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Economic viability of contracting models for financing and operating sustainable energy infrastructure in multi-storey residential buildings

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Supervisor: Associate Prof. Dipl.-Ing. Dr.techn. Johann Auer
Assistent: Dipl.-Ing. Sebastian Zwickl-Bernhard, BSc

by

Maria-Luisa Brüser, BSc
01307457

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Abstract

In its national climate goals, Austria has committed to reduce fossil fuel-based heating systems in the residential sector and to increasingly utilise buildings for the generation of decentralised renewable energy until 2030. *Energy contracting* concepts are a promising possibility to accelerate the energy transition by taking financial risks from house owners and providing green energy at reduced costs to the respective residents. The objective of this thesis is to determine which sustainable energy infrastructure is established in a multi-storey residential building in order to ensure the residents' minimal possible energy costs. A linear optimisation model is proposed, which minimises the total yearly energy costs of the tenants. This includes, among others, the profitability of the involved contracting party. In order to examine the limits concerning the applicability of contracting various technologies in the residential sector, three different building set-ups are analysed. The results show that *energy contracting* can lead to reduced energy costs for tenants as well as profitable investments for contractors. Especially contracted investments in photovoltaic plants prove to be economically viable within various building set-ups. The profitability of heat pumps differs depending on the existing heating system within the building. Nevertheless, an increasing CO_2 price triggers the profitability of heat pumps since the existing fossil fuel-based heating systems are more affected by the rising CO_2 price. Furthermore, solar thermal plants as well as battery systems are not beneficial for the tenants in the analysed contracting business model. The results indicate that a further decarbonsation of the building sector needs market incentives for additional contracting business models and the reduction of bureaucracy barriers for the stakeholders involved. This can lead to new contracting investment and service business cases (e.g. contracting of solar thermal plants, building retrofitting and active demand side management) being profitable for both tenants and contractors.

Kurzfassung

In seinen nationalen Klimazielen hat sich Österreich dazu verpflichtet, bis 2030 den Einsatz von fossilen Heizsystemen im Gebäudesektor zu reduzieren sowie Gebäude vermehrt für die Erzeugung von dezentraler, erneuerbarer Energie zu nutzen. *Energie-Contracting-Konzepte* haben hierbei das Potenzial, maßgeblich zur Beschleunigung der Energiewende beizutragen, da sie sowohl finanzielle Risiken für HauseigentümerInnen verringern als auch den MieterInnen nachhaltige Energieverorgung zu reduzierten Kosten ermöglichen. Ziel dieser Arbeit ist es, zu untersuchen, welche nachhaltige Energieinfrastruktur in einem mehrstöckigen Wohngebäude errichtet wird, um den BewohnerInnen möglichst geringe Energiekosten zu gewährleisten. Hierfür wird ein lineares Optimierungsmodell entwickelt, das die jährlichen Gesamtenergiekosten der MieterInnen minimiert. Unter anderem wird hierbei die Rentabilität der Investition für einen beteiligten Contractor berücksichtigt. Um die Grenzen der Anwendbarkeit von Contracting bei verschiedene Energietechnologien im Gebäude zu untersuchen, werden drei verschiedene Gebäudetypen analysiert. Die Ergebnisse zeigen, dass *Energie-Contracting* sowohl zu reduzierten Energiekosten für die MieterInnen als auch zu rentablen Investitionen für Contractoren führen kann. Insbesondere Contracting-Investitionen in Photovoltaikanlagen erweisen sich für alle untersuchten Gebäudetypen als wirtschaftlich rentabel. Die Rentabilität von Wärmepumpen ist je nach bestehendem Heizsystem des Gebäudes unterschiedlich. Allerdings wirkt sich ein steigender CO_2-Preis positiv auf die Rentabilität von Wärmepumpen aus, da die bestehenden, auf fossilen Brennstoffen basierenden Heizsysteme stärker von einem steigenden CO_2-Preis betroffen sind. Solarthermische Anlagen und Batteriesysteme führen in dem untersuchten Contracting-Geschäftsmodell nicht zu finanziellen Vorteilen für die MieterInnen. Die Ergebnisse verdeutlichen, dass für eine weitere Dekarbonisierung des Gebäudesektors Marktanreize für zusätzliche Contracting-Geschäftsmodelle sowie der Abbau von bürokratischen Hürden für die beteiligten AkteurInnen notwendig sind. Das kann dazu führen, dass neue Contracting-Investitionen und -Dienstleistungen (z.B. Contracting von solarthermischen Anlagen, Gebäudesanierung und aktives Demand-Side-Management) sowohl für die MieterInnen als auch für Contractoren profitabel werden.

Contents

Acronyms

BDV	binary decision variable
DH	district heating
DHW	domestic hot water
DSM	demand side management
EPC	energy performance contracting
ESC	energy supply contracting
EV	electric vehicle
EVSE	electric vehicle supply equipment
HP	heat pump
NPV	net present value
PV	photovoltaic plant
RoI	return of investment
ST	solar thermal plant

1 Introduction

1.1 Motivation

In accordance with the Paris Agreement (UNFCCC, 2015), Austria has set the national target to reduce the greenhouse gas emissions by transitioning the energy sector from fossil fuels to renewable energies and to lower the energy demand through efficiency measures until 2030. The building sector plays a crucial role in this transition since high energy savings can be achieved by retrofitting and additionally, local energy can be produced locally on the buildings site (e.g. heat pumps (HPs), photovoltaic (PV) or solar thermal plants (ST)).

More precisely, the Austrian national energy plan includes the national target to increase the renovation rate towards 3 % and to promote district heating (Bundeskanzleramt Österreich, 2020). At the same time, oil fired heating systems in new buildings are banned since 2020 and it will become mandatory to replace boilers older than 25 years until 2025 and the remaining ones no later than 2035 (Bundeskanzleramt Österreich, 2020). Taking a look only at Vienna, more than 10,000 households are still being supplied by an oil boiler and around 440,000 by natural gas (Statistik Austria, 2020). Furthermore, Austria wants to equip 1 million roofs with PV systems to increase the total installed capacity by the factor of ten (from 1.2 GW to 12 GW) (Bundeskanzleramt Österreich, 2020; Huneke et al., 2019).

Although the change of the heating system, retrofitting and the installation of energy producing plants come with significant investment costs, owners of private houses undertake these investments and benefit from the decreased energy costs. However, especially in multi-storey residential buildings with multiple owners and tenants, investments with high overnight-payments are a challenge but crucial in order to fulfill the climate targets. Barriers are the lack of financial resources and the circumstance that the financing party itself may not be the one that benefits from the energy savings[1].

Contracting efficiency measures and renewable energy plants offers a possibility to convert the high overnight-costs into variable energy costs while in the best case lowering the energy costs for the tenants and taking financial risks from the building owner.

[1]In literature this is often referred to as the *landlord-tenant* or the *split-incentive problem*, see the work of Petrov and Ryan (2021).

1.2 Research question

The aim of the thesis is to answer the following research questions:

> Which sustainable energy infrastructure is established in a multi-storey residential building in order to minimise the total yearly costs of the tenants? Under which conditions can an energy contractor make an economically viable offer to the building owner when financing the selected energy infrastructure?

A linear optimisation model is developed in the course of this thesis to determine which investment decision leads to the minimal total yearly costs of the tenants. Thereby, a urban, a suburban and a rural use case are investigated to show the different investments due to the varying building set-up. The thesis aims to evaluate, in which building setups the contractor is able to compete with a direct investment taken by the building owner. Furthermore, it shall be analysed how profitable various investments are from the contractor's point of view. The sensitivities, such as load profiles, CO_2 prices, technology costs and roof availability are investigated as well.

1.3 Applied methods

The developed linear optimization model is implemented in Python, using the Pyomo framework (Bynum et al., 2021). The objective function minimises the total yearly costs for the tenants, while fulfilling the energy demand of 30 households. As a result of the optimization, a cost efficient setup of energy supply infrastructure for three predefined buildings is proposed.

Used input parameters are the aggregated load profiles for electricity, heating, domestic hot water (DHW) and electric vehicle (EV) charging, which are generated in one-hour time steps using the *LoadProfileGenerator* (Pflugradt, 2020). The energy loads are created for three different types of households, which differ in their energy usage behaviour. The heating demand curves are adapted to the default heating system and the building type in each use case. Investments in new technologies can be done by the house owners themselves or through a contractor, while taking into account the contractor's profitability. At the final step, the model is solved with the GLPK optimizer (*GLPK - GNU Linear Programming Kit* 2022). The visualisation of results is done using the python-based, open-source plotting package Pyam (Huppmann et al., 2021).

1.4 Outline of thesis

After a short introduction to the topic, Chapter 2 gives an overview of the state of the art of various energy contracting models. The involved parties as well as existing business models are presented. Furthermore, the current research on energy contracting the later examined technologies is shown.

In Chapter 3 the methods of the thesis and the mathematical formulation of the optimisation model are outlined. This section shows which technologies can be installed, the input parameters used and the set-up of the conducted scenarios.

Chapter 4 shows the results of three use cases that differ in heat demand, electricity demand, the default heating system and the available roof area.

The sensitivity analysis in Chapter 5 examines the effects of changing parameters such as CO_2 price, expected return of investment (RoI) for the contractor, investment costs and the pricing model of the contractor.

In Chapter 6 the results of the work are discussed and concluded.

2 State of the art and progress beyond

This chapter provides an overview of the concept of energy contracting in section 2.1, more precisely the forms of contracting, the involved parties and the most common business models. In Section 2.2, the current state-of-the-art of contracting in literature is presented. The own contribution of this work is stated in the last section 2.3.

2.1 Overview of the concept of energy contracting

Energy Contracting is an umbrella term for various business models between a service provider (contractor) and a building owner or tenant with the aim to reduce energy costs and improve energy efficiency. In the following thesis, the term *contractor* will be used for the service provider, while in literature it is often referred to as *energy service company* (abbreviated *ESC*).

Tenant electricity sharing can be included in contracting models and is part of the legal framework to enable contracting. The term generally refers to decentrally generated electricity (e.g. by PV), which is locally shared between tenants. The electricity can be distributed within a single building or various buildings in the neighborhood. (Will and Zuber, 2017)
In the implementation of tenant electricity, several options exist with regards to the roles and responsibilities of property owners and tenant electricity service providers (contractors). In case that the owner of the property owns and operates the energy generation plant, the term tenant electricity sharing enabling (German: *Mieterstrom-Enabling*) is commonly used. If the plant is financed, operated and marketed by a service provider, this is usually called tenant electricity sharing contracting (German: *Mieterstrom-Contracting*). (Polarstern, 2021)

While in Germany this term is mostly referred to by *Mieterstrom*, in Austria the term *Energiegemeinschaft* is used. The amendment of the Austrian Electricity Industry and Organization Act (German: Elektrizitätswirtschafts- und -organisationsgesetz ElWOG) in 2017 created the legal framework for various contracting business cases with the definition of energy communities (German: Erneuerbare-Energie-Gemeinschaften) (ElWOG, § 16c) and citizen-energ y-communities (German: Bürgerenergiegemeinschaften) (ElWOG, §

16b). The following sections will not further emphasise on the legal framework, but on the possible business models of contracting.

2.1.1 Types of energy contracting

The following section explains the main forms of contracting that can be distinguished.

In **energy supply contracting**, the contractor is responsible for planning, building, financing and operating the energy system. In most cases, the contractor remains the owner of the plant and refinances his investment and running costs by selling the produced energy (electricity, heating, cooling) to the customer (Energieagentur Rheinland-Pfalz GmbH, 2016). This is the type of contracting applied in this thesis.

In **energy performance contracting** (in German literature also referred to as energy saving contracting), the contractor guarantees to lower the final energy consumption through efficiency measure. Common examples are the replacements of light bulbs, improvement in the thermal insulation, water-saving measures and other enhancements of the building equipment. The savings in energy costs, either calculated or actually measured, are shared between contractor and the building owner or the tenants. (Görlitz, 2018)

In **financial contracting**, similar to energy supply contracting, the contractor plans, builds and finances the energy system, but leaves it entirely to the tenant to operate it. The customer pays the contractor a fixed rental or leasing rate. Examples for this business model are plant leasing, heating system renewal or street light contracting. (Energieagentur Rheinland-Pfalz GmbH, 2016)

In **management contracting**, the contractor promises to save energy through the management of a plant that often already exists. This can be realised by more advantageous supplier conditions, an optimised operation of a power plant, better maintenance or the use of synergies (e.g. using waste heat). The economic and legal ownership of the plant remains with the customer. (Energieagentur Rheinland-Pfalz GmbH, 2016)

2.1.2 Energy contracting parties

The following gives an overview of the possible parties involved in contracting business cases found in the examined literature for Austria and Germany (Energie-Experten, 2021; Energieagentur Rheinland-Pfalz GmbH, 2016; Flieger, 2018).

On the contractor's side

- Building sector:
  - House owner
  - Housing company, property developers and private investors
  - Housing association
  - Property manager
- Energy sector:
  - Energy supply companies (especially green energy suppliers)
  - Energy cooperatives/municipal utilities
  - Plumbing and electrician companies (third party companies)

On the client's side

  - Housing company
  - Housing association members
  - Tenants
  - Private owners
  - Public institutions (e.g. schools, hospitals)
  - Private institutions (e.g. offices, retirement homes)
  - Municipalities
  - Private businesses (e.g. agriculture)

2.1.3 Possible profits and risks in energy contracting models

As previously stated, contracting is in the best case a win-win situation for all parties involved. Ideally, the building owner experiences an increase in the value of the property, the contractor successfully refinances the initial investment and the tenants have lower energy costs than before. However, the following possible disadvantages could be faced by the parties.

Risks and disadvantages of contracting models for the clients are tied to the dependency on the contractor. For instance, if the contracting is done by an energy supply company, the client must purchase the remaining grid electricity from the same energy supply company (e.g. see conditions of contracting PV at Verbund (VERBUND AG, 2021a)). Economic risks are given in cases with a fix rent payed to the contractor since the rent could be increased over the years. At the same time variable contractor tariffs are might be disadvantageous since the future self-consumption is unknown. Lastly, the two separate electricity bills (PV electricity and grid electricity) in some models can be seen as an additional bureaucratic effort for the client. (PV Austria, 2021)

Besides financial risks due to the initial investment, the main risks for the contractor lie in the economic uncertainty due to the actual participation of the tenants (e.g. termination of the leasing agreement or opt-out by tenants, actual self-consumption share changes). In addition, the contractor faces uncertainties concerning changing energy prices (e.g. when buying electricity in order to operate a HP). Potentially disadvantageous for the building owner is the limited possibility to use the roof for other purposes if e.g. PV contracting is carried out.

2.1.4 Existing contracting business cases in Austria

The above mentioned parties can have different concepts of business models agreed on between another. In Austria, four different concepts are common for PV electricity sharing according to PV Austria (2021).

- PV plant as infrastructure of the building
  The building owner invests in a PV plant and provides free of charge electricity to the tenants during the time when demand andPV production matches. Revenues by feed-ins go to the building owner. (PV-Gemeinschaft.at Informationsplattform, 2018b)
- Installation and operation by housing association
  Housing association members (German: Bewohner-Verein) invest in technologies such as PV and the produced electricity is shared between the association members. Not everyone living within the building needs to be member of the association. Revenues by feed-ins go to the association itself. (PV-Gemeinschaft.at Information-splattform, 2018c)
- Company installs and leases facility or sells electricity to residents
  An external party or contractor owns and runs the PV plant and sells the electricity, which has to be cheaper than from the energy supply company, or takes a fixed rent from the tenants (independent of the electricity used). (PV-Gemeinschaft.at Informationsplattform, 2018d)
- Energy supplier installs and operates PV plant
  The energy supply company owns and runs the PV plant, sells electricity for fixed price [€/kWh] to tenants (should be lower than the price of the electricity purchased from the grid). (PV-Gemeinschaft.at Informationsplattform, 2018a)

2.2 Current research on two relevant energy contracting models

The following section provides an overview on the current research conducted in the field of contracting sustainable infrastructure for buildings such as efficiency measures, PV, ST and HP.

Comprehensive definitions of various contracting models as well as an introduction on financing of contracting projects are provided in the work of Haas et al. (2021).

2.2.1 Energy performance contracting (EPC)

An overview regarding status, barriers, driving factors, best practices as well as impact of EU support of EPC in the European Union within the Public Sector is given by Moles-Grueso et al. (2021). Martiniello et al. (2020) examines how public infrastructure can be built by public-private-partnerships through a successful contractual arrangement based on EPC. One barrier to EPC is that it involves several parties to complete a transaction: an energy services company, the client and the financing institution. Aoun (2020) states the opportunities of Blockchain and smart contracts to provide a trading platform that enables the execution and enforcement of agreements.

The results of the work by Lu et al. (2017) show the effects of rebound effects due to higher energy consumption by tenants after refurbishment, which causes up to a 4-year difference of acceptable EPC contract length (17-year contract with 15% rebound effect, 13-year contract without rebound). In order to mitigate and eliminate tenants' rebound effect, a shared incentive strategy between owners and renters is proposed. The work by Zhou et al. (2020) emphasises on the necessary interplay between policies and business innovations for China's EPC market development. Further investigations about China's EPC market in conducted in Shang, Zhang, et al. (2017) and Shang, Yang, et al. (2020), the latter shows how trading carbon emissions can finance EPC projects.

2.2.2 Energy supply contracting (ESC)

The work of Monsberger et al. (2021) examines the profitability for energy contractors in a variety of business cases that simultaneously ensure energy cost savings for the residents (taking into account PV, a HP and a gas-fired mini combined heat and power unit). The results show that contracting within energy communities is highly profitable for both, the contractor and the resident. A combination of EPC and ESC is shown in the scientific work by Fina et al. (2020), which investigates profitability of implementing active and passive building retrofitting measures by using a linear optimisation model. The three use cases of firstly PV contracting, secondly renovation contracting, and thirdly PV plus renovation contracting including a heating system change are examined.

The literature research on ST contracting in residential buildings shows a research gap for further research in this fields, since most of the studies are performed on large-scale systems. Tschopp et al. (2020) provides an overview of the market and common technological solutions for large-scale solar thermal systems in various countries. The analysis shows the profitability of ST in combination with DH in Denmark. Furthermore, the concept of Solar Contracting in Austria is mentioned here. The work states the Austrian company S.O.L.I.D. to be the main driver behind solar contracting, which realized four large-scale ST plants feeding into the DH network of Graz. Selke et al. (2017) shows that contracting is particularly interesting for solar cooling, as large systems (>2.000 m^2 collector area) are appropriate in order to achieve the best possible economic efficiency due to economies of scale.

Calame-Darbellay et al. (2019) shows how retrofitting projects with air-to-water heat pumps perform compared to gas by providing a financial comparison of heating costs depending on building size and heat production technology. In this work, energy contracting has proven to be an efficient tool to enable the realisation of projects in multifamily buildings.

2.3 Own contribution

While the literature presented above focuses mostly on energy contracting of one specific technology (e.g. only PV), this work analyses a broader energy technology portfolio. In particular, the thesis includes energy performance contracting (EPC) in terms of retrofitting measures as well as energy supply contracting (ESC) of various energy technologies, namely PV, ST, HP, EVSE and batteries for electricity storage.

An additional contribution of this thesis is that the same contracting model is applied to three different building set-ups. On the contrary, previous work has examined how different contracting models can be applied to one single building.

This thesis optimises the minimal costs for the tenants and does not focus on the contractor's maximum profit. Therefore, the results of this work shall help socially motivated building owners or (public) energy contractors to ease investment decisions on the best sustainable infrastructure set-up in urban residential buildings.

3 Materials and methods

This chapter explains the developed methodology. First, section 3.1 shows the nomenclature used in the mathematical description of the model. Then, section 3.2 provides an overview of the model's functionalities. Building upon, section 3.2 presents the mathematical formulation of the model in detail. Section 3.4 describes the input data and section 3.5 the examined use cases.

3.1 Nomenclature

Indices

t	time step (one hour)
d	day (24 hours)
φ	financing options (contractor or self-financed)
τ	technology (default or newly installed)
ι	building efficiency measure (e.g. insulation)

Sets

N	total time steps
D	days
Ω_{new}	set of newly installed technologies
Ω_{def}	set of default technologies (heating system and electricity)
Ω_{all}	set of all technologies
Ω_{ins}	set of building efficiency measures
Φ	set of financing options

Parameters

<u>Cost and revenue parameters</u>

w	weight scales costs from length of N to a full year
α	annuity factor
i	interest rate
n	depreciation time

c_{inv}	specific investment costs per capacity or unit €$/kW$, €$/kWh$, €$/m^2$, €$/pc$
$c_{service}$	annual service and maintenance costs, €$/a$
p_{con}	annual price for specific capacity, €$/kW/a$
p_{def}	price for default energy (electricity and heat), €$/kWh$
p_{new}	price for new energy (electricity and heat), €$/kWh$
p_{shift}	bonus for shifted capacity, €$/kW$

Demand parameter

l_{th}	thermal load, kW/t
l_{el}	electric load, kW/t

Energy system parameter

i_{car}	number of EVs
i_{res}	number of residents
P_{irr}	solar irradiation, kW/m^2
A	area, m^2
PR	performance ratio PV
f_{surf}	surface factor PV
$f_{PV,temp}$	temperature factor PV panel, $-\%/°C$
$\rho_{cap,PV}$	capacity density of PV, kWp/m^2
f_{COP}	reduction factor compared to carnot COP
T_{out}	outside temperature, $°C$
T_{heat}	inside heating temperature, $°C$
T_{STC}	temperature at STC conditions, $25°C$
η_{ST}	efficiency of ST panel
η_{bat}	efficiency of stationary battery
η_{gas}	efficiency of gas boiler
$\hat{P}_{EVSE}$	maximum charging capacity charging station, kW
SOC	state of charge, kWh

Decision variables

Cost and revenue variables

C_{total}	total costs, €
C_{fix}	total annual fixed costs, €
C_{var}	summed variable costs over one year, €
C_{inv}	total investment costs, €
$C_{service}$	total service and maintenance costs, €
C_{con}	total connection costs, €
C_{Contr}	annual costs of contractor, €

R	revenue, €
R_{Contr}	annual revenue for contractor, €
CR	annual contractor rate, €
	Binary variables
BDV	binary decision variable
	Energy system variables
i_{EVSE}	number of charging stations, pc
P	current supply at a time step, kW/t
$\hat{P}$	installed peak or connection capacity, kW/t
P_{shift}	shifted capacity, kW
C	capacity battery, kWh
f_{PV}	produced power per installed PV capacity , kW/kWp
COP	coefficient of performance

3.2 Introduction into the model

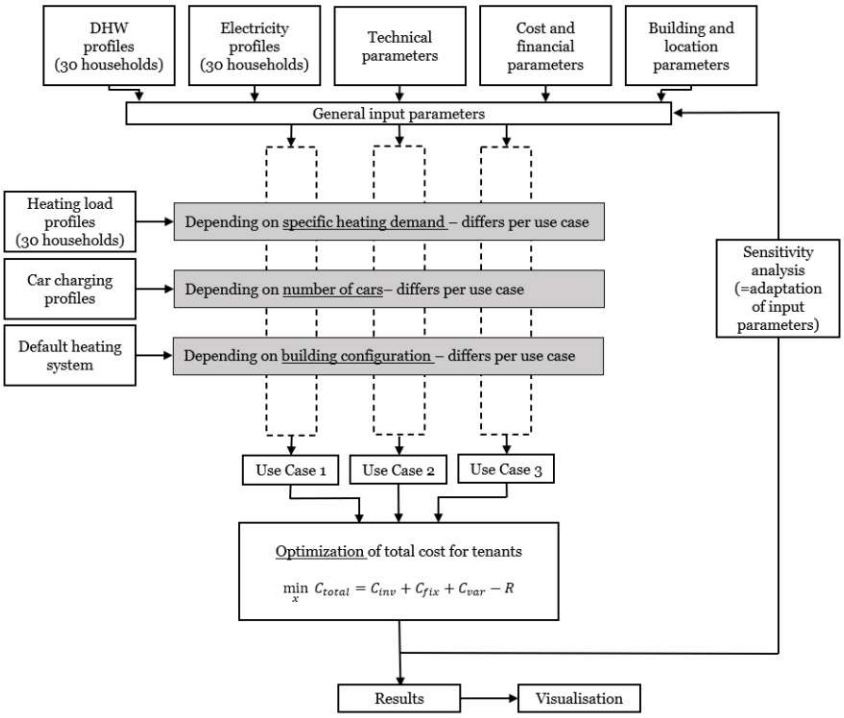
The core objective of the proposed optimisation model is to determine the optimised energy technology investments for three different houses (three use cases) in order to minimize the tenants yearly energy costs.

3.2.1 Flowchart

The flowchart of the optimisation model is shown in Figure 3.1 below. Accordingly, the procedure of this work can be divided into the following steps:

- Import of the input parameters that are the same for all use cases: DHW and electricity profiles, economical and technical parameters of the possible investment options as well as the location specific parameters
- Determination of the present energy system (including load profiles for EV charging and heating profiles for space heating) characterised by the specific use case
- Optimisation of the local energy system in terms of a cost-effective energy supply (using the python-based, open-source optimisation modeling language Pyomo (Bynum et al., 2021))
- Adaptation of input parameters for sensitivity analyses

- Visualisation of results (using the python-based, open-source plotting package Pyam (Huppmann et al., 2021))



Source: own work

Figure 3.1: Flowchart optimisation model

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3.2.2 Energy technologies

Default systems

The model includes two default heating systems, gas-based heating system and district heating (DH). The default heating system has to be chosen a priori, but can be replaced by an alternative heating system by the optimal energy supply decision. Furthermore, the electricity connection is assumed as a default system as well and cannot be replaced.

Possible new investments

The model has the options to undertake investments in the following technologies:

- roof top photovoltaic plant (PV) system, south facing, 45°tilted,
- roof top solar thermal plant (ST) system, south facing, 45°tilted,
- air-to-water heat pump (HP) system,
- thermal refurbishment of the building (possible insulation and efficiency measures are described in table 3.4),
- stationary electrical storage (battery), which can only supply the EVs,
- and electric vehicle supply equipment (EVSE). Electric vehicle supply equipments (EVSEs) are the only investments that have to be made in order to cater the charging demand of the EVs (they are necessary and therefore non-optional investments).

3.3 Mathematical formulation

3.3.1 Objective Function

The following linear optimisation model minimises the annual total costs for the tenants (C_{total}). The symbol x is used as decision variable vector and encompasses all decision variables of the model.

Equation 3.1 shows the objective function, where C_{inv} are the annualised total investment costs, C_{fix} the total annual fixed costs and C_{var} the summed variable costs over one year. The total costs (C_{total}) are diminished by the revenue (R) gained from feed-ins.

$$\min_{x} \; C_{total} = C_{inv} + C_{fix} + C_{var} - R \qquad (3.1)$$

Decision variable vector

The decision variable vector x is defined as followed,

$$x^T = (P_{t,\tau,\varphi}, \hat{P}_{\tau,\varphi}, P_{t,Shift}, BDV_{\iota,\varphi}, BDV_{ST+DH}, CR_{\tau}) \qquad (3.2)$$

where $P_{\mathrm{t},\tau,\varphi}$ is the amount of supply at each time step t per technology per financing option, $\hat{P}_{\tau,\varphi}$ the installed capacity per technology per financing option, $P_{\mathrm{t,Shift}}$ the shifted charging demand capacity, $BDV_{\iota,\varphi}$ the binary decision variable for efficiency measures, BDV_{ST+DH} the binary decision variable for the possibility to feed ST into DH and CR the fixed annual rate charged by the contractor to make the investment profitable for the contractor.

Cost functions for tenants

The total investment costs (C_{inv}) are annualised using the annuity factor (α),

$$\alpha = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{3.3}$$

multiplied by the installed capacity[1] ($\hat{P}$) and the specific investment costs (c_{inv}) for each technology (τ) and financing option (φ) chosen. The investment costs for the building efficiency measures ($c_{inv,\iota}$) are lump-sum costs that only apply if they are carried out (i.e. BDV_ι turns TRUE). Same principle applies for the investment costs ($c_{inv,\mathrm{ST2DH}}$) of the solar thermal plant (ST) to district heating (DH) infrastructure, which only apply if both ST and DH exist. The total investment costs (C_{inv}) include all installation costs.

$$\begin{aligned} C_{inv} = & \sum_{\tau\in\Omega_{new}} \sum_{\varphi\in\Phi} \alpha_\tau \cdot c_{inv,\tau,\varphi} \cdot \hat{P}_{\tau,\varphi} + \\ & \sum_{\tau\in\Omega_{ins}} \sum_{\varphi\in\Phi} BDV_{\iota,\varphi} \cdot c_{inv,\iota,\varphi} + \\ & BDV_{ST+DH} \cdot c_{inv,ST2DH} \end{aligned} \tag{3.4}$$

The total annual fixed costs (C_{fix}) encompass the annual total service and maintenance costs ($C_{service}$) (lump-sum costs, independent of installed capacity) as well as the annual total connection costs (C_{con}) (paid per unit of installed capacity).

$$C_{fix} = C_{service} + C_{con} \tag{3.5}$$

[1] The term capacity differs for each technology, e.g. in case of the solar thermal plant one unit equals one m^2.

The total service and maintenance costs ($C_{service}$) are annual lump-sum costs that consist of the annual service and maintenance costs ($c_{service}$) of the chosen technologies and the CR in case of investment by the contractor.

$$C_{service} = \sum_{\tau \in \Omega_{all}} \sum_{\varphi \in \Phi} BDV_{\tau,\varphi} \cdot c_{service,\tau,\varphi} + BDV_{\tau,\varphi} \cdot CR_{,\tau} \tag{3.6}$$

The total connection costs (C_{con}) are the sum of the annual price for specific capacity (p_{con}) times the installed capacity. For the default technologies (electricity and default heating system) the connection capacity (maximum demand load) is used.

$$C_{con} = \sum_{\tau \in \Omega_{all}} \sum_{\varphi \in \Phi} \hat{P}_{\tau,\varphi} \cdot p_{con,t,\tau,\varphi} \tag{3.7}$$

The summed variable costs over one year (C_{var}) depend on the chosen business model of the contractor. The factor *weight*

$$w = \frac{8760}{\sum_{t=1}^{N}} \tag{3.8}$$

scales the variable costs from length of the simulation (N) to a full year. The variable costs sum the price per kWh used of the perspective technology. It is assumed that only default technologies (electricity and heating systems) need to be paid in case of exclusively self-financed investments. In case of investments financed by the contractor additional prices occur for different energy flows depending on the contractor's pricing model.

$$\begin{aligned} C_{var} = w \cdot \{ \sum_{t=1}^{N} \sum_{\tau \in \Omega_{def}} P_{\tau} \cdot p_{def} + \\ \sum_{t=1}^{N} \sum_{\tau \in \Omega_{new}} P_{t,\tau} \cdot p_{new,\tau,contractor} \} \end{aligned} \tag{3.9}$$

Revenues (Rs) can be achieved through electric and thermal feed-ins as well as bonus payments for shifted car charging capacities (applied in use case 3, see section 3.5.3).

$$R = P_{shift,total} \cdot p_{shift} + \sum_{t=1}^{N} \sum_{\varphi \in \Phi} P_{t,PV2Grid,\varphi} \cdot p_{new,el,\varphi,feedin} + \sum_{t=1}^{N} \sum_{\varphi \in \Phi} P_{t,ST2DH,\varphi} \cdot p_{new,th,\varphi,feedin} \quad (3.10)$$

Cost functions for contractor

Similar to the tenants the total costs for the contractor consist of investment costs, the variable costs as well as the annual fix costs for any new investments diminished by the revenues.

$$C_{Contr} = C_{inv,Contractor} + C_{var,Contractor} + C_{fix,Contractor} - R_{,Contractor} \quad (3.11)$$

The variable costs for the contractor are the bonus payments for shifted car charging capacities (applied in use case 3, see section 3.5.3).

$$C_{var,Contractor} = P_{shift,total} \cdot p_{shift} \quad (3.12)$$

Revenues for the contractor consist of an fixed annual amount (annual contractor rate (CR)), variable costs payed by tenants depending on the installed technology (e.g. in case of PV costs per kWh produced by the PV plant used in households or cars) and feed-ins to the grid. The CR can also be negative in case the variable revenues are higher than necessary for providing an economically viable offer but minimising the tenant's cost at the same time.

$$R_{Contr} = CR + \sum_{\tau \in \Omega_{new}} P_{t,\tau} \cdot p_{new,\tau,contractor} \quad (3.13)$$

3.3.2 Constraints

Contractor guaranteed profit constraint

In order to asure the profibility of the investment by a contractor, the CR is chosen as high as necessary so that the contractor's net present value (NPV) is greater than zero.

$$NPV_{Contractor,\tau} = -C_{inv,Contractor} + \frac{\sum_{Y=1}^{20}(R_{Contractor} - C_{Contr})}{(1+i)^Y}$$
$$NPV_{Contractor,\tau} \geq 0 \tag{3.14}$$

For some sensitivity analyses the NPV is chosen to be at least 20% or 40% of the initial investment cost, forcing a return of investment (RoI) of 20% or 40% (see Chapter 5).

General supply and capacity constraints

The BDV becomes TRUE if the respective technology is selected. The integer M represents a large enough constant or the maximum possible capacity ($\hat{P}_{\max}$). This ensures that the chosen technology can only supply if the corresponding capacity is installed.

$$P_{t,\tau,\varphi} \leq BDV_{\tau,\varphi} \cdot M \tag{3.15}$$

At the same time the installed capacity has to be greater than the maximum supply at any time.

$$\hat{P}_{\tau,\varphi} \geq P_{t,\tau,\varphi} \tag{3.16}$$

Additionally, the non-negativity and maximum capacity constraints for all power terms have to be fulfilled.

Demand

Electricity Demand

At every time step the electricity demand curve of the multi-party house,

$$l_{el,t,house} = P_{t,grid2house} + \sum_{\varphi \in \Phi} P_{t,PV2House,\varphi} \tag{3.17}$$

as well as the EV (potentially shifted) charging curve needs to be met. It is assumed that the EVs can only be charged at home.

$$P_{t,el2car} = l_{el,t,car,shifted} \tag{3.18}$$

The shifted charging curve represents the originally imported charging curve lowered or raised by the shifts as a result of the demand side management (DSM).

$$l_{el,t,car,shifted} = l_{el,t,car} + P_{shift,t,up} - P_{shift,t,down} \tag{3.19}$$

Thermal Demand

The total thermal demand curve of the multi-party house needs to be met by the following options.

$$l_{th,t} = P_{t,gas} \cdot \eta_{gas} + P_{t,DH} + \sum_{\varphi \in \Phi} (P_{t,HP,\varphi} + P_{t,ST,\varphi}) \tag{3.20}$$

The total thermal demand consists of the domestic hot water (DHW) and the (potentially reduced) heating demand,

$$l_{th,t} = l_{th,t,DHW} + l_{th,t,reduced} \tag{3.21}$$

where the reduced heating demand represents the original heating curve lowered by the reduction due to efficiency measures.

$$l_{th,t,reduced} = l_{th,t,heating} - l_{th,t,reduction} \tag{3.22}$$

Electric vehicle (EV) and electric vehicle supply equipment (EVSE)

The total energy to the EV equals the supply from other various technologies. However, the EV can not feed back to any technologies.

$$P_{t,el2car} = \sum_{\varphi \in \Phi} P_{t,PV2car,\varphi} + P_{t,grid2car,\varphi} + P_{t,battery2car,\varphi} \tag{3.23}$$

The charging station capacity needs to be greater than the maximum charging supply at every time step.

$$\sum_{\varphi \in \Phi} i_{EVSE,\varphi} \cdot \hat{P}_{EVSE} \geq P_{t,el2car} \tag{3.24}$$

The total number of charging stations (i_{EVSE}) for all financing options needs to cover demand for charging stations given by the number of EVs (i_{car}). Future extensions of the model could include a simultaneity factor for the charging behaviour and thereby lower the required number of charging stations (see in this regard Netze BW GmbH (2019)).

$$i_{car} = \sum_{\varphi \in \Phi} i_{EVSE,\varphi} \tag{3.25}$$

The powerflow out of the battery into the car cannot extend the maximum possible battery powerflow.

$$0 \leq \sum_{\varphi \in \Phi} P_{t,el2car,\varphi} \leq \hat{P}_{max,car,out} \cdot i_{car} \tag{3.26}$$

As the EV is unable to feed back to the grid, there is no need for SOC constraints for the EV battery.

Stationary battery

In case of the stationary battery the maximum powerflow $\hat{P}_{\text{max,battery}}$ (in kW) and the capacity C_{battery} (in kWh) are the capacity variables used for the per unit payments.

$$\begin{aligned}\hat{P}_{Bat} &== \hat{P}_{max,battery}\\ \hat{P}_{BatCap} &== C_{battery}\end{aligned} \tag{3.27}$$

The stationary battery can exclusively feed into the EV.

$$P_{t,battery} = \sum_{\varphi\in\Phi} P_{t,battery2car,\varphi} \tag{3.28}$$

Total energy to the battery equals the supply from other various technologies.

$$P_{t,el2battery} = \sum_{\varphi\in\Phi} P_{t,PV2battery,\varphi} + P_{t,grid2battery,\varphi} \tag{3.29}$$

The relation between energy flows in and out of the stationary battery is given by the efficiency of battery.

$$P_{t,battery} \leq \eta_{bat} \cdot P_{t,el2battery} \tag{3.30}$$

The powerflow out of the battery,

$$0 \leq P_{t,battery} \leq \hat{P}_{max,battery,out} \tag{3.31}$$

as well as into the battery cannot extend the maximum possible battery powerflow.

$$0 \leq P_{t,el2battery} \leq \hat{P}_{max,battery,in} \tag{3.32}$$

SOC at every time step is limited by capacity of battery.

$$0 \leq SOC_{battery,t} \leq C_{battery} \tag{3.33}$$

The state of charge (SOC) of the battery is defined by energy flows in and out.

$$SOC_{battery,t} = SOC_{battery,t-1} + \sum_{\varphi\in\Phi} (P_{t,el2battery,\varphi} \cdot \eta_{bat} - \frac{P_{t,battery,\varphi}}{\eta_{bat}}) \tag{3.34}$$

At the beginning of the simulation the SOC of the battery is zero.

$$SOC_{battery,t=0} = 0 \tag{3.35}$$

The stationary battery is only financed by one party (either self-financed or financed by a contractor).

$$\sum_{\varphi \in \Phi} BDV_{battery,\varphi} \leq 1 \tag{3.36}$$

Photovoltaics (PV)

The produced electricity from PV equals the installed capacity lowered by capacity $f_{PV,\mathrm{t}}$ and temperature $f_{PV,temp,\mathrm{t}}$ factor.

$$P_{PV,t} = \hat{P}_{PV} \cdot f_{PV\,t} - (\hat{P} \cdot f_{PV,t}) \cdot f_{PV,tempt} \tag{3.37}$$

$$f_{PV,t} = \frac{P_{irr,t} \cdot f_{surf,t} \cdot PR_t}{P_{irr,STC}} \tag{3.38}$$

$$f_{PV,temp,t} = (T_{out} - T_{STC}) \cdot f_{PV,temp} \tag{3.39}$$

The PV plant supplies to various other technologies.

$$\begin{aligned} P_{t,PV} = \sum_{\varphi \in \Phi} & P_{t,PV2car,\varphi} + P_{t,PV2Grid,\varphi} + P_{t,PV2battery,\varphi} + \\ & P_{t,PV2House,\varphi} + P_{t,PV2HP,\varphi} + P_{t,PV,Curtailment,\varphi} \end{aligned} \tag{3.40}$$

The PV capacity is limited by maximum capacity given by the area of the roof and the capacity density $\rho_{cap,PV}$ of PV panel (in kWp/m^2). In case of a contractor-financed plant there may be a minimum capacity defined by the contractor.

$$0 \leq \hat{P}_{PV} \leq \hat{P}_{PV,max} \tag{3.41}$$

$$\hat{P}_{PV,max} = A_{roof} \cdot \rho_{cap,PV} \tag{3.42}$$

The area needed for the PV plant is defined by the installed capacity devided by the capacity density $\rho_{cap,PV}$.

$$A_{PV,total} = \frac{\sum_{\varphi \in \Phi} \hat{P}_{PV,\varphi}}{\rho_{cap,PV}} \tag{3.43}$$

The total roof area is shared by PV and ST.

$$A_{roof} = A_{PV,total} + A_{ST,total} \tag{3.44}$$

Solar thermal (ST)

In case of ST the area of the thermal panels (in m^2) equals the capacity variable used for the per unit payments.

$$\hat{P}_{ST} == A_{ST,total} \tag{3.45}$$

Produced energy from ST equals installed area times solar irradiation lowered by the efficiency of the panels.

$$P_{ST,t} = \hat{P}_{ST} \cdot P_{irr,t} \cdot \eta_{ST} \tag{3.46}$$

The ST plant supplies hot water to the households (DHW and heating) and can potentially feed into the DH system.

$$P_{t,ST} = \sum_{\varphi \in \Phi} P_{t,ST2DH,\varphi} + P_{t,ST2House,\varphi} \tag{3.47}$$

The ST capacity (area) is limited by the maximum capacity. In case of a contractor-financed plant there may be a minimum capacity defined by the contractor.

$$0 \leq \hat{P}_{ST} \leq \hat{P}_{ST,max} \tag{3.48}$$

The maximum capacity of ST depends on DH being installed. If ST can feed all surplus into DH, the maximum capacity ST is only limited by the area of the roof, otherwise ST is limited by the DHW demand per resident (area ST per resident, $A_{\mathrm{ST,p.p.}}$).

$$\hat{P}_{ST,max} = (1 - BDV_{DH}) \cdot i_{res} \cdot A_{ST,p.p.} \cdot f_{simultaneity} + BDV_{DH} \cdot A_{roof} \tag{3.49}$$

Solar thermal (ST) to district heating (DH)

Binary variable turns TRUE if ST and DH are installed.

$$BDV_{DH\&ST} \cdot M \geq (BDV_{ST} + BDV_{DH}) - 1 \tag{3.50}$$

In analogy to the other technologies, there is only supply from ST to DH if both are installed.

$$P_{t,ST2DH,\varphi} \leq BDV_{DH\&ST} \cdot M \tag{3.51}$$

Insulation and building efficiency measures

The reduction of the heating demand depends on the insulation option chosen.

$$\begin{aligned} l_{th,t,reduction} = l_{th,t,heating} \cdot (&\sum_{\varphi \in \Phi} 0.25 \cdot BDV_{25\%,\varphi} + \\ &\sum_{\varphi \in \Phi} 0.5 \cdot BDV_{50\%,\varphi} + \\ &\sum_{\varphi \in \Phi} 0.75 \cdot BDV_{75\%,\varphi}) \end{aligned} \tag{3.52}$$

The efficiency measures are only financed by one party (either self-financed or financed by a contractor).

$$\sum_{\tau \in \Omega_{ins}} \sum_{\varphi \in \Phi} BDV_{\iota,\varphi} \leq 1 \tag{3.53}$$

Heating systems

Only one heating system (HP, DH or gas) can be installed.

$$\sum_{\varphi \in \Phi} BDV_{HP,\varphi} + BDV_{DH} + BDV_{gas} \leq 1 \tag{3.54}$$

Default heating systems

Connection capacities are the maximal values of the thermal load, more precisely domestic hot water (DHW) and heating (before isolation).

$$\begin{aligned} \hat{P}_{gas,con} &= max(l_{th}) \\ \hat{P}_{DH,con} &= max(l_{th}) \end{aligned} \tag{3.55}$$

Heat pump (HP)

The thermal energy produced HP can exclusively feed into the household's heating system (no option to feed into DH available).

$$P_{t,HP} = \sum_{\varphi \in \Phi} P_{t,HP2House,\varphi} \tag{3.56}$$

Total energy to the HP equals the supply from other various technologies.

$$P_{t,el2HP} = \sum_{\varphi \in \Phi} (P_{t,PV2HP,\varphi} + P_{t,grid2HP,\varphi}) \tag{3.57}$$

The relation between electric energy flows into and thermal energy flows out of the HP is given by COP.

$$P_{t,HP} = \text{COP} \cdot P_{t,el2HP} \tag{3.58}$$

The COP is given by the $\mathrm{COP}_{\mathrm{carnot}}$, which depends on outside temperature (T_{out}), lowered by a factor.

$$\mathrm{COP} = \mathrm{COP}_{carnot} \cdot f_{COP} \tag{3.59}$$

$$\mathrm{COP}_{carnot} = \frac{T_{out}}{T_{heat} - T_{out}} \tag{3.60}$$

The HP is only financed by one party (either self-financed or financed by a contractor).

$$\sum_{\varphi \in \Phi} BDV_{HP,\varphi} \leq 1 \tag{3.61}$$

Electric grid

The electric grid feeds into the households as well as the cars, the battery and the HPs.

$$P_{t,Grid} = P_{t,Grid2House} + P_{t,Grid2car} + P_{t,Grid2battery} + P_{t,Grid2HP} \tag{3.62}$$

Connection capacity of the electric grid is the maximal value of the electric load, more precisely car charging and household electricity. If a HP is installed, the connection capacity stays the same even if this value should be increased in practice.

$$\hat{P}_{el,con} = max(l_{el}) \tag{3.63}$$

Demand side management (DSM)

Up and down shifts within the first time step are zero as the SOC of car equals zero.

$$P_{shiftup,t=0} = 0 \tag{3.64}$$
$$P_{shiftdown,t=0} = 0 \tag{3.65}$$

The up and down shifts are summed up over 24 hours to create shifts per day,

$$\sum_{t=1}^{24} P_{shift,t} = P_{shift,d} \tag{3.66}$$

which have to sum up to be the same within a day.

$$P_{shift,down,d} == P_{shift,up,d} \tag{3.67}$$

The yearly amount of shifts sums up to the total annual shifts, which are rewarded.

$$P_{shift,total} = \sum_{d=1}^{D} P_{shift,d} \tag{3.68}$$

The binary decision variable (BDV) becomes TRUE if shift is done,

$$P_{shift,down,t} \leq BDV_{Shift,down} \cdot M \tag{3.69}$$
$$P_{shift,up,t} \leq BDV_{Shift,up} \cdot M \tag{3.70}$$

which makes it possible to permit either an up or down shift exclusively within one time step.

$$BDV_{Shift,down} + BDV_{Shift,up} \leq 1 \tag{3.71}$$

3.4 Input parameters

The following section presents the technical and economical input parameters for the optimisation model.

3.4.1 Location and building

All use cases (see section 3.5) are based on the same building type in or nearby Vienna, Austria.

- Outside temperature and solar irradiation are taken from Stefan and Iain (2019) for the location of Vienna from the year 2019.

- The examined buildings have six floors (not including the roof storey, which is empty), on every floor there are five flats with 100 m^2 each. This sums up to 30 households with a total floor area of 3000 m^2.
- The specific heating demand of each building differs depending on the use case (see section 3.5).
- The dimensions of the buildings are 40 m*12.5 m, with either a flat roof or a 45° tilted, south-north orientated roof.
  - Buildings with a flat roof have a roof area of about 500 m^2. Assuming that 70% of the roof can be used (area diminished by chimneys etc.), 350 m^2 remain for PV and ST.
  - Buildings with a tilted roof have a south oriented roof area of about 350 m^2, which results in 245 m^2 for PV and ST.
- All buildings are connected to the electric grid and are either supplied by the DH or the gas grid.

3.4.2 Energy demands

The thermal and electricity demand data of the households are derived from load profiles generated by the *LoadProfileGenerator* provided by Pflugradt (2020). The load profiles are generated for three different types of households, whereby groups of ten households are assigned to the same type (this sums up to 30 households).

- Family with three children, both parents at work. 5 km commuting distance.
- Single with work. 15 km commuting distance.
- Retired Couple. 25 km commuting distance.

Thermal demand

The generated load profiles by Pflugradt (2020) provide a profile for domestic hot water (DHW) in liter, which therefore needs to be converted into kW h (equals kW in one hour time step) using,

$$Q = m \cdot c_p \cdot \Delta T \tag{3.72}$$

where ΔT is assumed to be 50 K (from 10°C to 60°C).

It is assumed that above 15°C outside temperature there is no heating demand.

Electricity demand

Additionally to the generated household electricity demand curves, the charging demand of the EVs is added. The base charging demand curve is calculated for three EVs tailored to the traveling purposes of each of the above stated three households. For the use cases two and three (see section 3.5), the base charging curve is scaled up to the required number of cars. It is assumed that the cars are only charged at home and with a power of 22 kW.

3.4.3 Costs

Costs for default system

The following table shows the used cost data for the default electricity and heating system provided by the grid.

Default system	serv-cost [€/a]	con-cost [€/kW/a]	fuel-price [€/kWh]	feedin-price [€/kWh]
Electricity	43.08[a]	33.00[b]	0.2130[a]	0.050[c]
District Heating	50.00[d]	39.09[e]	0.0575[e]	0.030[f]
Gas	43.08[g]	-	0.0589[g]	-

Table 3.1: Investment, connection and service costs, fuel prices as well as feed-in prices for the default systems

[a]Data obtained from (VERBUND AG, 2021b)
[b]Data obtained from (Wiener Netze, 2021)
[c]Data obtained from (VERBUND AG, 2021a)
[d]Data based on estimation
[e]Data obtained from (Kammer für Arbeiter und Angestellte für Wien, 2021)
[f]Data obtained from (Bucar et al., 2006)
[g]Data obtained from (VERBUND AG, 2021c)

Costs for direct investment

Table 3.2 below provides the cost data that occur in case the tenants or the building owners decide to undertake new investments without a contractor involved.

Investments (no contractor)	inv-costs [€/kW]	serv-cost [€/a]	con-cost [€/kW/a]
Photovoltaics	950[a]	20[b]	9.5[c]
Solarthermal	1,800[d]	20[b]	18[c]
Heat pump	1,100[a]	20[b]	22[e]
Battery Capacity	1,100[f]	-	0.5[g]
Charging Station	1,400[h]	20[i]	-

Table 3.2: Investment, connection and service costs of newly installed technologies as well as fuel prices without contractor

[a] Data obtained by (Fleischhacker et al., 2019) lowered by estimated learning effects
[b] Data based on estimation
[c] Estimated with 1% of c_{inv}
[d] here: €/m², data obtained by (Fleischhacker et al., 2019)
[e] Estimated with 2% of c_{inv}
[f] here: €/kWh, data obtained by (Fleischhacker et al., 2019)
[g] here: €/kWh/a, data obtained by (Fleischhacker et al., 2019)
[h] here: €/psc , data obtained by (ENERGIE AG, 2021)
[i] here: €/psc /a, data based on estimation

Costs for contractors

The following table provides cost parameters from the contractor's point of view. It is estimated that the service costs for a contractor are lower than for tenants or building owners. This is mainly due to the fact that contractors usually maintain more than one plant and can therefore operate them more cost efficiently than a private person could.

The fuel costs shown are not costs incurred by the contractor, but in fact costs that the client has to pay to the contractor. It is assumed that the contractor charges a certain percentage of the client's savings to the client. E.g.: The client consumes electricity from the PV plant and therefore saves the amount of money he/she would have paid when buying electricity from the grid, precisely 0.2130 €/kWh (see table 3.1). The contractor then charges 80% of these savings for every kW h consumed from the PV plant. Therefore, the customer effectively saves 20% compared to the electricity price from the grid.

The effect of lower investment costs from a contractor's point of view as a result of economy of scale are investigated in the sensitivity analysis in Chapter 4.

New Investments (with contractor)	inv-costs [€/kW]	serv-cost [€/a]	con-cost [€/kW/a]	fuel-price [€/kWh]
Photovoltaics	950[a]	10[b]	9.5[c]	$0.8 \cdot 0.2130$
Solarthermal	1,800[d]	10[b]	18[c]	$0.8 \cdot 0.0575$
Heat pump	1,100[a]	10[b]	11[c]	$0.8 \cdot 0.0589$
Battery Capacity	1,100[e]	-	0.5[f]	$0.1 \cdot 0.2130$
Charging Station	1,400[g]	10[h]	-	$0.1 \cdot 0.2130$

Table 3.3: Investment, connection and service costs of newly installed technologies as well as feed-in prices if investment is financed by contractor

[a]Data obtained by (Fleischhacker et al., 2019) lowered by estimated learning effects
[b]Data based on estimation, half of amount without contractor
[c]Estimated with 1% of c_{inv}
[d]here: €/m^2, data obtained by (Fleischhacker et al., 2019)
[e]here: €/kWh, data obtained by (Fleischhacker et al., 2019)
[f]here: €/kWh/a, data obtained by (Fleischhacker et al., 2019)
[g]here: €/psc , data obtained by (ENERGIE AG, 2021)
[h]here: €/psc /a, data based on estimation, half of amount without contractor

Costs for efficiency measures

In order to calculate the costs of different energy efficiency measures on the building (see table 3.4), a energy certificate software (Zehentmayer Software GmbH, 2021) with underlying data of 2017 is used. The calculated costs are raised by 20% to meet the realistic data of 2021. The base scenario without any efficiency measures is calculated based on the default building data for 1900 from the Austrian Institute for Building Technology (german abbreviation: OIB), (*OiB Richtlinie 6* 2019).

Efficiency Measure done	Specific heat demand [kWh/m^{2}a]	Costs of measures [€]
No measures done	143	0
All windows exchanged	129	195,360
+ insulation of the top floor ceiling and basement ceiling	100	285,960
+ exterior walls	23	460,534

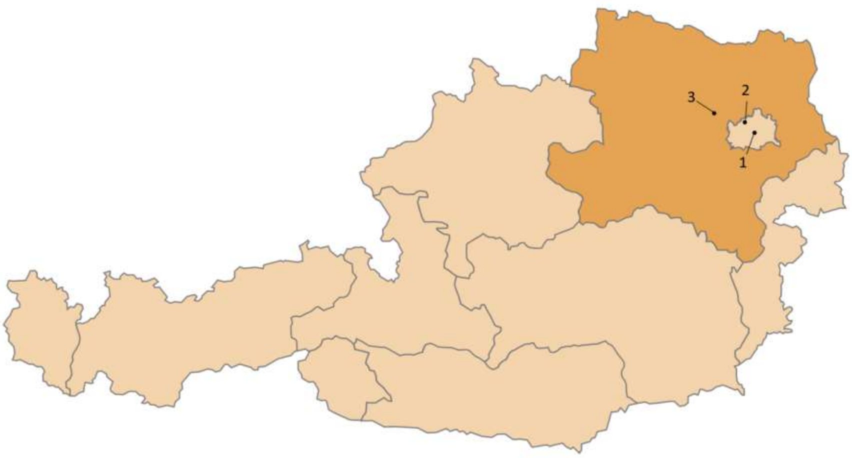
Table 3.4: Economic input parameters for insulation measures

Costs for feed-in ST to DH

It is assumed that the required infrastructure for feeding ST into the DH grid will cause additional investment costs of 500 € (estimated value without labor costs) on the contractor's side. The additional requirements include a pump, at least two four-way valves, a heat exchanger, and the control technology.

3.5 Definition of use cases

The following section describes the use cases that are examined in order to investigate which parameters influence the business models of contracting. Every use case consists of a multi-party house with 30 households in or just outside Vienna (see pinned areas in Figure 3.2), which all have the same dimensions but vary in their specific heating demand, default heating system, area of roof available, amount of EVs and the financial situation of the building owners. A summary of all three use cases can be found below in table 3.5.



Source: User:AleXXws, 2009 with own adaption

Figure 3.2: Map of Austria with location of use cases

3.5.1 Urban use case

The first use case is a typical multi-party house in the center of Vienna built in 1900. As it was the standard at that time, the house is made of brick walls without insulation.

This results in a specific heating demand of 140 kWh/m^{2}a which sums up to total heating demand of 420.000 kWh/a. Every flat has a decentralised gas heater, which is used for heating (radiators with 60°C flow temperature) and DHW.

As described in section 3.4.1 the house has a south-north orientated, tilted roof with a south side of 360 m^2(of which 245 m^2 can be used for PV and ST).

As the house is located in the inner city of Vienna, there is no underground car park but three parking spaces shall be equipped with EVSEs in front of the house.

The majority of the house is owned by a single owner who has enough capital available to undertake possible investments.

3.5.2 Suburban use case

The second use case is a multi-party house built around the year 2010 which is located in one of the outer districts of Vienna (e.g. 16th district). With an outside wall insulation in place, the house has a specific heating demand of 50 kWh/m^{2}a, which sums up to total heating demand of 150.000 kWh/a. The building is connected to the DH grid which supplies the floor heating (30°C flow temperature) and DHW for all 30 households.

As described in section 3.4.1 the house has a flat roof with an are of 500 m^2 (350 m^2 can be used for PV and ST).

The building has an underground garage with parking lots for each household. This use case assumes a higher market penetration of EVs and therefore one third of the parking lots (ten out of 30) should be equipped with EVSEs.

The house has several owners, as these are privately financed flats. The new investments were agreed upon in the owners' meeting, but there is not enough capital to make the investment. Furthermore, none of the owners want to be responsible for a large investment like this. Another reason for the reluctance to undertake the investment is that some of the flats are rented out and so the owners would not benefit from energy cost savings themselves.

3.5.3 Rural use case

The third use case examines a building that is currently in the planing phase. The house will be built in the countryside of lower Austria (e.g. in Tulln) and complies with the nearly zero energy building standards (see (*OiB Richtlinie 6* 2019)). This results in a specific heating demand 25 kWh/m^{2}a and a total heating demand of 75.000 kWh/a. The building has no connection to the gas or DH grid, so the only option (in this model) is to install a HP for the floor heating (30°C flow temperature) and DHW.

Analog to the use case 2, the house has a flat roof. However, in this use case there is the option to also install ground-mounted PV and ST plants on additional land next to the building. In total there are 500 m^2 available for PV and ST.

To examine the effects of very high market penetration, it is assumed that 30 EVSEs are provided (100% of the households need an EVSE). The parking lots might be realised as car ports (on the free land next to the building), using the area above for PV or underground parking.

As the building is still in the planing phase, the contractor could be the property developer himself/herself.

3.5.4 Overview of use cases

Parameter \ Use Case	Urban	Suburban	Rural
Location	city centre of Vienna	outer district (e.g. 16th) of Vienna	countryside Lower Austria (e.g. Tulln)
Specific heating demand [kWh/m²a]	140	50	25
Default heating system	gas heaters	DH	not existing
Roof area [m²]	245	350	500
Number of EVs	3 (10%)	10 (33%)	30 (100%)
Investment situation	enough equity available	no equity available	planning phase

Table 3.5: Overview use cases

4 Results

This chapter describes the most relevant results of the three use cases, using the modeling approach described in the previous Chapter. The results of each use case (section 4.1 to 4.3) include the newly installed capacities per technology, the energy flows as well as the resulting costs of supply. Section 4.4 provides a comparison of the results.

4.1 Results of the urban use case

4.1.1 Installed capacities and energy supply

Table 4.1 below shows the newly installed capacities for the urban use case. The required number of three EVSEs is installed as well as 38 kWp of PV. The installed PV capacity equals the maximum possible capacity which is limited by the given area of the roof. An investment in 85% reduction of the initial heating demand is made, which results in a remaining heating demand of 15% (in line with table 3.4, these efficiency measures cost around 460,500 €). As the building owner has enough equity to cover the total investment costs of around 500,800 €, all investments are done by himself/herself without a contractor in order to minimise the overall costs for the tenants.

Technology \ Financing	Financed without contractor
Battery [kWh]	0
Charging Stations [pcs.]	3
HP [kW]	0
PV [kWp]	38
ST [m²]	0
Reduction of heating demand [%]	85

Table 4.1: Urban use case - Capacities of new investments

The Figure below 4.1 displays the resulting energy flows over the scope of one year. Since no investment in an alternative heating system is chosen, the total thermal energy demand is covered by the gas supply. Around one third of the electricity supply can be covered by the PV plant directly.

Figure 4.1: Urban use case - Energy flows

4.1.2 Costs

The bar chart (Figure 4.2) demonstrates the annual costs for the building owner and tenants. It can be seen that the annuities of the investments (calculated over 30 years for insulation measures and 20 years for all other possible investments) are close to the yearly variable energy costs, 26,185 € and 28,607 € respectively. As mentioned above, the investment costs for refurbishment are around 460,500 € and therefore make up 91% of the total investment costs of 500,800 € (the diagram only shows the annuities of this investment (26,185 €)). Compared to initial situation before the investments, the total yearly costs have decreased from 71,882 € to 57,080 € (lowered by around 20%). This results in 484 € lower costs per household each year.

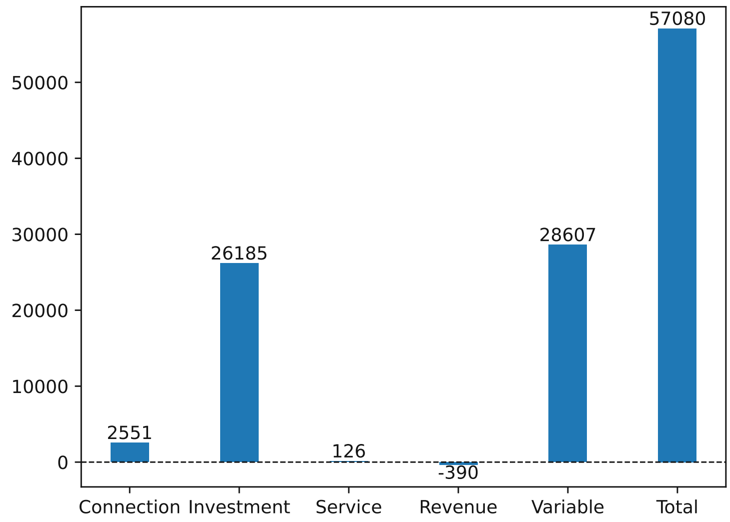


Figure 4.2: Urban use case - Annual costs for tenants

4.2 Results of the suburban use case

4.2.1 Installed capacities and energy supply

The table 4.2 below provides the newly installed capacities in the suburban use case. Since there is no equity available from the house owner's side, all investments are done through a contractor. The built PV plant has the maximum possible capacity (due to the given flat roof area) of 40 kWp. The requirement to install ten charging stations (EVSE) is fulfilled. Additionally to the heating supply by the DH grid, it is economically viable for the contractor to invest in a 15 kW HP. No investments in efficiency measures are conducted in this set-up.

Technology \ Financing	Financed by contractor
Battery [kWh]	0
Charging Stations [pcs.]	10
HP [kW]	15
PV [kWp]	40
ST [m²]	0
Reduction of heating demand [%]	0

Table 4.2: Suburban use case - Capacities of new investments

Figure 4.3 displays the energy flows over the scope of one year. The proportion of the supply by DH and HP to cover the heating demand as well as the supply from PV and the electric grid to fulfill the electricity demand of the household, the car charging activities and the HP can be seen. The demand for the ten cars is nearly exclusively covered by the electric grid due to the charging activities in the evenings (no PV generation). The HP is supplied by the electric grid and the PV system in the ratio of three quarters (electric grid) and one quarter (PV).

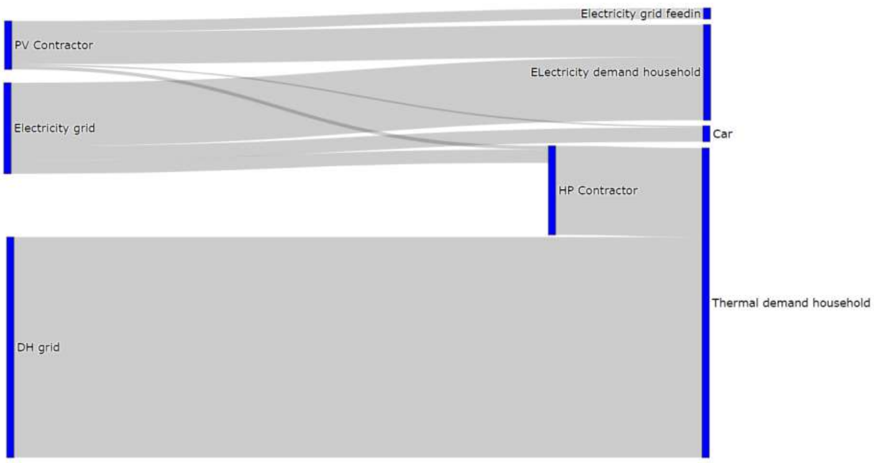


Figure 4.3: Suburban use case - Energy flows

4.2.2 Costs

The bar chart (Figure 4.4) depicts the yearly costs for the contractor as well as for the total of all tenants. It is apparent that compared to the costs in the urban use case (see Figure 4.2), the tenants' costs consist of about 80% of variable costs due to the business model of the contractor. This demonstrates how the total investment costs (over-night costs) of 68,500 € for the contractor are refinanced by the proportionally high variable costs for the tenants and the therefrom generated revenues for the contractor.
Compared to initial situation before the investments, the total yearly costs have decreased from 50,837 € to 44,486 € (lowered by around 12.5%). This results in 211.7 € lower costs per household each year.

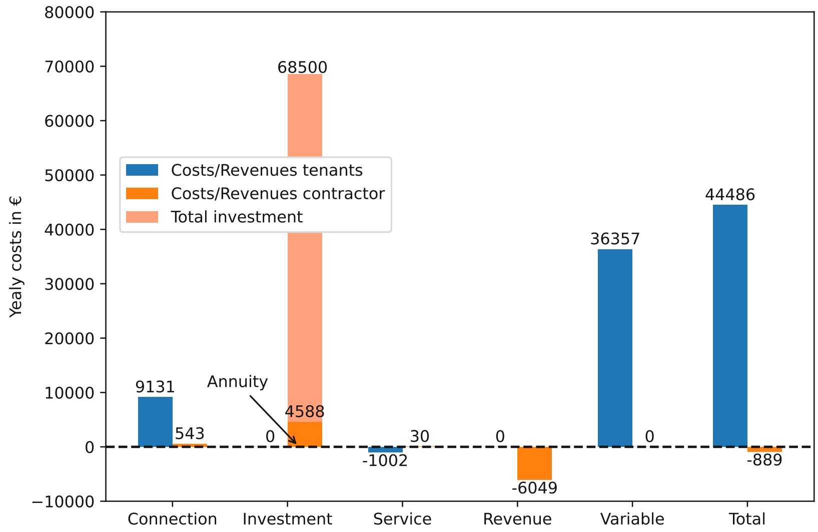


Figure 4.4: Suburban use case - Annual costs and revenues for contractors and tenants

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In Figure 4.4 the service costs for the tenants are negative. This can be explained by taking a look at Figure 4.5 below. The bar chart represents the total revenues for the contractor split into the two parts - contractor rate and variable revenues. The contractor rate represents the yearly fee that the tenants have to pay to the contractor in order for him/her to make an economically viable offer, while the variable revenues are the earnings through the energy costs paid to the tenants. These energy costs are a percentage of the alternative energy costs (e.g. 80% of electricity grid price for the PV electricity by the contractor). This does not apply to the charging sttions because the tenants always have to pay 10% of the electricity grid price in this model.

In this case, the contractor rate is negative for the investment of the PV system. In other words, it is still economically viable for the contractor to make an offer even if a yearly fee of around 2500 € is paid to the building owner. This negative contractor rate could, for example, represent a yearly rent for the area of the roof.

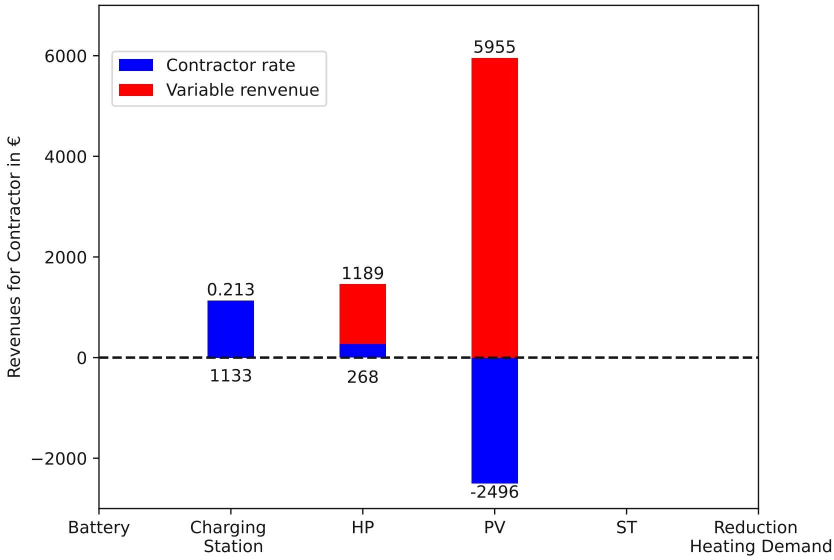

Figure 4.5: Suburban use case - Contractor rate and revenues for contractor

4.3 Results of the rural use case

4.3.1 Installed capacities and energy supply

The newly installed capacities of the rural use case can be found in table 4.3 below. Since the contractor is the property developer himself/herself in this use case, all investments are done by this contractor. The PV plant built has the maximum possible capacity of 57 kWp (due to the given flat roof and on the free land area next to the building). The requirement to install 30 charging stations (EVSE) is fulfilled. Due to the fact that the newly built house is not connected to a grid-bounded heating system (gas or DH), the investment in a HP is required. Hence, an optimum capacity of 92 kW is chosen to cover the house's heating and DHW demand. As expected, no investments in efficiency measures are conducted in this low-energy-building set-up.

Technology \ Financing	Financed by contractor
Battery [kWh]	0
Charging Stations [pcs.]	30
HP [kW]	92
PV [kWp]	57
ST [m²]	0
Reduction of heating demand [%]	0

Table 4.3: Rural use case - Capacities of new investments

Figure 4.6 depicts the energy flows in this use case. It is notable that due to the high EV penetration (one EV per household), only 4% of the electricity come from PV generation (over the course of one year).

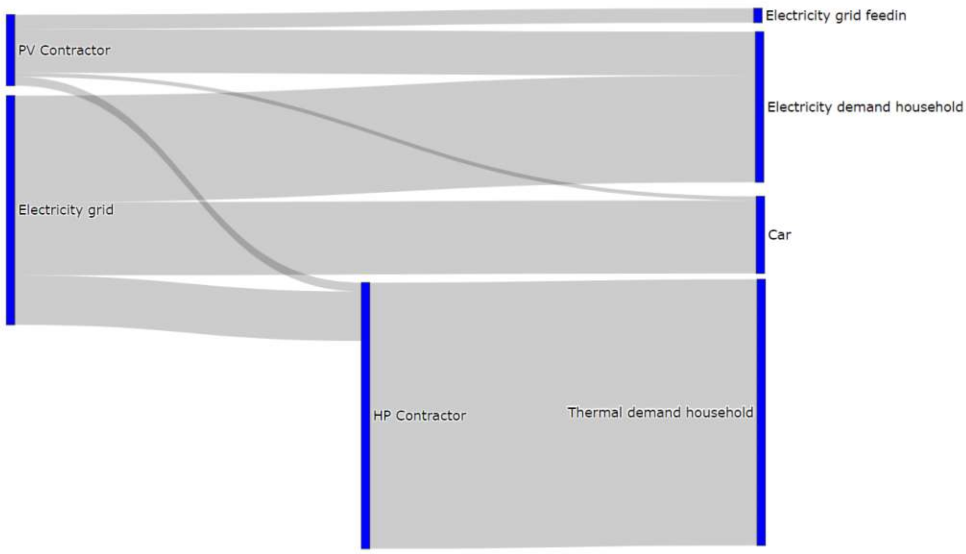

Figure 4.6: Rural use case - Energy flows

4.3.2 Costs

The Figure 4.7 depicts the yearly costs for the contractor as well as the costs for the sum of all tenants. It is noticeable that, compared to the total investment costs in use case 2 of 52,000 € (see Figure 4.2), the contractor invests nearly 200,000 € in this set-up.

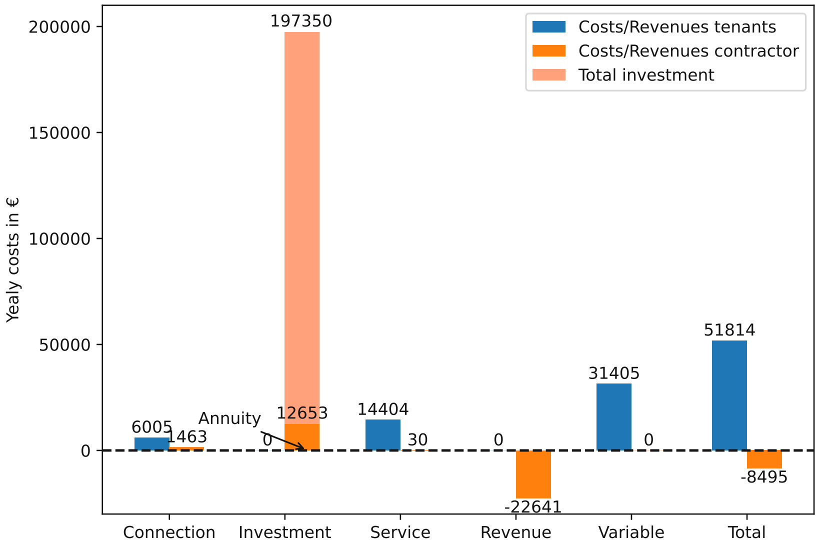

Figure 4.7: Rural use case - Annual costs for tenants and contractor

Taking a look at the revenues for the contractor within this use case (Figure 4.8), it is evident that the investment in the HP cannot be refinanced through the energy price charged to the tenants. This is explained by the proportionally high HP capacity needed since there is no other heating supply available. Only around 20% of the necessary revenues (in order to reach an NPV of at least zero) for the HP come from variable revenues, the other 80% have to be covered by the yearly contractor rate. However, the contractor is capable to increase the energy price for the HP due to the fact that the tenants have no other supply choice to cover their heating demand. The PV investment itself is economical in case of solely selling the electricity generated by the PV. Therefore, the contractor is willing to pay a low (330 € per year for 500 m^2) rent to the tenants or the house owner.

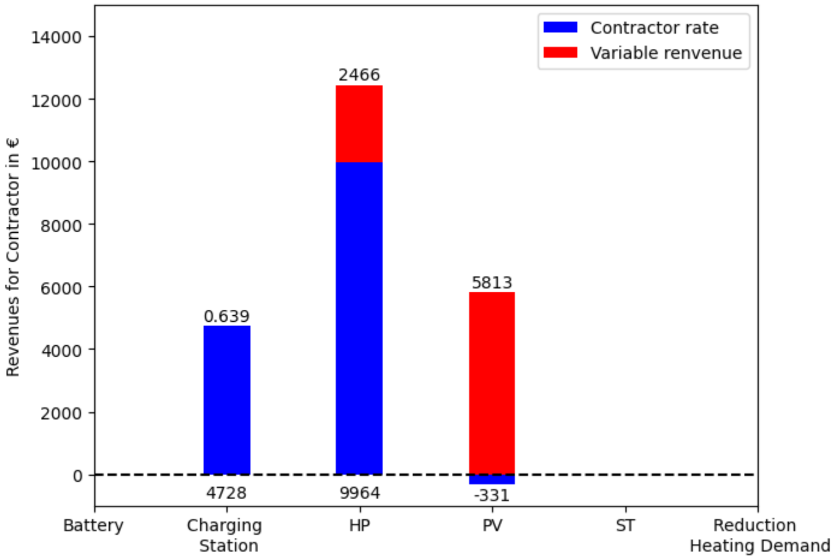

Figure 4.8: Rural use case - Contractor rate and revenues for contractor

4.4 Comparison of the three use cases

As a result of the three examined use cases, the installed capacities for each investment option vary significantly. Figure 4.9 provides an overview of the results presented in the previous sections of this Chapter. It can be noticed that in all use cases the investment in PV is undertaken while making use of the maximum capacity possible. Concerning the installation of PV, the urban and the suburban use case differ by only 2 kWp of installed capacity, despite that fact that the suburban use case offers 105 m^2 more roof area to be used. This can be explained by the different capacity density of PV in kWp/m^2 on a tilted or flat roof (area lost by tilting the panels).

As expected, efficiency measures are only carried out in the urban use case with an initial specific heating demand of 140 kWh/m^2a. The building standards of the other use cases are higher, leading lower flow temperatures needed in the heating system. Therefore, the resulting COP of a potential HP is higher. For this reason, investments in HPs can be seen in the use cases with higher building standards (suburban and rural).

The number of charging stations are defined as a necessary investment within the model, thus the results are determined by the definition of the use case itself and cannot be compared to each other (displayed here for the sake of completeness only).

In none of the use cases an investment decision is made for a battery system nor a ST plant by the optimisation model. A battery system is not economically viable because there is hardy any surplus PV due to the high electricity demand in a multi-storey residential building. This can be verified by taking a look at the low percentage of PV feed-ins to the grid (this electricity could potentially be stored in a battery). In case of ST, the investment competes directly with the investment in PV because of the limited roof area.

The results of the use cases illustrate, that an investment without a contractor will lead to minimised costs as long as sufficient equity is available to pay the investment costs. If the option for directly financed investments is not given (like in the suburban and rural use case), then the contractor is chosen.

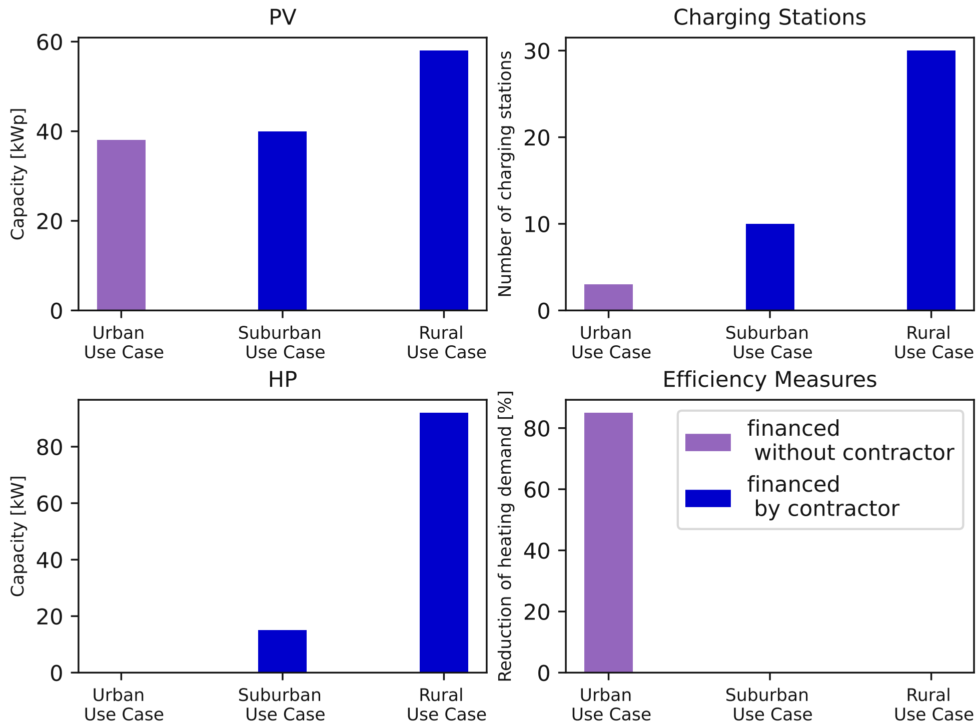

Figure 4.9: Comparison capacities of new investments

The optimisation model minimises the total costs of the tenants yearly costs by choosing the above presented technologies. The following Figure 4.10 compares the resulting costs of all use cases. It can be seen that the differences in the total costs are only around 12,000 €/a between the use cases. This would be an average difference of about 30 € per month per household. The essential part of the total costs in all use cases are the variable costs for purchasing electricity and thermal energy.

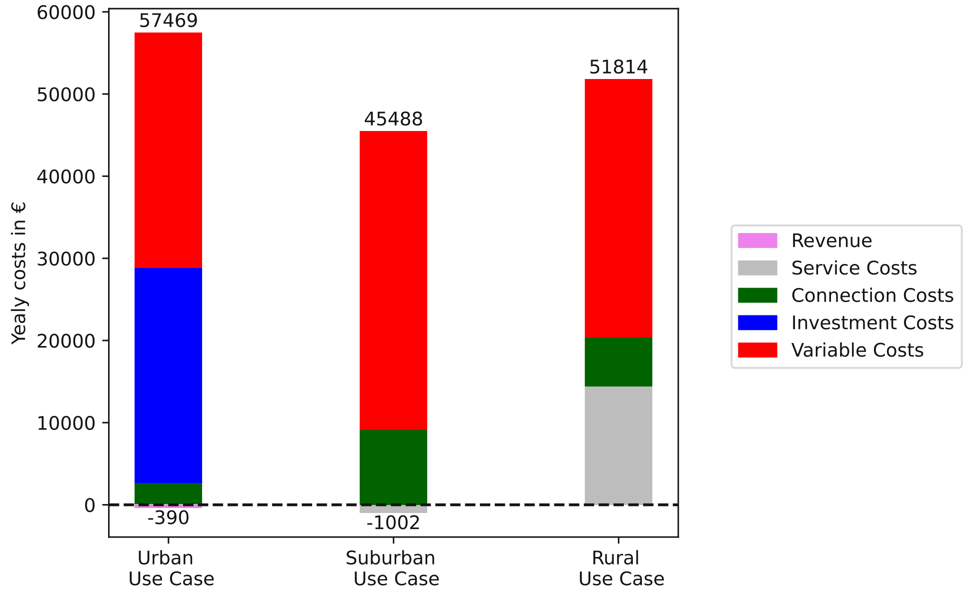

Figure 4.10: Comparison annual costs for tenants

Table 4.4 displays how the total yearly costs compare to the situation prior to the investments. It can be observed that the tenants in the urban use case experience a twice as high decrease in the total yearly costs compared to the suburban use case. For the rural use cases, no cost reduction is calculated since the building is new.

Use case	Yearly costs before investment [€/a]	Yearly costs after investment [€/a]	Lowered in percentage [%]
Urban	71,882	57,080	- 21
Suburban	50,837	44,486	- 12.5
Rural	-	51,814	-

Table 4.4: Comparison of yearly cost reduction of tenants

In order to see the environmental impact of every use case, the CO_2 emissions resulting from the electricity, gas and DH supply are calculated. Equation 4.1 shows the calculation of the CO_2 emissions, where P_t is the total supply per default technology and κ represents the conversion factor (see table 5.1).

$$Total\ \ CO_2 = \sum_{t=1}^{N} \kappa_{gas} \cdot P_{t,gas} + \kappa_{DH} \cdot P_{t,DH} + \kappa_{el} \cdot P_{t,Grid} \tag{4.1}$$

Table 4.5 shows that the highest reduction of CO_2 emissions (minus 70%) can be achieved in the first use case due to the high initial CO_2 emissions before the investments. Despite the drastic reduction, the suburban use case emits only a forth of the final value (after refurbishment and PV investment) of the urban use case. For the rural use cases, no reduction of CO_2 emissions is calculated since the building is new. The CO_2 emissions are not only import for an ecological evaluation of the results, but are also interesting in an economical aspect since avoided CO_2 emissions also result in avoided costs.

Use case	CO_2 emissions before investment [kgCO$_2$/a]	CO_2 emissions after investment [kgCO$_2$/a]	Lowered in percentage [%]
Urban	201,543	61,353	- 70
Suburban	37,994	26,869	- 30
Rural	-	16,229	-

Table 4.5: Comparison of CO_2 reduction

5 Sensitivity analysis

The following sensitivity analysis is used to verify the results of chapter 4 of changing various input parameters of the three use cases. The sensitivities analysed include:

- contractor's investment costs
- CO_2 price
- contractor's prices model
- feed-in tariff for ST
- contractor's expected RoI
- charging load curve (activation of DSM)

5.1 Sensitivity analysis of urban use case

5.1.1 Reducing contractor's investment costs

This first part of the sensitivity analysis examines under which conditions the contractor would be able to make an offer that can undercut the self-financed investment. It is assumed that contractors are able to source their components at better conditions than a private person could and therefore have lower specific investment costs. The graph below (Figure 5.1) indicates that, if the contractor is able to make an offer taking into account only 85% of the initial investment costs (compared to the private investment), he/she can already undercut the offer for the EVSEs and the PV system. For the efficiency measures (85% reduction of heating demand), the contractor needs 60% lower investment costs to make an economical offer to the building owner. Lowering the specific investment costs for the contractor below 60% shows no further effects.

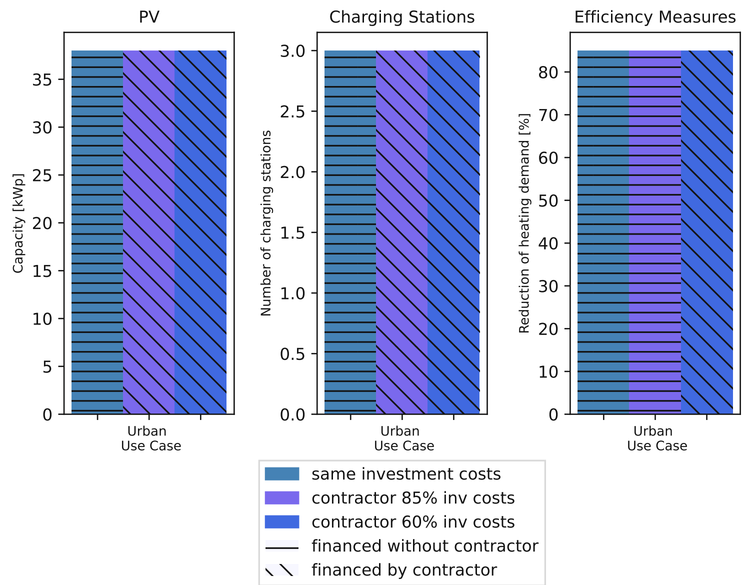

Figure 5.1: Urban use case - lower investment costs for contractor

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5.1.2 Rising CO2 price

This sensitivity analysis displays the effects of a rising CO_2 price. To conduct this analysis, new energy prices due to the rising CO_2 prices have to be calculated and used as new input parameters for the optimisation model.

The following table shows the conversion factor of the default electricity and heating systems that are used to calculate the changed energy prices. The conversion factors are obtained from obtained from Umweltbundesamt (2019) and E-Control (2021b).

Energy source	Conversion factor [kgCO$_2$/kWh]
Electricity mix from grid	0.258
Natural gas from grid	0.440
District heating	0.203

Table 5.1: CO_2 conversion factors (Umweltbundesamt, 2019), (E-Control, 2021b)

Assuming a current CO_2 price of 25 €/tCO$_2$, the following table shows the resulting energy prices with a CO_2 price of 70, 115 (Swedish CO_2 price, see IEA (2021)), 200, and 250 €/tCO$_2$.

Energy source	Default energy price [€/kWh]	New energy price [€/kWh] with CO_2 prices of:			
		70 [€/tCO$_2$]	115 [€/tCO$_2$]	200 [€/tCO$_2$]	250 [€/tCO$_2$]
Electricity	0.2130	0.2246	0.2362	0.2582	0.2711
Gas	0.0589	0.0787	0.0985	0.1359	0.1579
District Heating	0.0575	0.0666	0.0758	0.0930	0.1032

Table 5.2: Calculated energy prices for rising CO_2 price (own calculation)

As can be seen in the bar chart below, a rising CO_2 price does not enable the contractor to make an economically interesting offer as long as the same purchase prices are being assumed (as it is the case in the base scenario of the urban use case, section 4.1). Secondly, a rising CO_2 price leads to an increasing capacity of HP installed. This is due to the fact that the chosen electricity mix shows a lower conversion factor than natural gas. While no HP is installed at a current CO_2 price, it becomes economically reasonable to install 21 kW at 70 €/tCO$_2$. This trend continues up to 86 kW installed thermal capacity of a HP at CO_2 price of 115 €/tCO$_2$ and does not increase after this.

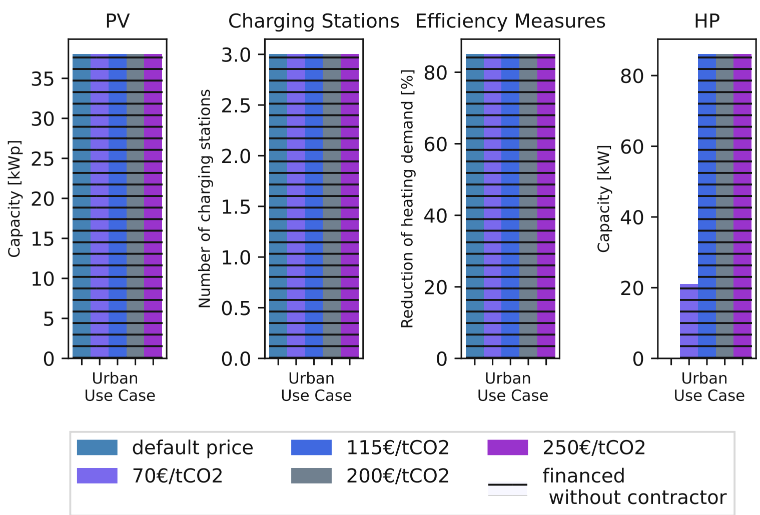

Figure 5.2: Urban use case - Capacities of new investments for rising CO_2 price

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The increasing capacity of HP can also be seen in the supply from the grid in the pie charts below. It appears that the supply from gas is decreasing and comes to zero for the scenarios with CO_2 prices from 115 €/tCO$_2$ on, where the HP capacity reaches its peak.
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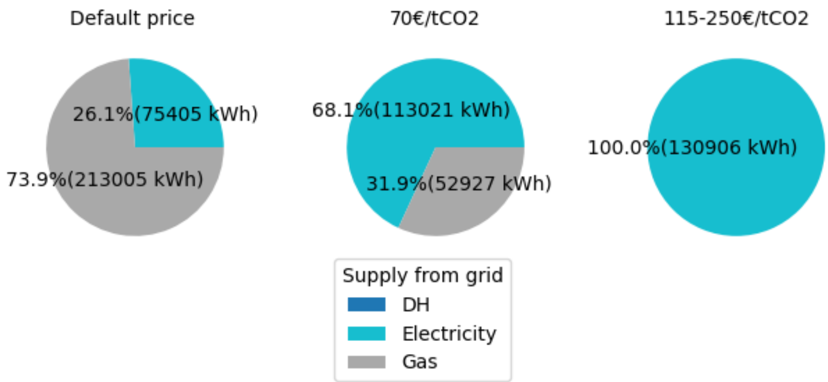

Figure 5.3: Urban use case - Electricity and heat supply from the grid for rising CO_2 price

The previous analysis does not take into account that installing a HP might be prohibited for old buildings (even with retrofitting in place) as efficiency due to energy shortage is moving into the spotlight of energy policies. Since the urban use case assumes a heating system using radiators with 60°C flow temperature, a common HP may operate on a poor efficiency level. For this reason, the calculation is redone without the option to invest into HPs. The following two graphs (Figure 5.4 and 5.5) illustrates the results of the recalculation without the option to invest into HPs. The are no changes in the capacities of the new investments as PV and efficiency measures are still on their maximum possible values.

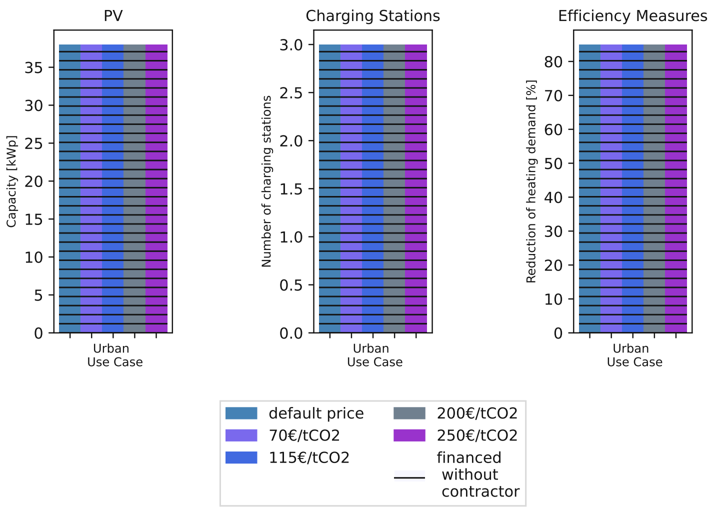

Figure 5.4: Urban use case - Capacities of new investments for rising CO_2 price with no HPs allowed

Figure 5.5 demonstrate that a change in the heating system, precisely the switch from gas to DH, occurs at a high CO_2 price of 250 €/tCO$_2$ (if the investment in HPs stays suppressed).

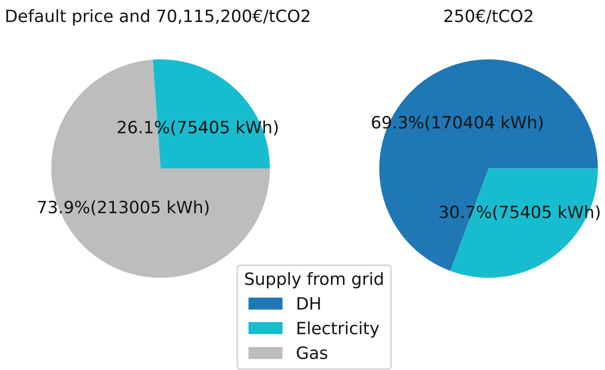

Figure 5.5: Urban use case - Electricity and heat supply from the grid for rising CO_2 price with no HPs allowed

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5.1.3 Implementing district heating

This last sensitivity analysis of the urban use case questions what the additional costs of switching the heating system from gas to DH at the current energy prices are. The bar chart below gives a comparison between the current costs (equal to Figure 4.2) and the costs of a forced switch to DH. It can be seen that additional costs of 8.800 € per year occur for the sum of all households in the examined building. This is the case due to higher connection and service costs of the DH supply. The investment costs are the same in both cases as they only include the initial investment costs for new technologies and not the change of the (grid connected) default heating system.

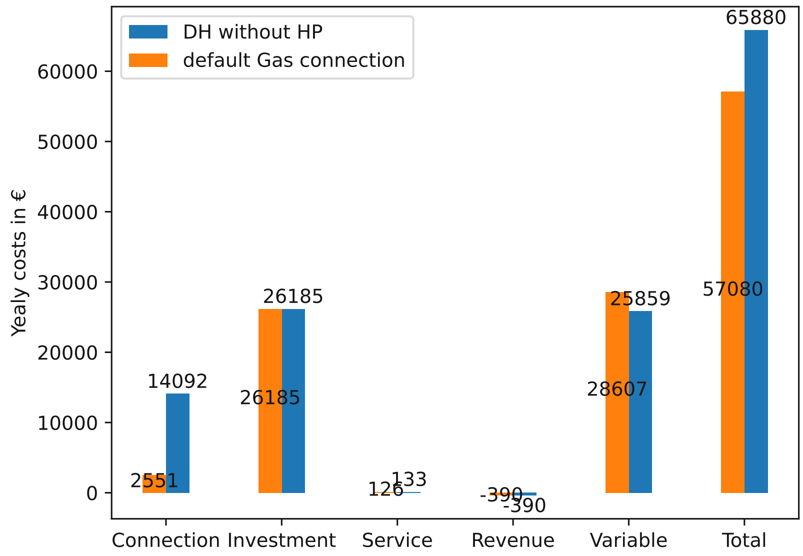

Figure 5.6: Urban use case - Costs of switching from gas to DH at the current energy price
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5.2 Sensitivity analysis of suburban use case

5.2.1 Lowering variable price charged by contractor

As explained above, the contractor charges a certain percentage of the alternative energy costs (e.g. 80% of electricity grid price for the PV electricity by the contractor). In this sensitivity analysis the variable price for the energy provided by the contractor is decreased by lowering the percentage on the alternative energy price that is charged. Figure 5.7 shows the effects of a lower percentage charged - and therefore lower variable revenues for the contractor - on the ratio of contractor rate and variable revenues for the contractor. In case of the investment in PV, it is observable that at 20% and 40% variable costs for the tenants, the contractor has to charge an additional contracting rate to make his offer economically viable. In the base scenario (80%) and at 60%, the contractor charges such a high energy price that he/she is willing to pay a contracting rate back to the tenants (e.g. in form of a renting model).

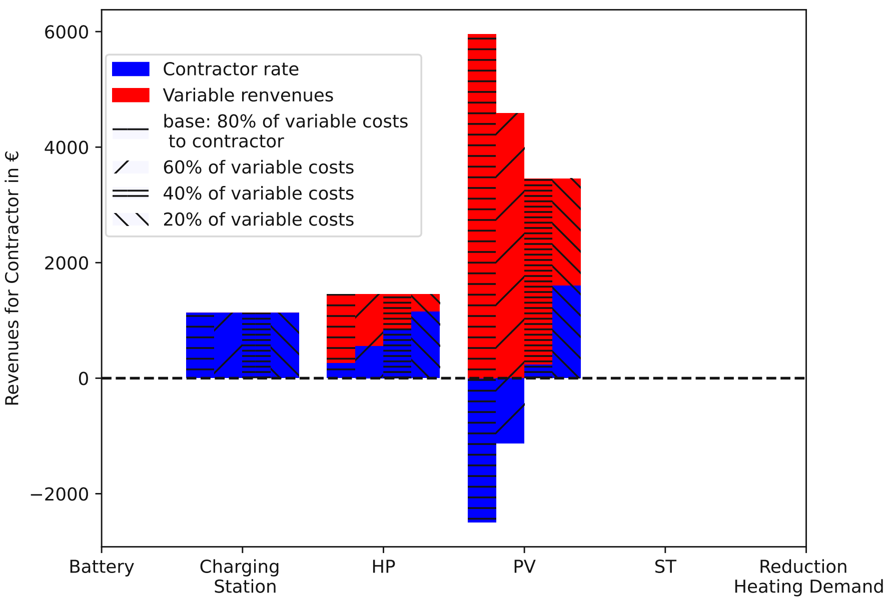

Figure 5.7: Suburban use case - Contractor rate and revenues for contractor at different variable energy prices for the tenants

The following Figure 5.8 displays the effects of lower variable costs on the costs for the tenants. Evidently, the total costs stay the same while only the ratio between the yearly service costs and the variable costs changes. It is debatable which business model - higher yearly fees or higher variable energy costs - gives an advantage to the tenants. However, it can certainly be said that higher variable costs set incentives for energy savings on the tenant's side.

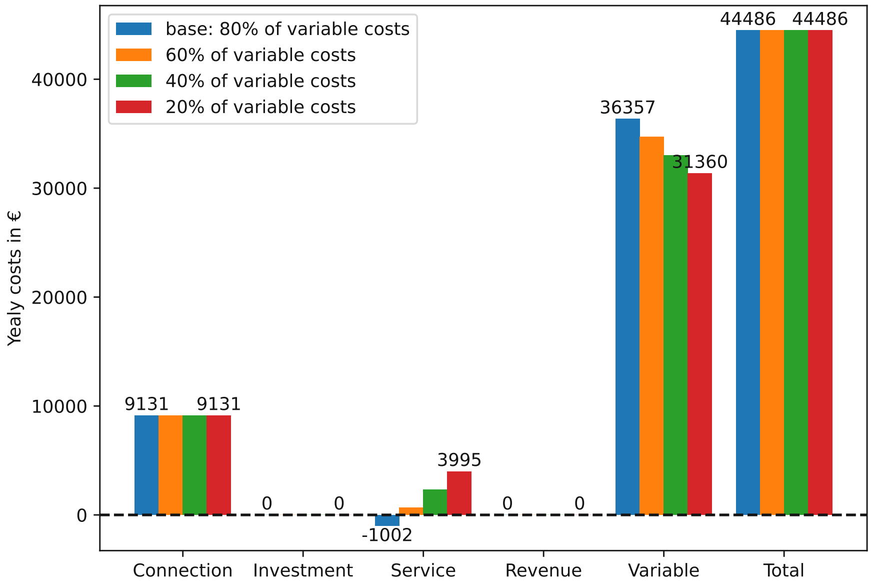

Figure 5.8: Suburban use case - Costs for tenants at different variable energy prices charged by the contractor

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5.2.2 Rising CO2 price

The following two figures (5.9 and 5.10) displays the effects of a rising CO_2 price on the installed capacities as well as on the supply from the grid. It can be seen that the PV capacity is not rising which is due to the fact that it is already installed at its maximum possible capacity in the base scenario. Furthermore, the number of charging stations stays the same as the model is only obliged to install the necessary amount of ten EVSEs. The capacity of the installed HP increases with a rising CO_2 price from initially 15 kW up to 53 kW at a CO_2 price of 115 €/tCO$_2$. A rising CO_2 price does not trigger any investments in efficiency measures, ST or battery.

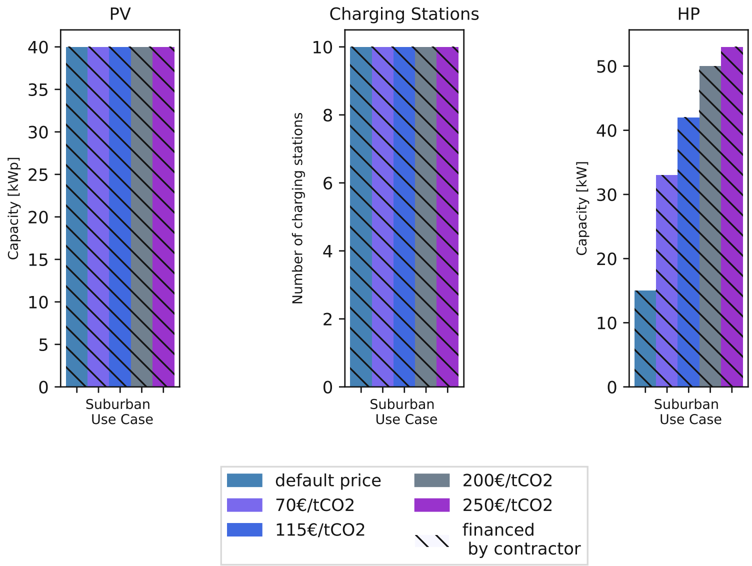

Figure 5.9: Suburban use case - Capacities of new investments for rising CO_2 price

In line with the installed capacities in the figure above, the pie charts below represent the increasing amount of supply by the HP and the proportionally decreasing supply by the DH grid.

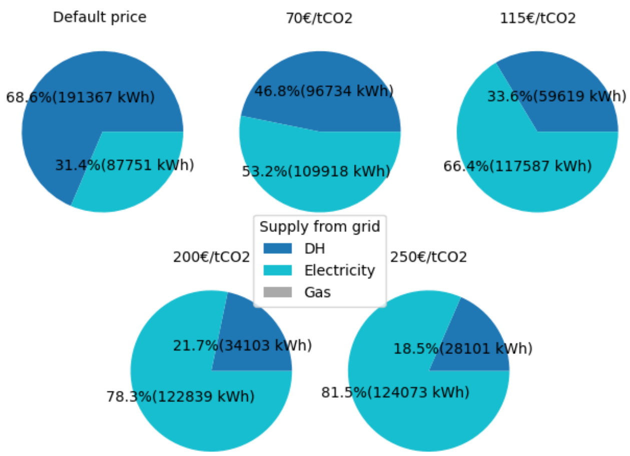

Figure 5.10: Suburban use case - Electricity and heat supply from the grid for rising CO_2 price

5.2.3 Investing in solar thermal and district heating

The previous analysis shows that a rising CO_2 price cannot trigger an investment in ST. Therefore, this sensitivity analysis answers the question at which feed-in tariff for ST into DH it is economically viable for the contractor to make an investment in ST. Additionally, it is investigated how the investments change for the case in which it may not be allowed to install PV (e.g. due to high PV penetration in the area). Table 5.3 summarises the results of this analysis.

Up to a feed-in tariff of 10 cents, no ST is installed independently if PV is prohibited or not. From 20 cents on, there is an investment in about 53 m^2 ST collector area (takes up 203 m^2 roof area) for the sake of 23 kWp PV. In this case the HP capacity is lowered to 11 kW. A further rise of the feed-in tariff to 30 cents triggers an investment to the maximum possible ST capacity of 91 m^2 collector area. If PV is not allowed, the full capacity of ST is already reached at a feed-in tariff of 20 cents. It can be observed that the investment of HP is closely tied to the PV capacity. In all cases without PV there is likewise no HP.

Feed-in tariff ST [€]	Installed PV [kWp]	Installed ST [m^2]	Installed HP [kW]
PV allowed			
0.1	40	0	15
0.2	17	53	11
0.3	0	91	0
PV not allowed			
0.1	0	0	0
0.2	0	91	0
0.3	0	91	0

Table 5.3: Sub urban use case - Overview of investments in PV, ST and HP at a rising feed-in price for ST to DH

Taking a look at the flow chart (Figure 5.11), it illustrates that the ST plant feeds around 25% of its generation throughout the year into the DH grid. Possible reasons for such a high feed-in paid by a DH operator are discussed in Chapter 6.

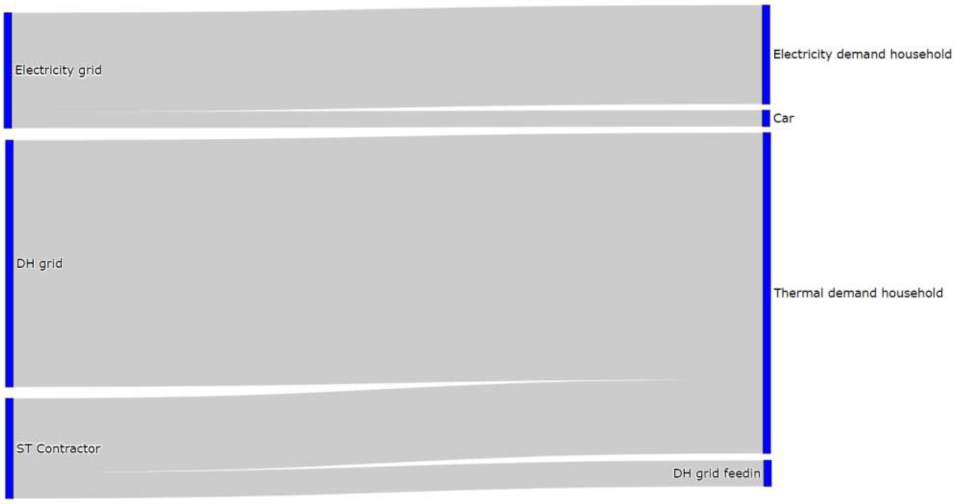

Figure 5.11: Suburban use case - Energy flows at a feed-in tariff for ST to DH of 30 cents

5.2.4 Increasing contractor's return on investment

The bar chart below (Figure 5.12) indicates the effects of a higher RoI expectation by the contractor. In this case, a RoI of e.g. 40% means an expected NPV of 40% of the initial investment costs. The bar chart clearly illustrates that PV stays an economical investment decision even for contractors with higher RoI expectations. In the case of HP, a decrease in the installed capacity can be noticed around 50% per 20% higher RoI step.

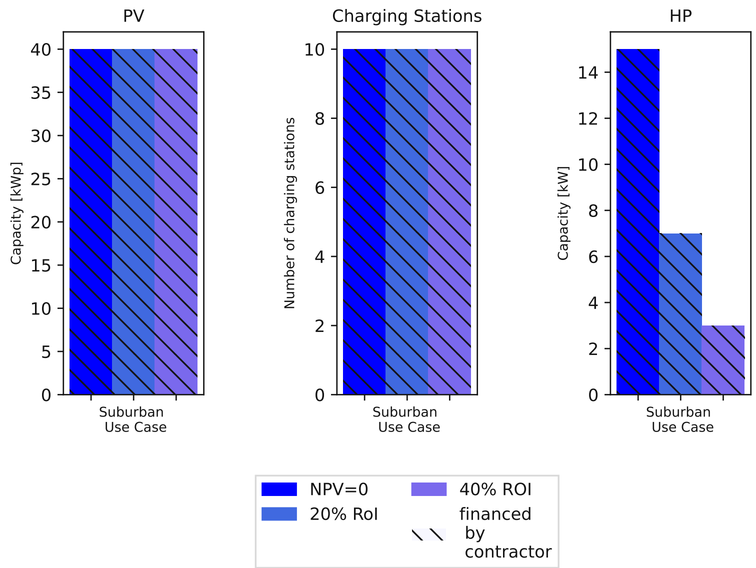

Figure 5.12: Suburban use case - Capacities of new investments for rising RoI expectations
.

Figure 5.13 illustrates the changing costs for the tenants with rising RoI expectations. For an expected RoI of 40%, the total costs for the tenants rise by around 5% compared to the base case with a minimal NPV.

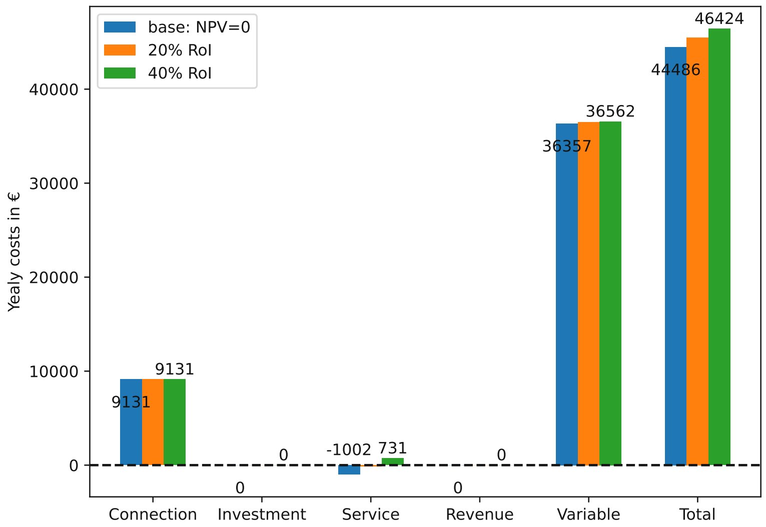

Figure 5.13: Suburban use case - Costs for tenants at rising RoI expectations

5.3 Sensitivity analysis of rural use case

5.3.1 Implementing demand side management for car charging

The Figure 5.14 below displays an arbitrary summer day (24 hours) of use case 3 without any further adaptions made. The upper part of the figure shows the sources of supply to fulfill the car charging demand (light blue line) over the scope of 24 hours. It can be noticed that the cars are mainly charged by electricity from the grid (orange line) because the charging demand does not match the supply from the PV plant (red line). Nevertheless, if the charging demand lies within the production time of PV (in other words, under the red line), the cars are charged using the PV electricity (green line). The lower part of the figure illustrates that this effect is also evident for the household electricity demand since most of the demand is needed in the mornings and evenings when the PV production is low or zero.

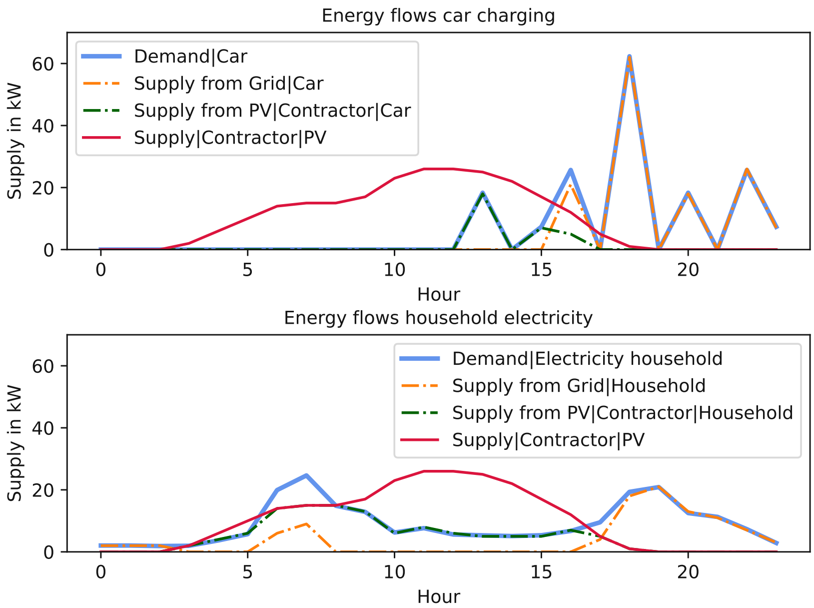

Figure 5.14: Rural use case - 24 hours no DSM implemented

Since the PV generated electricity can not be used efficiently by tenants themselves, the following sensitivity analysis allows the use of a DSM system (mathematical formulas can be found in section 3.3.2) for the car charging curve. The possible shift of the charging demand curve is set to 10 kW per time step (per hour). In the first part of the analysis, the contractor does not offer any bonus payments for the demand shifts and all prices stay the same as in the base scenario of the rural use case.

The results of allowing a demand shift of 10 kW per time step can be seen in Figure 5.15 below. The gray line shows the shifted demand while the light-blue line represents the initial charging curve. The set-up of the prices, 0.213 €/kWh for the grid electricity and 80% of it 0.1704 €/kWh for the electricity from the PV (paid to the contractor), trigger a shift of the demand curve following the PV generation. The total amount of up and down shifts within this 24 hours is 46 kW .

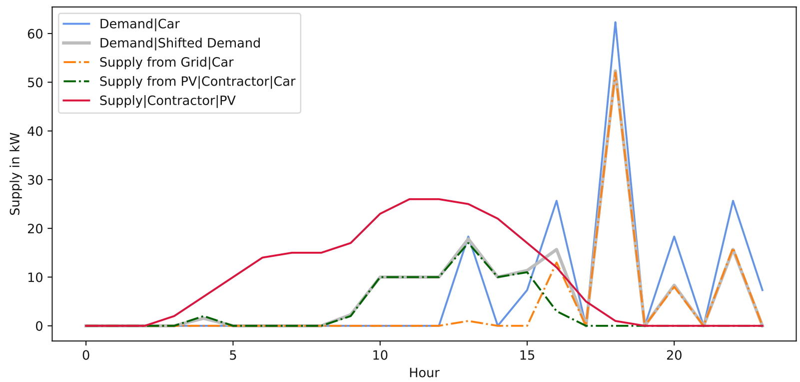

Figure 5.15: Rural use case - 24 hours with DSM, maximum shifts of 10 kW, default prices and no bonus payment

If the contractor charges the same for the PV generated electricity as for the grid electricity (both 0.213 €/kWh), the tenants have no incentive to perform any load curve shifts. Consequently, the contractor needs pay a bonus per every kW shifted to the tenants. Nevertheless, this will not trigger shifts aligning with the PV production since the bonus (in this model) is paid regardless of the moment of shifting. This leads to shifts in arbitrary time-steps. Above all, this analysis shall show the necessary monetary incentive for triggering shifts.

Figure 5.16 displays the shifted demand curve with a bonus payment of 0.02 €/kW. A total amount of 53 kW shifts occur within the 24 hours. For orientation, the secondary balancing reserve price for 2021 by the Austrian TSO (APG) is around 3.5/0.76 €/MWh (peak/off-peak time respectively) for positive shifts and 0.48/2.50 for negative shifts €/MWh (Austrian Power Grid AG, 2021). The estimated bonus payment of 0.02 €/kW is therefore 10 times higher than the current the secondary balancing reserve price.

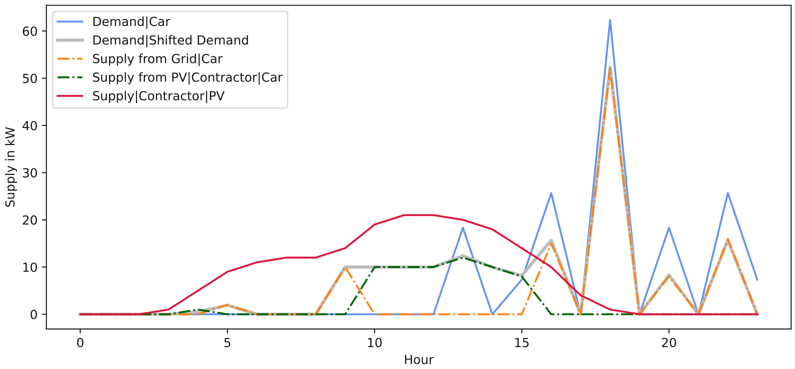

Figure 5.16: Rural use case - 24 hours with DSM, maximum shifts of 10 kW, same electricity price for PV and 0.02 €/kW bonus payment

Moderately increasing the bonus payment does not change the total shifts, unless the payments are raised up to 0.2 €/kW. Hence, a total shift of 65 kW is performed. Figure 5.17 displays the shifts.

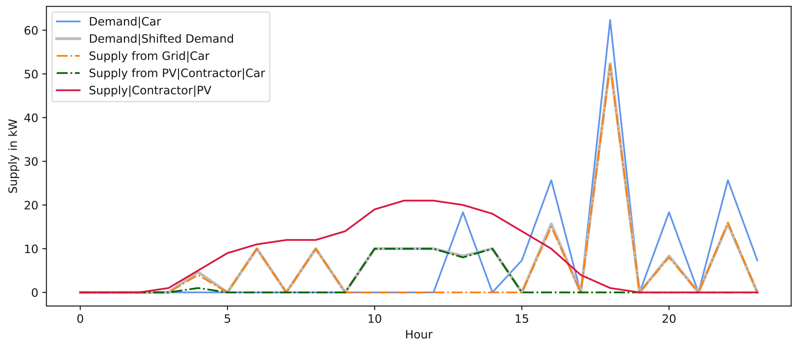

Figure 5.17: Rural use case - 24 hours with DSM, maximum shifts of 10 kW, same electricity price for PV and 0.2 €/kW bonus payment

5.3.2 Rising CO2 price

In this use case the contractor has already installed all necessary technologies to the full extend in the base scenario. Therefore, a rising CO_2 prise does not effect the results of the newly installed capacities. The tenants will be effected by a rising CO_2 prise since the variable energy price will rise as well. However, as it could be seen in the previous use cases, the energy prices rise in a lower proportion than the CO_2 price itself because the fuel price make up only about 40% of the total electricity price (E-Control, 2021a).

5.3.3 Investing in solar thermal

Since there is no DH grid connected to the house, the maximum ST capacity is not limited by the area available but by the DHW demand of the residents (see mathematical formulation in section 3.3.2). In this use case the maximum ST capacity is $75\,m^2$ collector area. The invest in ST is only undertaken if the electricity price rises up to 0.6 €/kWh while at the same time lowering the investment costs of ST to 60%.

5.3.4 Investing in battery systems

The investment in a battery system is under no circumstances (within the scope of this use case) economically viable for the contractor. This has various reasons, which are discussed in Chapter 6.

6 Synthesis of results and conclusions

In this thesis, a linear optimisation model is proposed to find the optimal investment decision for sustainable building infrastructure in order to minimise the tenants' yearly energy costs. In particular, this includes the option to finance various technologies through energy contracting while fulfilling the tenants' energy demand as well as assuring the contractor's profitability. The results of the three analysed use cases (urban, suburban and rural residential building) show how the pre-defined building parameters, such as heating demand, charging load and default heating system, influence the chosen technologies.

The results of the use cases show, that if building owners are capable to undertake the investments themselves (due to sufficient equity), it is advisable to finance the technologies without involving a contractor. This leads to the most economical situation for the tenants and decreases their yearly energy costs. In cases where the building owner is bound to delegate the investment to a third party, the contractor is able to make an offer that ensures a return of the initial investment within 20 years and at the same time lowers the yearly costs for the tenants.

The investment in roof-top photovoltaic is proven to be economically viable within various building set-ups independent from their location (urban or rural) and their building standard. Due to the high electricity demand through increasing electric vehicle penetration and the switch to heat pumps, the expected self-consumption within a residential building becomes an economical driver to install the maximum possible photovoltaic capacity. With the chosen business model applied, the contractor is able to pay a yearly rent to the house owner and still reach the demanded profitability.
Depending on the default heating system, the investment in heat pumps is differently beneficial to the tenants. While a natural gas-based heating system in combination with high flow temperature should not be replaced by a heat pump (from an economic perspective), the additional installation of a heat pump in combination with a district heating supplied heating system is suggested by the optimisation model.
Although, the portfolio provides the possibility to install solar thermal and battery systems, these options cannot be considered to bring an economical benefit to the tenants. Solar thermal directly competes with photovoltaic for the available roof area. Batteries are not economical viable since the excess surplus electricity from photovoltaic within a multi-storey residential building is close to zero, especially with additional electric vehicles being charged.

The sensitivity analysis shows that in terms of an investment in a photovoltaic plant, the contractor is able to compete with a equity financing by the house owner under the condition of 25% lower investment costs (enabled through special purchasing conditions due to economy of scale). The efficiency measures need an offer calculated with 40% lower investment costs. Consequently, contracting energy efficiency measures can be seen as a less profitable investment option for a contractor.
A rising CO_2 price cannot make it easier for a contractor to compete with a direct investment. In all inspected building types, an increased investment in additional heat pump capacity can be observed due to rising gas and district heating prices as a result of rising CO_2 prices. In case the investment in a heat pump is suppressed due to efficiency reason in buildings with high flow-temperature, the switch to district heating can be observed.
The expected return of investment shows to make an impact on the investment decision of heat pumps since it becomes less attractive to the tenants in case the contractor aims for a higher return of investment. On the contrary, photovoltaic has been proven to constantly stay attractive even when a return of investment of up to 40% are expected. Furthermore, the impact analysis shows that a solar thermal to district heating feed-in tariff of about four times of the current district heating price is needed to trigger investments in solar thermal. Using decentralised, contracted solar thermal can become an important factor in decarbonising district heating grids and hence, justify high feed-in tariffs.

The thesis shows that *energy contracting* can be seen as an opportunity for multi-storey residential buildings in urban as well as rural locations to finance sustainable building infrastructure with regards to a successful energy transition. This work proves that the chosen technologies can be financed without public funding and are already an attractive investment for contractors. However, efforts from the governmental side should be made to further ease and remove bureaucracy for the involved stakeholders to open the opportunity for broader business models.

Further research in this field could focus on the profitability on the contractor's side taking into account the market prices for purchasing the energy and reselling it to the tenants. This could also open up additional use cases including time-based pricing models with a more complex demand side management and including the role of electric vehicles and the upcoming possibility to feed back electricity. Additional analyses can be made applying contractor concepts to energy communities with multiple buildings.

Bibliography

Aoun, Alain (Mar. 2020). "Blockchain Application in Energy Performance Contracting." In: *Strategic Planning for Energy and the Environment* 2, p. 2 (cit. on p. 11).

Austrian Power Grid AG (2021). *Preisentwicklung Regelreservemarkt von KW1 2020 bis KW9 2021* (cit. on p. 64).

Bucar, Gerhard, Karin Schweyer, and Christian Fink (2006). "Dezentrale erneuerbare Energie für bestehende Fernwärmenetze." In: *Berichte aus Energie- und Umweltforschung* 78, p. 55 (cit. on p. 32).

Bundeskanzleramt Österreich (2020). *Aus Verantwortung für Österreich. Regierungsprogramm 2020– 2024.* URL: https://www.bundeskanzleramt.gv.at/bundeskanzleramt/die-bundesregierung/regierungsdokumente.html (visited on 02/18/2022) (cit. on p. 3).

Bynum, Michael L. et al. (2021). *Pyomo–optimization modeling in python.* Third. Vol. 67. Springer Science & Business Media (cit. on pp. 4, 15).

Calame-Darbellay, Nicole et al. (Nov. 2019). "Air to water heat pumps for heating system retrofit in urban areas: understanding the multi-faceted challenge." In: *Journal of Physics: Conference Series* 1343, p. 012079. DOI: 10.1088/1742-6596/1343/1/012079 (cit. on p. 12).

E-Control (2021a). *Zusammensetzung des Strompreises.* URL: https://www.e-control.at/industrie/strom/strompreis/preiszusammensetzung (visited on 02/09/2022) (cit. on p. 66).

E-Control (2021b). *Power labelling and disclosure.* URL: https://www.e-control.at/en/industrie/oeko-energie/stromkennzeichnung (visited on 10/12/2021) (cit. on p. 52).

Bundesgesetz, mit dem die Organisation auf dem Gebiet der Elektrizitätswirtschaft neu geregelt wird (Elektrizitätswirtschafts- und –organisationsgesetz 2010 – ElWOG 2010) (Feb. 2022) (cit. on p. 7).

ENERGIE AG (2021). *Wallbox Energie AG.* URL: https://www.energieag.at/Privat/Strom/Elektromobilitaet/Wallbox (visited on 09/12/2021) (cit. on pp. 33, 34).

Energie-Experten (Sept. 2021).
Ratgeber "Mieterstrom": Wie können sich Mieter mit Solarstrom versorgen?
URL: https://www.energie-experten.org/erneuerbare-energien/photovoltaik/direktvermarktung/mieterstrom#c18436 (visited on 10/25/2021) (cit. on p. 8).

Energieagentur Rheinland-Pfalz GmbH (Aug. 2016). *Geschäftsmodelle für Bürgerenergiegenossenschaften. Markterfassung und Zukunftsperspektiven.*
URL: https://www.energieagentur.rlp.de/fileadmin/user_upload/Buergerenergiegenossenschaften_Broschuere_160210_Small.pdf (visited on 10/27/2021) (cit. on p. 8).

Fina, Bernadette, Hans Auer, and Werner Friedl (2020).
"Profitability of contracting business cases for shared photovoltaic generation and renovation measures in a residential multi-apartment building."
In: *Journal of Cleaner Production* 265, p. 121549. ISSN: 0959-6526.
DOI: https://doi.org/10.1016/j.jclepro.2020.121549. URL:
https://www.sciencedirect.com/science/article/pii/S0959652620315961
(cit. on p. 11).

Fleischhacker, Andreas et al. (2019). "Portfolio optimization of energy communities to meet reductions in costs and emissions." In: *Energy* 173, pp. 1092–1105
(cit. on pp. 33, 34).

Flieger, Burghard et al. (2018). *Zukunftsfeld Mieterstrommodelle. Potentiale von Mieterstrom in Deutschland mit einem Fokus auf Bürgerenergie.*
Forschungsprojekt BuergEn. Carl von Ossietzky Universität Oldenburg
(cit. on p. 8).

PV-Gemeinschaft.at Informationsplattform (2018a).
Energieversorger errichtet und betreibt PV-Anlage „Vollversorger". Brochure
(cit. on p. 10).

PV-Gemeinschaft.at Informationsplattform (2018b).
Modell 1 PV-Anlage als Infrastruktur „Gratisstrom". Brochure (cit. on p. 10).

PV-Gemeinschaft.at Informationsplattform (2018c).
Modell 2 Errichtung und Nutzung durch Bewohner-Verein. Brochure (cit. on p. 10).

PV-Gemeinschaft.at Informationsplattform (2018d). *Modell 3 Unternehmen errichtet und verpachtet Anlage bzw. verkauft Strom an Bewohner.* Brochure (cit. on p. 10).

GLPK - GNU Linear Programming Kit (Feb. 15, 2022).
URL: https://www.gnu.org/software/glpk/ (cit. on p. 4).

Görlitz, Sascha (2018). *Energiespar- und Energieliefercontracting.*
DGRV – Deutscher Genossenschafts- und Raiffeisenverband e. V.
Bundesgeschäftsstelle Energiegenossenschaften (cit. on p. 8).

Haas, Reinhard et al. (2021).
"Financing the future infrastructure of sustainable energy systems."
In: *Green Finance* 3. ISSN: 2643-1092. DOI: 10.3934/GF.2021006.

URL: http://www.aimspress.com/article/doi/10.3934/GF.2021006 (cit. on p. 11).

Huneke, F, C Perez Linkenheil, and P Heidinger (Jan. 2019). *ÖSTERREICHS WEG RICHTUNG 100% ERNEUERBARE. EINE ANALYSE VON 2030 MIT AUSBLICK 2050* (cit. on p. 3).

Huppmann, D et al. (2021). "pyam: Analysis and visualisation of integrated assessment and macro-energy scenarios [version 2; peer review: 3 approved]." In: *Open Research Europe* 1.74. DOI: 10.12688/openreseurope.13633.2 (cit. on pp. 4, 16).

IEA (2021). *IEA/IRENA Renewables Policies Database. Sweden carbon tax.* URL: https://www.iea.org/policies/12725-sweden-carbon-tax (visited on 02/08/2022) (cit. on p. 52).

Kammer für Arbeiter und Angestellte für Wien (2021). *Heizkostenabrechnung bei der Fernwärme Wien.* URL: https://wien.arbeiterkammer.at/beratung/Wohnen/Heizkostenabrechnung/Heizkostenabrechnung_bei_der_Fernwaerme_Wien.html (visited on 09/12/2021) (cit. on p. 32).

Lu, Yujie, Nan Zhang, and Jiayu Chen (2017). "A behavior-based decision-making model for energy performance contracting in building retrofit." In: *Energy and Buildings* 156, pp. 315–326. ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2017.09.088. URL: https://www.sciencedirect.com/science/article/pii/S0378778817307375 (cit. on p. 11).

Martiniello, Laura et al. (2020). "Energy Performance Contracting and Public-Private Partnership: How to Share Risks and Balance Benefits." In: *Energies* 13.14. ISSN: 1996-1073. URL: https://www.mdpi.com/1996-1073/13/14/3625 (cit. on p. 11).

Moles-Grueso, S, P Bertoldi, and B Boza-Kiss (2021). Tech. rep. KJ-NA-30614-EN-N (online). Luxembourg (Luxembourg) (cit. on p. 11).

Monsberger, Carolin, Bernadette Fina, and Hans Auer (2021). "Profitability of Energy Supply Contracting and Energy Sharing Concepts in a Neighborhood Energy Community: Business Cases for Austria." In: *Energies* 14.4. ISSN: 1996-1073. URL: https://www.mdpi.com/1996-1073/14/4/921 (cit. on p. 11).

Netze BW GmbH (2019). *DIE E-MOBILITY ALLEE. Das Stromnetz-Reallabor zur Erforschung des zukünftigen E-Mobility-Alltags.* Brochure (cit. on p. 23).

OiB Richtlinie 6 (Apr. 2019). URL: https://www.oib.or.at/de/oib-richtlinien/richtlinien/2019/oib-richtlinie-6 (visited on 09/24/2021) (cit. on pp. 34, 36).

Petrov, Ivan and Lisa Ryan (2021). "The landlord-tenant problem and energy efficiency in the residential rental market."

In: *Energy Policy* 157, p. 112458. ISSN: 0301-4215.
DOI: https://doi.org/10.1016/j.enpol.2021.112458. URL:
https://www.sciencedirect.com/science/article/pii/S0301421521003281
(cit. on p. 3).

Pflugradt, Noah (2020). *LoadProfileGenerator*.
URL: https://www.loadprofilegenerator.de/ (visited on 09/08/2021)
(cit. on pp. 4, 31).

Polarstern (2021).
Mehr Wert für Immobilien. Mit wirklich besserer Energie. Wirklich Mieterstrom.
URL: https://www.polarstern-energie.de/fileadmin/files/mieterstrom/Mieterstrom_Whitepaper.pdf
(visited on 10/28/2021) (cit. on p. 7).

PV Austria (2021). *PV-GEMEINSCHAFT.AT Informationsplattform*.
URL: http://pv-gemeinschaft.at/ (visited on 10/25/2021) (cit. on pp. 9, 10).

Selke, T. et al. (2017). *IEA Solares Heizen und Kühlen (SHC) Task 48: Qualitätssicherung und Unterstützungsmaßnahmen für solare Kühlsysteme*. Bundesministerium für Verkehr, Innovation und Technologie (cit. on p. 12).

Shang, Tiancheng, Lan Yang, et al. (2020).
"Financing mode of energy performance contracting projects with carbon emissions reduction potential and carbon emissions ratings." In: *Energy Policy* 144, p. 111632. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2020.111632. URL:
https://www.sciencedirect.com/science/article/pii/S0301421520303670
(cit. on p. 11).

Shang, Tiancheng, Kai Zhang, et al. (2017). "A review of energy performance contracting business models: Status and recommendation."
In: *Sustainable Cities and Society* 34, pp. 203–210. ISSN: 2210-6707.
DOI: https://doi.org/10.1016/j.scs.2017.06.018. URL:
https://www.sciencedirect.com/science/article/pii/S2210670716303729
(cit. on p. 11).

Statistik Austria (2020). *Primäres Heizsystem nach überwiegend eingesetztem Energieträger und Art der Heizung 2019/2020*.
URL: https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/energieeinsatz_der_haushalte/index.html (visited on 11/02/2021) (cit. on p. 3).

Stefan, Pfenninger and Staffell Iain (2019). *Renewables.ninja*.
URL: https://www.renewables.ninja/ (visited on 09/08/2021) (cit. on p. 30).

Tschopp, Daniel et al. (2020). "Large-scale solar thermal systems in leading countries: A review and comparative study of Denmark, China, Germany and Austria."
In: *Applied Energy* 270, p. 114997. ISSN: 0306-2619.
DOI: https://doi.org/10.1016/j.apenergy.2020.114997. URL:

https://www.sciencedirect.com/science/article/pii/S0306261920305092 (cit. on p. 12).

Umweltbundesamt (Oct. 2019). *Berechnung von Treibhausgas (THG)-Emissionen verschiedener Energieträger.* URL: https://secure.umweltbundesamt.at/co2mon/co2mon.html (visited on 10/12/2021) (cit. on p. 52).

UNFCCC (2015). *Paris Agreement.* URL: https://unfccc.int/process/conferences/pastconferences/paris-climate-change-conference-november-2015/paris-agreement (visited on 02/26/2022) (cit. on p. 3).

User:AleXXws (2009). *Karte AT Niederoesterreich.* File: LambdaPlaques.jpg. URL: https://de.m.wikipedia.org/wiki/Datei:Karte_AT_Niederoesterreich.svg (cit. on p. 35).

VERBUND AG (2021a). *Verbund Photovoltaik.* URL: https://www.verbund.com/de-at (visited on 09/12/2021) (cit. on pp. 9, 32).

VERBUND AG (2021b). *Verbund Produktfolder Frühjahr 2021 STROM B2C.* URL: https://www.verbund.com/de-at/privatkunden/services/downloads (visited on 09/12/2021) (cit. on p. 32).

VERBUND AG (2021c). *Verbund Produktfolder Frühjahr GAS B2C.* URL: https://www.verbund.com/de-at/privatkunden/services/downloads (visited on 09/12/2021) (cit. on p. 32).

Wiener Netze (2021). *Das Netznutzungsentgelt und das Netzverlustentgelt.* URL: https://www.wienernetze.at/o/document/wienernetze/wn_ex0105-netznutzungs-und-netzverlustentgelt_2021_geschutzt (visited on 09/12/2021) (cit. on p. 32).

Will, Harald and Fabian Zuber (2017). "Geschäftsmodelle mit PV-Mieterstrom." In: Second. PV Financing Project (cit. on p. 7).

Zehentmayer Software GmbH (Sept. 9, 2021). *GEQ EBS.* Version 2017. URL: https://www.geq.at/ (cit. on p. 34).

Zhou, Yuanrong et al. (2020). "Linkages between policy and business innovation in the development of China's energy performance contracting market." In: *Energy Policy* 140, p. 111208. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2019.111208. URL: https://www.sciencedirect.com/science/article/pii/S0301421519307906 (cit. on p. 11).

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