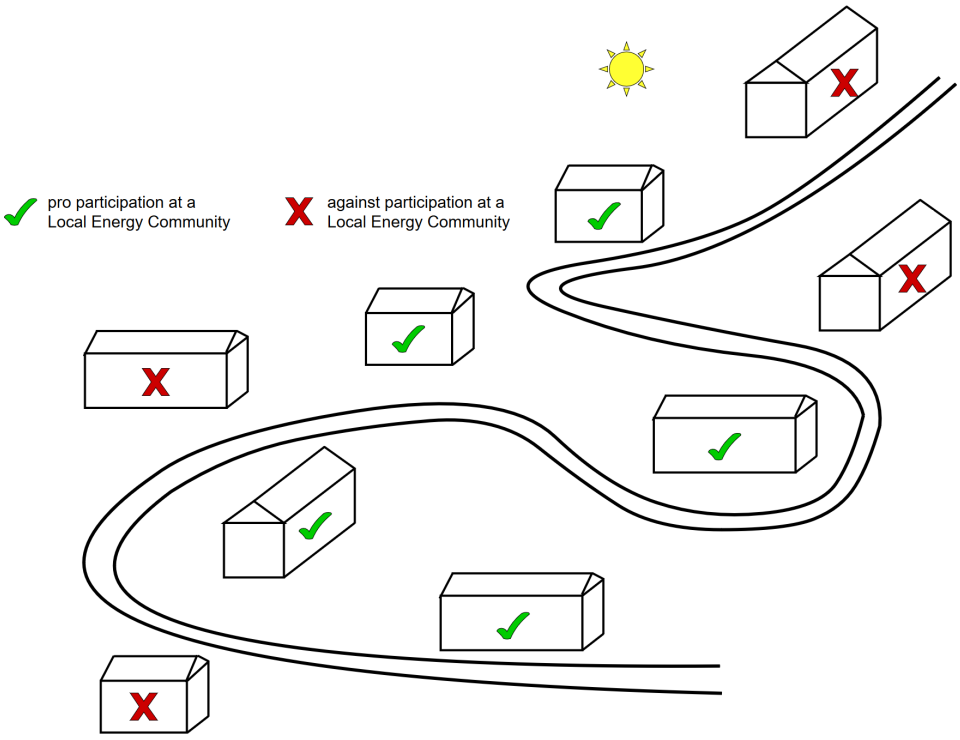

Figure 5.3.: Rural area.

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5.2.1.4. Mixed area

Figure 5.4 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.

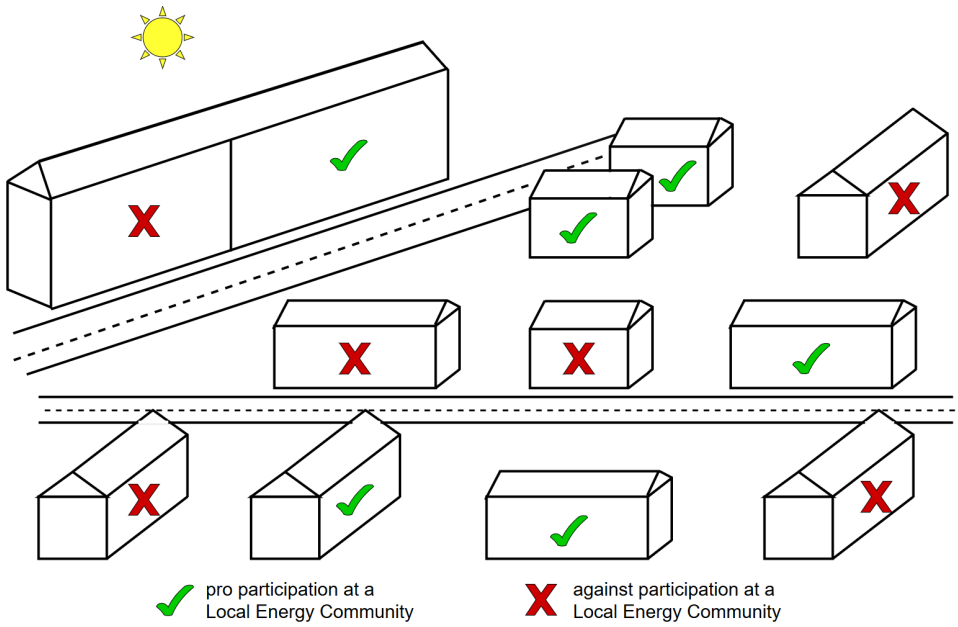

Figure 5.4.: Mixture of multi-apartment and single-family buildings.

5.2.2. Optimisation model adaptation: From individual buildings to neighbourhood scale

The optimisation model introduced in Chatper 3 needs to be adapted in order to encompass multiple buildings in the optimisation process instead of only one building. The original assumption of dynamically distributing the generated PV electricity remains active, despite stretching the border of the energy community (EC) beyond an individual building. This means that the individual building load profiles need to be combined to a total energy community load

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profile. Moreover, the individual building's heat loads need to be sorted by the installed heating systems and costs need to be determined accordingly in the course of the NPV calculation.

Energy community establishment between multiple buildings provides increased options for PV system installation. While individual buildings limit PV installation to the two directions of the roof's orientation, multiple buildings comprise multiple different rooftop areas with a variety of orientations. Thus, not only load profiles provide synergy effects that postively influence PV implementation, but also the buildings' geometries. This means, that the optimisation model's constraints concerning the availability of building surfaces for PV system implementation need to be adapted as well.

Besides adaptations concerning the model's extension from individual buildings to multiple buildings as described above the model does not need further adaptation. The modelling of different technologies[2] along with the general implementation of objective, constraints and according calculations remain unchanged, which emphasizes the good applicability of a modularily set-up optimisation model.

5.2.3. Energy community specification and 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 5.1. 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 5.3.

(i) 'Building Selection - Individual Approach':

[2]In this part of the thesis, the technology pool is enlarged by a hot water storage. The modelling details of this technology are provided in Appendix B.3.

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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[3,4]. 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 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.

[3]Reasons for not equipping buildings with PV are, for example: developed attic, personal reasons, prohibition, and so on.
[4]Whether PV is actually implemented is decided by the optimisation.
[5]The buildings are considered having saddle-roofs with a pitch of 30 °.
[6]The specific heat loads represent the diversity in building standard in the residential sector in Austria, based on the year of construction [11].
[7]Orientation refers to the orientation of the buildings' saddle roofs.
[8]By assigning different businesses randomly to some of the buildings the load profile diversity is further enhanced.
[9]Background information concerning the different heating systems is provided in B.4.

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Building[5]	Specific heat load[6] in kWh/m²/yr	Orientation[7]	Business included[8]	Heating system[9]
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

Table 5.1.: 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 B.2. The individual buildings' load profiles, resolved at 15-minute intervals, are shown in compact shape in B.1.

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5.2.4. Illustration of procedure

The flow chart presented in Figure 5.5 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 5.2.1, there are four different SPs predefined for this study. Each SP is assigned a number of different buildings, which are introduced in Section 5.2.3, Table 5.1. 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.1). The building's heat load profile is based on the specific heat load and its location[10]. 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 energy community. However,

[10] Based on a building's specific heat load, a constant indoor temperature of 20 °C, an outdoor temperature profile in 15-minute resolution and a heating degree day correction factor, a heat load profile is generated as explained in Appendix A.4

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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 building is considered as load only. Thus, the process of merging individual buildings to an energy community 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 energy community 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 energy community provides the possibilty of comparing results and thus evaluate the actual value of an energy community.

5.2.5. Empirical scaling

Cost assumptions remain unchanged to guarantee comparability of the gained results. The costs are listed previously in Chapter 3, Section 3.2.5.

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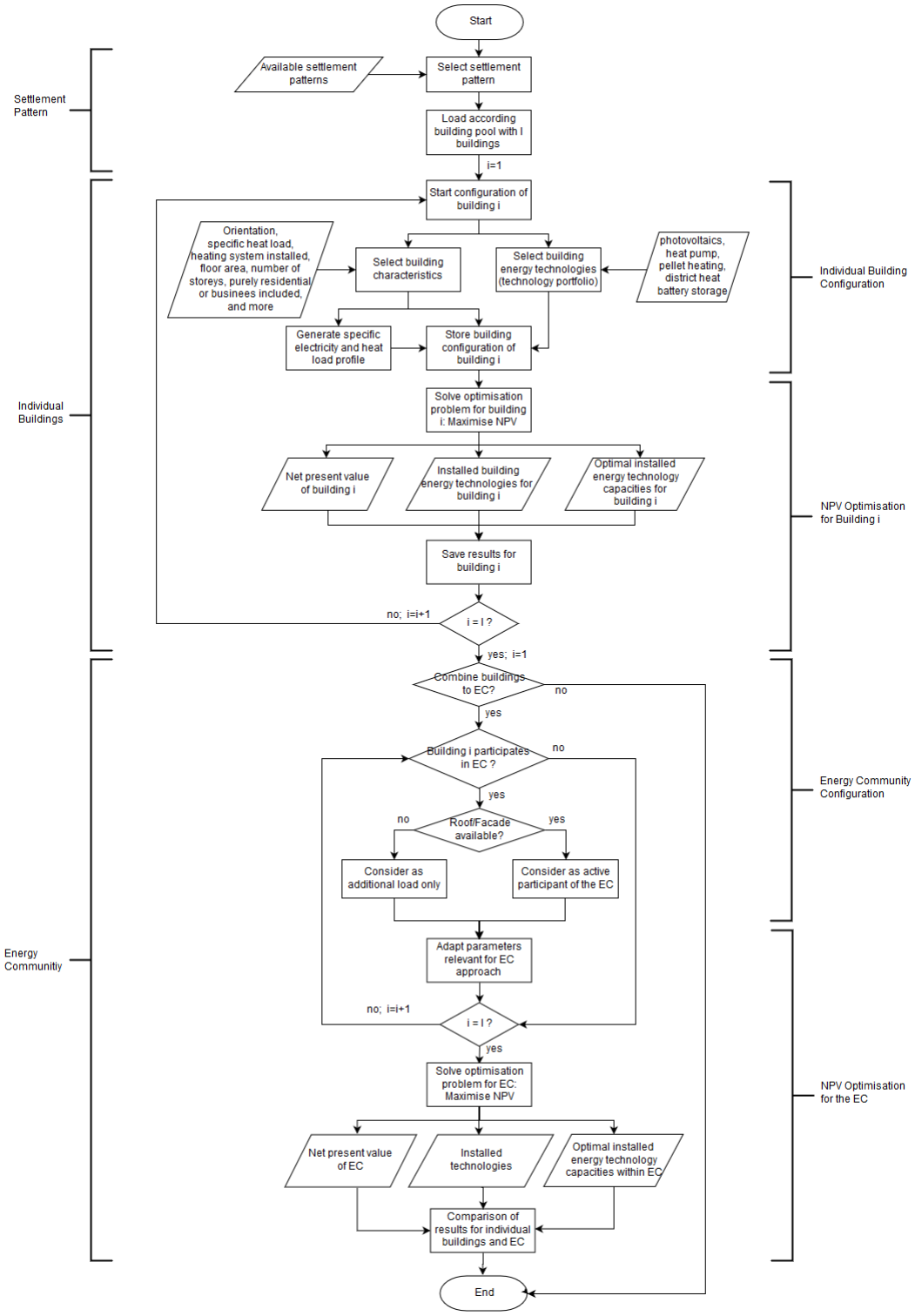

Figure 5.5.: Flow chart.

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5.3. Results

This section describes the results of the profitability of PV system installations for individual buildings and energy communities (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.

5.3.1. Multi-apartment building area

A total of 10 different multi-apartment buildings (MAB) are considered, as specified in Table 5.1. According to Figure 5.1, 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 and are considered in use cases (i) and (ii).
- MAB3,4,5,6 and 9 cannot implement PV systems and are considered in use case (iii) only.

(i) Building Selection - Individual Approach

Figure 5.6 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 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 Figure 5.7 - (i) 'Building Selection - Individual Approach'.

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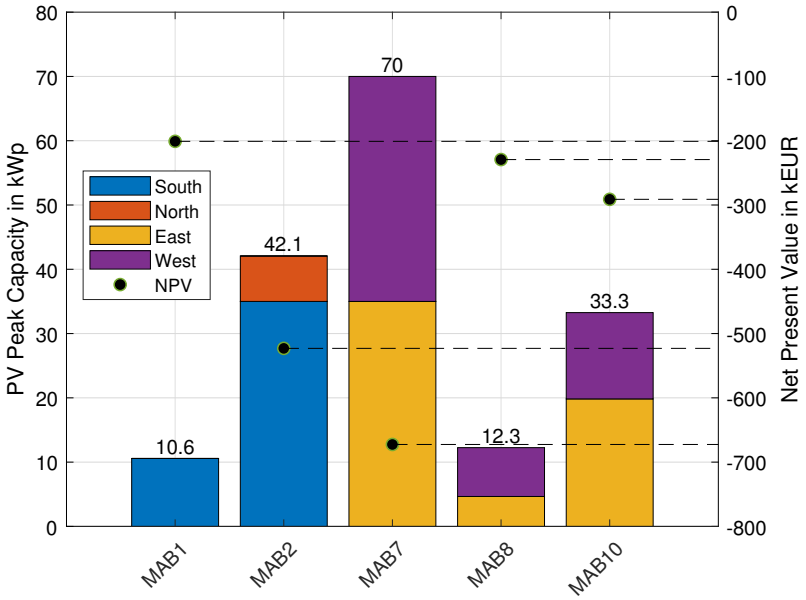

Figure 5.6.: Building-attached rooftop PV implementation for individual MABs.

(ii) Building Selection - EC Approach

In this use case, MAB1,2,7,8 and 10 form an EC providing their available facade and rooftop areas for community PV installation. It becomes immediately apparent when looking at Figure 5.7 - (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

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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 Figure 5.7 - (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.

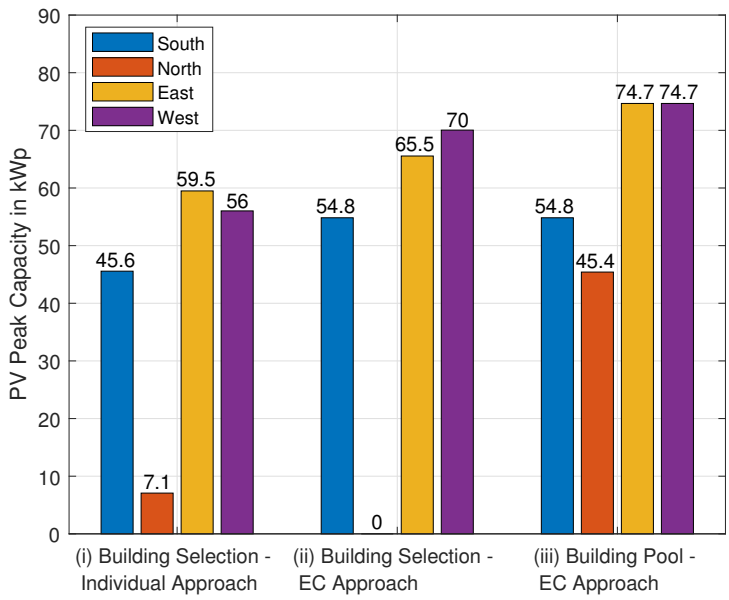

Figure 5.7.: Optimal building-attached rooftop PV implementation. Theoretical rooftop potential: 54.8 kW North/South and 74.7 kW East-/West.

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5.3.2. Rural area

A total of 10 single-family houses are considered, as specified in Table 5.1. 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 and are considered in use cases (i) and (ii).
- SFH2,3,7,9 and 10 cannot implement PV systems. These buildings are just considered in use case (iii).

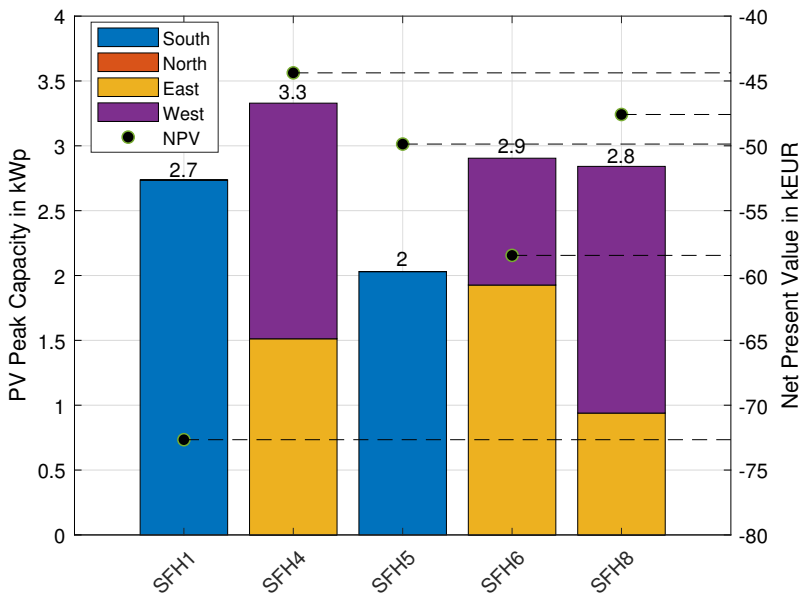

Figure 5.8.: Building-attached rooftop PV implementation for individual SFHs.

(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 Figure 5.8, 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

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optimal determined rooftop PV capacities of SFH1,4,5,6 and 8 is illustrated in Figure 5.9 - (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 Figure 5.9 - (ii) Building Selection - EC Approach.

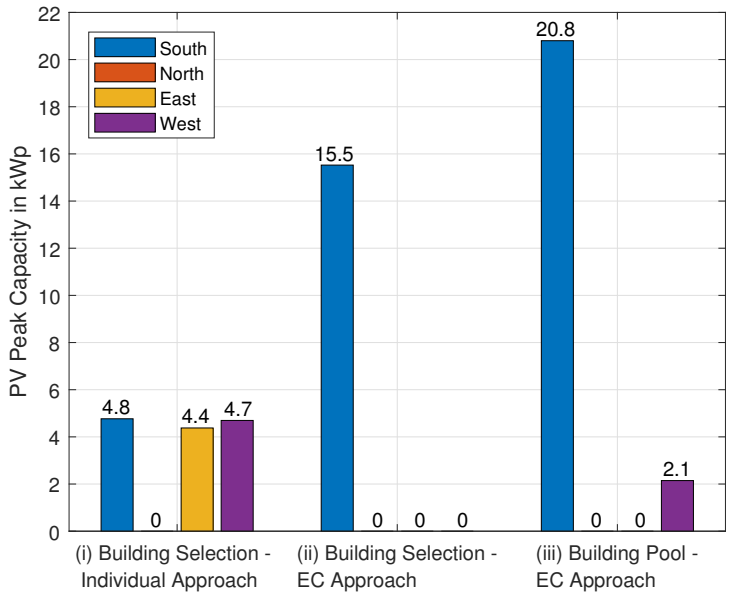

Figure 5.9.: Optimal building-attached rooftop PV implementation. Theoretical rooftop potential: 20.8 kW North/South and 28.5 kW East-/West.

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(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 (Figure 5.9 - (iii) 'Building Pool - EC Approach').

5.3.3. Historical area

A total of 10 historical buildings are considered, as introduced in Table 5.1. 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 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 and are considered as additional loads in case study (iii) only.

(i) Building Selection - Individual Approach

The modeling 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 [61][11], 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 (Figure 5.10). The sum of individually optimal determined

[11] The costs are listed in Table 3.4.

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rooftop PV capacities of HIST1,5,7,9 and 10 are illustrated in Figure 5.11 - (i) 'Building Selection - Individual Approach'.

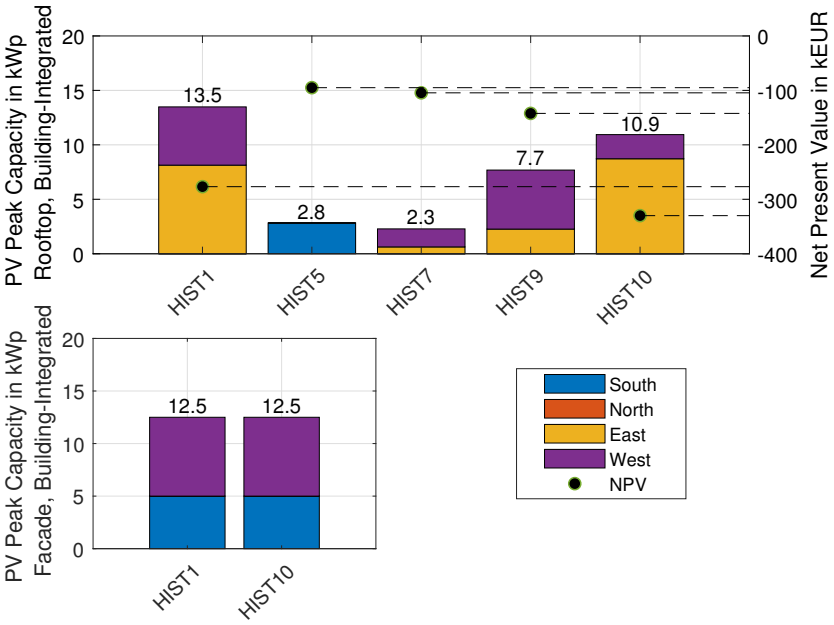

Figure 5.10.: Building-integrated rooftop/facade PV implementation for individual historical buildings.

(ii) Building Selection - EC Approach

In this case, HIST1,5,7,9 and 10 form an EC. According results of rooftop building-integrated PV implementation are shown in Figure 5.11 - (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 Figure 5.11-

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(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.

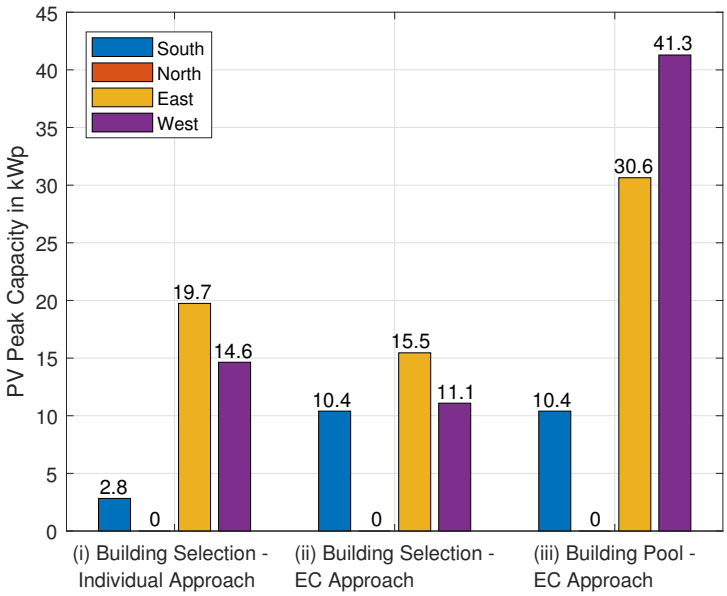

Figure 5.11.: Optimal building-integrated rooftop PV implementation. Theoretical rooftop potential: 10.4 kW North/South and 53.9 kW East/West.

5.3.4. Mixed area

Suburbia or city outskirts are characterised by a mixture of predominantly single-family and multi-apartment buildings (see Figure 5.4). The following assumptions are made:

- The building selection of SFH2,3,9,10 and MAB2,6 can be equipped with PV systems and are considered in use cases (i) and (ii).
- SFH1,4,5,6,7,8 cannot implement PV systems. These buildings are just considered additionally in use case (iii).

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(i) Building Selection - Individual Approach

Despite the availability of both roof and facade areas, only the roof is used for PV installation. The sum of optimal PV capacities for SFH2,3,9,10 and MAB2,6 is shown in Figure 5.12 - (i) 'Building Selection - Individual Approach'.

(ii) Building Selection - EC Approach

When comparing the situation of SFH2,3,9,10 and MAB2,6 establishing an EC (Figure 5.12 - (ii) 'Building Selection - EC Approach') to the situation of implementing PV systems independently, it can be seen that MAB2's Northern part of the roof doesn't need to be used anymore, as sufficient roof space with better solar irradiation is available due to the collaboration of different buildings. In total, a more of 25 kW is installed in case an EC is formed compared to the individual approach which emphasizes the impact of different load profiles' synergy effects.

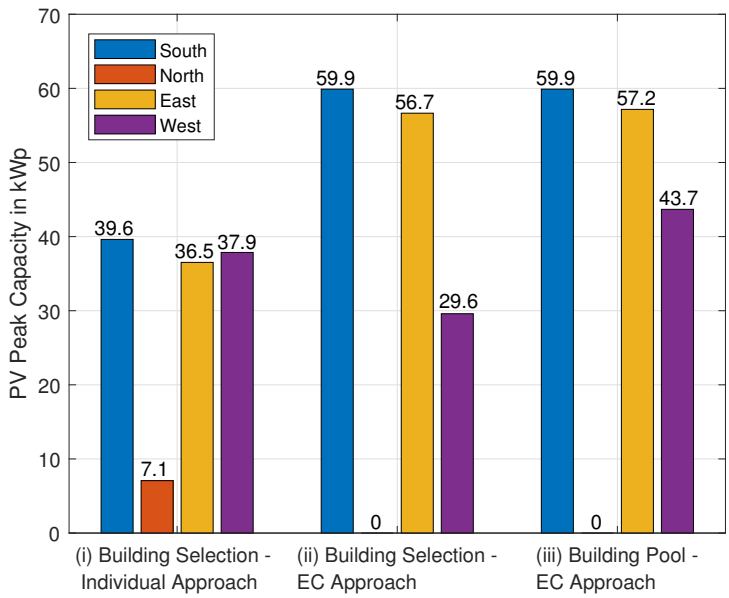

Figure 5.12.: Building-attached rooftop PV implementation for use cases (i), (ii) and (iii). The total rooftop installation potential of the buildings which can implement PV systems are 59.9 kW North/South and 57.2 kW East/West.

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(iii) Building Pool - EC Approach

In case buildings SFH1,4,5,6,7 and 8 are considered as additional loads for the EC, it can be noticed that the Eastern parts of available rooftop areas are totally saturnated with PV, the Western parts are used for installing a more of 14 kW compared to use case (ii).

5.3.5. Cost saving potential for each settlement pattern

Table 5.2 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) '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/-

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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.

	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 %

Table 5.2.: Cost reduction.

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5.3.6. Qualitative comparison of the results

Table 5.3 gives a concluding, qualitative overview of the results gained for the different SPs.

Settlement Pattern	Use Case	Number 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[12]	Cost Saving Potential[13]
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	✓✓✓

Table 5.3.: Comparison of results.

[12] North - N, East - E, South - S, West -W

[13] ✓ - insignificant (>0 % - 3 %), ✓✓ - ok (>3 % - 6 %), ✓✓✓ - good (>6 % - 9 %),✓✓✓✓ - very good (>9 %)

5.4. 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 5.4.1) and the set-up of an EC (Section 5.4.2) are provided:

- Technology portfolio sensitivities comprise the evaluation of the impact of a battery (Section 5.4.1.1) and a hot water storage (Section 5.4.1.2).
- 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 5.4.2.1), and the original set-up of the multi-apartment building area is altered in terms of the building standard and heating system (Section 5.4.2.2).

5.4.1. The impact of storage technologies

Two types of storages are taken into account in the following. Section 5.4.1.1 investigates the impact of a battery storage, being primarily relevant as supplement to a PV system. Section 5.4.1.2 takes into account a hot water storage, complementing a heat pump.

5.4.1.1. 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 5.4 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

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2900 EUR in 20 years. This value needs to be theoretically divided by the five different buildings, which contain 10 to 20 apartments each.

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	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

Table 5.4.: Comparison of results for the MAB area - without and with consideration of a battery storage.

5.4.1.2. Hot water storage

The results for complementing a heat pump with a hot water storage system are shown for an individual building (MAB1) in Figure 5.13 and an EC of five multi-apartment buildings (MAB1,2,7,8 and 10) in Figure 5.14. Therefore it is assumed that the original heating systems (as introduced in Table 5.1) 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 modeling assumptions of the hot water storage are provided in B.3.

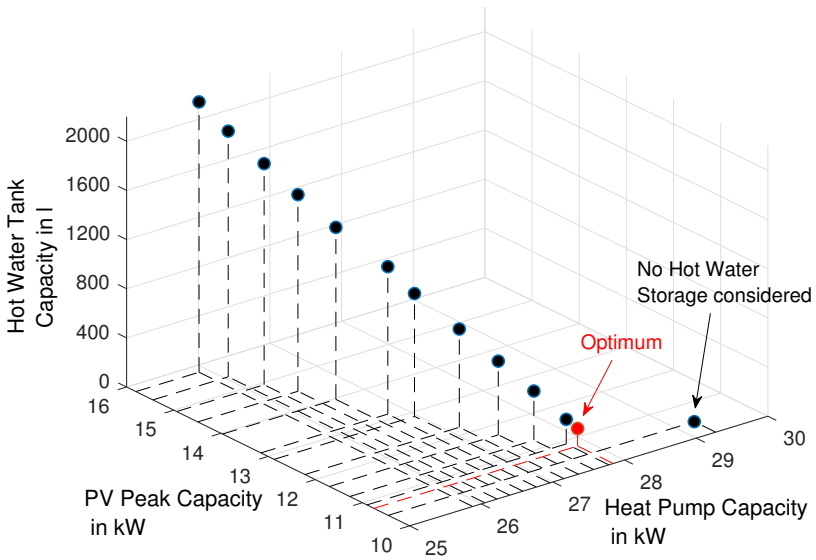

Figure 5.13.: Impact of different hot water storage sizes on optimal PV and heat pump capacity; Results for MAB1.

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 Figures 5.13 and 5.14 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

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is increased in 200 l steps[14], 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 (Figure 5.14), optimal PV system sizes show less change compared to the case of an individual building in Figure 5.13 because PV electricity can be used more efficiently right away in an EC due to synergy effects between buildings.

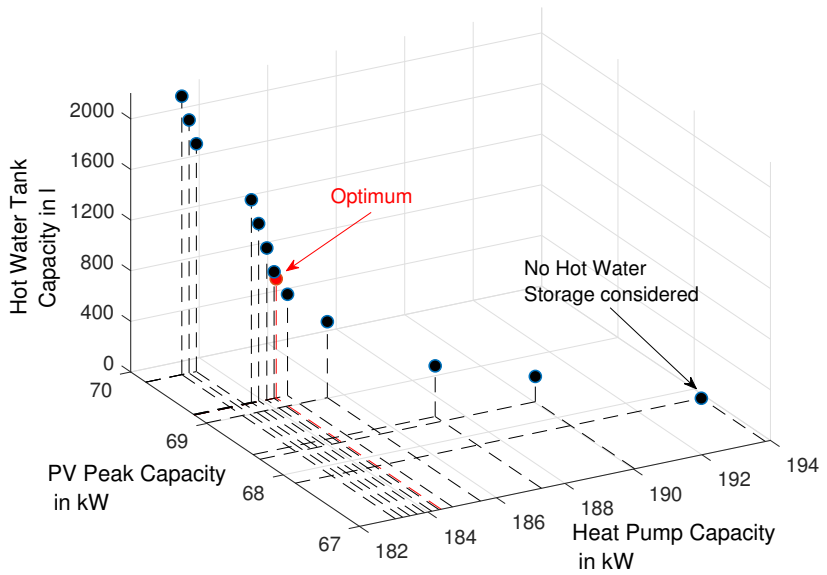

Figure 5.14.: Impact of different hot water storage sizes on optimal PV and heat pump capacities. The PV peak capacity depicted in this Figure is the one installed on the Western part of the facade. The Southern facade is fully saturated with PV in all cases (78.3 kW).

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

[14] 200 l steps have proven suitable for visualisation.

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of the sensitivity analysis provided in Section 5.4.2.2, 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.

5.4.2. The impact of the energy community set-up

The impact of an additional large consumer is investigated for rural energy communities in Section 5.4.2.1, whereas the effect of building renovation is investigated for multi-apartment building areas in Section 5.4.2.2.

5.4.2.1. Including a large non-residential consumer

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.4) is used for analysis and is scaled up to an average annual electricity demand of a dairy farm[15] of 22 000 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 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:

[15] 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 $kWh/m^2/yr$.

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- 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 5.3.2). 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.

5.4.2.2. Improving the buildings' standard

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 145 kWh/m^2/yr initially. This initial heat load is then decreased step-wise[16], to 125 kWh/m^2/yr, 115 kWh/m^2/yr, 80 kWh/m^2/yr, 60 kWh/m^2/yr until a passive house standard of 40 kWh/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.

Figure 5.15 shows that improving the building standard leads to significantly

[16]The downgrading of the specific heat load can be led back to an inventory of the existing housing stock in Austria conducted by [11].

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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 40 kWh/m^2/yr. However, [50] 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 5.5.

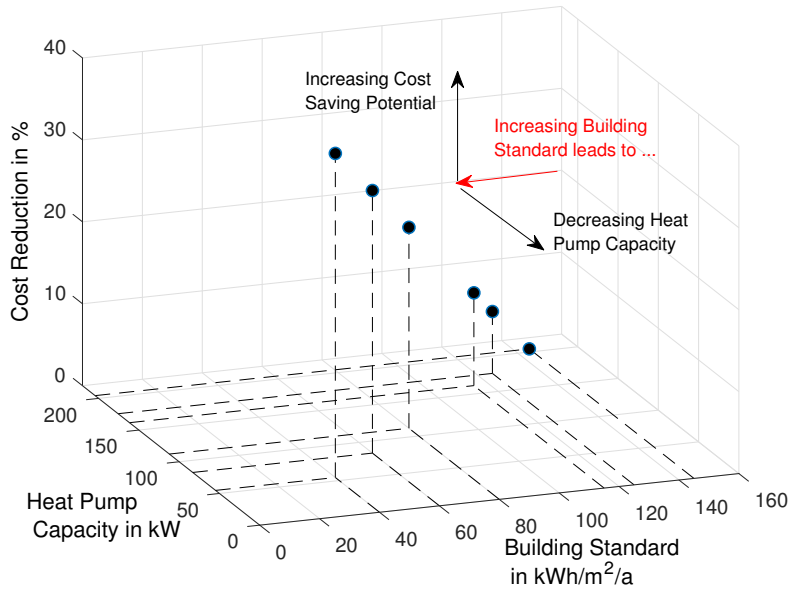

Figure 5.15.: Impact of improving the building quality of MAB 1,2,7,8 and 10 forming an EC.

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

Table 5.5.: Maximum passive renovation costs to break-even.

5.5. Resume

The definition of four settlement patterns combined with a thoughtful selection of characteristic buildings, representative for the building stock, makes the achieved results widely applicable. A comparison of results for individual buildings and their combination to a community enables an exact quantification of the positive financial impact of energy communties and thus answers the question of the actual added value of such concepts. Establishing energy communities increases the profitability of PV systems in all settlement patterns. Nevertheless, the significance of the added value of setting up an energy community highly depends on the settlement pattern itself, the building types and also the participants. Forming an energy community is most valuable for single-family buildings 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. Energy communities implemented in multi-apartment building areas therefore achieve the highest cost saving potential in total, as a result of the large 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 due to unfavourable roof construction, preservation orders or other obstacles. Moreover, a cost-optimal PV system implementation does not require every building in a community to install PV. Thus, an

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optimal composition of participants for ECs would, besides a large variety of load profiles, also include buildings with large available roof/facade areas to be used for community PV implementation.

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6. The large-scale cost-optimal economic potential of residential building PV on the basis of energy communities

6.1. Introduction - Building PV potential for a whole country

The increased implementation of energy communities is considered part of the solution to increase sustainabiliy in the residential building sector. The major purpose of establishing energy communities is to increase the renewable energy generation at a local level, ensuring high self-consumption rates at the same time. Analyses conducted so far in this thesis have shown that energy communities, independent of their scale and area of implementation, can be realised in a cost-optimal way for all participating parties.

Despite the fact that the energy community concept is currently hardly adopted in multi-apartment buildings and only tested in the course of lighthouse projects on medium scale between multiple buildings, this thesis finally aims to close the loop to large-scale implementation of shared PV systems. Therefore, the large scale potential of adopting the concept of PV sharing in residential buildings within neighbourhood energy communities all over the country is estimated, thereby keeping the focus on cost-optimality.

The estimation of the cost-optimal PV potential in residential buildings on country scale is all the more important when it comes to the need to achieve the European 2030 climate goals. Austria's policy goals are ambitiously set, since a 100 % renewable electricity supply shall be realised until 2030. This anticipates at least 9.7 GW_p of PV according to [49], and 11.9 GW_p according to [128]. In this context, the last part of this thesis aims to provide an

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answer to the question whether the ambitious goal of approximately 10 GW of installed PV capacities is achievable in the residential building sector, and, most importantly, in an economically viable manner.

6.2. Methods and model

The large-scale potential estimation is based on optimising shared PV systems for cost-optimal usage in neighbourhood energy communities of different settlement patterns. The optimisation model needed to determine cost-optimal PV system sizes for neighbourhood energy communtiies is already introduced in the course of Chapters 3 and 5. The energy community set up used in this chapter is defined in Chapter 6.2.1. For estimating the cost-optimal economic large-scale PV potential, an algorithm needs to be developed that countrywide allocates buildings within a political district to settlement patterns and further to individual energy communities. The logic of such algorithm is presented in detail in Section 6.2.2. The actual upscaling to country scale is explained in Section 6.2.3. Finally, the method of estimating the geographical potential, in order to assess the actual available rooftop area for PV implementation, is presented in Section 6.2.4.

6.2.1. Energy community set-up in different settlement patterns

Four model ECs - one for each settlement pattern (SP)[1] - are defined. It is assumed that individual ECs are formed at a neighbourhood level between a limited number of buildings[2]:

- A city EC consists of 10 large multi-apartment buildings (LMABs).

[1] The settlement patterns are in accordance with the ones presented in Chapter 5, Section 5.2.1. However, in this chapter, the former 'multi-apartment building area' is now referred to as 'city area' and the former 'historical area' is now called 'town' area.

[2] 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.

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- Town ECs include 10 small multi-apartment buildings (SMABs) each.
- Rural ECs consists of 10 single-family houses (SFHs).
- A mixed EC comprises 2 LMABs and 10 SFHs.

The model ECs are assigned characteristic buildings with real-measured electricity load profiles according to the number of apartments accomodated. Table 6.1 shows the building pool for city, town and rural model ECs, including the specific building characteristics which concern specifications such as heat load, heating system, orientation and, whether businesses are included in the otherwise residential buildings. The building specifications provided are based on statistical data for Austria [150] in order form model ECs out of a representative building sample[3]. Standard load profiles [5] are used for businesses.

[3]The building characteristics vary in comparison to the sample used in Chapter 5, in order to come as close as possible to a country-wide representative building sample.

[4]The buildings are considered to have saddle-roofs with a pitch of 30 °.

[5]The specific heat loads represent the diversity in building standard in the residential sector in Austria, based on the year of construction [11].

[6]Orientation refers to the orientation of the buildings' saddle roofs. The buildings' orientation can be assumed to be statistically equally distributed across all directions [77], i.e. the same number of buildings are oriented North-South and East-West.

[7]The selection of the different heating systems is based on statistical data from Austria, provided by Statistic Austria [150]. 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 [51].

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Building[4]	Specific heat load[5] in kWh/m^2/yr	Orientation[6]	Business included	Heating system[7]
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

Table 6.1.: Default setting of individual buildings considered, based on Austrian statistics [148, 150]

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6.2.2. Allocating 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. The large scale area of investigation is Austria. A map of Austria with the according political districts is provided by Statistik Austria in Figure 6.1.

Figure 6.1.: This map is provided by Statistik Austria [152]. 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.

Moreover, Statistic Austria [148] 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 to 6 units
- Large multi-apartment buildings (LMABs) with 10 or more units

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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 6.1).

$$S(bt, pd) = \frac{N(bt, pd)}{N_tot(pd)} \tag{6.1}$$

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[8]. 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 6.2.

$$\begin{aligned}
&\text{if the 4 \% LMAB threshold is exceeded} \\
&N_{LMAB_city}(pd) = N_{LMAB}(pd) \cdot 0.75 \\
&N_{LMAB_mixed}(pd) = N_{LMAB}(pd) - N_{LMAB_city}(pd) \\
&\text{if the 4 \% LMAB threshold is not exceeded} \\
&N_{LMAB_city}(pd) = 0 \\
&N_{LMAB_mixed}(pd) = N_{LMAB}(pd)
\end{aligned} \tag{6.2}$$

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. This information is provided in Table 6.2.

The number of LMABs allocated to city areas ($N_{LMAB_city}(pd)$) is divided

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

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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	-	-	$n_{SFH_rural} = 10$

Table 6.2.: Number of buildings and building types per model EC.

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 6.3).

$$N_{EC_city}(pd) = \frac{N_{LMAB_city}(pd)}{n_{LMAB_city}} \tag{6.3}$$

The number of mixed ECs ($N_{EC_mixed}(pd)$) is determined analogously (Equation 6.4).

$$N_{EC_mixed}(pd) = \frac{N_{LMAB_mixed}(pd)}{n_{LMAB_mixed}}. \tag{6.4}$$

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 6.5):

$$N_{SFH_mixed}(pd) = N_{EC_mixed}(pd) \cdot n_{SFH_mixed} \tag{6.5}$$

In Equation 6.6, the remaining SFHs are allocated to the rural areas ($N_{SFH_rural}(pd)$).

$$N_{SFH_rural}(pd) = N_{SFH}(pd) - N_{SFH_mixed}(pd), \tag{6.6}$$

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 6.7).

$$N_{EC_rural}(pd) = \frac{N_{SFH_rural}(pd)}{n_{SFH_rural}} \tag{6.7}$$

The number of town communities ($N_{EC_town}(pd)$) is determined analogously

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in Equation 6.8, with $N_{SMAB}(pd)$ being the number of SMABs per political district.

$$N_{EC_town}(pd) = \frac{N_{SMAB}(pd)}{n_{SMAB_town}} \tag{6.8}$$

6.2.3. Upscaling to large scale

After cost-optimal rooftop PV system sizes are determined for the four model ECs (Section 6.2.1) and the number of ECs per SP is calculated (Section 6.2.2), 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.

6.2.4. Estimating the 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 [77], the percentage of building types that are equipped with tilted roofs is as follows[9]:
   - 95 %-98 % of SFHs
   - 92 % of SMABs
   - 75 % of LMABs

[9] The cited literature provides data from Germany. Although this study provides results for Austria specifically, the data that is valid for the German building stock is, in this specific 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 suffered 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 flat areas (Germany in the North, Austria in the East).

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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 [77][10]. 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 6.3).

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 usable 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

Table 6.3.: Determining the technical rooftop potential [77].

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 6.2.2, the allocation of the different buildings to the four SPs is described. On that basis, the share of buildings per type that are

[10] 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.

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allocated to the different SPs can be derived. These shares can then be used to transfer the total rooftop area per building type to the different SPs (= geographical rooftop PV potential for the four SPs).

6.2.5. Empirical scaling

Cost assumptions remain unchanged due to guarantee comparability of the gained results. The costs are listed previously in Chapter 3, Section 3.2.5.

6.3. Results

The model developed for the purpose of upscaling is applicable to any large-scale area. However, the results are calculated for the country of Austria. Section 6.3.1 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 6.3.2.

6.3.1. Large-scale cost-optimal PV potential in Austrian residential buildings

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 Figure 6.2. 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 Figure 6.3.

- Regarding cost-optimal rooftop PV system implementation in the individual model ECs (Figure 6.2), 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

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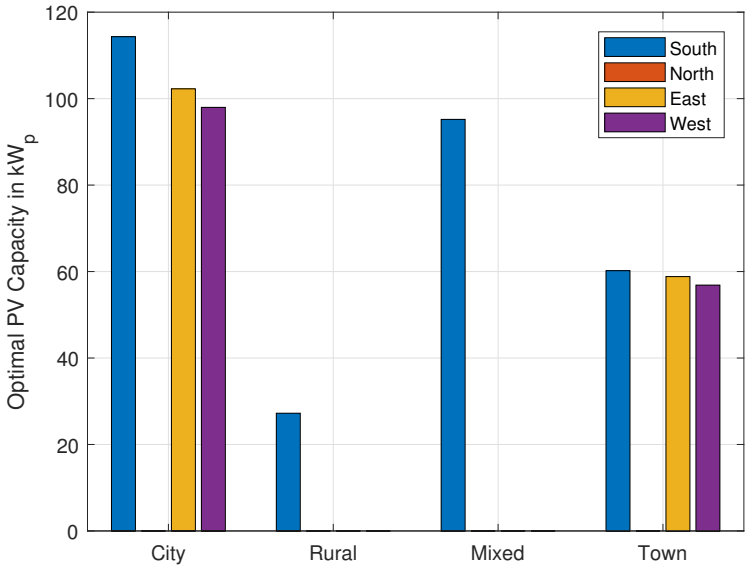

Figure 6.2.: Cost-optimal rooftop PV system sizes for individual model ECs.

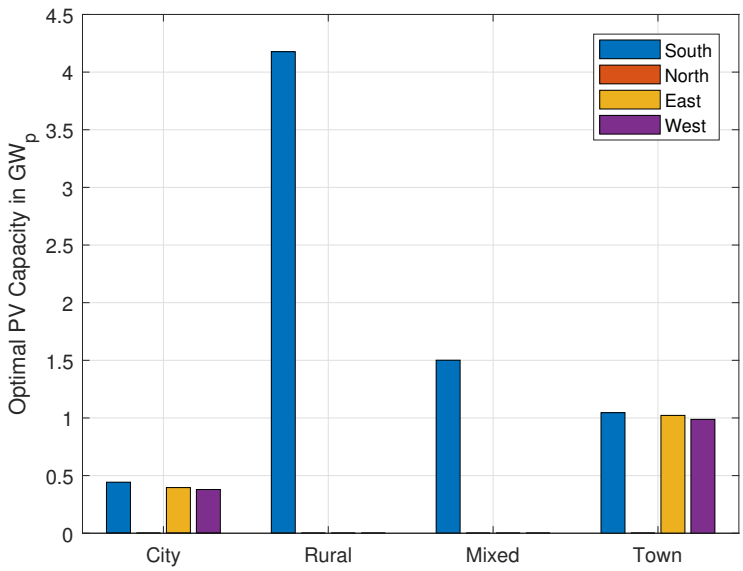

Figure 6.3.: Cost-optimal rooftop PV system sizes for whole Austria.

profile per building. However, the cost-optimal large-scale economic potential of rooftop PV (Figure 6.3) is highest for rural areas with more

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than 4 GW_p and lowest for city areas with about 1.2 GW_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 [77]). 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 10 GW_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[11] in residential buildings. This analysis is based 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.

[11] 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.)

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6.3.2. Juxtaposing the large-scale cost-optimal building PV potential with the geographical potential

In Figure 6.4, 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).

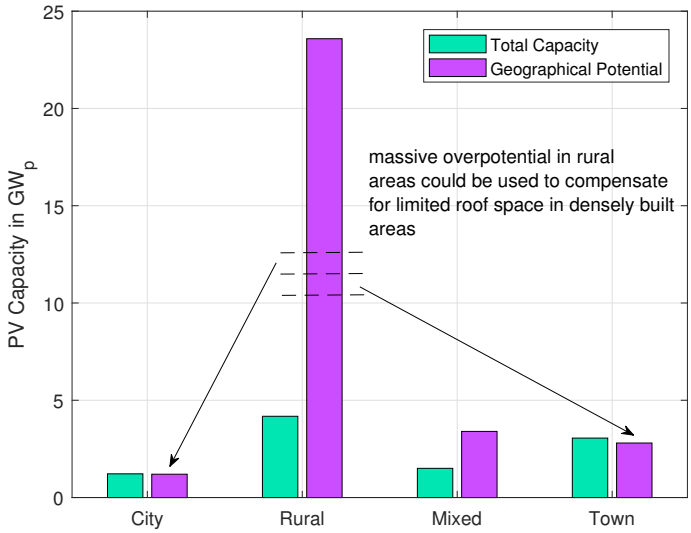

Figure 6.4.: Cost-optimal, EC-based rooftop PV capacity vs. geographical potential.

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. Figure 6.4 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

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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 Figure 6.4. 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 thesis.

6.4. Sensitivity analyses

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 6.4.1 and 6.4.2.

6.4.1. The impact of energy community sizes

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. 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 Figure 6.5.

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

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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 Figure 6.5, 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 noticable. As soon as the optimal EC size[12] is reached, the positive influence of synergy effects between load profiles is still present but no longer increases. As for the results of Section 6.3.2 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.

6.4.2. Retail electricity price versus per-unit 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 6.4.

In general, the retail electricity price consists of three parts – (1) energy costs,

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

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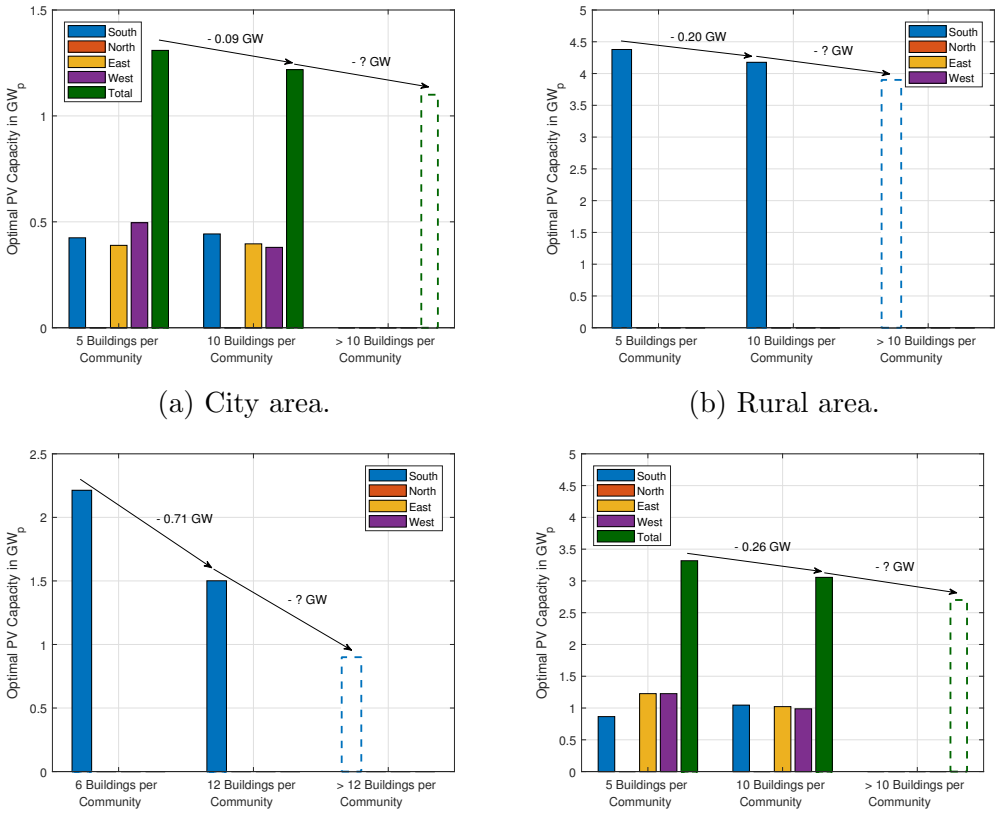

(a) City area.

(b) Rural area.

(c) Mixed area.

(d) Town area.

Figure 6.5.: Effects of changing the EC size on the cost-optimal economic large-scale rooftop PV potential.

(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 (EUR/kWh) across all three categories is assumed to be 0.22 EUR/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 0.18 EUR/kWh[13].

[13]The initial retail electricity price is assumed to be 0.22 EUR/kWh which is on the upper end of the retail electricity price range in Austria. Since the average retail price is

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

Table 6.4.: Case study definition for varying the retail electricity price and PV system costs.

Corresponding results of the cost-optimal economic large-scale potential are shown in Figure 6.6. The green bars indicate the results achieved for the default setting (i) as introduced in Table 6.4. The assumption of a decrease in retail electricity prices per unit (0.22 Euro/kWh → 0.18 Euro/kWh) in case study (ii) leads to a reduction of the estimated optimal rooftop PV potential (blue bars in Figure 6.6). 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 %[14] (1050 Euro/kW$_p$ → 840 Euro/kW$_p$, use case (iii)) is presumed at the same time, the red bars in Figure 6.6 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 that PV system costs have a significant impact on the results, to a remarkably larger extent than the retail electricity prices.

rounded 0.20 EUR/kWh [149], this sensitivity analysis aims to investigate the impact of a retail electricity price on the lower end of the price range (0.18 EUR/kWh) on the cost-optimal large-scale rooftop PV potential.

[14] The inital PV system cost assumption of 1050 Euro/kW$_p$ is in line with [57]. 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.

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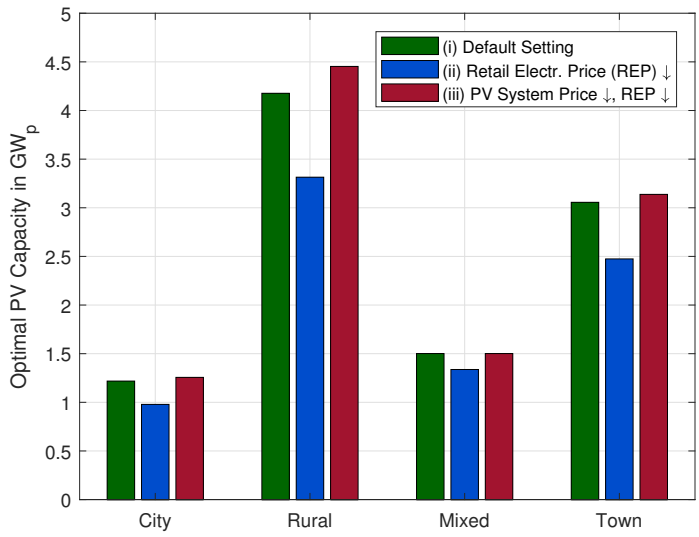

Figure 6.6.: Cost-optimal economic rooftop PV potential for the default setting, retail price and PV system price variations.

6.5. Resume

The question whether the ambitious 2030 target of 10 GW of installed PV capacities is achievable in an economical manner in the residential sector only, can be answered with 'yes'. 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. Due to usually slow political decisions and highly bureaucratic background processes it is to be doubted that the 2030 target will be actually achieved. Another crucial success factor - besides the legal and regulatory background - of energy community deployment on large scale is the people themselves. In a first step, to gain people's trust, energy community concepts need to be introduced on a small scale within indiviual buildings and only then extended to medium scale communities between buildings within geographical proximity. In the long term, however, based on the gained results in this part of the thesis, a relocation of the system boundaries of ECs across different SPs is recommended.

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This proposed step-wise distribution of PV systems and energy community boundaries is also recommendable concerning the probably necessary amendments of the electricity grid. Implementing PV capacities of approximately 10 GW 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.

Lastly it needs to be indicated, that the future success of energy community concepts might be significantly affected by the future retail price development. For example, a change in the distribution grid tariff structure has been under discussion for some time. 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. However, the tendency goes in the direction of reducing the per-unit charge, while the fixed component simultaneaously 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, expected learning effects that decrease PV system costs at the same time could counteract this effect in turn.

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7. Discussion and synthesis of results

This chapter synthesises the key findings of the thesis with respect to the research questions raised (Section 7.1) and states the strengths and limitations of the applied modelling approach (Section 7.2). Section 7.3 tackles the difficult topic of cost and revenue allocation between energy community participants. Last but not least, possible implications for future regulation and policy making are discussed in the course of Section 7.4.

7.1. Findings with respect to the research questions

This section takes a final stand on the four research questions raised in the course of Section 1.2. Firstly, the aim is to determine whether shared PV implementation is profitable in individual multi-apartment buildings (Section 7.1.1), followed by an analysis concerning the economic viability of contracting business models as solution to high upfront investment costs of PV installation and holistic building retrofit (Section 7.1.2). Going beyond the building border, the added value of establishing energy communities between multiple buildings in the neighbourhood is assessed (Section 7.1.3). Last but not least, the cost-optimal economic potential of PV in the residential building sector is estimated on country-scale (Section 7.1.4).

7.1.1. Profitability of shared PV in multi-apartment buildings

The initial research question seeks an answer to the question of the profitability of shared PV systems in multi-apartment buildings. Obviously, there does not exist a simple or straightforward answer, since the profitability of a shared PV

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system is significantly influenced by multiple factors. Therefore, in order to provide an answer to this question which would be applicable to many different situations and circumstances, and could thus be considered generally valid, a variety of different analyses are conducted. The full range of results shows that implementing PV sharing in multi-apartment buildings can be considered profitable in general. All situations and building set-ups examined in the course of Chapter 3 (variations in heating system, PV system implementation and roof-tilt, changes in tenant profiles, different building quality, variations in retail electricity and CO_2 price as well as interest rate variations) show a positive impact of PV installation on the building residents' costs. Based on these findings, policy makers are recommended to find ways to strongly push the deployment of such concepts, since the legal basis has been provided already in some countries and the argument of a lack of profitability is not valid anymore. Even a non-optimal building set-up in terms of PV implementation (e.g. only facade available for PV installation, not facing South) leads to a break-even within 20 years. Moreover it has to be taken into consideration that in this study - by using data representative for Austria - a moderate solar irradiation with approximately 1000 h/a full load hours, combined with moderate retail electricity prices, the profitability of PV sharing is not facilitated by external conditions. This emphasises the results of PV systems being determined profitable by optimisation.

When looking a few years ahead, the profitability of PV systems is predicted to increase, since PV system costs are likely to further drop with increasing shares of installed capacity due to learning effects. And, even more important, there is a high chance that the value of existing PV systems will rise as well due to recent efforts of internalising external costs - such as costs for CO_2 emissions - which will raise the retail price for grid electricity purchase and thus make PV self-generation more valuable.

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7.1.2. Contracting for PV in residential buildings

Despite PV sharing concepts in multi-apartment buildings have proven to be profitable for a large diversity of building set-ups, a remaining obstacle to increased deployment is the significant upfront costs. Therefore, the consequent research question addresses the issue of the profitability of shared PV systems within the framework of contracting. The results provided in Chapter 4 show that third party financing of PV systems reduces the profitability noticeably, depending on the contractor's expected return on investment. Nevertheless, in case of conditions which can be considered favourable for PV system implementation in Central Europe (moderately tilted roof, facing South) PV sharing in residential multi-apartment builings remains profitable, despite the necessity of sharing the gained profits with the contractor.

The European 2030 goals to increase energy efficiency, reduce emissions and increase the shares of renewable energy call for holistic building retrofit, which again attracts the attention of contractors. In case contractors are willing to keep their interest rates at a moderate[1] level, a triple-win situation could emerge: for the country, since achieving the optimistic 2030 goal becomes more likely; for property owners/residents, as the building quality is improved and the energy costs decrease; And for the contractor himself, indeed making some profit out of the whole situation. As already indicated before, the introduction of additional costs for CO_2 emissions would significantly facilitate investment decisions in the favour of thorough building retrofit since energy savings would become essentially more valuable.

7.1.3. The impact of forming energy communities beyond the building border

The proven profitability of PV implementation in multi-apartment buildings raises the consecutive question whether implementing energy communities be-

[1] Moderate is a relative term and highly depends on the individual situation.

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yond the building border can further enhance the financial benefits. There is no simple answer to that question either, since energy communities between multiple buildings can have entirely different characteristics, depending on the region and the according builing stock. To that end, four typical Central European settlement patterns are analysed regarding the profitability of PV system installation. Results show that the positive impact of forming an energy community beyond the border of individual buildings does significantly vary for the different settlement patterns. Energy community establishment is of greatest value for single-family home owners in rural areas, since the arising synergy effects are most significant. However, the profitabiliy of shared PV systems peaks in city energy communities between multi-apartment buildings as a result of the great number of different load profiles - multiple different households as well as small businesses are considered - and the therefore most efficient use of the generated PV electricity.

The general conclusion that can be derived from the results is that it would be worthy to establish energy communities beyond the borders of individual settlement patterns. For example, if an energy community would be set up between buildings in cities and rural areas, the large available roof space found in rural areas would facilitate optimal PV implementation and increase profitability for city residents. At the same time, the residents in rural areas would also account greater financial benefits due to increased synergy effects. To make such development happen within the coming years, legislators are required to provide the necessary legal and regulatory background shortly, also in order to enable broad diffusion and standardistation in the long-term. Moreover it will be necessary to elaborate on finding a adequate and transparent way of accounting the arising grid costs for community electricity transfer.

7.1.4. The contribution of residential PV to achieve national climate targets

The ambitious Austrian climate target of achieving effectively 100 % renewable electricity generation until 2030, would require approximately 10 GW of installed PV capacity, besides increased shares of other renewables. It is not

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decided yet how the 10 GW of PV will actually be realised, but the residential building sector will probably play an important role in this matter. Using the residential building sector for PV implementation does not only require available building surfaces, but also a certain profitability to motivate people to invest. Therefore, the results gained throughout Chapter 6 provide an estimation of the cost-optimal economic PV potential in residential buildings on country scale, based on optimal PV capacities for individual energy communities. Results indicate that it would indeed be possible to achieve the defined 2030 target in terms of PV installation in the residentail sector - even in a cost-optimal way.

An important finding in this context is that the cost-optimal economic PV potential in the residential building sector would be even higher when allowing to establish energy communities beyond the borders of individual settlement patterns. The reason is the largely available roof space on single-family buildings, from which only a small part is used for PV installation in rural communities. In city energy communities on the contrary, rooftop areas are a rare commodity for optimal PV installation. Allowing energy community installation overlapping different settlement patterns would bring synergies in optimal rooftop usage in addition to synergy effects between load profiles. The therefrom derived policy recommendation is to not necessarily limit energy communities to the neighbourhood level, but try to establish community interaction between settlement patterns where possible. To put this recommendation into practice, the difficult question concerning adequate charges for using the public grid for energy community electricity transfer needs to be answered in a first step.

7.2. Strengths and limitations of the proposed model

The results provided in the course of this thesis are gained by using system analysis as the modelling approach. As any other approach to modelling energy communities, the system view has its strength and limitations. The strengths of the holistic view are discussed in Section 7.2.1 and juxtaposed with the limitations in Sections 7.2.2 and 7.2.3.

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7.2.1. The strengths of the holistic system analysis approach

The possibly biggest advantage of using system analysis, in the way it is used in this thesis, is that the provided results show the overall optimum for a whole energy community. This means that the optimisation is not conducted for individual households, but for a community of households. This again implies dynamic allocation of the generated PV system electricity (consideration of the total community electriciy load instead of considering individual household load profiles) which leads to an optimal exploitation of synergy effects between individual household loadprofiles. The reason is that the generated PV electricity is optimally distributed to the participants by considering the energy community as a whole. Therefore, the results of this thesis indicate the highest achievable cost saving potential by installing optimally-dimensioned PV systems in energy communities on different scales.

Using the system analysis approach to maximse the NPV of an energy community within a specified time horizon implies that multiple households pursue the same target of reducing their electricity bill by sharing a PV system and its generation. Other possible modelling approaches such as game theoretical or agent-based modelling, on the contrary, focus on the various agents' competing interests and the process of finding an equilibrium. By using the system analysis modelling approach it shall be emphasised that in the context of energy community development and PV electricity sharing the focus should lie upon mutual agreements and common goals rather than the interests of individuals. The provided results further show that the more households pursue the same goal and the larger energy communities are set up, the better results can be achieved for the whole community.

Moreover, the system analysis approach gives a holistic view on a specified problem rather than depicting very specific situations. This has the advantage of achieving results that are generally valid and are therefore applicable to a variety of similar situations. Thus, the findings of this thesis can be used to guide policy makers concerned with the future development of energy communities through their decision making process.

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7.2.2. The limitation of omitting to display the interrelations between participants

With the holistic view of system analysis and the assumption of dynamic PV electricity allocation applied in this thesis, it is not possible to display the interrelations between energy community participants. This is a limitation of the applied modelling approach since individual energy flows within the community are not determined. Knowing about energy flows in detail would bring the advantage that the shares of PV electricity consumption by each household could be quantified. This would allow to analyse how the individual living situations impact the shares of directly consumed PV electricity. Moreover, such analysis would be necessary to elaborate on the ideal composition of households to further maximise monetary benefits within the energy community. However, when it comes to support policy decision making - which is the intention of this work by providing a holistic view - displaying specific interrelations between participants and energy flows in detail is irrelevant.

This model's limitation concerning the non-displayable electricity flows triggers another limitation, namely the limitation of disregarding grid charges for PV electricity transfer between properties. In case energy communities are established beyond the borders of individual buildings, the public grid needs to be used for PV electriciy transfer between participants (assuming that no sub-network structures are established). Using the public grid, grid charges according to the amount of electricity transferred, need to be accounted for by the grid operator. Since the applied approach to modelling energy communities does not display individual electricity flows, grid charges can not be considered. This limitation is discussed in detail in Section 7.2.3.

7.2.3. The limitation of disregarding grid charges

When looking at PV sharing in energy communites formed within one multi-apartment building, grid charges for electricity transfer between the individual participants is not an issue since the public grid is not used for sharing PV

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electricity. However, as soon as the borders of the energy community exceed individual buildings, using the public grid for PV electricity sharing between participants becomes necessary. Theoretically, energy communities could also establish individual lines for electricity transfer, however, this is not foreseen in terms of legislation or even prohibited by the law in different countries. Besides, regardless of different countries' regulations, it seems to be a mutual agreement that starting to establish sub-grid structures is not the aimed solution to implement energy communities between buildings. Therefore, using the structure of the public grid for community electriciy transfer seems to be the most reasonnable possibility so far.

In case the grid operators (need to) provide their infrastructure to be used for community electricity transfer, grid charges need to be paid by the community since additional electricity flows cause additional efforts to maintain reliable grid operation or even force an upgrade of the grid infrastructure. In case grid charges would be taken into account, the cost-optimal PV system capacities are expected to decrease, since electricity transfer between different buildings would become more expensive. However, the significance of the grid charge's impact on PV capacities and the profitability of PV sharing in energy communities depends heavily on the exact structure of the grid tariff[2]. Generally, the grid tariff can be split in a per-unit and a fixed component. The higher the fixed component of the grid tariff and the lower the per-unit component, the less significant the impact on the results in this thesis. Since recent discussions point towards a change in the grid tariff structure towards raising the fixed component of the grid tariff and reducing the per-unit component[3], it is to be expected that taking grid tariffs into consideration would just slightly impact the achieved results. Moreover, forming energy communities on larger scale brings the advantage of increased synergy effects between load profiles and rooftop usage, which again enhances profitability. Therefore, it is to be expected that energy communities between multiple buildings do still break-even, even if grid costs are accounted in full for community electriciy transfer.

[2]The composition of the total grid tariff varies significantly for different regions/countries.

[3]Due to the increasing shares of PV self-generation in residential buildings, the grid operators' revenues decrease. In case grid operators would increase the fixed component of the grid tariff, they could counteract this effect.

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Even more, it is merely a matter of time until the retail electricity price is increased due to efforts of internalising costs for CO_2 emissions. A rise in the per-unit component of the retail electricity price enhances the profitability of PV system installations and sharing concepts, since reducing electricity grid consumption becomes more valuable. In this case, a reduction of the per-unit component of the grid tariff would be countercompensated by an increase in the per-unit component of the retail electricity price, making the results of this thesis also valid for future changes in price and tariff structures.

7.3. Allocating costs and revenues to energy community participants

A challange of future energy community implementation will be the issue of an adequate distribution of costs and revenues between the individual participants. The people's ability in finding mutual agreements to settle monetary distribution issues within the community might pose an obstacle to the implementation and diffusion of energy communities, since the 'adequate distribution of costs and revenues' is a very subjective matter.

Therefore, market actors, who will be in charge of cost/revenue allocation within energy communities, need to be creative and propose transparent and convincing allocation schemes that prevent discrimination of individual participants. Since there are neither specifications nor special requirements concerning cost/revenue allocation schemes, the possibilities are numerous. A very transperent option would be to allocate cost/revenues according to the actual correlation of the individual household load profiles with the hours of sunshine. In this way, consumers could be incentivised to adapt their electricity consumption patterns such that the direct PV electricity consumption can be enhanced. Another option would be to entangle the cost/revenue allocation to the actual shares of the participants' direct consumption per timestep, per week or per month. Furthermore, thoughtful business models concerned with cost/revenue allocation should also consider the different participants' willingness to pay. While some energy community participants might have the only

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goal of reducing their electricity bills, others might as well aim at reducing their environmental footprint. The challenge of developing adequate business models is even more demanding in case not only households, but also businesses are part of the equation, since their expectations differ most likely to those of common household consumers.

In order to enable successful energy community implementation, a set of adequate cost/revenue allocation schemes need to be developed shortly. This, however, is not the task of policy makers, but of all stakeholders - such as energy suppliers and contractors - who offer their services to operate an energy community. Otherwise, if the people's interests are not secured to a certain extent or accordingly reflected in the offered business models, they might rather refrain from participating, which would hamper the promising energy community concepts in taking hold.

7.4. Context to future regulation and policy making

Common practice shows that energy communities are currently almost exclusively realised within the framework of lighthouse projects and demo regions. One reason for the slow diffusion of energy community concepts is the multiple gaps in the different countries' legislation. In the Europan Union, different aspects of energy communities are legally anchored in two supernational documents, the *Electricity Market Directive* (EMD) [41] and the *Renewable Energy Directive* (RED) [40], which are both part of the *Clean Energy for all Europeans Package*. Both directives provide a legal basis for energy community implementation, thereby leaving a certain room for the individual member states' national transposition. The transposition of the defined framework into national law shall enable energy communities to be established in an organised fashion, aligned with current national regulations. So far, however, the legislative and regulatory background to energy communities is far from complete in most countries and needs effective adaptation to close regulatory loopholes which cause uncertainty and thus hamper this novel concept from taking hold.

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Exemplary for the case of Austria, the legislative background of forming energy communities and implementing PV sharing concepts is provided for multi-apartment buildings only (*Electricity Industry and Organisation Act* - ElWOG, [110]). PV sharing between multiple buildings of adjacent properties is not foreseen[4] in the current legislation and forming energy communities between buildings of non-adjacent properties is not legally possible yet[5]. In this thesis, however, it is anticipated that energy communities can be established beween individual buildings, regardless of their direct geographical proximity. Since the results show a clear advantage of establishing energy communities on a scale beyond the border of individual buildings, it is now the task of Austrian legislators to speed in providing the adequate legal framework.

To achieve a diffusion of the energy community concept on a large scale, the whole process of setting up and operating energy communities needs to be standardised and transparent to the participants. In this context, it is necessary to specify a transparent set of preconditions and technical requirements that must be met. Moreover, it is of significant importance to keep the bureaucratic effort to a minimum, such that energy community implementation becomes as easy as a 'one-stop-shop' in the near future. Since the regulation concerning the establishment of energy commmunities between multiple buildings is not set in stone yet, there is the opportunity to learn from the experience of 'best-practice' examples and projects realised within 'regulatory sandboxes' in different countries. Pulling together the most significant learnings and transposing these experiences into national law might enable the efficient roll-out of the energy community concept in the near future.

[4]Theoretically, a building could transfer electricity via a direct line to other buildings under the premises that the direct line does not span over common property. Another premise is that there must not be an electricity backflow to the public grid at any time.

[5]Regulatory sandboxes are exempt.

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8. Conclusions and outlook

The establishment of energy communities and PV sharing concepts in the residential building sector is one of the most promising solutions to address a variety of pressing issues related to climate change: Firstly, the shares of renewable electricity generation are increased while the additional grid burden is simultaneously limited to a minimum due to direct self-consumption. Secondly, CO_2 emissions are reduced, since part of the conventional grid electricity is subsituted by PV generation. Thirdly, since PV implementation already comes with a violation of the building envelope, investments to generally increase the building standard might be triggered, which would lead to an increase in the building stock's energy efficiency. Despite the entirely positive impact such concepts would have, they have not taken hold yet. The reasons for that are multiple, and one of those reasons is financial issues. To facilitate increased deployment of PV sharing concepts in the future, this thesis elaborates on the profitability of implementing PV in energy communities of different scales. The models and methods necessary to answer the specific research questions are set up such that the gained results allow to draw conclusions which are generally valid. Thus, guidance can be provided for building owners and/or building residents in terms of investment decisions as well as for policy decision makers concerned with future regulations for energy communities.

The mixed-integer linear optimisation model developed in the first part of this thesis allows to determine the profitability of shared PV for small-scale energy communities in multi-apartment buildings with respect to the influence of a variety of exogenous influencing factors and building set-ups. The method of maximising the energy community's net present value to evaluate the profitabiliy of PV implementation in energy communities has proven to be suitable since cost-optimal results are achieved from a community perspective. This holistic system view is a strength of the analyses since it provides a perspective where all participants follow a common goal, namely the minimisation of overall costs. Having a common goal and distributing the generated PV electricity dynamically, the highest possible positive impact of PV sharing concepts can be harvested. Since bearing significant upfront investment

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costs in PV systems can pose a burden for private building owners or owner communities, the second part of the thesis elaborates on the question whether PV implementation remains profitable within the framework of third-party financing. The developed method of modelling the relations of clients and contractors without using contract theory and game theoretical modelling has proven suitable to mirror situations as they would occur in practice. Such approach is even more important for policy decision making, since policy makers are interested in results that provide a holistic view instead of depicting interrelations in detail. In the third part of the thesis, the model is further developed to quantify financial benefits of expanding energy communities beyond the building border with specific respect to different settlement patterns. Finally, an algorithm is developed to be able to upscale results for individual neighbourhood energy communities, in order to estimate the cost-optimal economic PV potential on country scale. The definition of four characteristic settlement patterns has proven to be of significant importance, since optimal PV system implementation and according profitability varies with the building stock. The algorithm developed to upscale results to country level has served its purpose. Since 'neighbourhood energy communities' imply a certain kind of geographical proximity, the algorithm provides reasonnable results clustering buildings within political districts to settlement patterns and then further to energy communities.

There are a variety of general conclusions that can be derived from the results gained throughout the analyses: PV sharing concepts in residential buildings are already profitable without subsidies and despite moderate retail electricity prices combined with moderate solar irradiation as assumed in the analyses. The significance of the positive impact on the NPV varies with the chosen PV system, the building set-up, the tenant portfolio and other exogenous influencing factors such as location specific climatic conditions. When assuming the most common version of PV implementation - namely building-attached to a moderately tilted roof - profitability is given, even when assuming third-party financing via a contractor. A way to increase the profitability of PV sharing concepts is to increase the number of energy community participants. This leads to a non-linear increase in profitability due to load profile diversity, until a certain point. The positive effects of forming energy communities between multiple buildings are not uniform, but depend significantly on the underlying

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settlement pattern. Since synergy effects do not only arise from load profile diversity but also from the availability of rooftop areas for example, the establishment of communities beyond the borders of settlement patterns can be recommended. The final estimation of country-wide PV capacities that can even be achieved in a cost-optimal manner based on neighboughood community optimisation illustrates the actual potential of PV in residential buildings. Since 10 GW of PV could be installed in a cost-optimal way in the residential building sector in Austria, it can be derived that the simple economic (but not cost-optimal) potential of PV in residential buildings is even higher. Thus, the general conclusion from all parts of this thesis is that there don't exist financial obstactles to implementing PV sharing concepts anymore. From now on, the linchpin to the actual implementation of PV sharing concepts is the people themselves and the legislators responsible to provide the necessary regulatory background.

The multiple issues in the field of PV sharing in energy communities which are tackled throughout this thesis provide a basis for subsequent questions to be answered in future research. Results provided in this work clearly show the financial advantages of extending the borders of energy communities from individual buildings to multiple buildings. Neighbourhood energy communities analysed in this thesis range from five to a dozen buildings per community. As indicated above, the positive impact of synergy effects which arise due to increased load profile diversity is expected to peak at some point. Since energy communities should be established as efficiently as possible, the optimal number of households/buildings needs to be determined in future research. Along with the optimal number of households or buildings, it would be important to analyse the optimal composition of load profiles. Thereby, not only household load profiles, but also business load profiles should be taken into account. A therefrom arising challenge, which should also be adressed, is the question how to deal with different interest rates of households and businesses within the same energy community. Another important issue in the context of establishing energy communities between multiple buildings is the adequate allocation of charges for using the public grid when transferring electricity between energy community participants. Therefore, future research would need to investigate and compare different possibilities of allocating grid costs, also taking into consideration a possible restructuring of the common grid tariffs

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schemes. In this context it needs to be investigated whether the effect of an increase in the fixed component of the grid tariff (and a simultaneous decrease in the per-unit component) could be countercompensated by an increase of the per-unit component of the retail electriciy price due to internalisting costs for emissions. Another important topic gaining importance is the allocation of costs and revenues between energy community participants. In this study, the most profitable solution is determined for the whole energy community. Thereby, however, the distribution of benefits between individual participants is not observed. In this context, future research should elaborate on business models for an adequate allocation of costs/benefits to meet the expectations of all participating parties. Thereby, the individual customers' willingness to pay also needs to be reflected in the business models. Ultimately, since this work introduces four typical Central European settlement patterns as a basis to energy community optimisation at a neighbourhood level, future work should specify characteristic settlement patterns outside Europe to be able to further quantify the differences in profitability of PV sharing concepts.

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Appendix

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A. Appendix to Chapter 3

A.1. Solar irradiation

To be able to determine the sun's irradiation angle on an arbitrarily tilted surface, it is necessary to know the azimuth as well as the elevation angle of the sun at any time. Both angles determine the position of the sun in the world coordinate system. The azimuth angle represents the horizontal angle of the sun and describes its position in horizontal direction by the deviation from the southern direction. The elevation angle describes the height of the sun's position and is measured from the horizontal plane towards the zenith. With azimuth and elevation angle, which determine the position of the sun, and the specific settings of the PV system - the tilt and orientation - the sun's irradiation angle on the PV system can be determined as given in Equation A.1. The nomenclature is given in Table A.1.

$$\Theta = \arccos(-\cos(\gamma_s) \cdot sin(\gamma_{pv}) \cdot \cos(\alpha_s - \alpha_{pv} - 180) + \sin(\gamma_s) \cdot \cos(\gamma_{pv})) \quad \text{(A.1)}$$

The irradiation angle Θ is used to determine the direct radiation of the sun on the PV panel. The total radiation (Equation A.2) on a PV panel consists of direct (Equation A.3), diffuse (Equation A.4) and reflected irradiation (Equation A.5).

$$E_{ges} = E_{dir} + E_{diff} + E_{refl} \quad \text{(A.2)}$$

The calculations of direct, diffuse and reflected irradiation are in line with [12].

$$E_{dir} = E_{dir,horizontal} \cdot \frac{\cos(\Theta)}{\sin(\gamma_s)} \quad \text{(A.3)}$$

$$E_{diff} = E_{diff,horizontal} \cdot \frac{1 + \cos(\gamma_{pv})}{2} \quad \text{(A.4)}$$

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$$E_{refl} = E_{glob,horizontal} \cdot alb \cdot \frac{1 - \cos(\gamma_{pv})}{2} \tag{A.5}$$

To determine the according PV generation, the calculated total irradiation on the PV system (E_{ges}) can then be adjusted for losses of different components and the PV panel's efficiency.

$$E_{kWh_per_kW} = E_{ges} \cdot 10^{(-3)} \cdot \eta_1 \cdot \eta_2 \cdot A_{module}/P_{module} \tag{A.6}$$

Abbreviation	Explanation	Value/Unit
α_{pv}	Azimuth angle of the PV system	
α_s	Azimuth angle of the sun	
η_1	PV module efficiency	0.17
η_2	Electrical components efficiencies	0.8
γ_{pv}	Tilt of the PV system	
γ_s	Elevation angle of the sun	
alb	Albedo[1]	0.2
A_{module}	Area of one PV panel	$1.5\,\mathrm{m}^2$
E_{diff}	Diffuse irradiation in $\mathrm{Wh/m^2}$	
E_{dir}	Direct irradiation in $\mathrm{Wh/m^2}$	
$E_{diff,horizontal}$	Diffuse component of horizontal radiation	$\mathrm{Wh/m^2}$
$E_{dir,horizontal}$	Direct component of horizontal radiation	$\mathrm{Wh/m^2}$
E_{ges}	Total irradiation on PV system	$\mathrm{Wh/m^2}$
$E_{glob,horizontal}$	Horizontal global radiation	$\mathrm{Wh/m^2}$
$E_{kWh_per_kW}$	Actual PV generation	kWh/kW
E_{refl}	Reflected irradiation	$\mathrm{Wh/m^2}$
P_{module}	Capacity of one PV panel	0.25 kW

Table A.1.: Variables for determining the solar irradiation on the PV panel.

Figure A.1 shows the annual generation of a southern-facing PV system tilted 30 °.

[1] Albedo is the ratio of the reflected radiation to the incident radiation.

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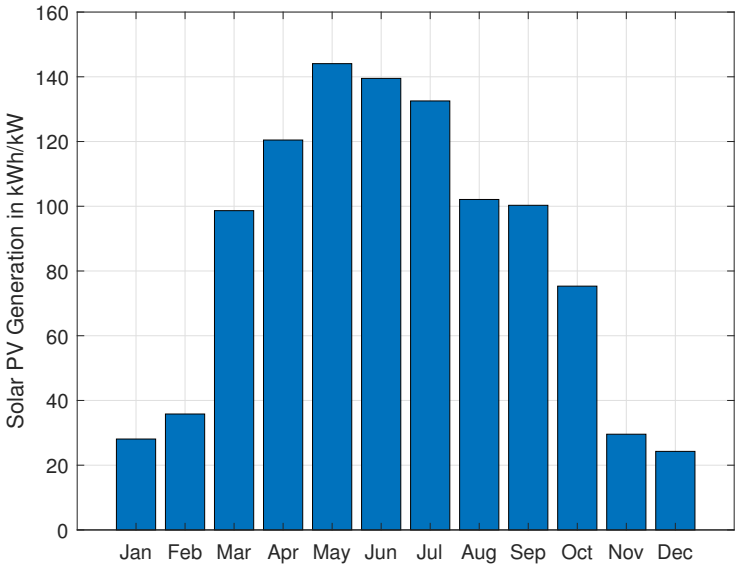

Figure A.1.: Solar irradiation on a PV panel of a reference size of 1 kW. Per year, full load hours of 1030 h are accounted.

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A.2. Load profiles

Figure A.2 presents the individual apartments' load profiles used for the case studies. The business load profile (grocery store) is presented in Figure A.3. The multi-apartment building's total load profile (the sum of the individual load profiles) is presented in Figure A.4 in comparison with the business load profile (grocery store). The load profiles are presented as the average load for every hour of all days within one year.

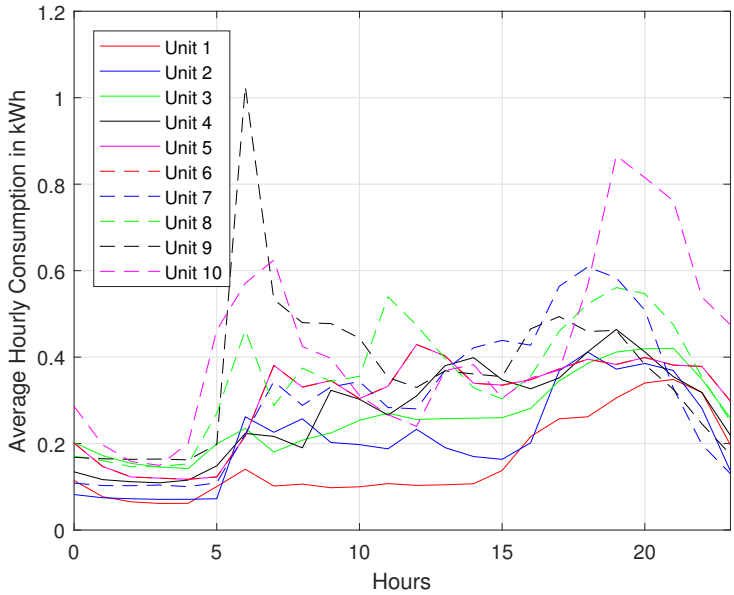

Figure A.2.: Individual apartments' load profiles [111], depicted as the average values for every hour (0 h-24 h) of every day within one year.

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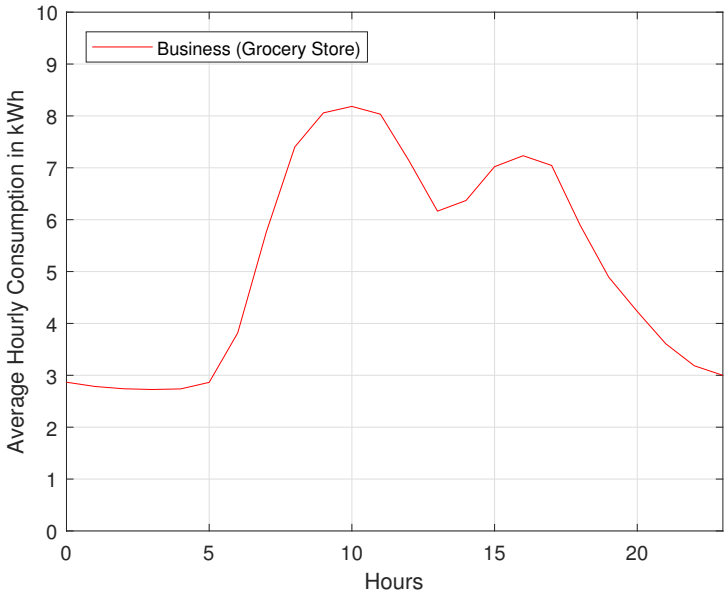

Figure A.3.: Grocery store load profile [9].

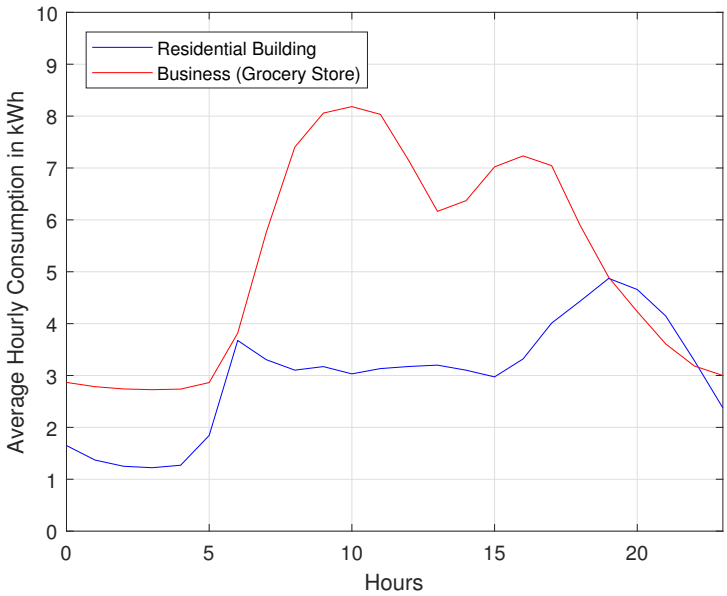

Figure A.4.: Multi-apartment building's total load and grocery store load profiles.

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A.3. Determination of the heat pump's coefficient of performance (COP)

The COP is assumed to be approximately linear with the outdoor temperature for reasons of simplicity, which is compliant with [65], [161]. At an outdoor temperature lower than or equal to −20 °C, the COP is one, which means that the ratio of the electricity-input and heat-output is 1:1. Furthermore, it is assumed that the heat pump's maximum COP is 4.5 at an outdoor temperature greater than or equal to 35 °C. The gradient is calculated to be 0.06 and, with this information, the COP can be calculated for every outdoor temperature. Having an outdoor temperature profile in a 15-minute resolution, the COP has the same resolution, allowing for a precise heat pump operation.

A.4. Heat load profile calculation

Name	Explanation	Unit
HDD	Heating degree days	
HDD_{korr}	HDD correction factor	
HDD_{norm}	Normed heating degree days	
HL	Building heat load at 15-minute resolution	kWh/m^2/15min
HL_{av_qh}	Specific heat load at 15-minute resolution	kWh/m^2/15min
HL_{av_yr}	Specific annual heat load	kWh/m^2/yr
t_a	Outdoor-temperature at 15-minute resolution	°C
t_{a_perday}	Average daily temperature	°C
t_{av}	Long-term temperature average	°C
t_i	Constant indoor-temperature	°C
t_{diff_norm}	Temperature difference, normed by long-term temperature average	
t_{diff_HDD}	Daily temperature difference for heating degree days calculation	°C

Table A.2.: Variables for heat load profile generation.

Starting point for the self-generation of outdoor-temperature dependent heat

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load profiles are specific heat loads as defined in Table 3.9. The used variables are listed in Table A.2. Since a heat load profile at 15-minute resolution is needed, the annual specific heat load is unrevaled to the requested resolution in a first step:

$$HL_{av_qh} = HL_{av_yr} \cdot \frac{1}{35040}$$

In a second step, the temperature difference between a constantly set indoor-temperature of 20 °C and the outdoor temperature trend (15-minute resolution) is calculated and normed to the long-term temperature average[2]:

$$t_{diff_norm} = (t_i - t_a)/t_{av}$$

Furthermore, it is important to note that temperature differences $t_i - t_a \leq 8$ are set to zero, as it is assumed that buildings are heated up to an outdoor temperature of 12 °C. According to [65], assuming an indoor set-point temperature of 20 °C and a heating limit of 12 °C outdoor temperature is the international standard.

In a third step, a heating degree day (HDD) correction factor has to be introduced in order to achieve climate-corrected heat load profiles. This is important since analyses are conducted for a time period of 20 years. Therefore, the daily temperature difference is needed ($t_{diff_HDD} = t_i - t_{a_perday}$) to calculate the heating degree days of one year:

$$HDD = \sum (t_{diff_HDD}) \quad \forall \quad t_{diff_HDD} > 8.$$

The constraint of $t_{diff_HDD} > 8$ again marks the temperature heating limit of 12 °C. The final HDD correction factor is then calculated as

$$HDD_{korr} = HDD_{norm}/HDD,$$

whereas the HDD_{norm} can be found for any location and is usally provided by local metereological businesses (for Vienna: $HDD_{norm} = 3350$ [171]).

[2]Due to a lack of further temperature data, the average temperature of one year is taken in this case as the long-term average temperature.

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Finally, the heat load profile at a 15-minute resolution can be calculated:

$$HL = HL_{av_qh} \cdot t_{diff_norm} \cdot HDD_{korr} \tag{A.7}$$

A.5. Retail energy price assumptions

Retail electricity price

[42] shows the household electricity price development from 2008 to 2018. The average EU household electricity price is about 20.5 c/kWh, the average retail electricity price within the Euro-area is 22 c/kWh. The historical price development shows a price stagnation over the last five years. Therefore, as a basis for the analyses, the retail electricity price of 22 c/kWh is assumed to remain constant.

However, as there is no guarantee for retail electricity prices to remain constant, even though prices have stagnated within the last five years, the sensitivity analyses are conducted based on an annual average retail electricity price increase of 2.37 %. This percentage can be approximated from the historical price developments, when assuming a linear price development, which is reasonable as short-term price effects can be averaged out. Furthermore, a double price increase of 4.74 % and also, despite being unlikely, an average price decrease of 2.37 % per year is assumed for the analysis in Section 3.4.1.

Retail gas price

The retail gas price development is shown in [43]. Starting from a price of 5.2 c/kWh in 2010, the gas price has increased to a peak of 7.2 c/kWh in 2014. Since then, the retail gas price has been declining and has fallen below 6 c/kWh. Considering this trend, a retail gas price of 5 c/kWh is assumed as basis for the analyses.

For sensitivity purposes, an average retail gas price increase of 1.15 % can be approximated from the historical gas price series, shown in [43], when assuming a linear development (averaging out short-term price effects).

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Retail wood pellet price

The International Energy Agency of Bioenergy specifies prices for European residential wood pellet consumers between 0.2 EUR/kg and 0.3 EUR/kg [157]. Since the VAT is not included in this price range, a pellet price of 0.28 EUR/kg (VAT included) is assumed for the analysis.

For a sensitivity analysis in Section 3.4.2, a wood pellet price increase of 1.4 % per year is assumed for household consumers. This percentage is derived from the historical retail wood pellet price development in [122], again assuming a linear development.

Retail district heating price

The district heating prices for household consumers are taken from [6]. They are proven to be in line with [162], taking into account that the district heating price in this study is split into a base price per square metre, a specific price per kWh and a price for measurement.

[162] provides historical price data for Europe. From that, an average retail price increase of 5 % per year can be approximated for Europe. This price increase is used for the sensitivity analysis in Section 3.4.2.

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B. Appendix to Chapter 5

B.1. Load profiles

The total electricity load profiles of all multi-apartment buildings, historical buildings and single-family buildings are shown in Figures B.1, B.2 and B.3, respectively. The total load of buildings with multiple apartments is composed out of individual, real-measured apartment load profiles. The load profiles are measured in 15-minute intervals and presented as the average load for every hour of every day within one year.

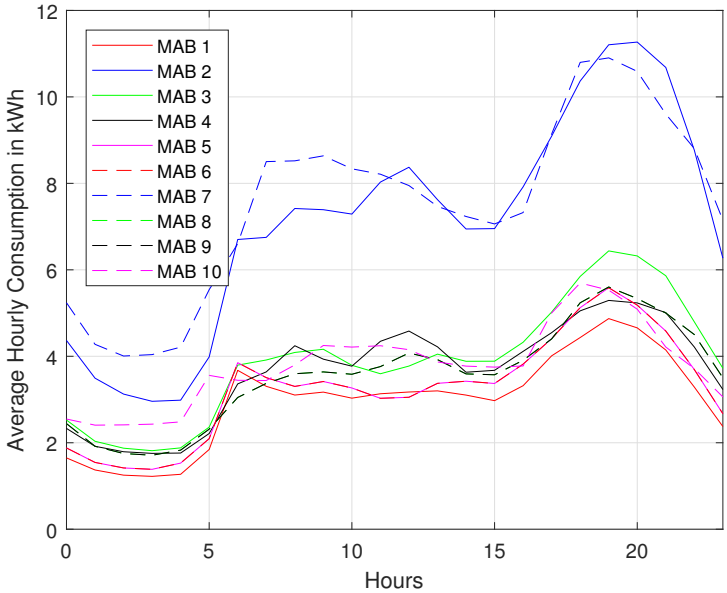

Figure B.1.: Load profiles of 10 differently sized multi-apartment buildings; presented as the average load for every hour of every day within one year.

For those use cases, which take business load profiles into account, standard load profiles are used [9]. They are shown in Figure B.4, normed to an annual load of 1000 kWh. For a realistic upscaling of said standard business load profiles, the bakery is assumed with a specific electricity demand of 500 kWh/m^2 [123], gastronomy with 230 kWh/m^2 [146], grocery with 413 kWh/m^2 [113],

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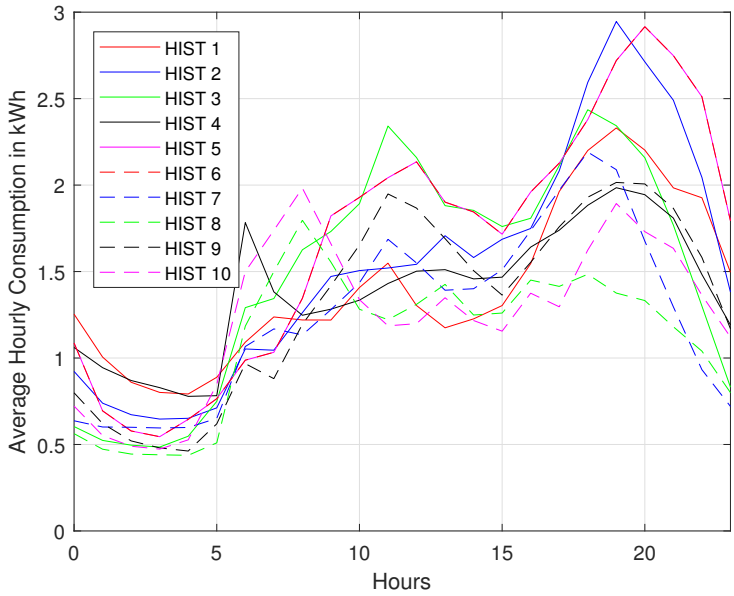

Figure B.2.: Load profiles of 10 different historical buildings; presented as the average load for every hour of every day within one year.

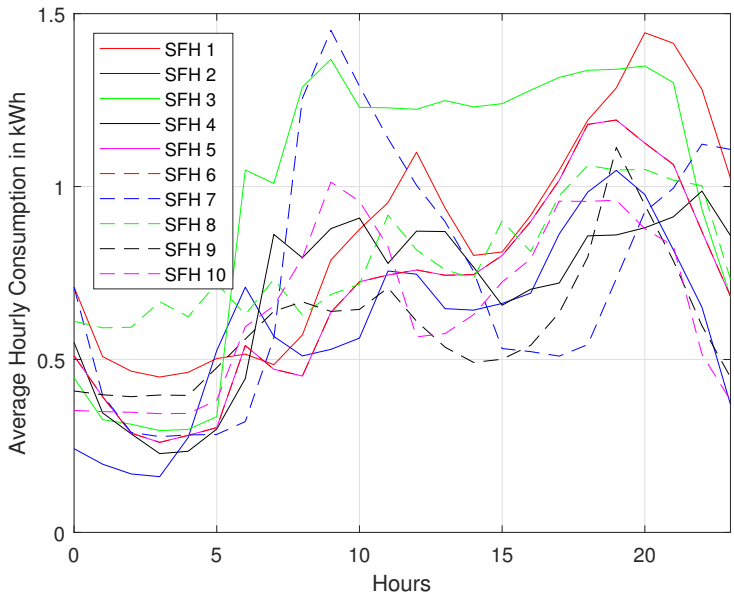

Figure B.3.: Load profiles of 10 differently sized single-family houses; presented as the average load for every hour of every day within one year.

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shops with 198 kWh/m^2 [113] and the agricultural business is assumed to have an average annual electricity demand of 22 000 kWh [16].

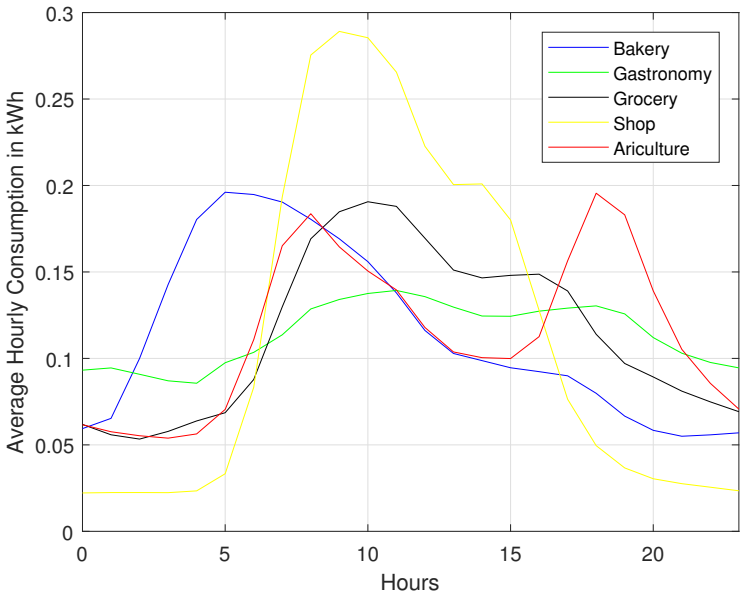

Figure B.4.: Load profiles of individual businesses.

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B.2. Building geometry

The building geometries for the buildings used in the analyses are provided in Tables B.1 B.2 and B.3. The facade areas, if they are used for PV implementation, need to be adapted by a mark-up coefficient of 0.5 to spare windows, doors and the area too close to the ground.

Building Type	Roof area in m^2	Facade areas in m^2	Floor space in m^2	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

Table B.1.: Building geometry of single-family buildings.

Building Type	Roof area in m^2	Facade areas in m^2	Floor space in m^2	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 B.2.: Building geometry of multi-apartment buildings.

Building Type	Roof area in m^2	Facade areas in m^2	Floor space in m^2	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

Table B.3.: Building geometry of historical buildings.

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B.3. Hot water storage

Hot water storage can be implemented as a supplement to a heat pump. If storing heat produced by the heat pump and using it at later points in time for heat load coverage is profitable, then the optimisation model determines the optimal hot water storage capacity greater than zero. Then, the according installation costs are considered[1]:

$$I_{0_hstor} = i_{0_hstor} \cdot Cap_{hstor_l}, \tag{B.1}$$

Abbreviations and technical data concerning the hot water storage is given in Table B.4. The hot water storage is modeled such that

- The state of charge at every point in time is determined by the state of charge 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 B.4.
- The state of charge 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 [139]:

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

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

[1] Assuming that 1 Dollar equals 0.88 Euro (as constituted in February 2019).

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Specification	Abbreviation	Value/Unit
Charging/Discharging efficiency	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 [106]
Specific heat capacity of water	c_w	4.182 kJ/kgK
Hot water storage capacity	Cap_{hstor_l}	kg or l
Heating storage capacity	Q	kWh

Table B.4.: Empirical scaling and assumptions for the hot water storage.

B.4. Heating systems

The distribution of different heating systems differs from region to region. For the example of Austria, information on the distribution of heating systems can be extracted from the national statistical institute [147]. Table B.5 shows the two most commonly used heating technologies per federal state.

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

Table B.5.: Ranking of the heating systems per federal state; 'Wood' comprises wood, pellets, wood chips and wood briquettes.

It is stated by [13] that any kind of biomass heating is widely distributed in rural areas, where wood is easily available. This is in line with [138], showing single family homes being mostly equipped with oil, biomass or gas heating.

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Multi-family houses are mostly heated by district heat and gas, followed by oil and electricity. The older the building, the more often gas is used [138]. Heat pumps are often used in retrofitted buildings.

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