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# Profitability of energy supply contracting and tenant electricity sharing models in a mixed urban neighborhood

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# Abstract

The European Union aims at achieving climate goals such as emission reduction, energy efficiency increase and enforced renewable energy diffusion. In order to promote a broad application of decentralized and local renewable energy generation, legal framework conditions for apartment buildings and residential/business districts are needed. Germany and Austria are taking a pioneering role in this area, since they have already legally enabled *tenant electricity sharing* models and *energy contracting* concepts.

In the context of this Master's thesis, selected business models of different players are examined for profitability. Relevant stakeholders are the housing industry, the energy industry and other external companies (third parties). A MATLAB optimization model is developed to maximize the profit of the contractor or energy system provider. At the same time, the contractor's profit is constrained such that the contracting measure in the neighborhood must always result in a reduction in energy costs for the tenants and owners.

The results show that *energy (supply) contracting* is already highly profitable for both the contractor and the tenants/owners. The business models considered are consistently profitable, with the exact numbers being heavily dependent on the economic parameters of interest rate and depreciation times. In addition, those models, where energy prices are not pre-defined, are to be favoured, because the model can determine an optimum between technology capacity and sales price. Mixed usage in the neighbourhood, high energy prices from the grid (see German electricity price and district heating) and the electrical and thermal grid as a possible surplus storage have particularly positive effects on the profitability.

In the future, it will be necessary to intensify the regulatory development in this area, but also to disseminate information among relevant stakeholders. Furthermore, in addition to the development of other innovative business models, electric vehicles and diverse storage systems are to be included in contracting services.

# Kurzfassung

Die Europäische Union strebt eine Erreichung der Klimaziele bezüglich Emissionsreduzierungen, Steigerung der Energieeffizienz und dem forcierten Ausbau erneuerbarer Energien an. Um eine breite Anwendung von dezentralisierter und lokaler erneuerbarer Energiebereitstellung zu forcieren, braucht es unter anderem rechtliche Rahmenbeidingungen für Mehrparteienhäuser und Wohn-/Geschäftsquartiere. Eine Vorreiterrolle nehmen hier Deutschland und Österreich ein, welche bereits *Mieterstrommodelle* und *Energie-Contracting-Konzepte* rechtlich ermöglichen.

Im Rahmen dieser Diplomarbeit wird die Wirtschaftlichkeit ausgewählter Geschäftsmodelle unterschiedlicher Akteure untersucht. Relevante Stakeholder stellen die Wohnungswirtschaft, die Energiewirtschaft und andere externe Unternehmen (Drittanbieter) dar. Hierfür wird ein MATLAB Optimierungsmodell entwickelt, welches den Gewinn des Contractors oder des Energiesystem-Anbieters maximiert. Gleichzeitig wird die Wirtschaftlichkeit des Contractors so eingeschränkt, dass die Contracting-Maßnahme im Quartier stets zu einer Energiekostenreduktion für die MieterInnen und EigentümerInnen führen muss.

Die Ergebnisse zeigen, dass *Energie(liefer)contracting* bereits höchst profitabel für den Contractor als auch für die MieterInnen/EigentümerInnen ist. Die betrachteten Geschäftsmodelle sind durchgehend wirtschaftlich, wobei die exakten Zahlen stark von den ökonomischen Parametern Zinssatz und Abschreibdauer abhängig sind. Zudem sind jene Modelle zu favorisieren, bei welchen die Energiepreise nicht a priori festgesetzt sind, sondern das Modell ein Optimum zwischen Technologiekapazität und Verkaufspreis eruieren kann. Nutzungsdurchmischung im Quartier, hohe Energiepreise aus dem Netz (siehe deutscher Strompreis und Fernwärme) und das elektrische und thermische Netz als möglicher Überschussspeicher wirken sich besonders positiv auf die Wirtschaftlichkeit aus.

Künftig gilt es, die regulatorische Weiterentwicklung auf diesem Gebiet, aber auch die Informationsverbreitung unter relevanten Stakeholdern zu verstärken. Zusätzlich sollen - neben der Entwicklung weiterer innovativer Geschäftsmodelle - künftig auch Elektrofahrzeuge und diverse Speicher in Contracting-Angebote eingebunden werden.

# Contents

# 1. Introduction

## 1.1. Background and motivation

To achieve national and international climate goals, such as defined in the Paris agreement and the Austrian National Energy and Climate Plan (NEKP), the shift from fossil fuels to renewable energies and the focus on energy demand reduction through efficiency measures are essential. Especially in the building sector, high energy savings can be achieved with the help of active and passive retrofitting strategies and stringent requirements concerning energy demand and local energy generation. The building sector offers the framework to advance in the area of integrated energy systems, also called sector coupling, to reduce the demand of fossil fuels for electricity, heating and mobility. Moreover, decentralization of energy supply, mainly through local renewable energy technologies such as photovoltaics (PV), is seen as an essential contribution to the sustainable energy transition. Furthermore, electricity sharing in buildings is made possible by recent regulatory adaptions that can enhance the distribution of local renewable and/or energy efficient energy technologies. However, due to great financial barriers concerning the installation of local energy systems, new business models for a wide variety of different stakeholders are to be established and their profitability still needs to be examined.

*Energy contracting* and *tenant electricity sharing* models (see definitions of terms in Sections 1.2.1 and 1.2.2) offer new possibilities to increase the share of renewable and/or efficiently generated energies in the grids. At the same time, making housing, education and working cheaper and more attractive and additionally generating profit for the system provider. These models need to be further investigated in order to highlight advantages in more detail and to achieve broad application.

## 1.2. Definition of terms

### 1.2.1. Energy contracting

*Energy contracting* is a contractual energy service settled between a building owner and a service provider (contractor) with the aim of reducing energy consumption and energy costs. Hereby, two main forms can be distinguished:

- *Energy performance contracting* (German: Energiespar-Contracting ESC) aims at optimizing the energy system (energy generation and consumption) through the contractor, whereas energy savings are contractually guaranteed upon in a set time period. Upfront investment costs as well as maintenance costs are refinanced by annual energy cost savings. Additional savings can be considered to be a profit for the building owner.

- *Energy supply contracting* (German: Energieliefer-Contracting ELC), on the other hand, is an energy service, in which the contractor is responsible for the planning, financing, construction, operation, maintenance and/or fuel purchase of the energy system. Costs (for service and investments) are refinanced through the sale of energy (heating, cooling, electricity, vapor, compressed air) to the building owner.

There also exist mixed forms of energy contracting and altered concepts such as *plant contracting* (*technical facility management*) and *financing contracting*. *Energy supply contracting* for electricity can be carried out taking into account the regulations for *tenant electricity sharing* (see Section 1.2.2) [12] [13] [58].

In this work, the focus is on *energy supply contracting* for heat and electricity (as part of a *tenant electricity sharing* concept), whereas regulatory settings in Austria and Germany are explored and challenges depicted. Different business models are examined and rentabilities are analyzed in order to show the optimal stakeholder and energy system constellation for *energy (supply) contracting* (see Section 1.2.2).

### 1.2.2. Tenant electricity sharing

The term *tenant electricity sharing* (German: Mieterstrom) refers to decentrally generated PV, other renewable or block-heat power plant (micro or mini combined heat and power $\mu$/mCHP) electricity which is locally shared by tenants (or owners in general). Electricity sharing is possible in one (apartment) building or various buildings in physical approximity (e.g. urban neighborhoods). These sharing models are sometimes combined with storage facilities. Additionally, there must be no transmission through the public electricity grid. The direct, shared electricity is supplied by providers/operators (housing companies, contractors or tenant associations) to the tenants. Furthermore, excess electricity from decentralized generation which cannot be used on-site is fed into the public grid. The additional electricity - to meet demand - is supplied by the public grid.
*Tenant electricity sharing* can be included in an *energy contracting* model (see Section 1.2.1), but can also be installed by the tenants/owners themselves [83] [6] [28] [58].

This thesis focuses on *tenant electricity sharing* by which electricity is generated by PV systems, both building-attached (roof) and building-integrated (facade) and mini combined heat and power systems (mCHP). Mini CHP systems, in contrast to micro

CHP systems, have higher capacities (over 100 $kW_{th}$) and can supply several buildings with energy [11] [86].

## 1.3. Research questions

The aim of this thesis is to define the involved stakeholders of *energy (supply) contracting* and *tenant electricity sharing* models in a first step and to concisely analyze some of their business models as well as the current legal framework of Austria, Germany and the European Union. This knowledge is then implemented into a profitability optimization model for a mixed urban neighborhood, consisting of an apartment-, an office- and a school building, in order to determine the most optimal energy system configuration. The profitability for both the contractor and the tenants/owners is examined. The sensitivities, such as load profiles, energy- and $CO_2$ prices, technology costs and roof availability are investigated.

The optimization model developed in MATLAB maximizes the monetary profit for the contractor (or provider of the energy system), while taking into account the tenants' and other users' goal of energy cost reduction compared to the default system. This thesis helps in the decision-making process of selecting the optimal business model for contracting or electricity sharing for a specific building or neighborhood and its usage composition. By taking into account the contractor's goal of profitability and the client's aim of energy cost reduction simultaneously, a win-win situation can be achieved. Further considerations like the engagement of external service providers, rent for roofs/basements and the additional offering of energy performance contracting measures (e.g. the increase of insulation and the installation of efficient lighting) extend the question of profitability for the contracting parties involved.

Conclusions from the model are drawn for building renovation strategies in terms of contracting business models, optimal funding, future scenarios for the building stock and further research.

## 1.4. Structure of thesis

Chapter 2 gives a concise overview of the state of the art of *energy contracting*, whereas the legal situation in the EU, Austria and Germany is discussed. Furthermore, the current research concerning *tenant electricity sharing* and *energy contracting* is presented. Existing business models and the involved stakeholders are described.

In Chapter 3, the method of the thesis and the developed MATLAB optimization model are outlined. The examined use cases, the energy technology options and the gathered data are presented. Furthermore, the flow chart of the model as well as the mathematical foundation for the optimization are described.

Chapter 4 presents the results for the following use cases:

- Various constellations of energy technology options
- Gas or district heating (DH) as default heating systems
- Business cases discussed in Chapter 3
- Sensitivity analyses

Conclusions concerning the results and state of the art are drawn in Chapter 5 and a future outlook for possible development is given.

# 2. State of the art

## 2.1. Legal and regulatory situation

*Energy (supply) contracting*, especially combined with (PV) electricity supply, touches a wide range of laws and directives throughout the fields of the housing industry, the commercial and the energy sector. The European Union aims at increasing its share of renewable energies by enabling profitable business cases. Some concepts of the recently established EU rulebook *Clean energy for all Europeans package*[1] (short: Clean Energy Package) are discussed, although the exact implementation into national laws until 2020 and 2021 cannot be predicted. Furthermore, Austrian and German legislature is discussed as these countries are pushing contracting and electricity sharing in apartment buildings as profitable business models. Due to the different legislative frameworks in Austria and Germany, both countries with their respective regulations concerning heating and electricity supply in the contracting setting are presented concisely.

### 2.1.1. European Union: Clean Energy Package

The Commission's aim is for the EU to take the lead in the transition to an environmentally friendly energy system. Specifically, it intents to treat energy efficiency as a top priority, to become the world's technology leader in renewable energy and to provide a fair service for consumers. The *Clean Energy for all Europeans Package* of 2019 consists of seven pieces of legislation [34]:

- the Building Efficiency Directive,
- the Energy Efficiency Directive,
- the Renewable Energy Directive,
- the Governance Regulation,
- the Electricity Market Directive,
- the Electricity Market Regulation and
- the ACER (Agency for the Cooperation of Energy Regulators) Regulation

The Renewable Energy Directive shall provide for renewable energy communities (REC) to be possible which produce, consume, store and sell renewable energy. Local grid tariffs for the usage of the low voltage grid shall be established. Furthermore, the Electricity Market Directive aims at setting the framework for citizen energy communities (CEC)

[1] The Clean energy package was approved by the European Parliament on 03/26/2019.

that also produce, consume and store local renewable energy and provide energy services, however, the focus is on the distribution of energy. For these communities, a separate distribution grid for local energy is installed [66] [34].

The implementation of the EU directives and regulations into national laws is set for 2019 and 2020.

### 2.1.2. Austria

In Austria, *energy contracting* involves the regulatory framework of

- the *Energy Efficiency Act* (German: Energieeffizienzgesetz EEffG) which aims at reducing energy consumption,
- the *Green Electricity Act* (German: Ökostromgesetz) with its aim to expand renewable energy generation,
- the *Green Electricity Feed-In Tariff Regulation* (German: Ökostrom-Einspeisetarif-verordnung),
- the *Green Electricity Compensatory Payment Regulation* (German: Ökostromförder-beitragsverordnung) and
- the *Electricity Industry and Organization Act* (German: Elektrizitätswirtschafts- und -organisationsgesetz ElWOG) with its 2017 amendmend concerning 'Community Generation Plants' (German: gemeinschaftliche Erzeugungsanlagen) [15].

Additionally, provisions of the Housing Law, Building Codes (for every federal state of Austria, mostly derived from the *OIB guidelines*) and regulations concerning the Housing Subsidies (German: Wohnbauförderung) need to be considered as well as other norms and regulations [15].

Depending on the building and apartment residents,

- the *Tenancy Act* (German: Mietrechtgesetz MRG) (if a rented item is not subject to the MRG, the provisions of the *General Civil Code* (ABGB) are applicable),
- the *Law of Condominiums* (German: Wohnungseigentumsgesetz WEG) or/and
- the *Limited Profit Housing Act* (German: Wohnungsgemeinnützigkeitsgesetz WGG) are applied [38].

The legal implementation of *energy supply contracting* is easiest in new construction buildings (especially if the contractor is already integrated in the planning phase) or in an existing building that is used by one entity, i.e. there are not various tenants or apartment owners [38].

**Heat/energy supply contracting for buildings considered in the Tenancy Act MRG**
If the switch to *energy supply contracting* does not affect the direct living area of the tenants and there already exists a central heating supply, the tenants have no opportunity

to object. In the case of the landlord offering the heat supply, the tenants only have to pay the operating costs of the system, such as the costs for fuel, regular maintenance and more. The costs of maintaining operation, such as repairs and the investment costs of a new system, do not have to be paid by the tenant. If an external contractor installs the new heating system, operating and investment costs can be allocated to the tenants. Furthermore, the efficiency dictate has to be taken into account at all times which obligates the landlord to pick the most economical contracting offer at market prices. Additionally, if the heat supply contract is not signed with the landlord but directly with the individual tenants, the provisions of the *Consumer Protection Act* (German: Konsumentenschutzgesetz KSchG) must also be observed. The situation is different if the apartments are heated with individual stoves or floor heating systems. In this case, the tenants must agree to be connected to the central heating supply system [38].

#### Heat/energy supply contracting for buildings considered in the Law of Condominiums WEG

In order to apply *heat/energy supply contracting*, a simple majority of condominium owners is sufficient. This involves building maintenance measures, energy efficiency measures (e.g. measures for *energy performance contracting*), maintenance of existing heat supply systems and the renewal of the entire heating system, if economically viable.
Unanimity is not required and the court can uphold the decision if it concerns improvements that benefit all owners. The contracting contract is signed with each individual condominium owner. If an apartment is sold, the new owner enters into the heat supply contract [38].

#### Heat/energy supply contracting for buildings considered in the Limited Profit Housing Act WGG

*Energy supply contracting* is applicable for non-profit housing associations as well, as long as the measures do not interfere with the private area of the tenants (if this is the case, the tenants have to approve based on the MRG) . The energy, e.g. heat, is then paid by the tenants [38]. In contrary to buildings considered in the MRG and WEG, the WGG allows saved operating (energy) costs to be used to finance energy-saving maintenance measures, including central heating systems. Nevertheless, cost neutrality for the tenants concerning energy costs has to be guaranteed [53].

#### 'Community Generation Plants' in conformity with the Electricity Industry and Organization Act

The amendment of the *Electricity Industry and Organization Act ElWOG* of 2017 enables tenants and owners to share and consume electricity of a 'Community Generation Plant' (PV, local CHP or other energy technologies). Through the joint installation and operation of such a plant, previously only consumers of electricity can jointly generate electricity, use the generated electricity for their own purposes and thus become self-sufficient to a certain extent [29].

Electricity from 'Community Generation Plants' is not charged with grid costs for the consumers. These plants are not bound to the number of included buildings, property lines or propertyship, but, however, must be located in the vicinity and must have only one house service connection [68] [66].

Legally, the following *tenant electricity sharing* models are possible (inter alia):

- Self-supply for tenants: The building owner finances the electricity system and provides the tenants with electricity free of charge. Housing associations can refinance the investment via the maintenance and improvement contribution (German: Erhaltungs- und Verbesserungsbeitrag EVB) paid by the tenants.
- Self-supply for association/cooperative: The tenants/owners form an (energy) cooperative to finance, operate and maintain the electricity system. All requirements regarding financing costs, energy costs and cash flows are laid down in the statutes of the association.
- Contracting for external business: An external business finances, operates and maintains the electricity system and charges the tenants for the locally produced electricity with a price per kilowatt hour or a fixed rent for a period of time.
- Contracting for energy supplier: An energy supply company (ESCo) finances, operates and maintains the electricity system and charges the tenants for supply. Additionally, the operator offers the residual grid electricity to the tenants as well [29].

**Funding for energy contracting**

There do not exist specific funding programs for *energy supply contracting*. Nevertheless, energy technologies such as PV systems are being subsidized by the state, federal states and/or municipalities. However, there does exist funding for *energy performance contracting* in Upper Austria. It is stated in literature that *energy performance contracting* is likely to be profitable for buildings with energy costs of more than 50 000 €/year (see [42]) which is forwarded to the funding scheme 'Energy Conctracting Program of Upper Austria' [41].

### 2.1.3. Germany

The regulations concerning *energy supply contracting* in Germany are based on

- the *Renewable Energies Act* (German: Erneuerbare-Energien-Gesetz EEG) which aims at increasing the share of renewable energies in the grids,
- the *Energy Economics Act* (German: Energiewirtschaftsgesetz EnWG) to secure an efficient and environmentally friendly energy supply,

- the *Combined Heat and Power Act* (German: Kraft-Wärme-Kopplungsgesetz KWKG) concerning i.a. block-heat power plants,
- the *Energy Savings Act* and the *Energy Savings Regulation* (German: Energieeinspargesetz EnEG und -verordnung EnEV) to reduce energy consumption by enforcing energy efficiency measures and
- the *Renewable Energies Heat Act* (German: Erneuerbare-Energie-Wärmegesetz EEWärmeG) for expanding the application of renewable heating and cooling [60] [50] [65].

Additional regulation can be found in

- the tenancy law, which is included in the *German Civil Code* (German: Bürgerliches Gesetzbuch BGB),
- the *Heat Supply Regulation* (German: Wärmelieferverordnung WärmeLV),
- the *Energy Service Act* (German: Energiedienstleistungsgesetz EDL-G),
- the *Act for the Digitalization of the Energy Transition* (German: Gesetz zur Digitalisierung der Energiewende) and
- the entire German tex regulation (in particular the *Trade Tax Act* (German: Gewerbesteuergesetz GewStG) and the *Corportation Tax Act* (German: Körperschaftsteuergesetz KStG)) [60] [50] [65].

Concerning *heat supply contracting* in Germany, the housing industry is not homogeneous and different laws and regulations apply for real estate companies / cooperatives, condominium owner's associations and private building owners [50].

**Heat/energy supply contracting for buildings considered in the tenancy law in the German Civil Code BGB**

The tenant must pay for the operating costs for the heat and/or hot water, if the operation of the central heating system is changed to an independent commercial supply of heat. For this, the heat must be supplied with improved efficiency from a new heat supply system (or a grid) and the costs of the heat supply may not exceed the operating costs for the previous self-supply of heat and hot water (cost neutrality) [50] [43].

Furthermore, one-off costs are not operating costs (preparation of a concept for energy efficiency management, modernisation measures etc.) and can not be apportioned by the landlord to the tenants [65].

The *Ordinance on General Conditions for the Supply of District Heating* (German: Verordnung über Allgemeine Bedingungen für die Versorgung mit Fernwärme AVBFernwärmeV) provides for 10 year heating supply contracts with the possibility of a 5-year extension (individual agreements longer than 10 years are possible) [50].

### Heat/energy supply contracting for buildings considered in the Law of Condominiums WEG

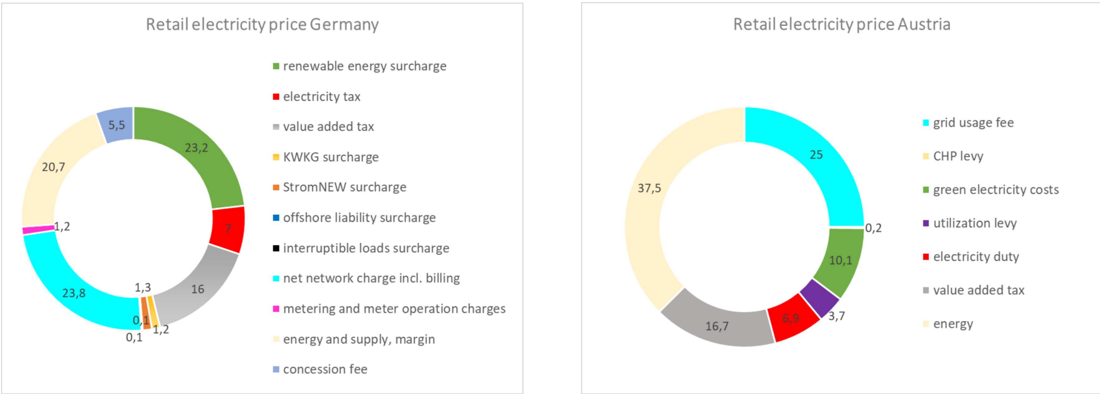
Structural modifications and expenses that go beyond the maintenance or repair of the common property may be decided or can be demanded if every owner, whose rights are impaired, agrees. However, modernization measures or adaptation of the common property to the state of the art, which do not change the character of the housing estate and do not unreasonably disadvantage any owner in relation to others can be agreed upon with a three-quarter majority of the condominium owner's association. Furthermore, challenges concerning cost neutrality and applicable time limits can arise for owners that rent their property. Moreover, new construction offers favourable conditions for the implementation of contracting in condominium owner's associations [65] [50].

### Tenant Eletricity Sharing in conformity with the Renewable Energies Act EEG and the Energy Economics Act EnWG

Different *tenant electricity sharing* models have been implemented in Germany for years based on the *Energy Economics Act EnWG*. The law designates operators of these local plants as energy suppliers, but they are subject to fewer obligations than typical energy supply companies (ESCos) since only one customer system is installed and operated. Furthermore, the law provides for the comprehensive electricity supply of the consumer (tenant, owner, user), including the residual grid electricity. The contract between the provider or contractor is signed for one year with the possibility of extension for another. The entire energy price (local and from the grid) may not exceed 90% of the basic supply tariff [65].

Since the amendmend of the *Renewable Energies Act EEG* of 2017, direct subsidies for shared PV systems are granted as a bonus, making PV *tenant electricity sharing* models more profitable. This bonus applies only for PV systems of a maximum size of 100 kWp. The electricity can be distributed within the building(s) or in direct spatial connection (without using the public grid). Additionally, the building(s) need to have a minimum of 40% of residential usage. Electricity from *tenant electricity sharing* models is charged with the full EEG-levy (see also Figure 2.1). For local CHP systems, a bonus is established for the electricity that is not fed into the grid [65] [39].

Since the full EEG levy needs to be paid in *tenant electricity sharing* models, those subsidies enhance economic competitiveness with PV systems for e.g. single family homes. For *tenant electricity sharing* models, no grid costs and concession fees have to be paid. Figure 2.1 (a) shows the detailed electricity price shares in percent for private households with an electricity demand of 2500 to 5000 kWh for 2018 in comparison to Austria (b). In absolute numbers, the current electricity price for Germany is approximately 0.31 €/kWh, while in Austria consumers pay 0.20 €/kWh on average [35] [23].




(a) (b)

Figure 2.1.: Shares in percent of retail electricity price for (a) Germany (adapted from [8]) and (b) Austria (adapted from [16]).

Additionally, housing companies profit from an extended trade tax reduction. However, the reduction does not apply if the company carries out other transactions in addition to the management of its own real estate property. These transactions include the electricity supply of tenants from their own plants, often leading to the formation of subsidiaries. Furthermore, (non-profit) housing associations are only tax-exempt in their rental business if income from the supply of electricity from *tenant electricity sharing* models does not exceed a share of 20% of the total income (applicable only for PV and not local CHP electricity) [65] [67] [22].

#### Funding for energy contracting

There exist few independent contracting funding programs, since profitability on the market is given. Nevertheless, the subsidies for PV and local CHP *tenant electricity sharing* can be considered as funding although with the purpose of reducing the EEG levy. Additionally, energy technologies such as PV systems are being subsidized by the state, federal states and/or municipalities. Furthermore, some environmental funding and energy audit programs are applicable (see 'KfW funding' and 'Contracting-Check'). Some federal states support the application of energy efficiency measures (e.g. 'GREEN invest' Thüringen) [10] [14] [20].

## 2.2. Current research in the field

A selection of current literature concerning *tenant electricity sharing* as well as *energy contracting* is given in the following.

### 2.2.1. Tenant electricity sharing

The changing legislative landscape in (European) countries leads to the application of *tenant electricity sharing* models in apartment buildings and urban neighborhoods, offering increased profitability for energy contractors. PV electricity sharing enhances self-supply of tenants while contributing to an increase in renewable generation and financial benefits for tenants [63]. Various business models for PV systems in multiapartment buildings are discussed in [27]. [64] presents barriers for shared PV implementation, such as the existing building stock and the regulatory framework. Policy and market challenges, as well as feed-in-tariffs for building PV are examined in [89]. Business models for the deployment and operation of customer-sited PV systems by solar firms are compared in [78]. [36] examines local energy sharing possibilities for energy from cogeneration plants within mixed-usage buildings.

### 2.2.2. Energy contracting

[26] investigates economic profitability for various heating systems in addition to PV electricity sharing. Renewable energy business models for utilities on customer-property are discussed in [62]. *Energy performance contracting* models are presented on the basis of a detailed literature research in [69]. These models can overcome barriers concerning retrofitting of the existing building stock, as examined in [59]. [25] focuses on sensitivities for the profitability of *energy performance contracting* in office buildings, while [88] points out success factors for hotel buildings. Comprehensive definitions, existing contracts and business models are presented in [47]. While a great research emphasis lies on *energy performance contracting*, few studies have been conducted examining the profitability of *energy supply contracting*. A combination of both contracting forms in public buildings, residential, commerce and industry is researched in [4]. [74] presents barriers of *energy contracting* and investigates how *energy supply contracting* can reach broader application.

## 2.3. Existing business models and involved stakeholders

The current legal situation in Austria and Germany enables a wide variety of stakeholders to take part in the *energy contracting* business (see Table 2.1). For this thesis, the focus is on *energy supply contracting*, while some business models examined take into account additional measures of *energy performance contracting* as well. It can be observed that contractors (or providers of the energy system in general) can be entities of the property sector, the energy industry or can be other external businesses (third parties).

**Property sector**

Housing companies, other property developers and private investors are usually not seen as contractors, since they are the owners of the building(s), but can be providers of the energy system. These entities supply their tenants (private, businesses, associations etc.) with heat, if a central heating system is installed. Heat from gas floor heating systems are settled directly between the tenants and the energy supply company (ESCo). Electricity from local energy technologies (PV, mCHP) can be offered to the tenants and for other services (such as charging stations for electric vehicles) via a *tenant electricity sharing* model. This can be provided either as self-supply for the respective consumers or identical to *energy supply contracting* for electricity - also depending on the legal possibilities. A further variant for the company would be to lease the electrical, but also thermal energy system to the tenants for a fixed rent ('Rent Model'). This self-supply for the tenants leads to a lower billing effort for the company/investor, but also gives the tenants little incentive to save energy [29] [19] [21] [28] [85].

A housing association represents a special case since the tenants are co-owners of the building. Therefore, this constitutes a form of *tenant electricity sharing*, in which the investor, operator and consumer is the same party. Furthermore, a subsidiary of a housing company represents a typical contractor, often established to facilitate taxing challenges concerning the selling of local energy to tenants [29] [19].

**Energy sector and external businesses**

Businesses from the energy sector offering contracting can be ESCos, municipal utilities and (citizen) energy cooperatives or energy companies. These entities represent typical contractors, whereas (citizen) energy cooperatives often realize contracting projects for their own members, making the investor, operator and consumer the same party. This could lead to a lower profit orientation. Furthermore, ESCos can also offer 'Enabling Models' in which the entire locally generated energy is sold by the building owner to the ESCo and is redistributed to the tenants for lower prices compared to retail energy prices. This model dates from times before *tenant electricity sharing* models were legally possible [19] [87] [57] [31].

Additionally, third party companies can constitute energy contractors for all sorts of tenants and property owners such as private, business and public entities [19].

| Contractors/providers | | | Host institution/recipient | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Housing company (HC) | Association/ cooperation members | Tenants (private, w/o cooperative members) | WEG or property manager | Individual private owners (SFH/ TFH) | Social services (e.g. kindergarten, retirement homes) | Public institutions (e.g. schools, hospitals, public offices) | SMEs and other businesses, associations | Agricultural businesses |
| | **Property sector** | Housing company (HC)/ property developer/ private investor [1] | - | - | T/S(?) | T | T | T | T | T | - |
| | | especially: Housing association [2] | - | T/S | - | T | T | - | - | - | - |
| | | especially: Subsidiary of a HC | - | - | C | C | C | C | C | C | C |
| | | Condominium owner's association (Ger.: Wohnungseigentümer-gemeinschaften WEG)/ property managers | - | - | T/S | - | T/S | - | - | - | - |
| | **Energy sector** | ESCo | C | C | C | C | C | C | C | C | C |
| | | especially: municipal utility | C | C | C | C | C | C | C | C | C |
| | | especially: green power supplier | C | C | C | C | C | C | C | C | C |
| | | (Citizen) energy cooperative [3]/ GbR [4] | C | C/S(?)[5] | C | C | C | C | C | C | C |
| | | Energy company (w/o cooperatives, mostly GmbH or associations) [6] | C | C | C | C | C | C | C | C | C |
| | Other **external service provider** | (mostly corporations) | C | C | C | C | C | C | C | C | C |

S...tenant electricity sharing as self-supply (must be individually investigated)
T...tenant electricity sharing for consumption based price (analogous to energy supply contracting for electricity)
} for electricity
C...energy supply contracting (tenant electricity sharing included) } for electricity and heat

[1] Obtained from [19].
[2] Obtained from [19].
[3] Contracting often in combination with service providers, technical experts or green power suppliers (e.g. Polarstern), see [21]. Also, prosumers energy communities (Ger.: Prosumentenenergiegenossenschaft) are considered [28].
[4] Obtained from [19] and [85].
[5] Self-supply for electricity and heat possible (must be individually investigated).
[6] Obtained from [19] and [85].

Table 2.1.: Possible stakeholders in energy supply contracting according to literature

# 3. Method and model

## 3.1. Examined contracting business cases

Following on the literature review of existing business models in *energy supply contracting*, depicted in Table 2.1, certain business cases are selected in order to examine profitability for both the contractor and the tenants. Moreover, the great variety of business models available on the market is shown. The selected and discussed contracting use cases in this thesis are shown in Table 3.1.

| Contractor/ provider | Model | Interest rates, times of depreciation | Optimization problem | Notes |
|---|---|---|---|---|
| Housing association /private investor | **Full Contracting**: contractor invests, installs and operates/maintains system | 1.7% (inflation) / 3%<br>20 years | $\max_{P,(p)} G = \Sigma p \cdot P - \Sigma C$<br>→ p...energy price paid by tenants<br>→ P...amount of power/energy consumed by tenants<br>→ C...costs on contractor side<br>**optimization variables:**<br>• for energy supply contracting: $P$<br>• for additional energy efficiency measures: $P, p$ | • price for heat could rise *<br>• price for local electricity has to be lower for tenants to join model, price for grid electricity paid by tenants (residual electricity suppliers chosen by tenants)<br>• all tenants take part in model |
| | **Rent Model**: contractor refinances investment via rent of tenants | 3%<br>20 years | | • refinancing of investment via rent paid by tenants |
| | **Full Contracting with Energy Efficiency Measures**: taking into account additional measures, such as increase of insulation, efficient lighting | 3%<br>20 years | | • see 'Full Contracting' housing association<br>• additional costs for energy efficiency measures, but possibility for higher energy prices (total product p*P has to be lower) |
| Other external provider | **Full Contracting**: contractor invests, installs and operates/maintains system | 12%<br>5 years | | • prices for heat cannot rise**<br>• price for local electricity has to be lower for tenants to join model, price for grid electricity and gas paid by tenants (residual energy suppliers chosen by tenants)<br>• What if only 50% of tenants take part in model? |
| Energy industry (ESCo, municipal utility) | **Full Contracting**: contractor invests, installs and operates/maintains system | 7%<br>10 years | | • price for heat (in total) cannot rise**<br>• price for electricity (in total) has to be lower for tenants to join model<br>• tenants have to buy energy from contractor when joining model<br>• contractor provides two prices for local and residual energy (residual energy price is higher compared to default case)<br>• What if contractor has to pay rent for roof and basement? |
| Housing association + ESCo | **Enabling Model**: contractor sells total electricity to ESCo and is then sold to tenants | 3%<br>20 years | | • all energy is sold to external ESCo (no direct distribution to tenants) |
| (Citizen) energy cooperative | **Full Contracting**: contractor invests, installs and operates/maintains system | 3%<br>25 years | $\max_{P} P_{local\_total} = \Sigma P_{local}$<br>→ P...amount of local power/energy consumed by tenants | • price for heat cannot rise**<br>• price for electricity has to be lower for tenants to join model; price for grid electricity and gas paid by tenants (residual energy suppliers chosen by tenants)<br>• What if external service provider has to be paid? |
| | **Full Contracting with Energy Efficiency Measures**: taking into account additional measures, such as increase of insulation, efficient lighting | 3%<br>25 years | | • see 'Full Contracting' energy cooperative<br>• additional costs for energy efficiency measures, but possibility for higher energy prices (the total product p*P has to be lower) |

... forms of *Energy Supply Contracting* only

... additional *Energy Efficiency* measures applied

* legally, price for heat could rise (for housing association) due to modernization of heating system. For the model, energy costs for tenants are even lowered.

** legally, price for heat cannot rise. For the model, energy costs are even lowered.

Table 3.1.: Examined contracting business cases

## 3.2. Building configuration and location data

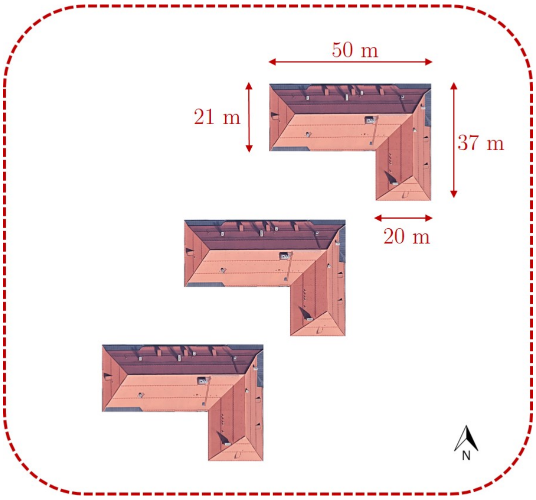



Figure 3.1.: Assumed neighborhood and dimensions (building detail from [30])

For the model, a mixed urban neighborhood consisting of three area- and orientation-identical buildings (one residential building, one office building with a supermarket and one school building with a swimming pool) is chosen (see Figure 3.1). The net floor space of each building is approximately 7000 m$^2$, resulting in 70 housing units of about 100 m$^2$ each for the residential building. The building structure of each building is derived from [77].

The following data sources for one year are used to complete the data set for the neighborhood:

1. Load data for the **residential building**
    - The electricity load profile is generated by the LoadProfileGenerator [45] for 70 housing units of different occupation with the location of Vienna
    - The heat load profile is acquired from Austrian Gas Clearing & Settlement AGCS, for an annual heating demand for each of the 70 housing units of 10 000 kWh [1][24]
2. Load data for the **office building with a supermarket**
    - The electricity load profile is collected as OpenEI data [51] for the location of Boston in the United States of America[1], while the data is adapted to Austrian standards according to [52], [33] and [84][2]

[1]The climate of Boston, USA, is similar to Austrian conditions. Furthermore, the energy profiles are adapted to fit Austrian standards.

[2]The electricity demand of the 6500 m$^2$ office part of the building is scaled to approximately 135 kWh/m$^2$, whereas the electricity demand for the 500 m$^2$ supermarket is scaled to about 330 kWh/m$^2$.

  - The heat load profile is also acquired as OpenEI data (see above) and also adapted to reflect Austrian characteristics[3]

3. Load data for the **school building with a pool**
  - The electricity load profile is derived from [77] for the location of Munich, Germany[4]
  - The heat load profile is collected from [77] (see above)
4. **Temperature** data for Coefficient of Performance (COP) calculations for the heat pump (HP) system are derived from [48] for the location of Basel, Switzerland[5]
5. **PV generation** data per kilowatt peak (kWp) in all cardinal directions and with different tilts is acquired from [61] for the location of Vienna

All data is adjusted accordingly to fit the weekdays of the year 2015 (not a leap year), starting with a Thursday on January 1. Additionally, the data sets are derived or adapted to depict quarter-hourly profiles for one year.

## 3.3. Default heating systems

Two options of default heating systems are examined: central gas heating and district heating (DH). Further information concerning the default heating system used for the individual use cases can be found in Section 4.2 and in the respective use case chapters of Section 4.3. Additionally, it is assumed that the neighborhood has both a gas and a district heating (DH) grid connection at all times and in all use cases. This provides the possibility to fuel the mini combined heat and power (mCHP) system with gas, even when the buildings are heated by a DH system. On the other hand, the feed-in of thermal energy into the DH grid is possible, even if the neighborhood uses gas heating as the main heating system.

## 3.4. Energy technologies

As installable energy technologies for the model, the following technologies are available:

- A building-attached photovoltaic (BAPV) system on the roof area of the buildings in all cardinal directions with a tilt of 30°,
- a building-integrated PV (BIPV) system on the facade of the buildings in all directions as well (90°-tilt respectively),

[3]The heating demand of the 6500 $m^2$ office part of the building is scaled to approximately 93 $kWh/m^2$, whereas the heating demand for the 500 $m^2$ supermarket is scaled to about 125 $kWh/m^2$.

[4]Munich, Germany, has similar climatic conditions compared to Austria.

[5]Basel, Switzerland, has similar climatic conditions compared to Austria.

- a gas-fired block heat generation unit (mini combined heat and power mCHP unit) and
- an air-to-water heat pump (HP) system.

The maximum installable technology capacities for the model and the sources for technology prices are listed in Table 3.4.

The facade PV system (BIPV) is limited to 50% of the entire facade area with windows, calculated roughly by examining the building structure of the school building investigated in [77] via [30]. The complete roof surface (calculated analogously to the facade area) is assumed to be usable for the installation of a PV system (BAPV). Additionally, shading is neglected in all calculations.

## 3.5. Cost and capacity data

The assumed grid prices ($p_{grid}$), connection prices ($p_{con}$) and maintenance costs ($c_{main}$) - without value-added tax - paid by the contractor or the tenants depending on the use case, can be found in the following Table 3.2.

| | $p_{grid}$ [€/kWh] | $p_{con}$ [€/kW] | $c_{main}$ [€/year] |
|---|---|---|---|
| **Costs for electricity** | | | |
| Default use case | 0.213[6] | 16.47[7] | 50[8] |
| Use case ESCo | 0.200 | 16.47 | 50 |
| Use case Enabling | 0.200 | 16.47 | 50 |
| **Costs for heat** | | | |
| Default use case gas | 0.061[9] | 8.97[10] | 50[11] |
| Use case ESCo gas | 0.055 | 8.97 | 50 |
| Use case Enabling gas | / | / | / |
| Default use case DH | 0.077[12] | 28.51[13] | 50[14] |
| Use case ESCo DH | 0.070 | 28.51 | 50 |
| Use case Enabling DH | 0.070 | 28.51 | 50 |

Table 3.2.: Costs for default energy system

[6] Data obtained from [79]
[7] Data obtained from [79]
[8] Data based on estimation.
[9] Data obtained from [79].
[10] Data obtained from [79].
[11] Data based on estimation.
[12] Data obtained from [75].
[13] Data obtained from [75]
[14] Data based on estimation.

The contractor's revenues for local energy ($p_R$), grid energy resold to the tenants ($p_{R_{grid}}$), energy fed into the grids ($p_{2grid}$) and connection costs passed on to the tenants ($p_{R_{con}}$) can be found in the following Table 3.3, depending on the considered use case.

| | $p_R$ [€/kWh] | $p_{R_{grid}}$ [€/kWh] | $p_{2grid}$ [€/kWh] | $p_{R_{con}}$ [€/kW] |
|---|---|---|---|---|
| **Costs (tenants) and revenues (contractor) for electricity** | | | | |
| Default for use cases | $0.9 \cdot 0.213$ | $0.9 \cdot 0.213$ | 0 | $0.9 \cdot 16.47$ |
| Use case ESCo | $0.8 \cdot 0.213$ | 0.223 | 0 | $0.9 \cdot 16.47$ |
| Use case Enabling | $0.8 \cdot 0.213$ | 0.223 | 0.050 | 16.47 |
| **Costs (tenants) and revenues (contractor) for heat** | | | | |
| Default for use cases gas | $0.9 \cdot 0.061$ | $0.9 \cdot 0.061$ | 0 | $0.9 \cdot 8.97$ |
| Use case ESCo gas | $0.8 \cdot 0.061$ | 0.071 | 0 | $0.9 \cdot 8.97$ |
| Use case Enabling gas | / | / | / | / |
| Default for use cases DH | $0.9 \cdot 0.077$ | $0.9 \cdot 0.077$ | 0 | $0.9 \cdot 28.51$ |
| Use case ESco DH | $0.8 \cdot 0.077$ | 0.087 | 0 | $0.9 \cdot 28.51$ |
| Use case Enabling DH | $0.8 \cdot 0.077$ | 0.087 | 0.040 | 28.51 |

Table 3.3.: Costs for local and grid energy supply for tenants

The following Table 3.4 shows the assumed costs, i.e. investment costs ($C_{I_0}$), installation costs ($c_{inst}$) and maintenance costs ($c_{main}$), and maximum capacities (for PV in all cardinal directions) for the local installable energy systems:

| | $C_{I_0}$ | $c_{inst}$ | $c_{main}$ | max. capacity |
|---|---|---|---|---|
| **PV system** | | | | |
| BAPV (roof) | 994.00 €/kWp[15] | 500.00 €/kWp[16] | | 240 kWp (S)<br>60 kWp (E)<br>120 kWp (W)<br>195 kWp (N) |
| BIPV (facade) | 2 800.00 €/kWp[17] | 710.45 €/kWp[18] | | 30 kWp (S)<br>30 kWp (E)<br>15 kWp (W)<br>45 kWp (N) |
| | | | 250.00 €/year[19]<br>(for all PV) | |
| **mCHP system** | | | | |
| | 1 084.38 €/$kW_{th}$[20] | 5 000.00 €[21] | 1 000.00 €/year[22] | 200 $kW_{th}$ |
| **HP system** | | | | |
| | 859.38 €/kW[23] | 1 000.00 €[24] | 66.67 €/year[25] | 200 kW |

Table 3.4.: Costs for new energy system technologies

## 3.6. Optimization model based on maximum profit for provider

### 3.6.1. Flow chart

The flow chart for the optimization model is depicted in the following Figure 3.2. The model's sequence can be divided into the following steps:

- Selection of the present energy system, the installable technology options, the building composition and the form of *energy contracting*
- Determination of the contracting use case
- Optimization for maximum profit of contractor while reducing the tenant's energy costs

[15] Data obtained from [56].
[16] Data obtained from [70].
[17] Data obtained from [72].
[18] Data obtained from [71].
[19] Data obtained from [76].
[20] Data obtained from [2].
[21] Data obtained from [40].
[22] Data obtained from [81].
[23] Data obtained from [2] and is in line with [3].
[24] Data obtained from [73].
[25] Data obtained from [18].

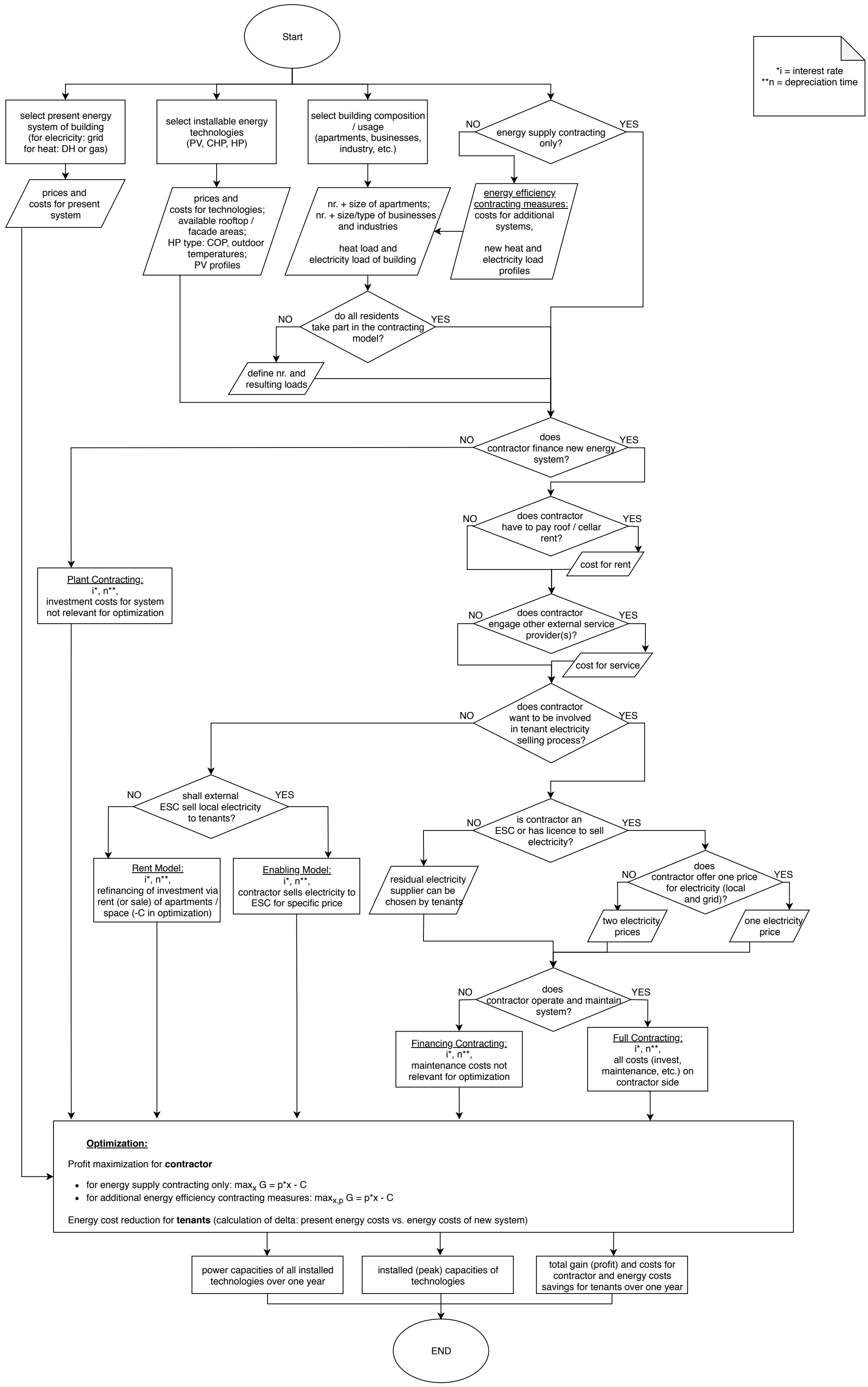



Figure 3.2.: Flow chart for model

### 3.6.2. Implementation of default contracting use case in MATLAB

The model is based on a mixed-integer linear programing (MILP) optimization in MATLAB [46]. YALMIP is used as a toolbox and Gurobi as a solver [44] [32]. In the following Figure 3.5, the variables used in the model are listed and described, while bold symbols represent matrices, italic symbols express vectors (column and row vectors, depending on context) and standard symbols depict scalars. These variables are used in the following equations of Section 3.6.2 and 3.6.3.

**Energy system variables**

| | |
|---|---|
| $\alpha$ | ... annuity factor |
| $\mathrm{b_{gas}}$ | ... binary variable for gas as default heating system |
| $\mathrm{b_{th}}$ | ... binary variable for DH as default heating system |
| COP | ... coefficient of performance of HP system |
| $\mathrm{COP_{Carnot}}$ | ... maximum coefficient of performance possible |
| $\eta_{\mathrm{gas}}$ | ... efficiency of gas boiler |
| $\eta_{\mathrm{CHP_{el}}}$ | ... electric efficiency of mCHP system |
| $\eta_{\mathrm{CHP_{th}}}$ | ... thermal efficiency of mCHP system |
| $\mathrm{f_{COP}}$ | ... reduction factor compared to Carnot COP (set to 0.45) |
| $f_{kWp}$ | ... factor for kilowatt peak of PV system installed |
| i | ... interest rate of examined use case |
| $l_{el}$ | ... electric load |
| $l_{th}$ | ... thermal load |
| n | ... depreciation time of examined entity |
| $P_{el_{grid}}$ | ... electric power from electricity grid |
| $P_{el_{grid2supply}}$ | ... electric power from electricity grid to supply |
| $P_{el_{grid2pump}}$ | ... electric power from electricity grid to HP system |
| $P_{el_{con}}$ | ... connection capacity of electricity grid |
| $P_{gas}$ | ... gas from gas grid |
| $P_{gas_{th}}$ | ... gas from gas grid to boiler heating |
| $P_{gas_{CHP}}$ | ... gas from gas grid to mCHP system |
| $P_{gas_{con}}$ | ... connection capacity of gas grid |
| $P_{th_{grid}}$ | ... thermal power from DH grid |
| $P_{th_{con}}$ | ... connection capacity of DH grid |
| $P_{CHP_{el}}$ | ... electric power from mCHP generation |
| $P_{CHP_{el2supply}}$ | ... electric power from mCHP generation to supply |
| $P_{CHP_{el2grid}}$ | ... electric power from mCHP generation to grid |
| $P_{CHP_{el2HP}}$ | ... electric power from mCHP generation to HP system |
| $P_{CHP_{th}}$ | ... thermal power from mCHP generation |
| $P_{CHP_{th2supply}}$ | ... thermal power from mCHP generation to supply |
| $P_{CHP_{th2grid}}$ | ... thermal power from mCHP generation to grid |
| $\mathrm{P_{CHP_{th_{peak}}}}$ | ... peak/connection capacity of mCHP system |
| $P_{HP}$ | ... thermal power from HP generation |
| $P_{HP_{2supply}}$ | ... thermal power from HP generation to supply |
| $P_{HP_{2grid}}$ | ... thermal power from HP generation to grid |
| $P_{el_{2pump}}$ | ... electric power from all sources to HP supply |
| $\mathrm{P_{HP_{peak}}}$ | ... peak/connection capacity of HP system |
| $\boldsymbol{P}_{PV_{1kW}}$ | ... electric power of one kilowatt peak PV system |
| $\boldsymbol{P}_{PV_{2supply}}$ | ... electric power from PV generation to supply |
| $\boldsymbol{P}_{PV_{2grid}}$ | ... electric power from PV generation to grid |
| $\boldsymbol{P}_{PV_{2HP}}$ | ... electric power from PV generation to HP system |
| $s/e/w/n$ | ... south, east, north or west direction of PV generation |
| 30/90 | ... 30°-tilt for roof BAPV or 90°-tilt for facade BIPV generation |
| $\mathrm{T_h}$ | ... temperature of heat distribution system (set to 35°C) |
| $\mathrm{T_l}$ | ... outside temperature over year |

| **Flag variables for energy systems** | |
|---|---|
| $b_{flag_{PV}}$ | ... binary flag variable, if all or one BAPV/BIPV system is installed |
| $b_{flag_{BAPV}}$ | ... binary flag variable, if all or one BAPV system is installed |
| $b_{flag_{CHP/HP}}$ | ... binary flag variable, if mCHP and/or HP system is installed |
| **Revenue and cost variables** | |
| $b_{ext}$ | ... binary variable, if external provider (e.g. planner) is paid by contractor |
| $b_{HP}$ | ... binary variable, if HP system is installed |
| $b_{CHP}$ | ... binary variable, if CHP system is installed |
| $b_{PV}$ | ... binary variable, if PV system is installed (available in all directions and tilts) |
| $b_{rent_{cellar}}$ | ... binary variable, if rent for basement is paid by contractor |
| $b_{rent_{roof}}$ | ... binary variable, if rent for roof is paid by contractor |
| $C_{fix}$ | ... fixed costs of contractor |
| $C_{I_0}$ | ... investment costs for local energy systems of contractor |
| $C_{var}$ | ... variable costs of contractor |
| $c_{delta}$ | ... energy cost savings for tenants (delta between previous and current costs) |
| $c_{el_{main}}$ | ... annual maintenance costs for electricity connection |
| $c_{gas_{main}}$ | ... annual maintenance costs for gas connection |
| $c_{el_{main}}$ | ... annual maintenance costs for DH connection |
| $c_{ext}$ | ... one-time costs for external provider (e.g. planner) paid by contractor |
| $c_{rent_{cellar}}$ | ... annual rent costs for basement paid by contractor |
| $c_{rent_{roof}}$ | ... annual rent costs for roof paid by contractor |
| $c_{inst_{CHP}}$ | ... one-time installation costs of CHP system |
| $c_{inst_{HP}}$ | ... one-time installation costs of HP system |
| $c_{inst_{BAPV}}$ | ... one-time installation costs of BAPV system |
| $c_{inst_{BIPV}}$ | ... one-time installation costs of BIPV system |
| $costs_{additional}$ | ... additional costs paid by tenants in energy efficiency model |
| $G$ | ... gain/profit of contractor |
| $I_{\alpha_{CHP}}$ | ... investment costs of CHP system multiplied with annuity factor |
| $I_{\alpha_{HP}}$ | ... investment costs of HP system multiplied with annuity factor |
| $I_{\alpha_{BAPV}}$ | ... investment costs of BAPV system multiplied with annuity factor |
| $I_{\alpha_{BIPV}}$ | ... investment costs of BIPV system multiplied with annuity factor |
| $p_{el_{grid}}$ | ... price for grid electricity paid by contractor (in some cases by tenants) |
| $p_{el_{con}}$ | ... price for electric capacity paid by contractor (in some cases by tenants) |
| $p_{gas_{grid}}$ | ... price for grid gas paid by contractor (in some cases by tenants) |
| $p_{gas_{con}}$ | ... price for gas capacity paid by contractor (in some cases by tenants) |
| $p_{th_{grid}}$ | ... price for DH grid heat paid by contractor (in some cases by tenants) |
| $p_{th_{con}}$ | ... price for DH capacity paid by contractor (in some cases by tenants) |
| $pR_{el}$ | ... price for local electricity to tenants as revenue for contractor |
| $pR_{elgrid}$ | ... price for grid electricity to tenants as revenue for contractor |
| $p_{el2grid}$ | ... price for local electricity to grid as revenue for contractor |
| $pR_{el_{con}}$ | ... price for electric capacity as revenue for contractor |
| $pR_{th}$ | ... price for local heat to tenants as revenue for contractor |
| $pR_{thgas}$ | ... price for grid gas for heating to tenants as revenue for contractor |
| $pR_{th_{grid}}$ | ... price for DH grid heat to tenants as revenue for contractor |
| $p_{th2grid}$ | ... price for local heat to DH grid as revenue for contractor |
| $pR_{gas_{con}}$ | ... price for gas capacity as revenue for contractor |
| $pR_{th_{con}}$ | ... price for DH capacity as revenue for contractor |
| $R_{el}$ | ... revenues related to sell of electricity |
| $R_{th}$ | ... revenues related to sell of heat |
| rent | ... annual rent paid by tenants to contractor |

Table 3.5.: Variables and explanation

The model optimizes for a non-leap year in quarter-hourly intervals, leading to N=35040 time steps. The one-time investment and installation costs are multiplied with the annuity factor to shift them into yearly costs of a constant amount over the examined period. This puts the costs of the local energy technologies into the perspective of depreciation time of the discussed companies/cooperatives and the life cycle of the energy systems.

The annuity factor is calculated using the following equation:

$$\alpha = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{3.1}$$

The connection capacity of the energy system is defined as the maximum power demanded over the year:

$$P_{el_{con}} = max(P_{el_{grid}}) \tag{3.2}$$

$$P_{gas_{con}} = max(P_{gas_{grid}}) \tag{3.3}$$

$$P_{th_{con}} = max(P_{th_{grid}}) \tag{3.4}$$

To guarantee that power demand is met at all times, the load can be supplied with the following sources:

$$l_{el} = P_{el_{grid2supply}} + P_{CHP_{el2supply}} + \sum_{orien=1}^{8} (\boldsymbol{P}_{PV_{2supply}}) \tag{3.5}$$

$$l_{th} = \mathrm{b_{th}} \cdot P_{th_{grid}} + \mathrm{b_{gas}} \cdot \eta_{\mathrm{gas}} \cdot P_{gas_{th}} + P_{CHP_{th2supply}} + P_{HP_{2supply}} \tag{3.6}$$

The PV generation to supply matrix is portrayed in the following equation:

$$\boldsymbol{P}_{PV_{2supply}} = \begin{pmatrix} P_{PV_{2supply_{s30}}} \\ P_{PV_{2supply_{e30}}} \\ P_{PV_{2supply_{w30}}} \\ P_{PV_{2supply_{n30}}} \\ P_{PV_{2supply_{s90}}} \\ P_{PV_{2supply_{e90}}} \\ P_{PV_{2supply_{w90}}} \\ P_{PV_{2supply_{n90}}} \end{pmatrix}^T \tag{3.7}$$

Additionally, the subsequent contstraints are set for the PV, HP and mCHP system. For the PV system, each kilowatt peak profile for every orientation over the year ($\boldsymbol{P}_{PV_{1kW}}$)

is multiplied by the factor of installed capacity ($f_{kWp}$) in order to determine the entire PV generation for all orientations.

$$\boldsymbol{P}_{PV_{1kW}} \cdot f_{kWp} = \boldsymbol{P}_{PV_{2grid}} + \boldsymbol{P}_{PV_{2supply}} + \boldsymbol{P}_{PV_{2HP}} \tag{3.8}$$

$$P_{el_{grid}} = P_{el_{grid2pump}} + P_{el_{grid2supply}} \tag{3.9}$$

$$P_{el_{2pump}} = P_{el_{grid2pump}} + \sum_{orien=1}^{8} (\boldsymbol{P}_{PV_{2HP}}) + P_{CHP_{el2HP}} \tag{3.10}$$

$$P_{HP} = P_{HP_{2grid}} + P_{HP_{2supply}} \tag{3.11}$$

$$P_{HP} = P_{el_{2pump}} \cdot \mathrm{COP} \tag{3.12}$$

$$\mathrm{COP} = \mathrm{COP_{Carnot}} \cdot \mathrm{f_{COP}} \tag{3.13}$$

$$\mathrm{COP_{Carnot}} = \frac{\mathrm{T_h}}{\mathrm{T_h} - \mathrm{T_l}} \tag{3.14}$$

$$P_{gas} = P_{gas_{CHP}} + P_{gas_{th}} \tag{3.15}$$

$$P_{CHP_{el}} = P_{gas_{CHP}} \cdot \eta_{\mathrm{CHP_{el}}} \tag{3.16}$$

$$P_{CHP_{el}} = P_{CHP_{el2supply}} + P_{CHP_{el2grid}} + P_{CHP_{el2HP}} \tag{3.17}$$

$$P_{CHP_{th}} = P_{gas_{CHP}} \cdot \eta_{\mathrm{CHP_{th}}} \tag{3.18}$$

$$P_{CHP_{th}} = P_{CHP_{th2supply}} + P_{CHP_{th2grid}} \tag{3.19}$$

It is also assumed that e.g. maintenance costs for the BAPV system are only paid once a year, regardless if a system is put on one or more sides of the roof. For this assumption, so-called flag constaints are defined which are set to be true if only one up to all systems are installed.

$$\begin{aligned} \mathrm{b_{flag_{PV}}} \geq (&\mathrm{b_{PV_{s30}}} + \mathrm{b_{PV_{e30}}} + \mathrm{b_{PV_{w30}}} + \mathrm{b_{PV_{n30}}} \\ &+ \mathrm{b_{PV_{s90}}} + \mathrm{b_{PV_{e90}}} + \mathrm{b_{PV_{w90}}} + \mathrm{b_{PV_{n90}}}) \div 8 \end{aligned} \tag{3.20}$$

$$\mathrm{b_{flag_{BAPV}}} \geq (\mathrm{b_{PV_{s30}}} + \mathrm{b_{PV_{e30}}} + \mathrm{b_{PV_{w30}}} + \mathrm{b_{PV_{n30}}}) \div 4 \tag{3.21}$$

$$\mathrm{b_{flag_{CHP/HP}}} \geq (\mathrm{b_{CHP}} + \mathrm{b_{HP}}) \div 2 \tag{3.22}$$

The model maximizes the contractor's gain (G), later called profit, while all revenues diminished by related costs are optimized. Therefore, the objective function can be defined as:

$$\max_{P} \; \mathrm{G} = \max_{P} \left( \mathrm{R_{el}} + \mathrm{R_{th}} - \mathrm{C_{var}} - \mathrm{C_{fix}} \right) \tag{3.23}$$

The following revenue and cost factors are determined and taken into account for the optimization:

$$\begin{aligned} \mathrm{R_{el}} = & \sum_{t=1}^{N}\Big(\sum_{orien=1}^{8}(\boldsymbol{P}_{PV2supply}) + P_{CHP_{el}2supply}\Big)\cdot \mathrm{p_{R_{el}}} + \sum_{t=1}^{N}(P_{el_{grid2supply}})\cdot \mathrm{p_{R_{elgrid}}} \\ & + \sum_{t=1}^{N}\Big(\sum_{orien=1}^{8}(\boldsymbol{P}_{PV2grid}) + P_{CHP_{el}2grid}\Big)\cdot \mathrm{p_{el2grid}} + \mathrm{P_{el_{con}}}\cdot \mathrm{p_{R_{el_{con}}}} \end{aligned} \tag{3.24}$$

$$\begin{aligned} \mathrm{R_{th}} = & \sum_{t=1}^{N}(P_{HP2supply} + P_{CHP_{th}2supply})\cdot \mathrm{p_{R_{th}}} + \sum_{t=1}^{N}(P_{gas_{th}})\cdot \mathrm{p_{R_{thgas}}} \\ & + \sum_{t=1}^{N}(P_{th_{grid}})\cdot \mathrm{p_{R_{thgrid}}} + \sum_{t=1}^{N}(P_{HP2grid} + P_{CHP_{th}2grid})\cdot \mathrm{p_{th2grid}} \\ & + \mathrm{P_{gas_{con}}}\cdot \mathrm{p_{R_{gas_{con}}}} + \mathrm{P_{th_{con}}}\cdot \mathrm{p_{R_{th_{con}}}} \end{aligned} \tag{3.25}$$

$$\mathrm{C_{var}} = \sum_{t=1}^{N}(P_{el_{grid}})\cdot \mathrm{p_{el_{grid}}} + \sum_{t=1}^{N}(P_{th_{grid}})\cdot \mathrm{p_{th_{grid}}} + \sum_{t=1}^{N}(P_{gas})\cdot \mathrm{p_{gas_{grid}}} \tag{3.26}$$

$$\begin{aligned} \mathrm{C_{fix}} = & \mathrm{P_{el_{con}}}\cdot \mathrm{p_{el_{con}}} + \mathrm{P_{gas_{con}}}\cdot \mathrm{p_{gas_{con}}} + \mathrm{P_{th_{con}}}\cdot \mathrm{p_{th_{con}}} + \mathrm{c_{el_{main}}} + \mathrm{b_{th}}\cdot \mathrm{c_{th_{main}}} \\ & + \mathrm{b_{gas}}\cdot \mathrm{c_{gas_{main}}} + \mathrm{b_{flag}}\cdot \mathrm{c_{main_{PV}}} + \mathrm{b_{flag_{BAPV}}}\cdot \mathrm{b_{rent_{roof}}}\cdot \mathrm{c_{rent_{roof}}} + \mathrm{b_{ext}}\cdot \alpha\cdot \mathrm{c_{ext}} \\ & + \mathrm{b_{HP}}\cdot \mathrm{c_{main_{HP}}} + \mathrm{b_{CHP}}\cdot (\mathrm{c_{main_{CHP}}} + \mathrm{b_{flag_{CHP/HP}}}\cdot \mathrm{b_{rent_{cellar}}}\cdot \mathrm{c_{rent_{cellar}}} + \mathrm{C_{I_0}}) \end{aligned} \tag{3.27}$$

$$\begin{aligned} \mathrm{C_{I_0}} = & \mathrm{I_{\alpha BAPV}}\cdot \sum_{orien=1}^{4}(P_{f_{kWp_{BAPV}}}) + \mathrm{I_{\alpha BIPV}}\cdot \sum_{orien=5}^{8}(P_{f_{kWp_{BIPV}}}) + \mathrm{b_{flag_{BIPV}}}\cdot \alpha\cdot \mathrm{c_{inst_{BIPV}}} \\ & + \mathrm{b_{flag_{BAPV}}}\cdot \alpha\cdot \mathrm{c_{inst_{BAPV}}} + \mathrm{I_{\alpha HP}}\cdot \mathrm{P_{HP_{peak}}} + \mathrm{b_{HP}}\cdot \alpha\cdot \mathrm{c_{inst_{HP}}} \\ & + \mathrm{I_{\alpha CHP}}\cdot \mathrm{P_{CHP_{th_{peak}}}} + \mathrm{b_{CHP}}\cdot \alpha\cdot \mathrm{c_{inst_{CHP}}} \end{aligned} \tag{3.28}$$

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

The tenants' energy cost savings as the delta between previous and current energy costs are calculated after the optimization in the default use case, using the following equation (here shown for the case of gas heating as default heating system applied):

$$
\begin{aligned}
\mathrm{c_{delta}} &= \sum_{t=1}^{N}(l_{el}) \cdot (\mathrm{p_{el_{grid}}} - \mathrm{p_{R_{el}}}) + \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}}) \cdot (\mathrm{p_{gas_{grid}}} - \mathrm{p_{R_{th}}}) \\
&+ (max(l_{el}) - \mathrm{P_{el_{con}}} \cdot 0.9) \cdot \mathrm{p_{el_{con}}} + (max(\frac{l_{th}}{\eta_{gas}}) - \mathrm{P_{gas_{con}}} \cdot 0.9) \cdot \mathrm{p_{gas_{con}}} \\
&+ \mathrm{c_{el_{main}}} + \mathrm{c_{gas_{main}}}
\end{aligned} \tag{3.29}
$$

### 3.6.3. Model extensions for discussed business cases in MATLAB

For the individual contracting use cases (see Table 3.1), the model is extended and adapted to portray the contractor's and the tenants' responsibilities. This section features the equations added or adapted in comparison to the default contracting case of Passage 3.6.2 in the same order as the results are listed in Section 4.3.

**Housing association/private investor: Full Contracting**

For this use case, the grid electricity for the HP system and the grid gas for the mCHP system are paid by the provider/contractor. The objective function of this use case is therefore reduced to:

$$
\begin{aligned}
\mathrm{R_{el}} &= \sum_{t=1}^{N}(\sum_{orien=1}^{8}(\boldsymbol{P}_{PV2supply}) + P_{CHP_{el}2supply}) \cdot \mathrm{p_{R_{el}}} + \sum_{t=1}^{N}(P_{el_{grid2supply}}) \cdot \mathrm{p_{R_{elgrid}}} \\
&+ \sum_{t=1}^{N}(\sum_{orien=1}^{8}(\boldsymbol{P}_{PV2grid}) + P_{CHP_{el}2grid}) \cdot \mathrm{p_{el2grid}}
\end{aligned} \tag{3.30}
$$

$$
\begin{aligned}
\mathrm{R_{th}} &= \sum_{t=1}^{N}(P_{HP2supply} + P_{CHP_{th}2supply}) \cdot \mathrm{p_{R_{th}}} + \sum_{t=1}^{N}(P_{gas_{th}}) \cdot \mathrm{p_{R_{thgas}}} \\
&+ \sum_{t=1}^{N}(P_{th_{grid}}) \cdot \mathrm{p_{R_{thgrid}}} + \sum_{t=1}^{N}(P_{HP2grid} + P_{CHP_{th}2grid}) \cdot \mathrm{p_{th2grid}}
\end{aligned} \tag{3.31}
$$

$$
\mathrm{C_{var}} = \sum_{t=1}^{N}(P_{el_{grid2pump}}) \cdot \mathrm{p_{el_{grid}}} + \sum_{t=1}^{N}(P_{gas_{CHP}}) \cdot \mathrm{p_{gas_{grid}}} \tag{3.32}
$$

$$
\begin{aligned}
\mathrm{C_{fix}} &= max(P_{el_{grid2pump}}) \cdot \mathrm{p_{el_{con}}} + max(P_{gas_{CHP}}) \cdot \mathrm{p_{gas_{con}}} + \mathrm{b_{flag}} \cdot \mathrm{c_{main_{PV}}} \\
&+ \mathrm{b_{HP}} \cdot \mathrm{c_{main_{HP}}} + \mathrm{b_{CHP}} \cdot (\mathrm{c_{main_{CHP}}} + \mathrm{C_{I_0}})
\end{aligned} \tag{3.33}
$$

$$C_{I_0} = I_{\alpha_{BAPV}} \cdot \sum_{orien=1}^{4} (P_{f_{kWp_{BAPV}}}) + I_{\alpha_{BIPV}} \cdot \sum_{orien=5}^{8} (P_{f_{kWp_{BIPV}}}) + b_{flag_{BIPV}} \cdot \alpha \cdot c_{inst_{BIPV}}$$
$$+ b_{flag_{BAPV}} \cdot \alpha \cdot c_{inst_{BAPV}} + I_{\alpha_{HP}} \cdot P_{HP_{peak}} + b_{HP} \cdot c_{inst_{HP}}$$
$$+ I_{\alpha_{CHP}} \cdot P_{CHP_{th_{peak}}} + b_{CHP} \cdot c_{inst_{CHP}} \tag{3.34}$$

The energy cost savings for the tenants are determined using the following equation:

$$c_{delta} = \sum_{t=1}^{N}(l_{el}) \cdot p_{el_{grid}} - (\sum_{t=1}^{N}(l_{el} - P_{el_{grid2supply}}) \cdot p_{R_{el}} + \sum_{t=1}^{N}(P_{el_{grid2supply}}) \cdot p_{el_{grid}})$$
$$+ \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}}) \cdot p_{gas_{grid}} - (\sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}} - P_{gas_{th}}) \cdot p_{R_{th}} + \sum_{t=1}^{N}(P_{gas_{th}}) \cdot p_{gas_{grid}})$$
$$+ (max(l_{el}) - P_{el_{con}}) \cdot p_{el_{con}} + (max(\frac{l_{th}}{\eta_{gas}}) - P_{gas_{con}}) \cdot p_{gas_{con}} \tag{3.35}$$

**Housing association/private investor: Rent Model**

This specific use case needs a modification of the optimization model, leading to the deployment of an additional constraint and the adjustment of the objective function:

$$\left(\sum_{t=1}^{N}(P_{el_{grid}}) \cdot p_{el_{grid}} + \sum_{t=1}^{N}(P_{gas}) \cdot p_{gas_{grid}} + max(P_{el_{grid}}) \cdot p_{el_{con}} + max(P_{gas}) \cdot p_{gas_{con}} + rent\right)$$
$$\leq 0.9 \cdot \left(\sum_{t=1}^{N}(l_{el}) \cdot p_{el_{grid}} + \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}}) \cdot p_{gas_{grid}} + max(l_{el}) \cdot p_{el_{con}} + max(\frac{l_{th}}{\eta_{gas}}) \cdot p_{gas_{con}}\right) \tag{3.36}$$

$$R_{el} + R_{th} = rent \tag{3.37}$$

$$C_{fix} = b_{flag} \cdot c_{main_{PV}} + b_{HP} \cdot c_{main_{HP}} + b_{CHP} \cdot (c_{main_{CHP}}$$
$$+ b_{flag_{CHP/HP}} \cdot b_{rent_{cellar}} \cdot c_{rent_{cellar}}) + C_{I_0} \tag{3.38}$$

The tenants' energy cost savings are determined differently due to the additional rent for the local energy system that has to be paid to the contractor:

$$c_{delta} = \sum_{t=1}^{N}(l_{el} - P_{el_{grid}}) \cdot p_{el_{grid}} + \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}} - P_{gas}) \cdot p_{gas_{grid}} - rent$$
$$+ (max(l_{el}) - P_{el_{con}}) \cdot p_{el_{con}} + (max(\frac{l_{th}}{\eta_{gas}}) - P_{gas_{con}}) \cdot p_{gas_{con}} \tag{3.39}$$

**Housing association/private investor: Full Contracting with energy efficiency measures**

The objective function in this use case is analogous to the 'Rent Model' in the upper paragraph in order to keep the model linear. ' $\mathrm{costs}_{\mathrm{additional}}$' represent the extra costs paid by the tenants in addition to the grid energy prices, which still lead to energy cost reductions because of smaller loads that have to be met due to the energy efficiency measures applied.

$$\begin{aligned}\mathrm{c}_{\mathrm{delta}} = &\sum_{t=1}^{N}(l_{el} - P_{el_{grid2supply}}) \cdot \mathrm{p}_{\mathrm{el}_{\mathrm{grid}}} + \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}} - P_{gas_{th}}) \cdot \mathrm{p}_{\mathrm{gas}_{\mathrm{grid}}} - \mathrm{costs}_{\mathrm{additional}} \\ &+ (max(l_{el}) - \mathrm{P}_{\mathrm{el}_{\mathrm{con}}}) \cdot \mathrm{p}_{\mathrm{el}_{\mathrm{con}}} + (max(\frac{l_{th}}{\eta_{gas}}) - \mathrm{P}_{\mathrm{gas}_{\mathrm{con}}}) \cdot \mathrm{p}_{\mathrm{gas}_{\mathrm{con}}}\end{aligned} \tag{3.40}$$

**Other external provider: Full Contracting**

In this case, the 'Full Contracting' model for housing association/private investor with its constraints and objective function is used, also the calculation for the energy cost savings for the tenants is identical. Adaptions are made only concerning the higher interest rate and the lower depreciation time.

**Energy industry: Full Contracting**

The default contracting use case (Section 3.6.2) is extended to portray this use case. To guarantee cost savings for the tenants, an additional constraint is added to the model:

$$\begin{aligned}&\Bigg(\sum_{t=1}^{N}(P_{el_{grid2supply}}) \cdot \mathrm{p}_{\mathrm{R}_{\mathrm{elgrid}}} + \sum_{t=1}^{N}(l_{el} - P_{el_{grid2supply}}) \cdot \mathrm{p}_{\mathrm{R}_{\mathrm{el}}} + \sum_{t=1}^{N}(P_{gas_{th}}) \cdot \mathrm{p}_{\mathrm{R}_{\mathrm{thgrid}}} \\ &+ \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}} - P_{gas_{th}}) \cdot \mathrm{p}_{\mathrm{R}_{\mathrm{th}}} + max(P_{el_{grid}}) \cdot \mathrm{p}_{\mathrm{el}_{\mathrm{con}}} + max(P_{gas}) \cdot \mathrm{p}_{\mathrm{gas}_{\mathrm{con}}}\Bigg) \leq 0.9 \cdot \\ &\Bigg(\sum_{t=1}^{N}(l_{el}) \cdot \mathrm{p}_{\mathrm{el}_{\mathrm{grid}_{\mathrm{old}}}} + \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}}) \cdot \mathrm{p}_{\mathrm{gas}_{\mathrm{old}}} + max(l_{el}) \cdot \mathrm{p}_{\mathrm{el}_{\mathrm{con}}} + max(\frac{l_{th}}{\eta_{gas}}) \cdot \mathrm{p}_{\mathrm{gas}_{\mathrm{con}}} \\ &+ \mathrm{c}_{\mathrm{el}_{\mathrm{main}}} + \mathrm{c}_{\mathrm{gas}_{\mathrm{main}}}\Bigg)\end{aligned} \tag{3.41}$$

Whereas $\mathrm{p}_{\mathrm{el}_{\mathrm{grid}_{\mathrm{old}}}}$ is $\mathrm{p}_{\mathrm{el}_{\mathrm{grid}}}$ for the default use case and $\mathrm{p}_{\mathrm{gas}_{\mathrm{old}}}$ is $\mathrm{p}_{\mathrm{gas}_{\mathrm{grid}}}$ for the default use case in Table 3.2.

The energy cost savings differ from the default contracting use case due to different energy prices paid:

$$\begin{aligned}\mathrm{c_{delta}} &= \sum_{t=1}^{N}(l_{el})\cdot \mathrm{p_{el_{grid_{old}}}} - \sum_{t=1}^{N}(P_{el_{grid2supply}})\cdot \mathrm{p_{R_{elgrid}}} - (\sum_{t=1}^{N}(l_{el}-P_{el_{grid2supply}}))\cdot \mathrm{p_{R_{el}}} \\ &+ \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}})\cdot \mathrm{p_{gas_{old}}} - \sum_{t=1}^{N}(P_{gas_{th}})\cdot \mathrm{p_{R_{thgrid}}} - (\sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}} - P_{gas_{th}}))\cdot \mathrm{p_{R_{th}}} \\ &+ (max(l_{el}) - \mathrm{P_{el_{con}}}\cdot 0.9)\cdot \mathrm{p_{el_{con}}} + (max(\frac{l_{th}}{\eta_{gas}}) - \mathrm{P_{gas_{con}}}\cdot 0.9)\cdot \mathrm{p_{gas_{con}}} \\ &+ \mathrm{c_{el_{main}}} + \mathrm{c_{gas_{main}}}\end{aligned} \tag{3.42}$$

**ESCo and housing association: Enabling Model**

For this use case, the model needs major adaptions. The default heating system is changed to a DH system (see ‘Enabling Model’ in Section 4.3.4 for further explanations). In order to guarantee the tenants’ cost savings, the following constraint is added to to the model:

$$\left(\sum_{t=1}^{N}(P_{el_{grid2supply}})\cdot \mathrm{p_{R_{elgrid}}} + \sum_{t=1}^{N}(P_{R_{thgrid}})\cdot \mathrm{p_{th_{grid}}} + \sum_{t=1}^{N}(\sum_{orien=1}^{8}(\boldsymbol{P}_{PV_{2supply}}) + P_{CHP_{el2supply}})\cdot \mathrm{p_{R_{el}}} \right. \\ \left. \sum_{t=1}^{N}(P_{HP_{2supply}} + P_{CHP_{th2supply}})\cdot \mathrm{p_{R_{th}}}\right) \leq 0.9\cdot\left(\sum_{t=1}^{N}(l_{el})\cdot \mathrm{p_{el_{grid}}} + \sum_{t=1}^{N}(l_{th})\cdot \mathrm{p_{th_{grid}}}\right) \tag{3.43}$$

The objective function is adapted to depict the different business case:

$$\mathrm{R_{el}} = \sum_{t=1}^{N}(\sum_{orien=1}^{8}(\boldsymbol{P}_{PV}) + P_{CHP_{el}})\cdot \mathrm{p_{el2grid}} \tag{3.44}$$

$$\mathrm{R_{th}} = \sum_{t=1}^{N}(P_{HP} + P_{CHP_{th}})\cdot \mathrm{p_{th2grid}} \tag{3.45}$$

$$\mathrm{C_{var}} = 0 \tag{3.46}$$

$$\mathrm{C_{fix}} = \mathrm{b_{flag}}\cdot \mathrm{c_{main_{PV}}} + \mathrm{b_{HP}}\cdot \mathrm{c_{main_{HP}}} + \mathrm{b_{CHP}}\cdot(\mathrm{c_{main_{CHP}}} + \mathrm{C_{I_0}}) \tag{3.47}$$

$$\mathrm{C_{I_0}} = \mathrm{I_{\alpha BAPV}} \cdot \sum_{orien=1}^{4} (P_{f_{kWp_{BAPV}}}) + \mathrm{I_{\alpha BIPV}} \cdot \sum_{orien=5}^{8} (P_{f_{kWp_{BIPV}}}) + \mathrm{b_{flagBIPV}} \cdot \alpha \cdot \mathrm{c_{instBIPV}}$$
$$+ \mathrm{b_{flagBAPV}} \cdot \alpha \cdot \mathrm{c_{instBAPV}} + \mathrm{I_{\alpha HP}} \cdot \mathrm{P_{HP_{peak}}} + \mathrm{b_{HP}} \cdot \mathrm{c_{instHP}}$$
$$+ \mathrm{I_{\alpha CHP}} \cdot \mathrm{P_{CHP_{th_{peak}}}} + \mathrm{b_{CHP}} \cdot \mathrm{c_{instCHP}} \tag{3.48}$$

The following equation is used for the calculation of the profit of the energy supply company (ESCo):

$$\begin{aligned}
\mathrm{R_{ESCo}} = &\sum_{t=1}^{N}(P_{el_{grid2supply}}) \cdot (\mathrm{p_{R_{elgrid}}} - \mathrm{p_{el_{grid}}}) \\
&+ \sum_{t=1}^{N}(P_{th_{grid2supply}}) \cdot (\mathrm{p_{R_{thgrid}}} - \mathrm{p_{th_{grid}}}) \\
&+ \sum_{t=1}^{N}(P_{HP_{2supply}} + P_{CHP_{th2supply}}) \cdot (\mathrm{p_{R_{th}}} - \mathrm{p_{th2grid}}) \\
&+ \sum_{t=1}^{N}(\sum_{orien=1}^{8} (\boldsymbol{P}_{PV_{2supply}}) + P_{CHP_{el2supply}}) \cdot (\mathrm{p_{R_{el}}} - \mathrm{p_{el2grid}}) \\
&+ \sum_{t=1}^{N}(P_{HP_{2grid}} + P_{CHP_{th2grid}}) \cdot (\mathrm{p_{generation_{th}}} - \mathrm{p_{th2grid}}) \\
&+ \sum_{t=1}^{N}(\sum_{orien=1}^{8} (\boldsymbol{P}_{PV_{2grid}}) + P_{CHP_{el2grid}}) \cdot (\mathrm{p_{generation_{el}}} - \mathrm{p_{el2grid}})
\end{aligned} \tag{3.49}$$

The tenants' energy cost savings are determined using the following equation, whereas connection capacities in this use case are not changed when local energy technologies are installed:

$$\mathrm{c_{delta}} = \sum_{t=1}^{N}(l_{el}) \cdot \mathrm{p_{el_{grid}}} - \sum_{t=1}^{N}(P_{el_{grid2supply}}) \cdot \mathrm{p_{R_{elgrid}}} - \sum_{t=1}^{N}(l_{el} - P_{el_{grid2supply}}) \cdot \mathrm{p_{R_{el}}}$$
$$+ \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}}) \cdot \mathrm{p_{gas_{old}}} - \sum_{t=1}^{N}(P_{gas_{th}}) \cdot \mathrm{p_{R_{thgrid}}} - \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}} - P_{gas_{th}}) \cdot \mathrm{p_{R_{th}}} \tag{3.50}$$

**(Citizen) energy cooperative: Full Contracting**
For this use case, the 'Full Contracting' model for the housing association/private investor is adapted. In order to depict the main goal for energy cooperatives, the objective function is altered to maximize local energy supply:

$$\Bigg(\sum_{t=1}^{N}(l_{el} - P_{el_{grid2supply}}) \cdot \mathrm{p_{R_{el}}} + \sum_{t=1}^{N}(P_{el_{grid2supply}}) \cdot \mathrm{p_{el_{grid}}} + \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}} - P_{gas_{th}}) \cdot \mathrm{p_{R_{th}}}$$
$$+ \sum_{t=1}^{N}(P_{gas_{th}}) \cdot \mathrm{p_{gas_{grid}}} + max(P_{el_{grid2supply}}) \cdot \mathrm{p_{el_{con}}} + max(P_{gas_{th}}) \cdot \mathrm{p_{gas_{con}}}\Bigg)$$
$$\leq \Bigg(\sum_{t=1}^{N}(l_{el}) \cdot \mathrm{p_{el_{grid}}} + \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}}) \cdot \mathrm{p_{gas_{grid}}} + max(l_{el}) \cdot \mathrm{p_{el_{con}}} + max(\frac{l_{th}}{\eta_{gas}}) \cdot \mathrm{p_{gas_{con}}}\Bigg) \tag{3.51}$$

$$\mathrm{R_{el}} + \mathrm{R_{th}} \geq \mathrm{C_{var}} + \mathrm{C_{fix}} \tag{3.52}$$

$$\max_{P} \ \mathrm{P_{localsupply}} = \max_{P} \Bigg(\sum_{t=1}^{N}(P_{CHP_{el2supply}}) + \sum_{t=1}^{N}(P_{CHP_{th2supply}}) + \sum_{t=1}^{N}(P_{HP_{2supply}}) + \sum_{t=1}^{N}\sum_{orien=1}^{8}(\boldsymbol{P}_{PV_{2supply}})\Bigg) \tag{3.53}$$

The energy cost savings of the tenants are determined with the following equation:

$$\mathrm{c_{delta}} = \sum_{t=1}^{N}(l_{el}) \cdot \mathrm{p_{el_{grid}}} - \sum_{t=1}^{N}(P_{el_{grid2supply}}) \cdot \mathrm{p_{el_{grid}}} - \sum_{t=1}^{N}(l_{el} - P_{el_{grid2supply}}) \cdot \mathrm{p_{R_{el}}}$$
$$+ \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}}) \cdot \mathrm{p_{gas_{grid}}} - \sum_{t=1}^{N}(P_{gas_{th}}) \cdot \mathrm{p_{gas_{grid}}} - \sum_{t=1}^{N}(\frac{l_{th}}{\eta_{gas}} - P_{gas_{th}}) \cdot \mathrm{p_{R_{th}}}$$
$$+ (max(l_{el}) - \mathrm{P_{el_{con}}}) \cdot \mathrm{p_{el_{con}}} + (max(\frac{l_{th}}{\eta_{gas}}) - \mathrm{P_{gas_{con}}}) \cdot \mathrm{p_{gas_{con}}} \tag{3.54}$$

**(Citizen) energy cooperative: Full Contracting with energy efficiency measures**
This model is analogous to the 'Full Contracting with energy efficiency measures' use case for the housing association/private investor with the adaption of the depreciation time and the objective function (as can be seen in the paragraph above). The tenants' energy cost savings are also determined using the equation from the 'Full Contracting with energy efficiency measures' case for the housing association/private investor.

# 4. Results: profitability and installed capacities

## 4.1. Energy technology options

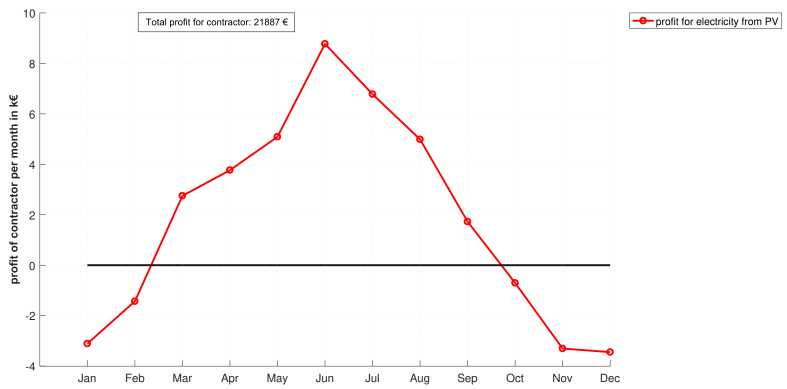
In order to examine the interactive elements, such as total profit for the contractor, total cost savings for the tenants and installed technology capacities, the energy technologies are consecutively introduced into the model. As a first step, the PV system can be installed by the optimization (Section 4.1.1). As a second step, an additional HP system is available (Section 4.1.2). Only as a third step, completing the model presented, the mCHP is introduced and the opimization can choose between the three local technology options or a combination thereof. To display the reasonableness of installing both an HP and an mCHP system, the variation of a PV system in combination with an mCHP system is discussed concisely as well (see Section 4.1.4).

For the following cases, central gas heating is set as the default heating system for the neighborhood (further information regarding the default heating systems can be derived from Sections 3.3 and 4.2), wheras it is assumed that a suitable heat distribution system (low-temperature heating) is already available in the neighborhood and does not have to be considered as an additional cost factor when an HP system is installed.

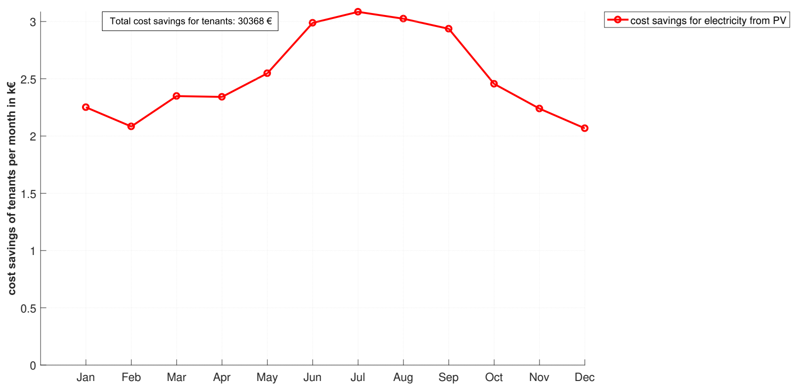
The imputed interest rate and the depreciation times for the components of the installed energy systems for all basic calculations up to the examination of different business cases are set to be 3% and 20 years, respectively. Additionally, the entire energy (locally produced and withdrawn from the grids) is sold by the contractor to the tenants at different specific prices for electricity and heat (consisting of a consumption-based amount in €/kWh and a power-based amount in €/kW).

### 4.1.1. Photovoltaic system

The portrayed numbers (contractor's profit and tenants' energy cost savings) for the model with a PV system only cannot be directly compared to the ones with the possible installation of an HP and/or mCHP system. This is because of the non-existent cost reduction for the tenants concerning the thermal energy supply. Due to only offering electric energy locally, the contractor is not required to reduce energy costs for the heating system as well, resulting in a relatively higher profit for the contractor and relatively lower energy cost savings for the tenants, 21 887 € and 30 368 €, respectively. The following Figure 4.1 shows the monthly as well as the annual profit of the contractor and the energy cost savings for the tenants. It can be seen that the highest profit for the contractor is made during the summer months, where PV generation is at its maximum and electricity is used for operating the office building's cooling devices. This leads to relatively high energy savings for the tenants. The contractor faces losses (equals negative profit) during the winter months, where PV generation is low and the most part of the electricity needed to cover the load has to be bought from the grid and is resold to the tenants for a lower price, leading to additional cost savings for the tenants.




(a)




(b)

Figure 4.1.: (a) Profit for contractor and (b) energy cost savings for the tenants per month and in total

The optimization installs a PV system in all cardinal directions of the roofs (only the north side is not fully fitted with PV modules). The facade is not equipped with modules due to the reduced generation as a result of the 90°-tilt and due to the high system and installation costs. The size of the PV system installed can be seen in Figure 4.2.

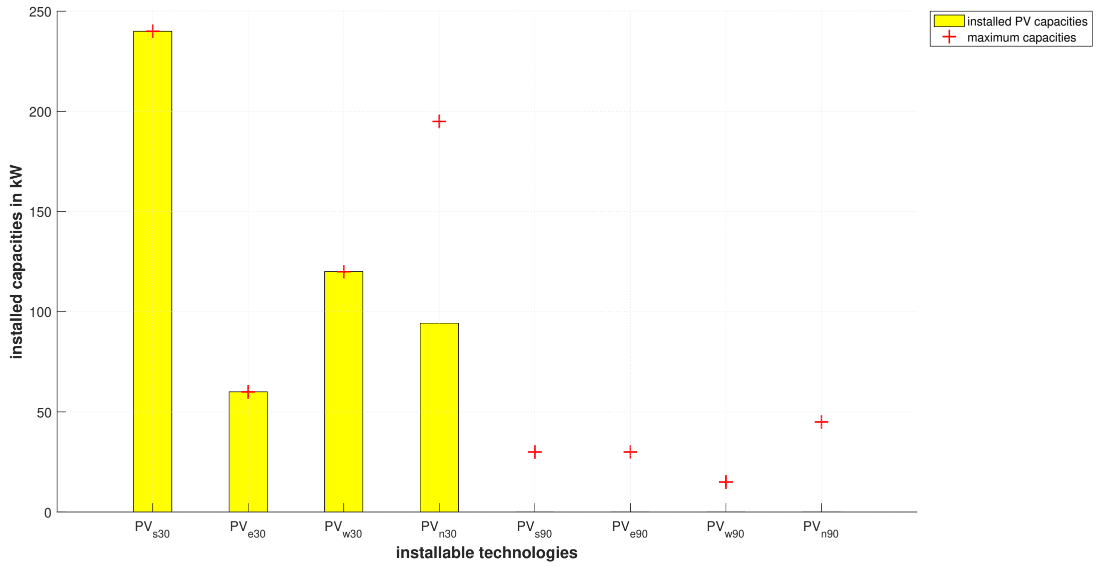
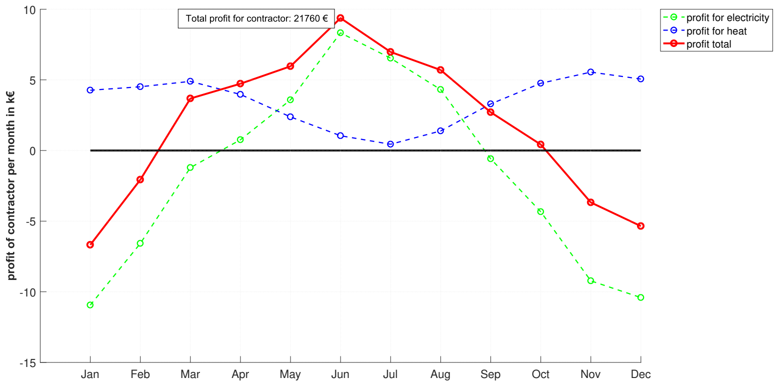



Figure 4.2.: Installed technology capacities

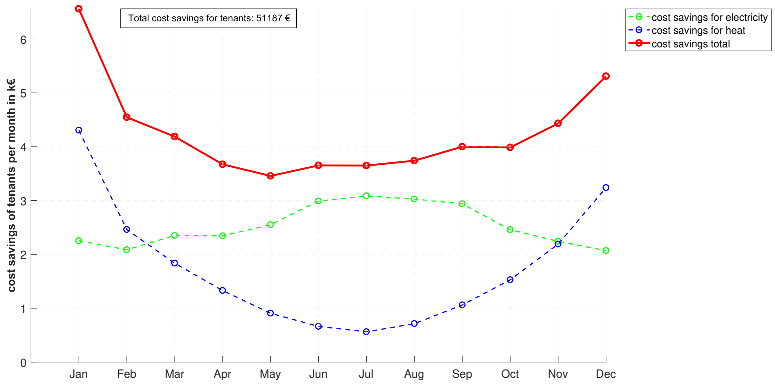
High time resolution graphs for a summer and winter week with the corresponding supplied energy for every quarter of an hour can be found in Appendix A.1.

### 4.1.2. Photovoltaic and heat pump system

When adding the HP system to the model, it can be seen that the contractor's profit decreases slightly to 21 760 €, while the cost savings for the tenants increase by 68.6% to 51 187 € (Figure 4.3). The decrease of the profit compared to Section 4.1.1 is due to the compulsory cost reduction of 10% for the tenants concerning heat supply. It is cheaper for the contractor to install the maximum capacity of the HP system (Figure 4.4) than to resell grid gas for a lower price, although the electricity for running the HP system has to be fully paid by the contractor. This leads to a decrease of profit from electricity compared to Section 4.1.1. The energy cost savings for the tenants are highest in winter due to the lower heating costs compared to the default case.




(a)




(b)

Figure 4.3.: (a) Profit for contractor and (b) energy cost savings for the tenants per month and in total

The installed technology capacities for the model can be seen in Figure 4.4, where the plus in capacity installed on the north side of the roofs can be explained by the cheap PV electricity for powering the HP system.

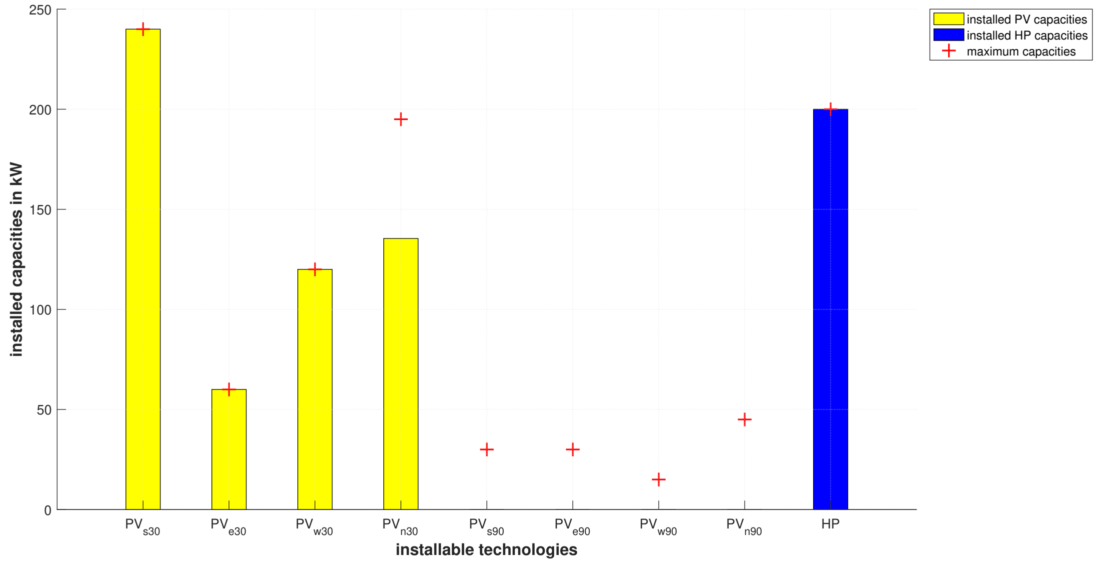


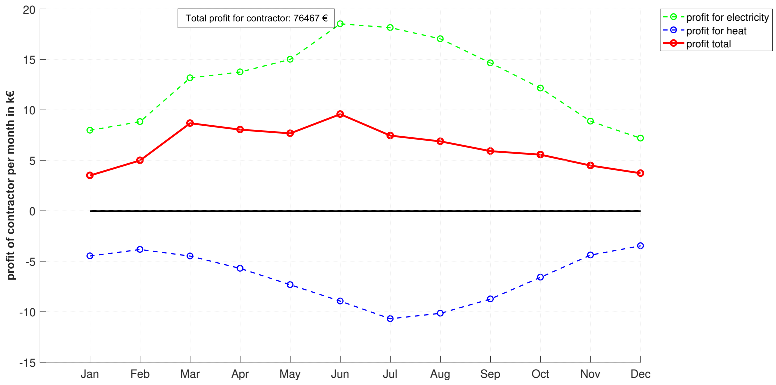

Figure 4.4.: Installed technology capacities

The high time resolution graphs for a summer and winter week with the corresponding supplied energy for every quarter of an hour can be found in Appendix A.2 .

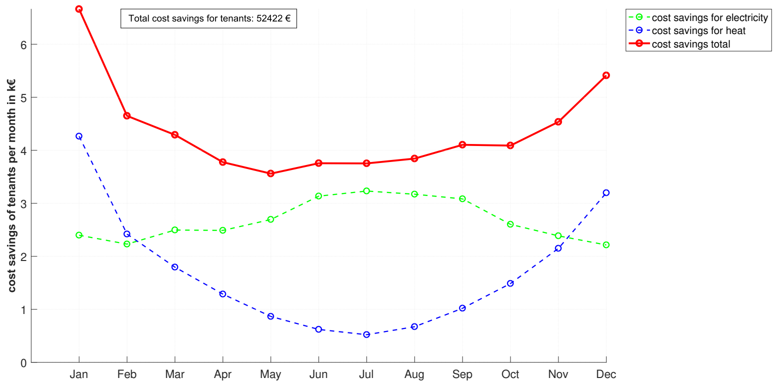
### 4.1.3. Photovoltaic, heat pump and mini combined heat and power system

Taking into account the mCHP system in the model results in an increase of the contractor's profit by more than 350% to 76 467 € compared to the case when no mCHP system (see Section 4.1.2) is installable. The tenants' energy cost savings also slightly increase by 2.4% to 52 422 € due to a lower grid electricity consumption, provoked by a capacity reduction of the HP system (see also Figure 4.6). The maximum mCHP capacity is installed because of the cheap gas electricity that can be generated and resold to the tenants by a significantly higher price. Figure 4.5 (a) shows that the redundant heat generation systems (HP and mCHP) lead to profit losses for heat at all times during the year but are compensated by the high electricity profits for the contractor.

This case is referred to in this work as the 'default contracting use case'.




(a)




(b)

Figure 4.5.: (a) Profit for contractor and (b) energy cost savings for the tenants per month and in total

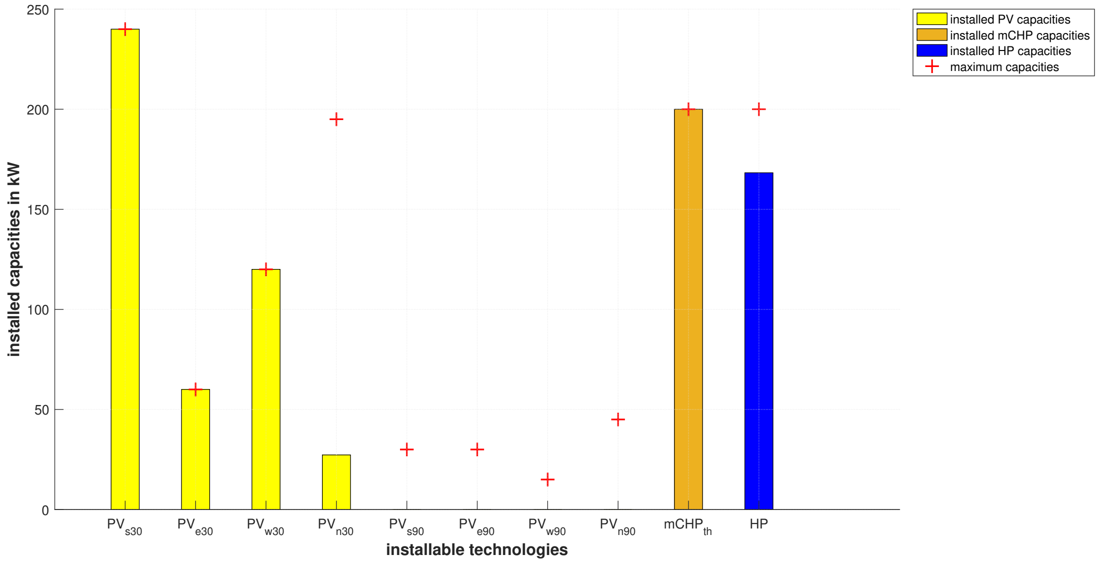



Figure 4.6.: Installed technology capacities

The allocation of the tenants' cost savings for electricity (left) and heat (right) can be seen in Figure 4.7. The electricity cost savings are mainly provoked by the office building with electric cooling in the summer months. The heat cost savings are caused by all three buildings of the neighborhood similarly. It has to be stated that the swimming pool in the school building is not being heated during the summer vacation months. The correct allocation of the energy cost savings to each tenant of the neighborhood could be subject to e.g. Blockchain technology in the future.

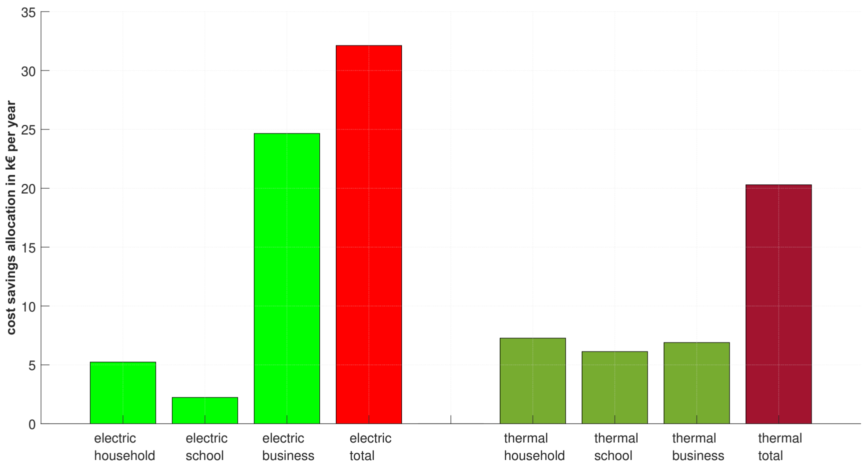



Figure 4.7.: Allocation of cost savings of the tenants for electricity and heat

The high time resolution graphs for a summer and winter week with the corresponding supplied energy for every quarter of an hour can be found in Appendix A.3.

### 4.1.4. Photovoltaic and mini combined heat and power system

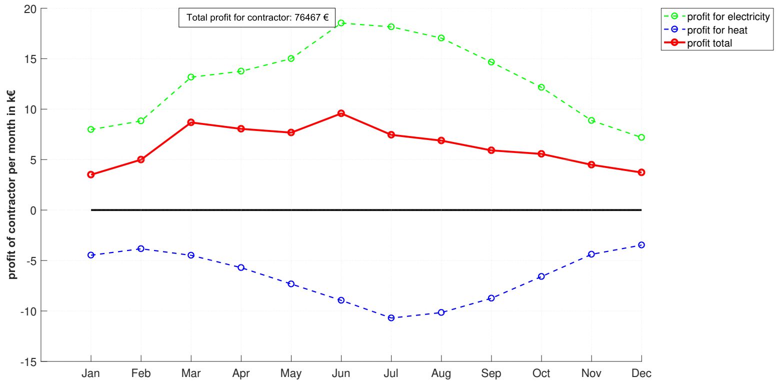
The case of installable PV and mCHP technologies in the optimization shows similar results to the one of the additional HP system in Section 4.1.3. The monthly profit of the contractor and the monthly cost savings for the tenants show nearly identical patterns, although the profit is reduced by 13% to 66 263 € and the energy cost savings by 4% to 50 471 € compared to the complete default case of the three installable local energy technologies. The similar curve patterns for the monthly profit representation are caused by the mCHP system, which runs mainly to meet electricity demand (because of the higher revenues). The reduction in profit is mainly provoked by the absence of an additional heating system to generate revenues for the contractor, also leading to smaller cost savings for the tenants regarding grid capacity costs. Concerning the installed local energy capacities in comparison to the complete optimization model, there is no BAPV system installed on the north side of the roof due to smaller electricity demand as a result of the missing HP system. The mCHP system, as in the full-featured model, is installed to maximum capacity.

High time resolution graphs for a summer and winter week (quarter-hourly) are shown in Appendix A.4.

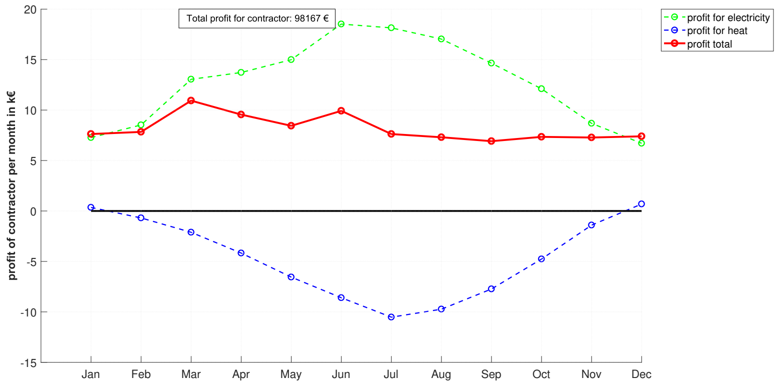
## 4.2. Comparison of default heating systems

As default heating systems for the neighborhood, a central gas heating or a DH system are available. Due to the wide distribution of gas heating in Austria, this system is mainly chosen for the following calculations of the contracting business cases (Section 4.3) [37]. Only for the 'Enabling Model' (see Section 4.3.4), a DH system is used due to restrictions discussed in the respective section.

The comparison of the profits for the contractor for gas heating (a) and district heating (b) in Figure 4.8 depict that the low gas price leads to a lower profit for the contractor (76 467 €) compared to the DH system (98 167 €).




(a)




(b)

Figure 4.8.: Profit for contractor for (a) gas heating and (b) district heating system per month and in total

Comparisons regarding the cost savings of the tenants can be found in Appendix A.5.

## 4.3. Contracting business cases

In this section, the results of the selected contracting use cases from Table 3.1 are presented and discussed, whereas the profitability of the contactor and the tenants, as well as the installed capacities of the local energy technologies are highlighted.

Additionally to presenting the economic indicators and technology capacities, the individual use cases and their immanent cash flows between the grid (i.e. the energy supply company), the contractor and the tenants are portrayed graphically, while the amount of cash flow is represented qualitatively by the thickness of the pictured arrows.

### 4.3.1. Housing association/private investor

A housing association or a private investor (as owners of a building) are not actually 'contractors' by the definition of the term, but can be providers of the energy (i.e. electricity and heating) system and can make use of *tenant electricity sharing* models. Additional revenues, increase of the value of the building and ecological considerations amongst other reasons could be the impulses for the investment in renewable and/or energy-efficient energy technologies (such as PV, HP and mCHP systems) in the buidings.

Housing associations and private investors will most likely not buy electricity and heat/gas from the grid and resell it to their tenants, since this concept would lead to considerable extra work for the energy billing process and legal issues. Therefore, the residual grid electricity and grid gas (or heating, if a DH system is applied) is paid by the residential and commercial tenants separately, which means that they have contracts for the residual grid energy with energy providers of their choice.
Additionally, the relative energy cost savings of the tenants are reduced by the maintenance costs for the electric and thermal energy system, since these costs are forwarded by the housing association or the private investor to the teanants via the utility bill.

### Full Contracting

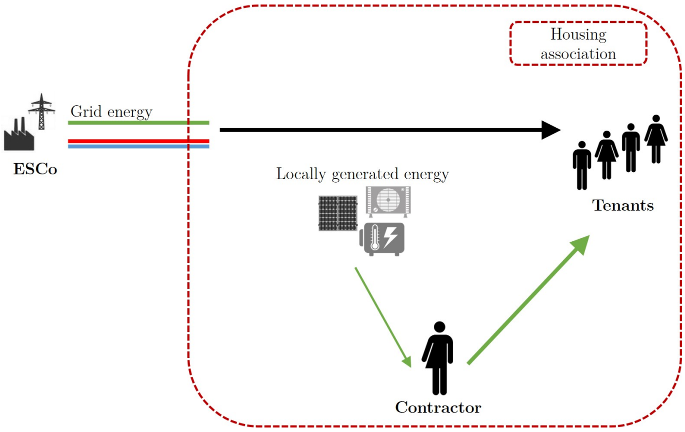
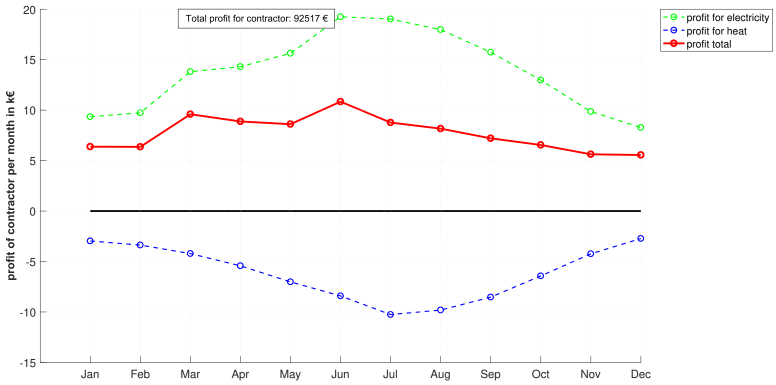



Figure 4.9.: Configuration of cash flows in the housing association use case

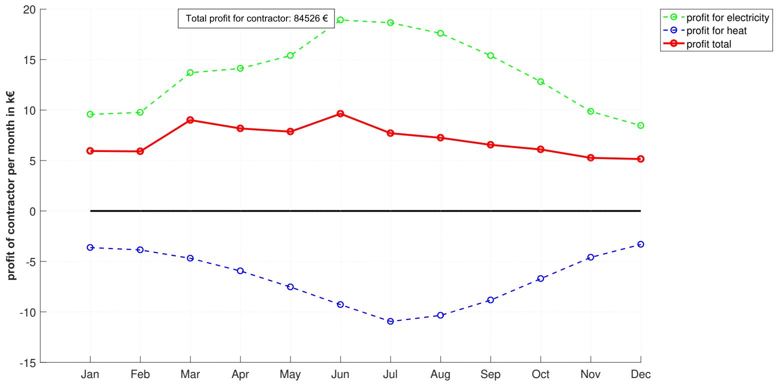
The configuration of cash flows in this use case is shown in Figure 4.9. The thickness of the lines can be associated with the profit made by the energy selling entity.

The profit for the contractor and the tenants is shown for a depreciation time of the components of 20 years and interest rates of 1.7% (inflation only) and 3%, assumed that housing associations/private investors need to achieve a comparably low return on investments. For an interest rate of 3%, the contractor/provider gains a profit of 84 526 €, whereas the energy cost savings for the tenants are determined to be 42 660 €. For the case of an interest rate equal to inflation (1.7%), the contractor's profit increases to 92 517 € and the tenants' cost savings also rise to 42 660 €.

The profit for the contractor, as well as the energy cost savings for the tenants for both interest rates can be seen in Figure 4.10 and Figure 4.11, respectively, while it is visible that the gain for the contractor shows similar patterns to the default contracting case of Section 4.1.3. The cost savings for the tenants are lower in the winter months due to no cost reduction of the grid gas. A comparison of the monthly profits for the contractor for all housing association/private investor use cases and the case of an external provider (Section 4.3.2) is shown in Figure 4.19.

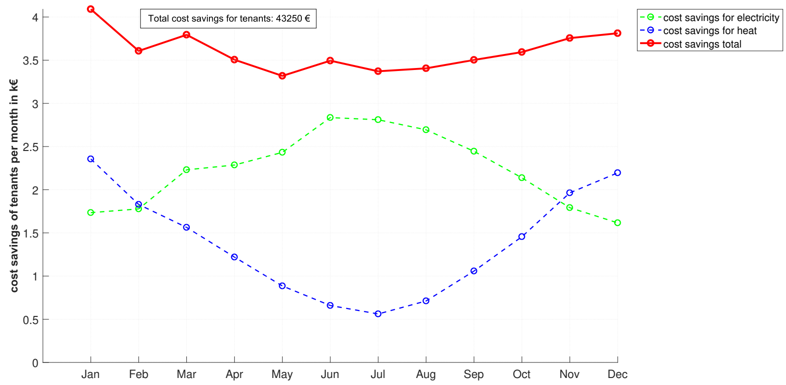



(a)

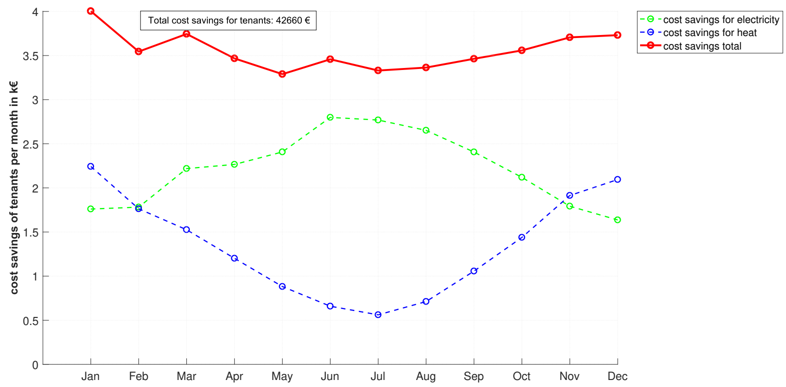



(b)

Figure 4.10.: Profit for contractor for (a) 1.7% and (b) 3% interest rate per month and in total




(a)




(b)

Figure 4.11.: Cost savings for tenants for (a) 1.7% and (b) 3% interest rate per month and in total

Quarter-hourly high resolution graphs for the 'Full Contracting' use case with a chosen interest rate of 3% for one week in the summer and one week in the winter, splitted into elecricity and thermal supply, can be seen in Appendix A.6.1.

### Rent Model

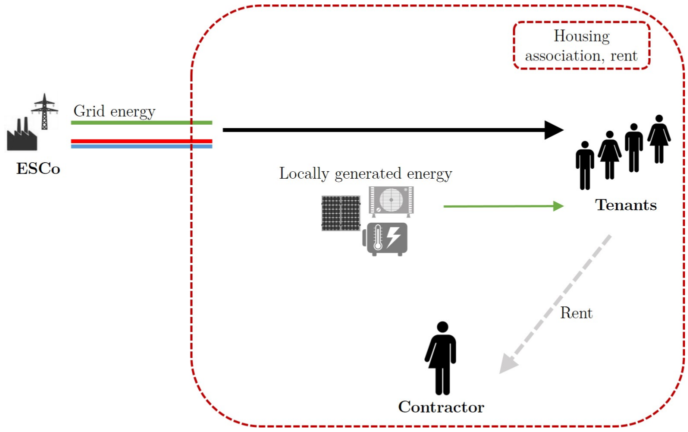
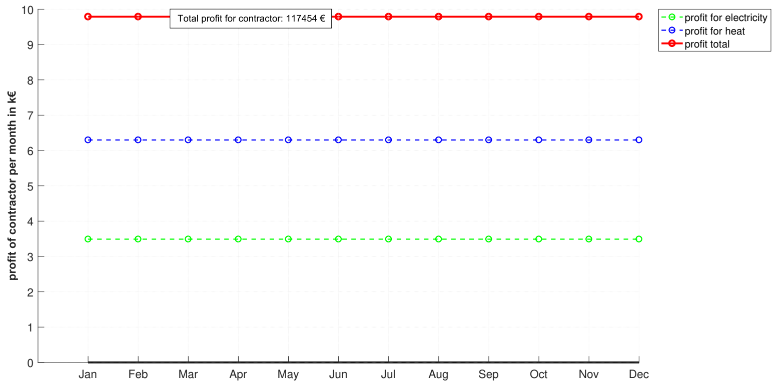



Figure 4.12.: Configuration of cash flows in the housing association 'Rent Model' use case

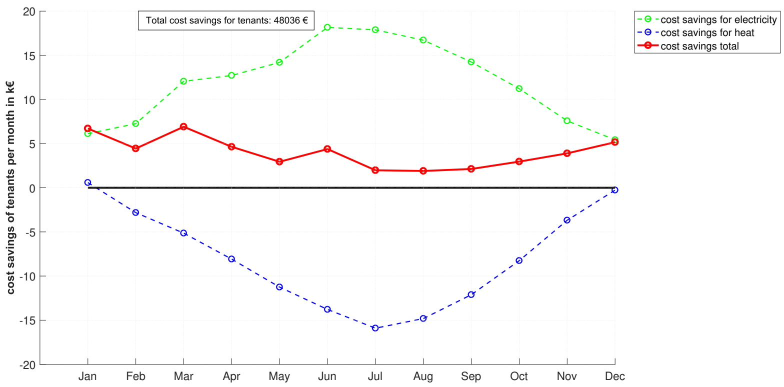
In comparison to the case of 'Full Contracting', the housing association or the private investor could also refinance their investments in renewable and/or energy-efficient energy systems for the buildings via increasing the tenants' rent, in order to facilitate billing processes. This means that the tenant pays an additional amount of money per month to the building owner for the purpose of renting parts of the electric and thermal energy system for 'self-supply' of the locally generated energy. The residual power needed to meet demand is supplied by the gas and electricity grid and is paid by the tenants separately. The configuration for cash flows in this use case is shown in Figure 4.12.

In order to facilitate and minimize the involvement of the provider/contractor in this specific use case, the grid electricity for the HP system and the grid gas for the mCHP system are also paid by the tenants.

The results show that the 'Rent Model' is the more profitable case for both the contractor and the tenants (see Figure 4.13) compared to the default 'Full Contracting' case of the housing association or private investor. This can be explained by the model finding an optimum between local energy prices and installed technology capacities. In this case, the local energy prices are not set at 90% of the grid prices. The total energy costs only have to be 10% lower than those of the default case, enabling the optimization to define the prices. The profit of the contractor rises to 117 454 € and the cost savings for the tenants are determined to be 48 036 € over the year. The 'Rent Model' offers the possibility of not allocating a price to the supplied energy but an aggregated sum of money for the total energy (both thermal and electric) combined. The entire annual rent is determined to be 190 440 € for the neighborhood.




(a)




(b)

Figure 4.13.: (a) Monthly profit and (b) cost savings for tenants for the 'Rent Model'

Figures displaying the electric and thermal load and its supply in quarter-hourly resolution can be found in Appendix A.6.1.

### Full Contracting with energy efficiency measures

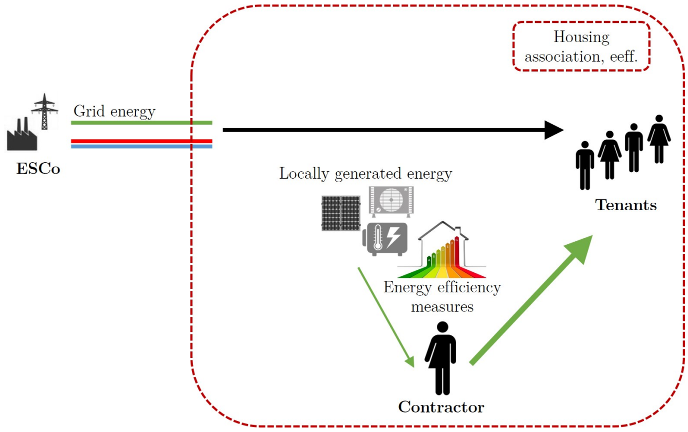



Figure 4.14.: Configuration of cash flows in the housing association with energy efficiency measures use case

Additionally to the presented *energy supply contracting* considered in the previous use cases, the provider/contractor could also apply energy efficiency measures on and in the building(s), leading to lower heat and electricity loads. The refinancing of the investments is then not only guaranteed through the selling of the locally generated energy to the tenants, but additionally by the possibility of raising the energy prices. This still results in energy cost savings for the tenants compared to the costs paid for the default loads supplied by the grids. This use case shows a combination of *energy supply contracting* and *energy performance contracting*. The configuration for cash flows in this specific use case is shown in Figure 4.14.

The considered costs for the energy efficiency measures and the resulting reduction of the loads are shown in the following Table 4.1:

| | Costs per unit | Costs for all buildings | Resulting load reduction |
|---|---|---|---|
| **Energy efficiency measures for heat** | | | |
| Insulation of facade of 13 cm [1] | 82 €/m² | 137 760 € | |
| Insulation of top and ground floor[2] | 30 €/m² | 123 300 € | 21.88% |
| **Energy efficincy measures for electricity** | | | |
| Efficient LED lighting[3] | 20 000 €/building | 60 000 € | 4% |

Table 4.1.: Energy efficiency measures applied

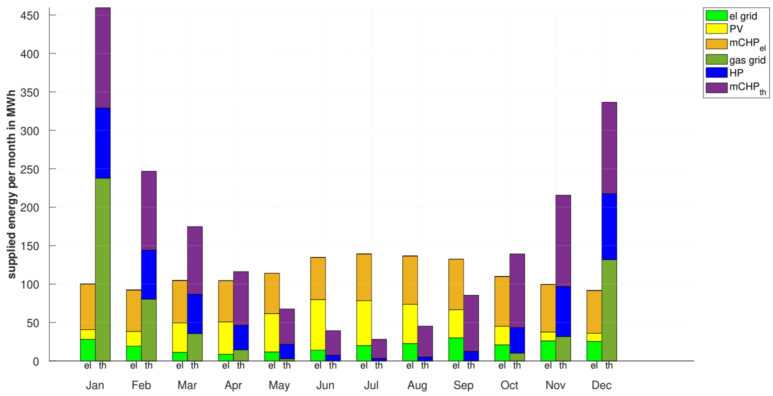
[1] Data obtained from [26].
[2] Data obtained from [26].
[3] Estimation based on [55], [9], [80] and [52].

In order to keep the optimization linear, the energy prices are not left as variables and are not multiplied with the energy consumed, but are set as an additional sum paid by the tenants, analogously to the ‘Rent Model’ of Section 4.3.1. Thus, the following energy prices to be paid by the tenants are calculated (see Table 4.2), still generating energy cost savings due to the energy efficiency measures applied.

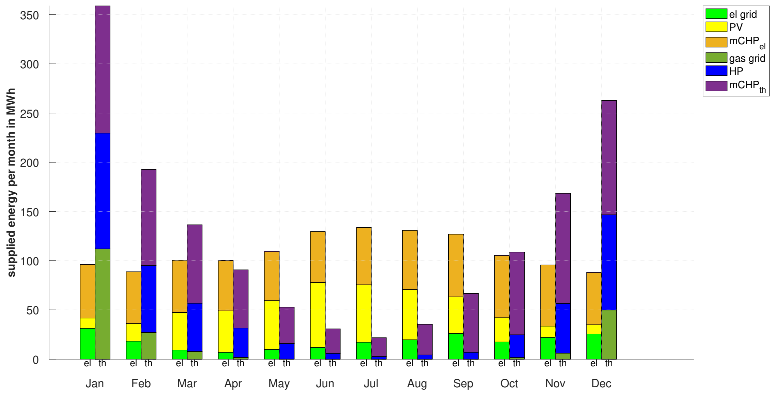
| | Energy grid price default case [€/kWh] | Energy price after energy efficiency measures [€/kWh] |
|---|---|---|
| Electricity | 0.213 | 0.245 |
| Gas | 0.061 | 0.070 |

Table 4.2.: Prices for energy before (default case) and after energy efficiency measures are applied

The following Figure 4.15 shows the monthly energy supplied to the tenants, whereas electricity can be seen in the left columns and thermal energy in the right columns (grid feed-in is not depicted). The decrease of energy consumed monthly can be seen for both electric and thermal energy.




(a)




(b)

Figure 4.15.: Supplied energy (electric, thermal) per month (a) before and (b) after energy efficiency measures are applied

The monthly profit for the contractor can be seen in the following Figure 4.16, leading to a profit increase for the contractor/provider of close to 10% to 130 183 € compared to the 'Rent Model' (without energy efficiency measures applied) by keeping the cost savings for the tenants at the same level (48 036 €).

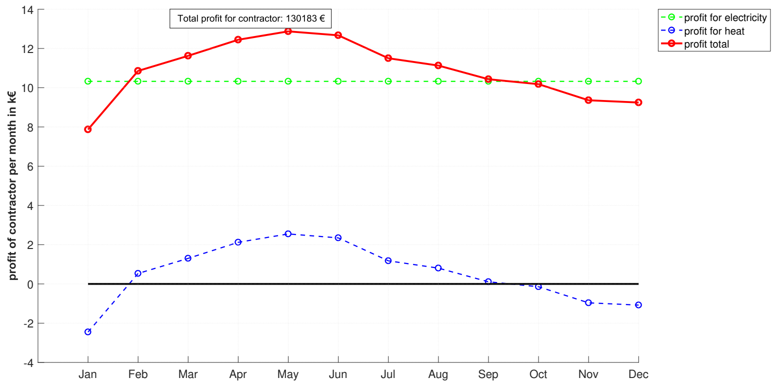



Figure 4.16.: Monthly profit of contractor for the additional energy efficiency measures

The electric and thermal loads for two characteristic weeks of the year with the supplied local and grid energies for this use case can be found in Appendix A.6.1.

### 4.3.2. Other external provider

#### Full Contracting

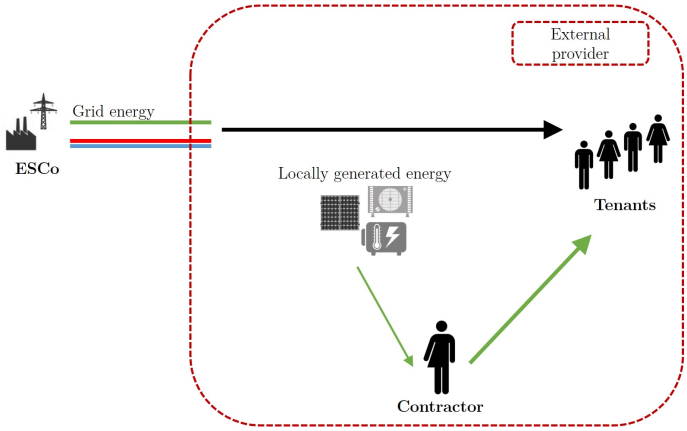



Figure 4.17.: Configuration of cash flows in the external provider use case

This use case which is based on assumptions made in Section 4.3.1 ('Full Contracting') depicts a variation for external contractors that expect a high return on investment (12%) and a low depreciation time of the energy systems (5 years). The configuration of cash flows (Figure 4.17) is equivalent to the 'Full Contracting' use case of Section 4.3.1.

This case shows the rapid decrease of profit for the contractor to 10 818 €, caused by the enforced amortization periods of the installed local energy systems (equal to the depreciation times) of 5 years, leading to an installation of an mCHP system only (see Figure 4.18). The energy cost savings for the tenants also decrease significantly to 20 508 €.

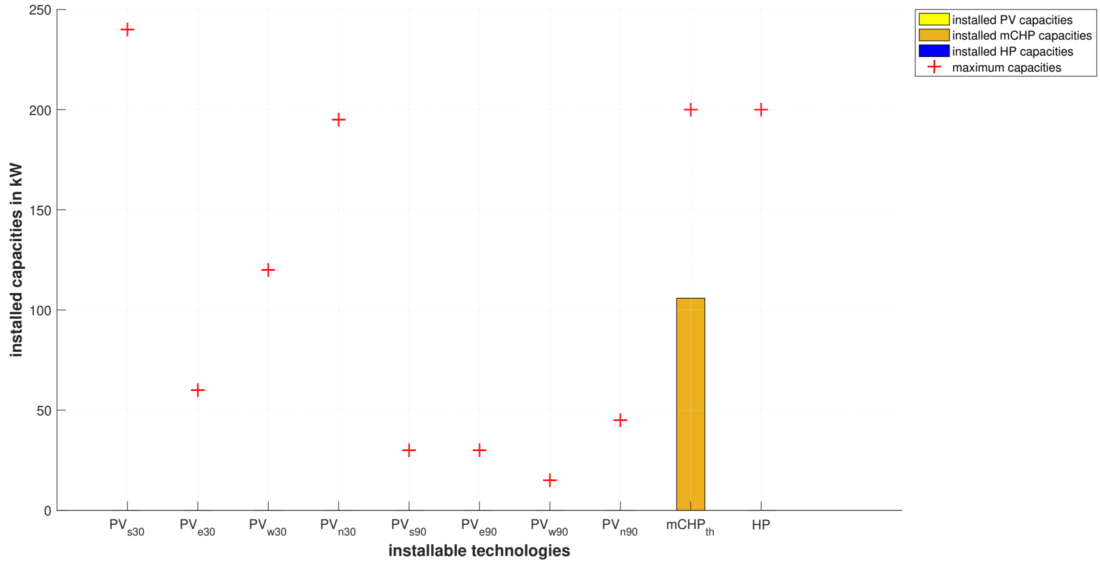



Figure 4.18.: Installed technology capacities

Additionally, it is examined, if local energy systems are installed in the case of only 50% tenant participation in the model (50% of the heating and electricity loads assumed). Since the installation costs (multiplied with the annuity factor) and the also assumed fixed annual maintenance costs of the mCHP system are relatively low (5000 € and 1000 €, respectively), half of the capacity of the mCHP system is installed if only 50% of tenants take part in the model. The cost savings for the individual tenant remain the same as if all tenants would participate. However, the profit for the contractor is not only 50% but even 61% lower compared to the original case. The reason is the fixed costs described above.

Figure 4.19 shows the comparison of the profits for the different housing use cases and the external provider over the months of a year. Attention has to be paid to the different interest rates and depreciation times.

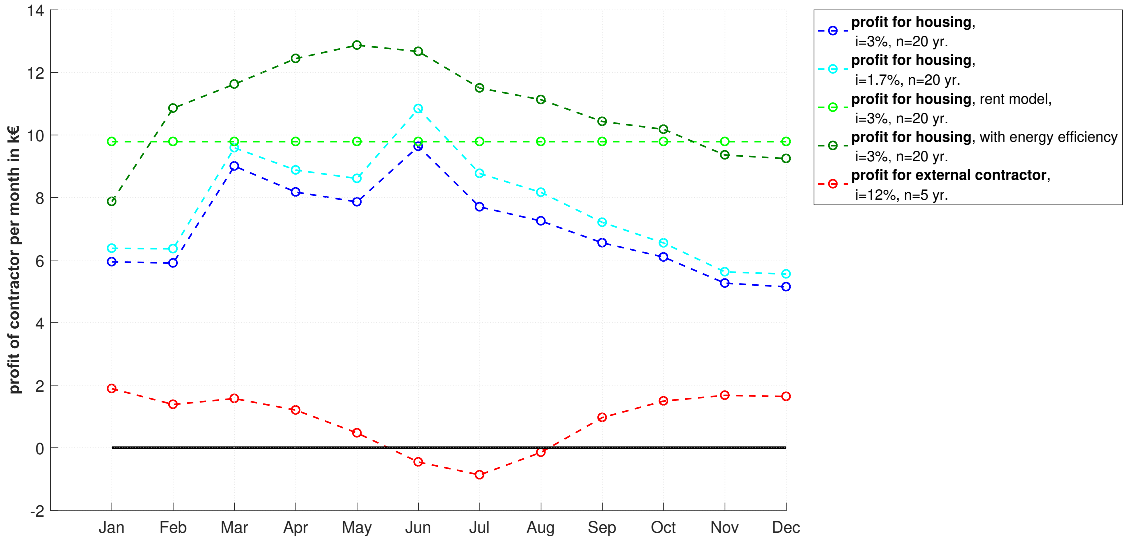



Figure 4.19.: Comparison of profits for a housing association and an external provider

High time resolution graphs of the loads and its supply for the use case of the external provider for a week in the winter and in the summer can be seen in Appendix A.6.2.

### 4.3.3. Energy industry (ESCo, municipal utility)

#### Full Contracting

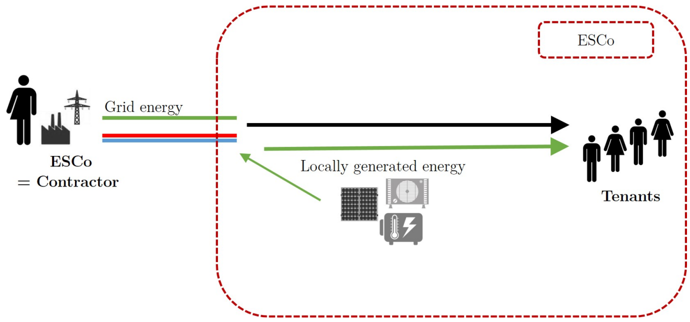
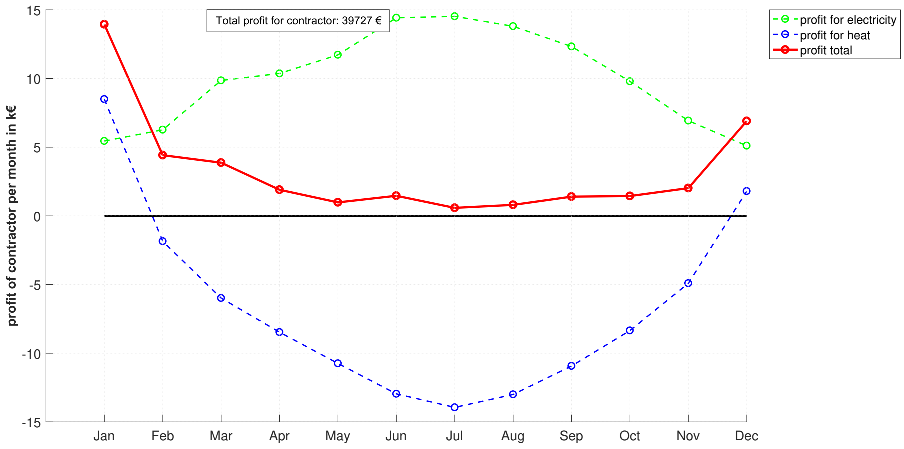


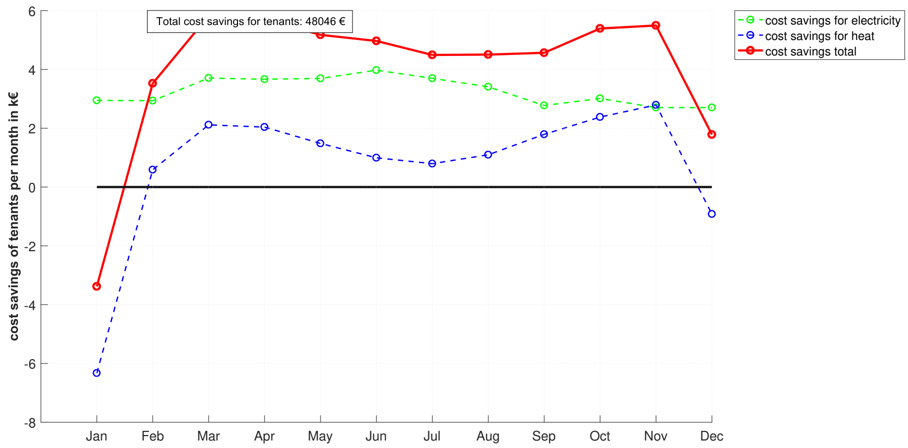

Figure 4.20.: Configuration of cash flows in the ESCo use case

The 'Full Contracting' model for the energy industry (an energy supply company - ESCo - or a municipal utility) is based on the model developed in Section 4.1.3. This is due to the contractor not only providing locally generated thermal and electric energy, but also the residual energy needed from the electricity and gas grid. The prices paid by the contractor and the tenants differ from the other use cases (see Tables 3.2 and 3.3). It is assumed that the energy utility profits from the selling of their own products, which are cheaper in purchase for the contractor and are forwarded to the tenants for a higher price compared to the default value. This depicts the case of when joining the model as a tenant, the locally generated energy can be bought for a cheap price. On the other hand, the grid energy price might be higher compared to the energy provided by a standard energy provider. The configuration of cash flows, as shown in Figure 4.20, is similar to the default contracting use case, but the grid energy provider here also functions as the contractor at the same time.

This specific use case shows that the contractor makes the most profit during the winter months when the heat demand is high and the contractor profits both from the local generated heat and the heat additionally supplied by the gas grid. This leads to an annual profit of 39 727 €. The cost savings for the tenants show negative results in January and December (see Figure 4.21). This is due to the relatively high share of heat supplied by the grid during the months of January, February, March and December, and the tenants paying a higher rate for the energy coming from the grid compared to the default case. The annual cost savings for the tenants are determined to be 48 046 €. The lower profit for the contractor compared to the default case can be explained by the higher interest rate of 7% and the lower depreciation time of 10 years.




(a)




(b)

Figure 4.21.: (a) Profit for contractor and (b) cost savings for tenants for the 'Full Contracting' model of the energy industry

If the contractor has to pay a rent for the roof space and the basement area to install the local energy system (an annual rent of 6000 € for both the rent of the roof and the basement), the profit for the contractor is reduced by 30%.

Illustrations of the electric and thermal loads and its supply for two weeks in the year for this use case are shown in Appendix A.6.3.

### 4.3.4. Housing association and ESCo

#### Enabling Model

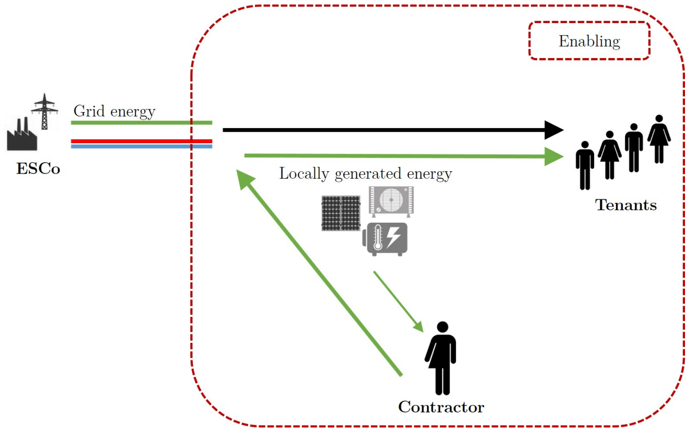



Figure 4.22.: Configuration of cash flows in the 'Enabling Model' use case

Another business case that was particularly applied before tenant sharing models were legally ensured, is the 'Enabling Model'. In this case, the entire locally generated energy is sold to the energy supplier and then forwarded to the tenants by the energy utility. There does not exist a contractor but two profiteers (the housing association and the energy supply company), whereas cost savings for the tenants have to be guaranteed as well. This configuration of selling energy to the ESCo and redistributing it to the tenants makes it clear that the default heating system for the neighborhood has to be a DH system, otherwise the generated heat could not be resold to the tenants. With the 'Enabling Model', a contract is signed by three parties - the housing association, which sells electricity and heat for a defined price, the energy utility, which is obliged to pay for the entire locally produced energy, and the tenants, who get a lower price for the locally generated energy. However, the tenants are obliged to buy the residual (higher priced) energy from this energy utility, when joining the contract. The cash flow configuration of this use case can be found in Figure 4.22. The assumed prices for this use case can be found in Tables 3.3 and 3.4 in Section 3.5.

The profit of 165 746 € for the housing association is high due to the applied default DH system, the low interest rate (3%) and the high depreciation time (20 years). Additionally, the complete remuneration of every kilowatt hour by the feed-in-tariff increases the profit significantly, wheras in the previously introduced business cases the feed-in of the local surplus energy is not paid for.

The ESCo's profit in this model is determined to be 180 970 € assuming that every kilowatt hour of electricity or heat fed into the respective grid can be sold to other costumers. The equation used to calculate the profit of the ESCo can be found in the Paragraph 'Enabling' in Section 3.6.3. The following prices for the cost of energy generated in power or heat plants, paid by the ESCo, are assumed (Table 4.3):

| | $p_{generation}$ [€/kWh] |
|---|---|
| **Costs (contractor) for electricity** | |
| Use case Enabling DH | 0.060 |
| **Costs (contractor) for heat** | |
| Use case Enabling DH | 0.050 |

Table 4.3.: Costs for the generation of energy in power or heat plants for the ESCo

It has to be noted that this profit(s) cannot be directly compared to the 'Full Contracting' use case for the energy industry in Section 4.3.3, since a lower interest rate and a higher depreciation time is considered.

The energy cost savings for the tenants are determined to be 44 000 €. It can be seen in Figure 4.23 that only an HP and mCHP system are installed, due to the relatively high remuneration of heat and the non-existent possibility of using the electricity generated from PV to power the HP system.

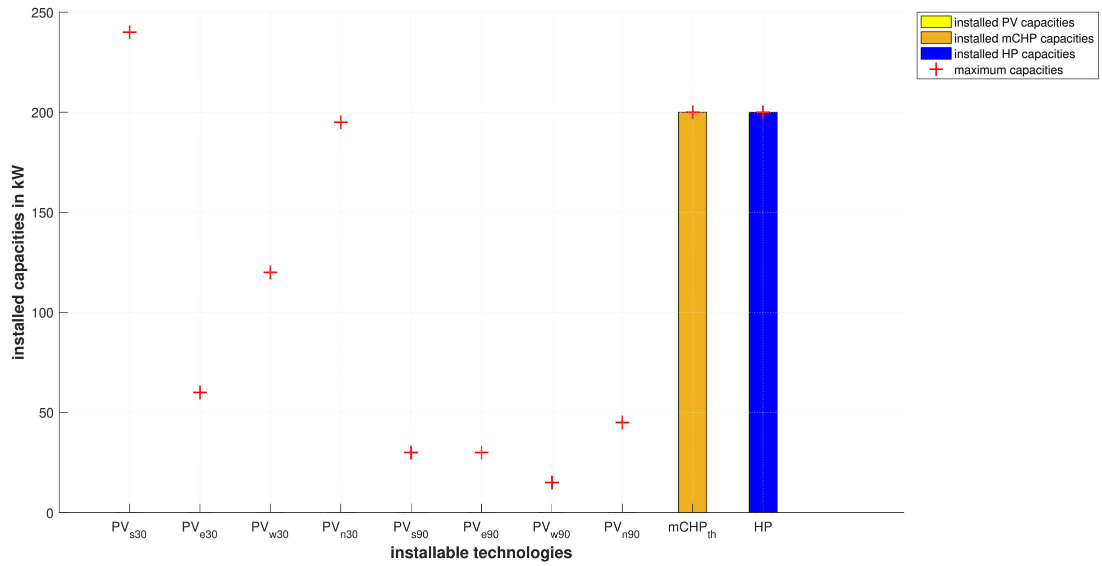



Figure 4.23.: Installed capacities of local energy systems

High time resolution illustrations of the loads and their supplied energies for a winter and summer week for the 'Enabling' use case are shown in Appendix A.6.4.

### 4.3.5. (Citizen) energy cooperative

#### Full Contracting

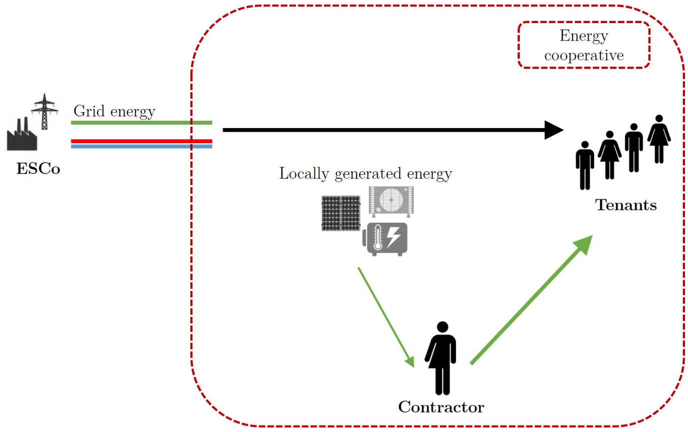



Figure 4.24.: Configuration of cash flows in the energy cooperative use case

In order to examine the use case of citizen energy cooperatives offering contracting, the MATLAB model is adapted to maximize local energy supply, since contributing to the energy transition is often the key goal of such cooperatives (see e.g. [49]). In addition to the adaption of the objective function and related constraints, the model of Section 4.3.1 for 'Full Contracting' is used exept for the depreciation time being raised to 25 years. The cash flow configuration is equivalent to the one for the housing association 'Full Contracting' case of Section 4.3.1 and is shown in Figure 4.24.

It is observed that even when the objective function of maximizing the contractor's profit is replaced by one that maximizes local energy consumption, the configuration is still profitable for both the contractor, and the tenants. The profit for the contractor is determined to be 50 322 €, while the tenants' energy cost savings are 47 311 €. The illustrations for the monthly profit of the contractor and energy cost savings for the tenants for this use case can be seen in Appendix **??**.

Since energy cooperatives are not necessarily experts in planning processes needed for contracting, the profit decrease for the contractor - if an external planner has to be paid - is examined. The results show that the contractor's loss of profit due to the need to assign planning experts (remunerated by a one-of expense of 6300 €) is just 0.7% over the long depreciation time of 25 years. The cost savings for the tenants remain at the same level.

Illustrations of the thermal and electric loads and their energy supply is shown in Appendix A.6.5.

### Full Contracting with energy efficiency measures

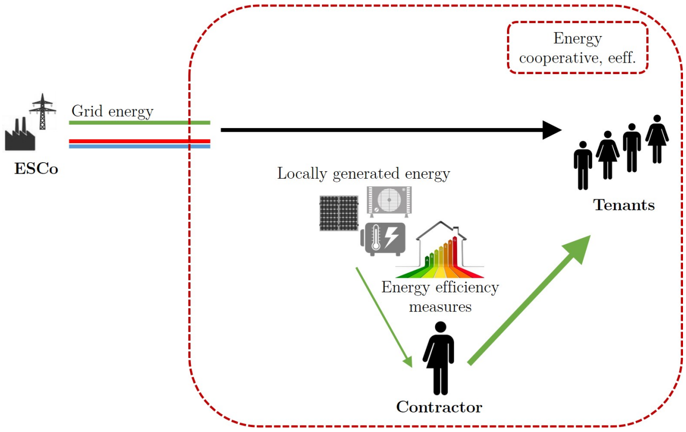



Figure 4.25.: Configuration of cash flows in the energy cooperative with energy efficiency measures use case

In this use case, *energy supply contracting* and *energy performance contracting* are combined by applying energy efficiency measures, leading to a decrease in electricity and heat consumption of the buildings (more detailed information is provided in Section 4.3.1, 'Full Contracting'). It can be observed in Figure 4.26 that PV is even installed on the facades due to the adaption of the objective function for the energy community to maximizing local energy consumption and the longer depreciation time of 25 years. The contractor's profit is determined to be 105 196 €, while the energy cost savings for the tenants are calculated to be 48 036 € (detailed graphs on a monthly scale can be found in Appendix A.6.5). The configuration for cash flows of this use case is identical to the housing association's 'Full Contracting with energy efficiency measures' use case of Section 4.3.1 and can be seen in Figure 4.25.

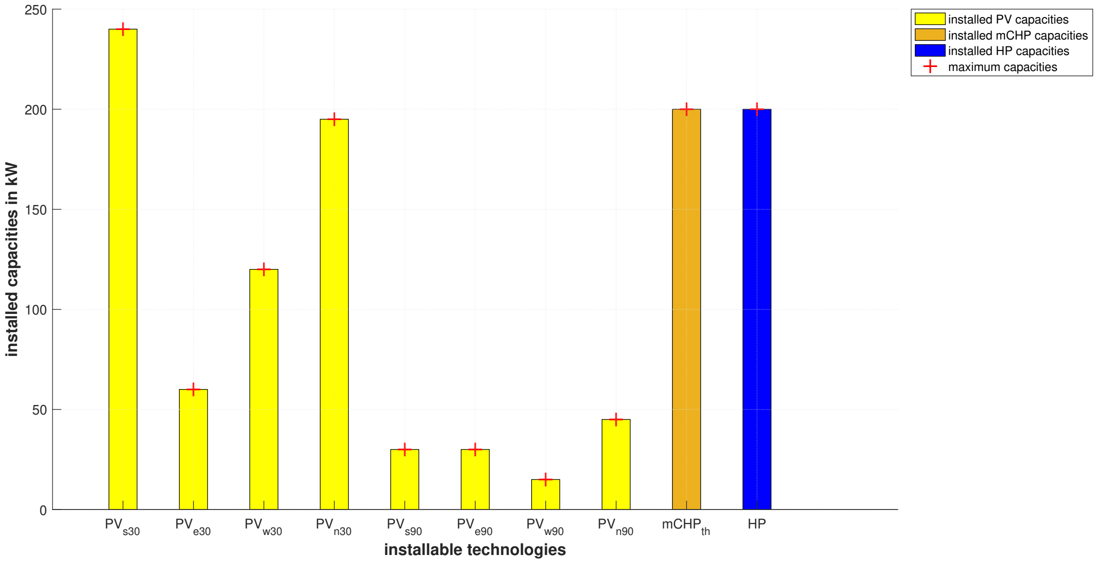



Figure 4.26.: Installed capacities of local energy systems

The following energy prices to be paid by the tenants are determined by the optimization (see Table 4.4), still generating energy cost savings due to the energy efficiency measures applied, leading to smaller electricity and heating demands.

| | Energy grid price default case [€/kWh] | Energy price after energy efficiency measures [€/kWh] |
|---|---|---|
| Electricity | 0.213 | 0.243 |
| Gas | 0.061 | 0.069 |

Table 4.4.: Prices for energy before (default case) and after energy efficiency measures are applied

Graphs illustrating the thermal and electric load and its supply for a characteristic week in the summer and in the winter can be found in Appendix A.6.5.

### 4.3.6. Comparison of business cases

When comparing the individual use cases of Sections 4.3.1 to 4.3.5, there can be seen a great variation concerning the contractor's profit, the tenants' energy cost savings and the installed technology capacities.

**Housing association**
The basic 'Full Contracting' use cases of the housing association/private investor (see 'housing default' and 'housing i=1.7%' on the x-axis in Figure 4.27 and 4.28) in comparison to the default contracting use case introduced in Section 4.1.3 both show a higher profit for the contractor. This is the case since grid energy is not bought from the grids and resold to the tenants for a lower price by the contractor, like in the default case, and maintenance costs are not paid by the contractor but by the tenants. The energy cost savings for the tenants are lower in these cases compared to the default case because of the tenants paying a lower price for local energy, but still the default grid prices for the residual grid energy. Additionally, tenants do not profit from a price reduction for the grid connection costs (see Table 3.3). Only a reduction of costs occurs caused by the minimization of the connection capacity of the electricity and gas grid.

The 'Rent Model' of the housing association/private investor use case (indicated as 'housing rent' in Figure 4.27 and 4.28) shows a way higher profit for the contractor compared to the previous use cases. This can be explained by no compulsory price reduction for the heat/gas and the electricity price individually. Contrarily, an overall 90% reduction of energy costs for the tenants is set as a constraint in the optimization. Therefore, an optimum between local energy prices and installed energy capacities can be found by the optimization, only considering cost savings for the tenants in total.

The housing association/private investor 'Full Contracting with energy efficiency measures' use case leads to an even higher profit for the contractor compared to the use cases above (see 'housing energy efficiency' in Figure 4.27 and 4.28).

**External provider**
A loss of profit of more than 85% is described for increasing the interest rate drastically from 3% to 12% and by lowering the depreciation time significantly from 20 years to 5 years, as it is done for the use case of an external contracting provider (see 'external' in Figure 4.27 and 4.28). The tenants' energy cost savings are insignificant as well, since the installation capacities are kept low by optimization and thus large parts of the energy need to be purchased from the electricity and gas grids.

**Energy industry**
The 'Full Contracting' use case of the energy industry (the objective function is identical

to the default contracting use case) shows a lower profit for the contractor and lower cost savings for the tenants compared to the default case. This is due to the higher interest rate of 7% and the lower depreciation time of 10 years (indicated as 'ESCo' in Figure 4.27 and 4.28). However, the tenants' cost savings are relatively high in comparison to the use case of the external contracting provider. The reason is a low price for local energy (see Table 3.3), even though the grid energy prices bought from the ESCo are higher compared to a standard energy supplier. Additionally, the grid capacity costs are reduced because of the lower price per connected kilowatt and the lower grid capacity in total provoked by local generation.

**Housing association and ESCo**

The 'Enabling' use case (labelled as 'enabling' in Figure 4.27 and 4.28) leads to high profts for the contractor due to the installed DH system. For the tenants however, the cost saving potential is low because of the obligation to pay for grid connection (i.e. full capacity and its default costs) and grid maintenance costs.

**(Citizen) energy cooperative**

The profit for the (citizen) energy cooperative (see 'energy coop' in Figure 4.27 and 4.28) as a contractor is lower compared to the other use cases with a moderate interest rate of 3%, even though the depreciation time is assumed to be even higher compared to the default contracting case (25 years). The lower profit can be explained by the altered objective function, which does not maximize the contractor's profit but the local energy supply for the neighborhood. Still, it can be shown that profitability for both the contractor and the tenants is given even by maximizing local energy consumption.

The profit for the contractor increases when additional energy efficiency measures are applied (illustrated as 'energy coop, energy efficiency' in Figure 4.27 and 4.28). This is due to the increase of local energy prices, still leading to cost savings for the tenants due to the load reductions through energy efficiency.

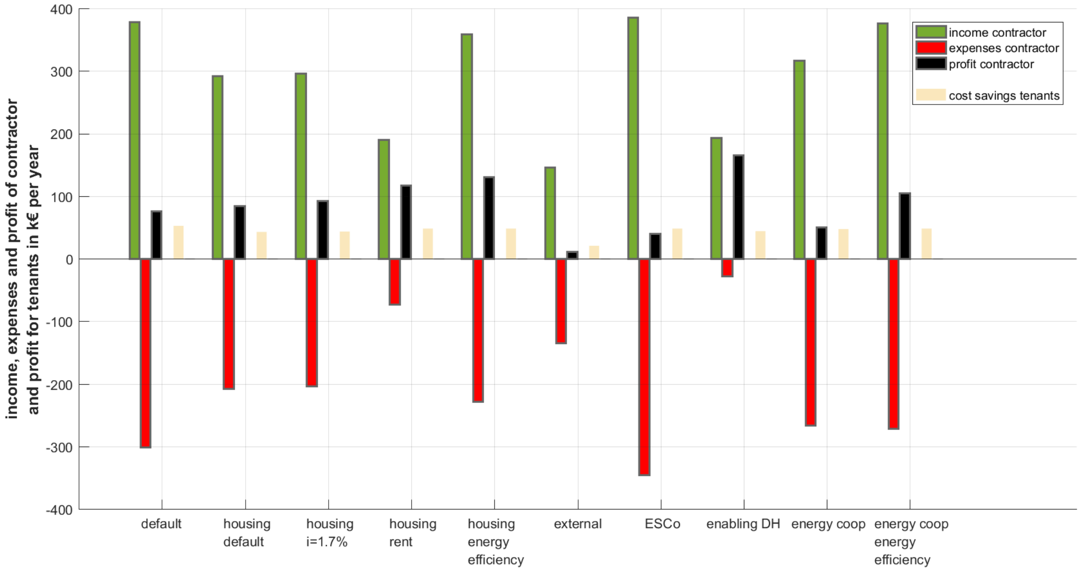



Figure 4.27.: Comparison of expenses, income and profit of the contractor and cost savings for the tenants of all use cases examined

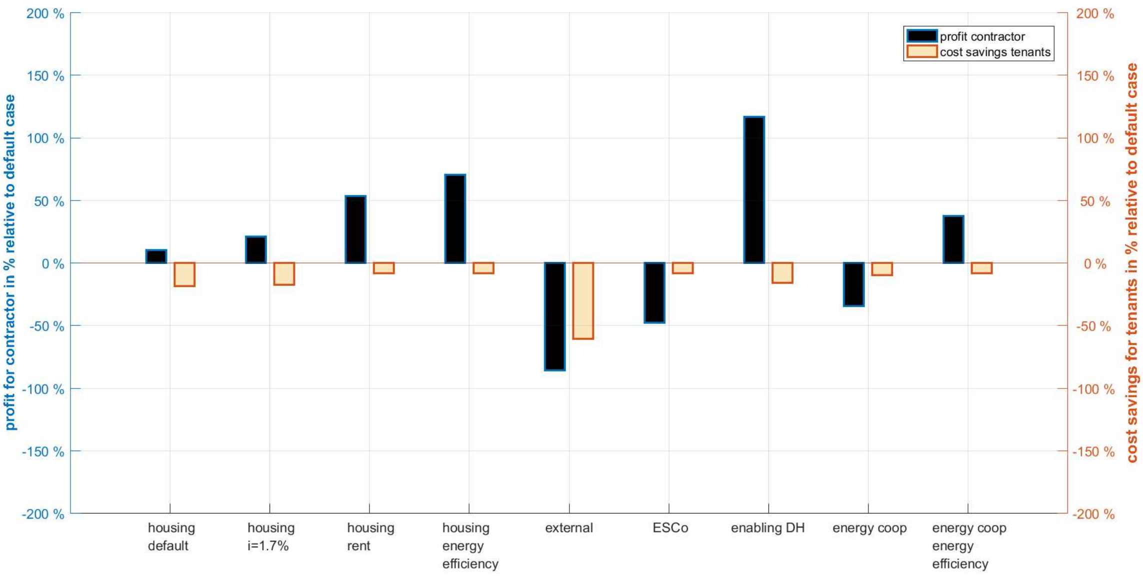



Figure 4.28.: Comparison of profit of the contractor and cost savings forthe tenants of all examined use cases in percent compared to default use case

## 4.4. Sensitivity analyses

For the following analyses, the default contracting use case from Section 4.1.3 is adapted to depict the main sensitivities concerning the contractor's profit and the tenants' energy cost savings. Firstly, the mixed urban neighborhood is reduced to being a residential neighborhood only (consisting of three usage-identical buildings). In a second analysis, German electricity prices are assumed in order to show changes for higher retail electricity prices. Thirdly, it is examined, how the impossibility of feed-in into the grids is impacting the economic gains. Moreover, limited roof availability as well as reduced technology costs are investigated in the following. Last but not least, increasing costs for $CO_2$ emissions (and thus increasing energy prices) are examined. The results in this chapter show only selected examples of a wide range of possible sensitivity analyses.

### 4.4.1. Residential neighborhood

For a purely residential neighborhood, the optimization model installs approximately 175 kWp of PV on the southern roof parts only. This is the result of a smaller electric load during summer time (no electric cooling in the residential buildings) and a small yield of the PV system in the winter months. The mCHP and HP system are installed to maximum capacities.

As can be seen in Figure 4.29, the profit for the contractor is reduced drastically by 38% (47 220 €). A slightly higher profit compared to the default case is only gained in the winter months of December and January, because of the higher HP capacity installed (the heat load for the residential building is insignificantly higher than that of the office or school building). Concerning the tenants' energy cost savings, there can also be seen a reduction in savings (of approximately 27% to 38 465 €) since less PV capacity is installed.

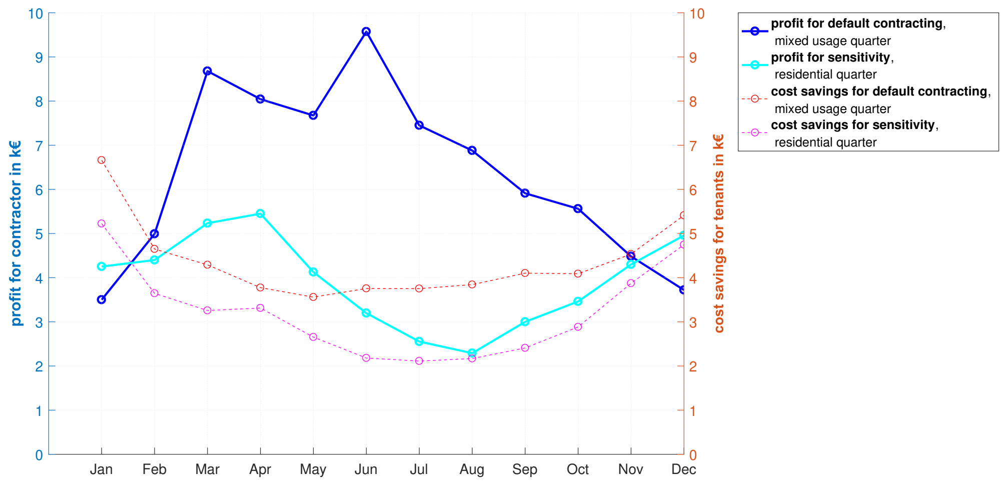



Figure 4.29.: Comparison of monthly profit for contractor and cost savings for tenants between the mixed urban default neighborhood and a purely residential neighborhood

### 4.4.2. German electricity price

To examine the sensitivity electricity price, prices from Germany (see [7]) of 0.3085 €/kWh are assumed, while the prices for gas/heat and all installation and maintenance costs are not changed. Figure 4.30 shows an increase in profit for the contractor of 125% to 172 301 € and an increase in the tenants' energy cost savings of 23% to 64 710 € within the period of one year.

The installed capacities in this case are similar to the default use case, although more PV capacity is installed on the north side of the roof (approximately 70 kWp additionally) while the HP capacity shrinks, both due to the high grid electricity price.

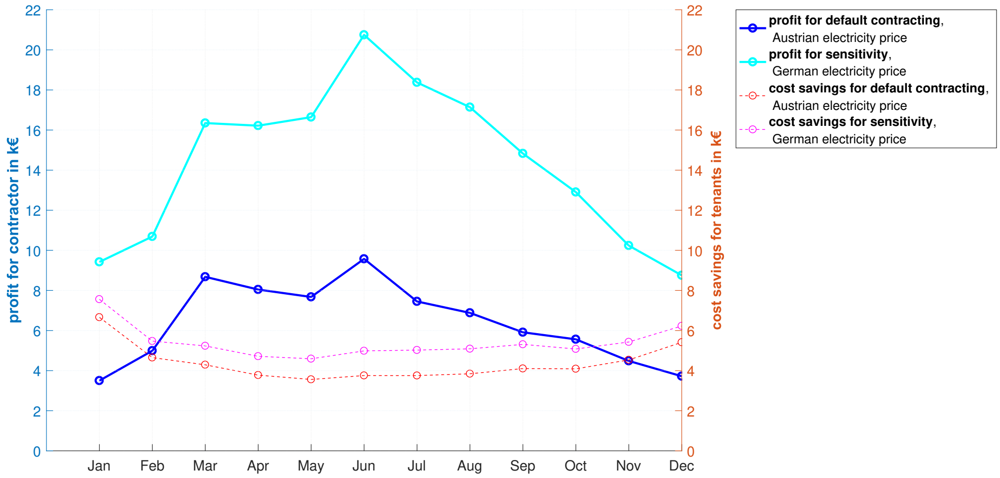



Figure 4.30.: Comparison of profit for contractor and cost savings for tenants monthly between the Austrian default and the German electricity price

### 4.4.3. No surplus feed-in into grids (thermal, electric) possible

For this sensitivity analysis, the default contracting model is adapted to prevent feed-in of local energy (electricity and heat) into the grids by setting all power feed-in terms from the PV, HP and mCHP system to zero. This assumption is justified in cases where grids are temporarily overloaded and do not have enough capacities for additional feed-in at this point of the feeder. In this case, local power generation has to meet demand at all times (maximum local energy capacities are equal or lower compared to the loads of the neighborhood).

As a result, the profit for the contractor decreases significantly by 48% to 40 150 € since smaller technology capacities are installed (see Figure 4.31). This is due to the fact that local power generation has to meet the neighborhood's demand at all times and neither the electricity nor the heating grid can be used as storages. This effect can be seen by the PV installation capacities, where the south side roof is now only fitted with a third of the modules compared to the default contracting case. Additionally, only parts of the east and west side of the roof are used for further PV generation. The flexible mCHP system is installed to maximum capacity, but is used mostly in the winter period, where heat demand is high enough to consume the generated energy locally. During summer, a large amount of electricity has to be bought from the grid due to the small PV capacities. Moreover, the heating demand is not high enough to run the mCHP system in a higher output range. An HP system is also installed by the optimization to offer additional heat in the winter months, although the capacity is just about two thirds compared to the default contracting case.

Due to less local energy capacities, the tenants' cost savings also decrease by 4% to 50 472 € (see Figure 4.31).

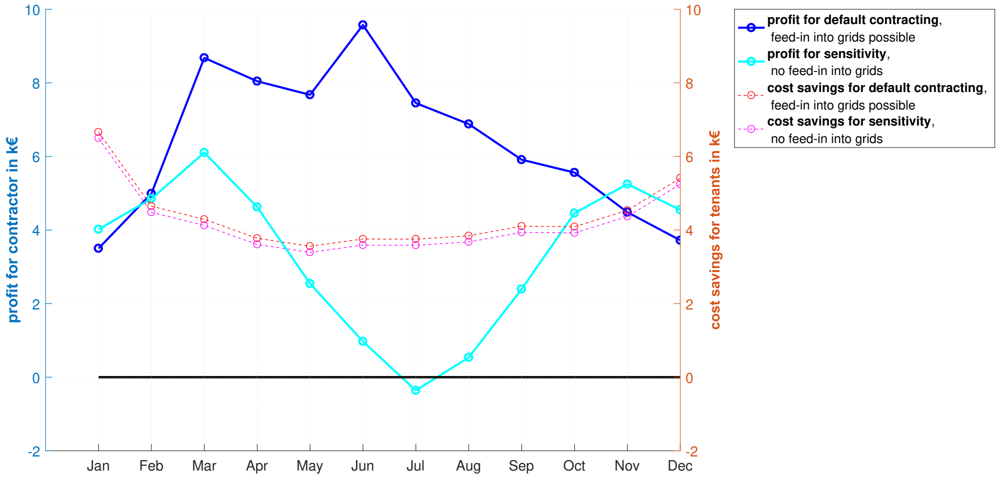



Figure 4.31.: Comparison of mothly profit for contractor and cost savings for tenants between the default contracting case and no feed-in into the grids

### 4.4.4. Limited roof availability

The buildings' roofs offer space for diverse utilization, whereof conflicts of interest can arise. If rooftop gardens or terraces are built, or if intensive green roofs are required, the available area for installing PV is reduced. This case examines how the contractor's profit and the tenants' energy cost savings change if only 50% of the roof area is available for PV system installation. The surface area for the BIPV system on the facade is not modified.

Figure 4.32 shows that if the surface area for PV installation on the roof is reduced by half, the profit for the contractor is reduced by 15% to 65 110 €, while the tenants' energy cost savings remain at a similar range (decrease of less than 1% to 52 020 €). The cost savings remain at a certain level due to the grid connection capacities being changed only insignificantly when the PV system's size is reduced (the electricity grid has to supply the full required power on cloudy days, when PV generation - no matter the size of the system - is low). The profit for the contractor is lower because less PV electricity can be sold to the tenants, making it more expensive for the contractor to buy electricity from the grid and resell it for the reduced price to the tenants.

When only 50% of the roof area is available, the BAPV system is installed to (the reduced) maximum capacity (even on the north side) and the HP system size is reduced by about 30 kW due to less cheap PV electricity being available to power the HP system directly.

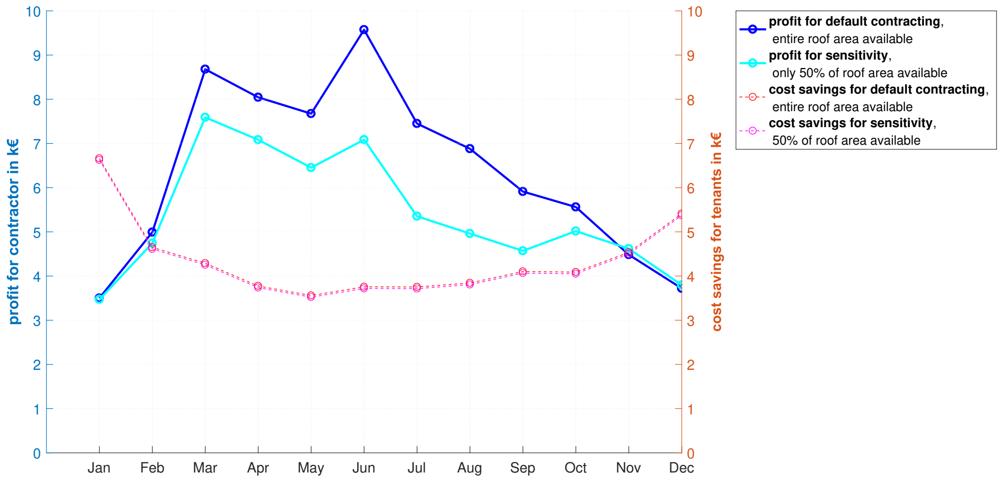



Figure 4.32.: Comparison of monthly profit for contractor and cost savings for tenants between the entire and only 50% of roof area available for BAPV installation

### 4.4.5. Lower technology costs

For this analysis, the investment costs of the BAPV, BIPV, HP and mCHP system are reduced by 30% in order to examine the impact of reduced costs on the optimally determined installation capacities and thus on profits and cost savings.

The results show that about 100 kW of additional PV capacity is installed on the north side of the roof. However, the facade is still not used for PV implementation. The HP system is raised to maximum capacity.

The profit of the contractor is raised by 23% to 94 506 € (see Figure 4.33) and the energy cost savings for the tenants, like in Section 4.4.4, stay in a similar range (rise less than 1% to 52 910 €).

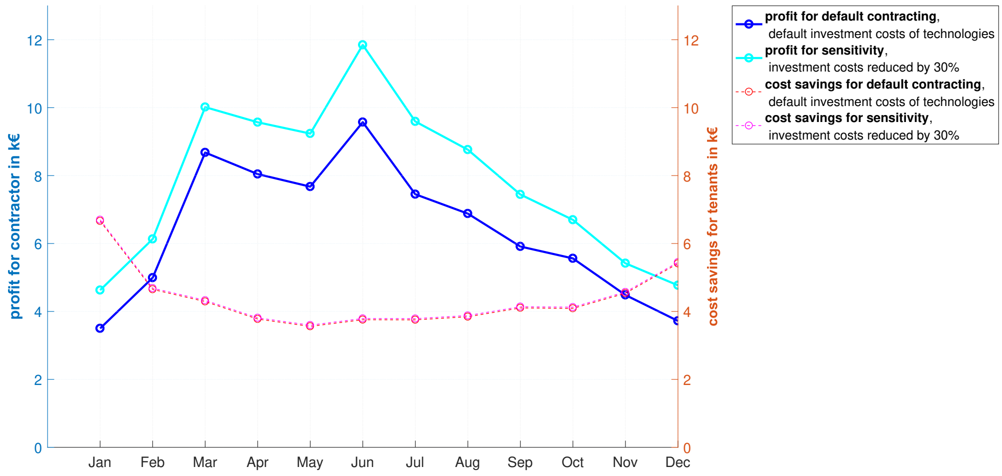



Figure 4.33.: Comparison of monthly profit for contractor and cost savings for tenants between default and 30% reduced investment costs of the local energy technologies

Furthermore, a decrease in technology investment costs of 45% is examined, analogously to the electricity price increase for the sensitivity analysis for a German electricity price of Section 4.4.2. The further reduction of investment costs lead to an increase in the contractor's profit of 36% to 104 254 €.

### 4.4.6. Increasing $CO_2$ price

In order to examine how rising $CO_2$ prices effect the profitability of contracting, the carbon dioxide emissions of the heating and electricity technologies are calculated using the conversion factors of Table 4.5, taken from [54]:

| | Conversion factor [$kg_{CO_2}$/kWh] |
|---|---|
| Electricity from grid | 0.417 |
| Gas from grid | 0.236 |
| District heat from grid | 0.073 |

Table 4.5.: $CO_2$ conversion factors used in calculations [54]

As a next step, the annual $CO_2$ emissions for the whole neighborhood are calculated for the default contracting case of Section 4.1.3 and are shown in Figure 4.34 (a). A similar comparison where the only change is the default heating system being DH can be found in Appendix A.7. Additionally to the amout of emissions per year, the resulting costs per ton $CO_2$ are depicted on the second y-axis, whereas the current European Emission Allowance (European Union Emission Trading System EU ETS) price of 24.34 €/$t_{CO_2}$ is assumed [17].

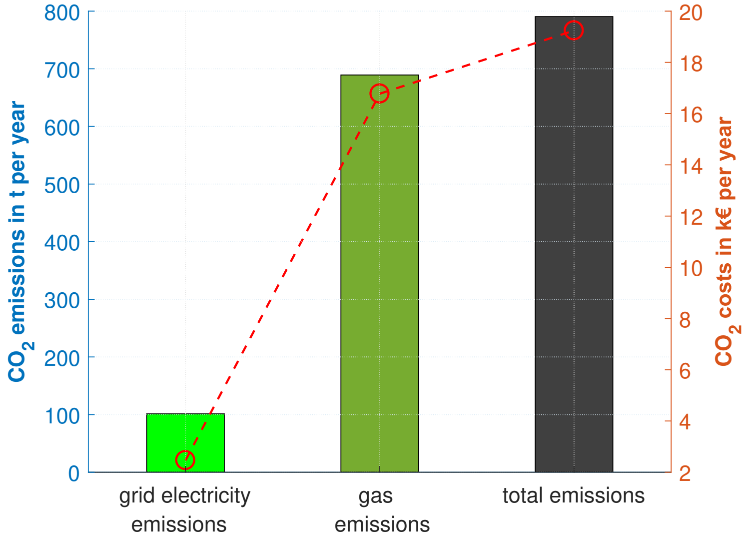
It is assumed that (EU ETS) $CO_2$ prices rise to 70 €/$t_{CO_2}$ by 2030, in consonance with a high price scenario of [82]. This leads to an increase in energy prices according to the conversion factors introduced in Table 4.5. The higher energy prices for electricity, gas and thermal energy in comparison to the default prices can be derived from Table 4.6 and are in line with a low price scenario of [5], see also [26]:

| | Default energy price [€/kWh] | Assumed energy price 2030 [€/kWh] |
|---|---|---|
| Electricity from grid | 0.213 | 0.232 |
| Gas from grid | 0.061 | 0.071 |
| District heat from grid | 0.077 | 0.080 |

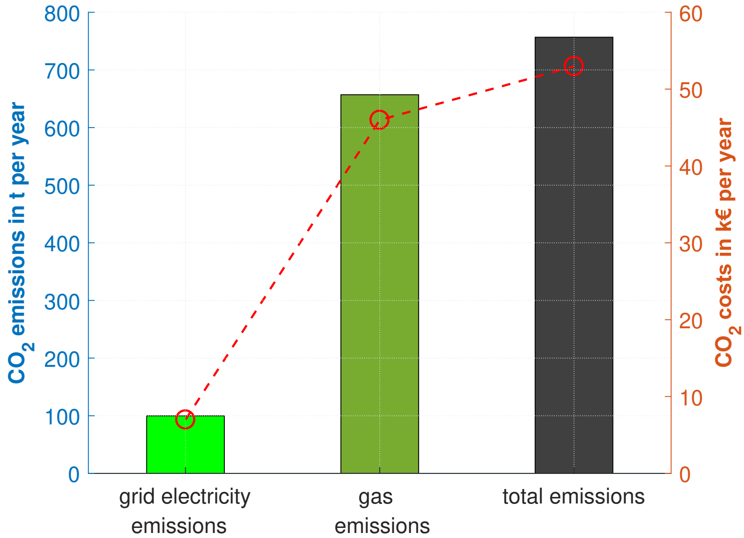
Table 4.6.: Energy price increase due to a raise of the $CO_2$ price

Figure 4.34 compares the emitted amount of $CO_2$ in the default case with the case of the higher emission price of 70 €/$t_{CO_2}$, as well as the costs for the emissions.

The optimization determines maximum HP capacities due to the higher $CO_2$ price. Additionally, about 55 kW of PV is added to the north side of the roof to supply the HP system and to generate cheaper electricity (from PV) and heat (from HP) to resell to the tenants. Figure 4.35 shows that both the contractor's profit and the tenants' energy cost savings rise by about 12% to 85 154 € and to 58 404 €, respectively, when the $CO_2$ price is raised by 188%. The increasing $CO_2$ costs lead to a rise in retail energy prices. The said rise highly depends on the assumed conversion factors depicted in Tables 4.5 and 4.6. The energy cost savings are higher in this case due to the higher grid energy prices of heat and electricity, saving more money, if a locally generated kilowatt hour is consumed in comparison to grid energy.




(a)




(b)

Figure 4.34.: Resulting $CO_2$ emissions and costs per year for (a) default contracting case and (b) higher emission price of 70 €/$t_{CO_2}$

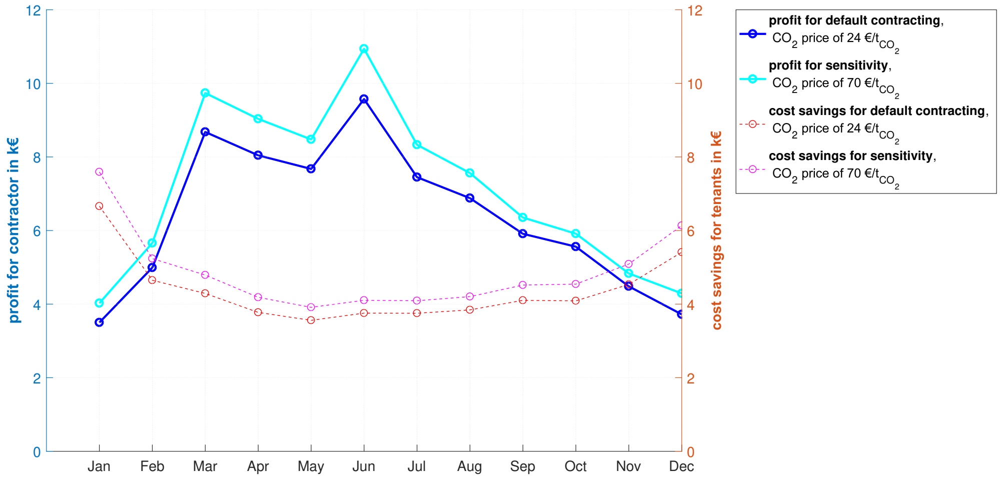



Figure 4.35.: Comparison of monthly profit for contractor and cost savings for tenants between default and higher emission price of 70 €/$t_{CO_2}$

### 4.4.7. Comparison of sensitivity analyses

Table 4.7 shows a comparison of the sensitivity analyses discussed, whereas it is indicated if the profit for the contractor and the energy cost savings for the tenants are higher ($\oplus$) or lower ($\ominus$) compared to the default contracting case of Section 4.1.3. The cases are marked with "/", if the deviation from the default case is lower than 5%. It can be seen that the height of the electricity price has the most impact on the contractor's and the tenants' profit.

| | Influence on profit for contractor | Influence on energy cost savings for tenants |
|---|---|---|
| Residential neighborhood | $\ominus\ominus$ | $\ominus$ |
| German electricity price | $\oplus\oplus\oplus\oplus$ | $\oplus\oplus\oplus\oplus$ |
| No surplus feed-in into grids | $\ominus\ominus$ | / |
| Limited roof availability | $\ominus$ | / |
| Lower technology costs | $\oplus$ | / |
| Increasing $CO_2$ price | $\oplus$ | $\oplus$ |

Table 4.7.: Comparison of influence of sensitivities on profit for contractor and energy cost savings for tenants

# 5. Conclusion

The possibility for the model to install a PV, an HP and an mCHP system has proven to be more profitable than limiting the installable systems to one or two technologies. Those results are highly dependent on the examined neighborhood, its size and in particular its usage composition, as well as fuel prices and other retail energy prices (as discussed in the sixth paragraph of this chapter concerning sensitivities).

The default heating system (gas or DH) and its underlying costs have a significant impact on the contractor's and the tenants' profitability. Higher profits for one party lead to an increase in profits for the other party. In this approach, a DH system is always accessible for feed-in of surplus heat from local generation and the gas grid is available for powering the mCHP system. This grid configuration is highly location dependent.

The use cases for the housing industry, the energy sector and third parties examined in the thesis can only display a small number of available use cases on the market. Nevertheless, they have been proven to encompass a wide range concerning profitability, involved stakeholders and installed sizes of local energy technologies. A list of findings for the individual use cases is provided in Table 5.1. Concerning profitability, the following ranking of use cases can be made:

- The highest profits for the contractor are achieved with the 'Enabling Model' due to the default DH heating system applied.
- The housing association/private investor's 'Full Contracting model with energy efficiency measures' brings second highest profits for the contractor. This is due to the low interest rates and high depreciation times chosen for the housing association. Furthermore, additional profits can be generated through the application of energy efficiency measures.
- The 'Rent Model' of the housing association shows the third highest profit for the contractor. The fact that no specific price per kilowatt hour is assigned to electricity and heat enables the model to find an optimum between energy price and local energy technology capacities.
- The lowest profit for the contractor is generated by the external provider due to the high interest rate and the low depreciation period.

Additional costs paid by the contractor and their economic effects are contingent on the frequency of payment, whereas one-time costs, such as costs for planning activities, have little impact on profitability. Contrarily, annual costs, such as renting costs for the roof and basement, can lead to a significant decrease of profit.

The highest energy cost savings for the tenants are generated by the default contracting case due to the low interest rate, high depreciation time, the low energy prices paid by the tenants (even for grid electricity and gas) and the absorption of maintenance costs by the contractor.

The sensitivity analyses show that

- an increase in electricity price (analogously to the German retail electricity price) has the biggest positive effect on the contractor's and the tenant's profitability,
- a purely residential neighborhood and feed-in restrictions for local energy to the grid lead to the highest decrease in profitability and
- a 50% reduction of roof availability, lower technology investment costs of 30% and an increase in the $CO_2$ price (188%) have moderate impact on the profitability.

*Energy (supply) contracting* and *tenant electricity sharing* concepts offer great opportunities for the development and application of innovative business models. This thesis shows that such business models include a great variety of stakeholders, whereas the housing industry and the energy sector are likely to profit the most in the future. The changing legal framework in the housing sector (housing companies and housing associations in particular) is expected to result in a broader application of contracting (especially electricity sharing) models. The results show clearly that specific funding of *energy (supply) contracting*, at least in mixed neighborhoods, is obsolete and profitability for the contractors is given already.

Further research in the field of *energy contracting* can include the possible installation of additional local energy technologies, the consideration of electric vehicles (and a diversity of energy storage options) in the neighborhood and the inclusion of entire districts as energy communities.

| Contractor/ provider | Model | Interest rates, times of depreciation | Results |
|---|---|---|---|
| Housing association /private investor | **Full Contracting**: contractor invests, installs and operates/maintains system | 1.7% (inflation) / 3%<br>20 years | → Profitability given for contractor and tenants<br>→ Increase of interest rate from 1.7% to 3% (1.3% in total) leads to decrease of profit of nearly 9% |
| | **Rent Model**: contractor refinances investment via rent of tenants | 3%<br>20 years | → Highly profitable (27% increase compared to 'Full Contracting') due to not splitting into heat and electricity price |
| | **Full Contracting with Energy Efficiency Measures**: taking into account additional measures, such as increase of insulation, efficient lighting | 3%<br>20 years | → Higher profitability due to possible increase of local energy price (dependent on used energy efficiency measure costs) |
| Other external provider | **Full Contracting**: contractor invests, installs and operates/maintains system | 12%<br>5 years | → Profitability is low due to high interest rate and low depreciation time (85% profit loss compared to 'Full Contracting' case of housing association)<br>→ Cost savings for tenants are significantly low due to little installation of local capacities (only mCHP) |
| Energy industry (ESCo, municipal utility) | **Full Contracting**: contractor invests, installs and operates/maintains system | 7%<br>10 years | → Profits for contractor are lower due to higher interest rate and lower depreciation time<br>→ Energy cost savings for tenants relatively high due to very low local energy tariff (but higher grid energy tariff)<br>→ Rent of roof/basement for 6000€/year reduces profit by 30% |
| Housing association + ESCo | **Enabling Model**: contractor sells total electricity to ESC and is then sold to tenants | 3%<br>20 years | → Profitability given, but highly dependent on feed-in tariff for locally generated heat and electricity<br>→ Profitability also given for participating ESCo (highly dependent on cost and economic framework)<br>→ Lower cost saving potential for tenants due to no change in grid capacities |
| (Citizen) energy cooperative | **Full Contracting**: contractor invests, installs and operates/maintains system | 3%<br>25 years | → Contracting is even profitable for not maximizing profit for contractor but local energy supply<br>→ One-time expenses for planners (e.g. 6800€) lead to a very small decrease of profit of 0.7% |
| | **Full Contracting with Energy Efficiency Measures**: taking into account additional measures, such as increase of insulation, efficient lighting | 3%<br>25 years | → Higher profitability due to possible increase of local energy price (dependent on used energy efficiency measure costs) |

... forms of *Energy Supply Contracting* only

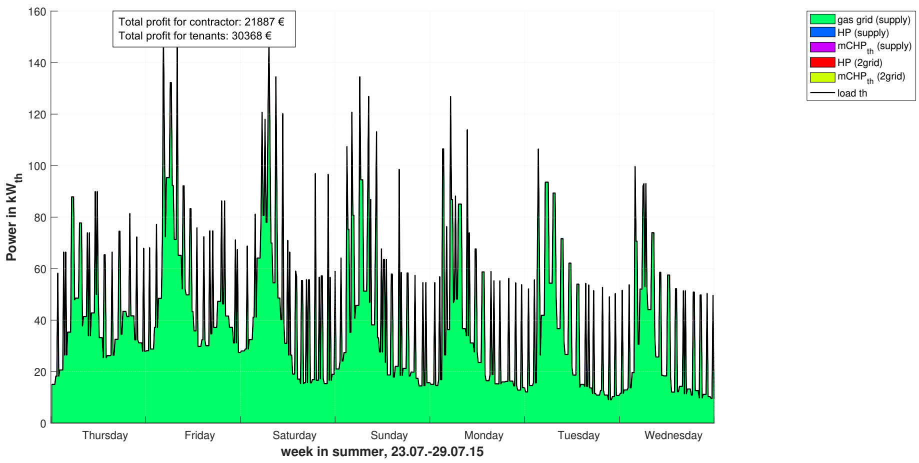
... additional *Energy Efficiency* measures applied

Table 5.1.: Results for examined contracting business cases

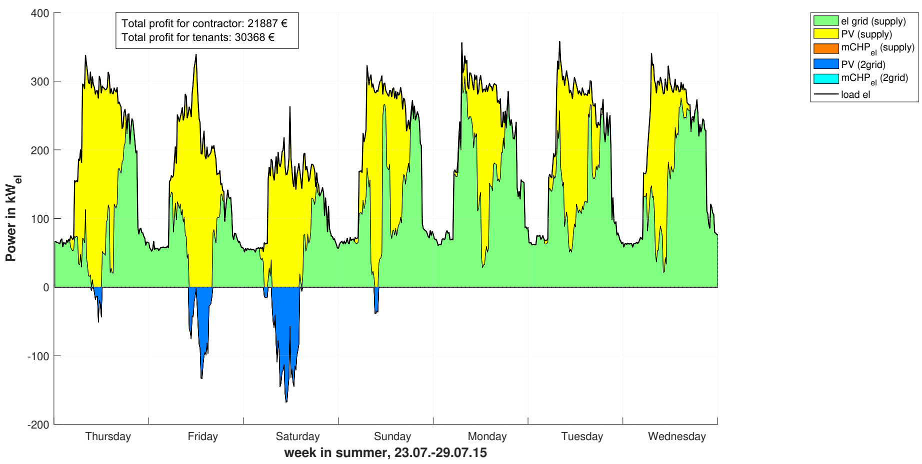
# Appendix A.

# Additional graphs

## A.1. Photovoltaic system

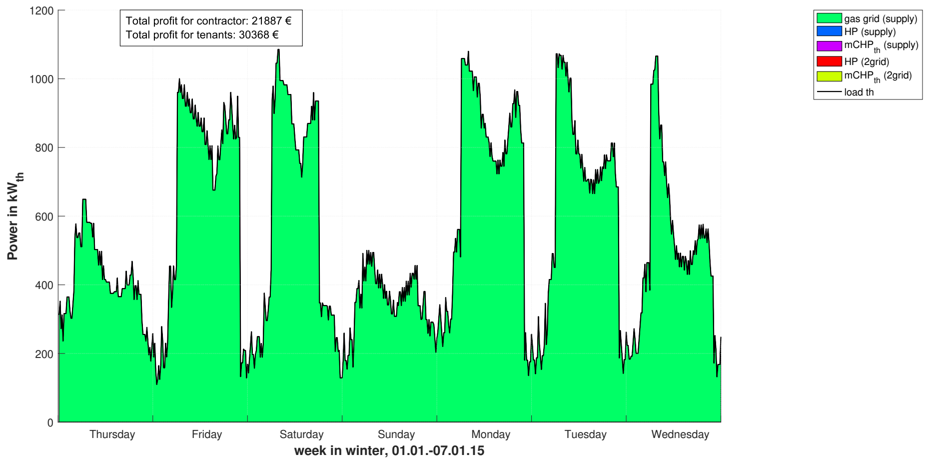



(a)

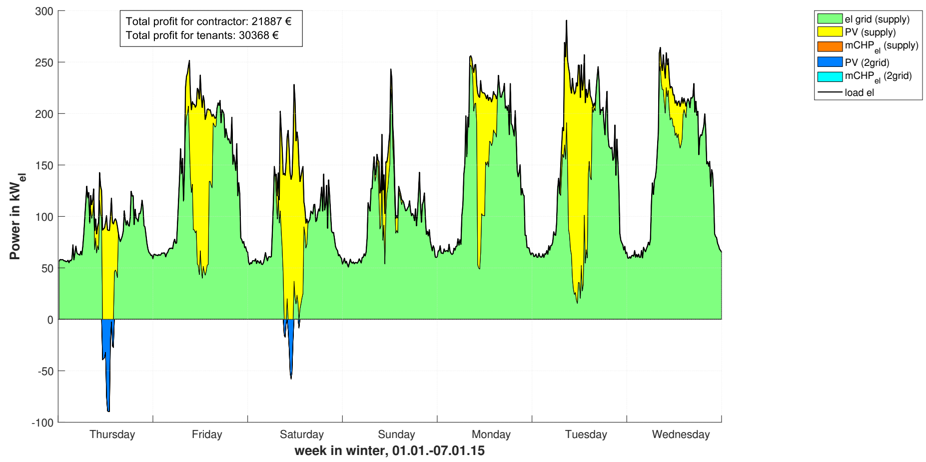



(b)

Figure A.1.: (a) Thermal and (b) electric load and supply, one week in summer



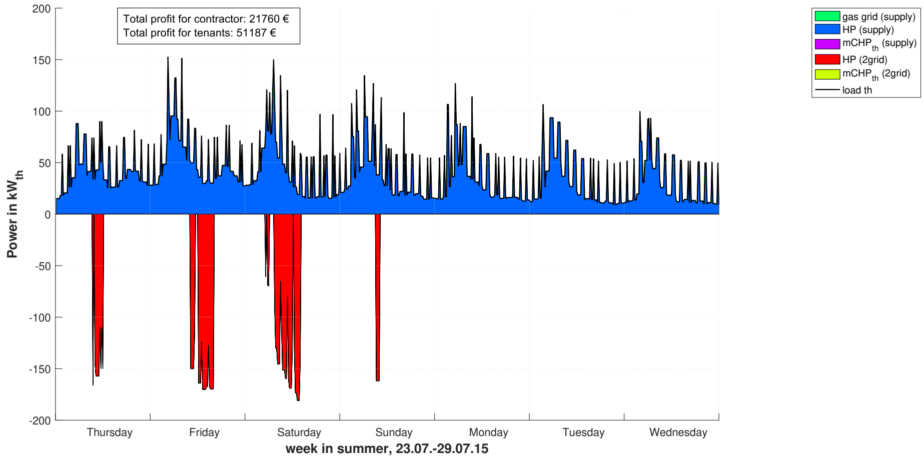

(a)




(b)

Figure A.2.: (a) Thermal and (b) electric load and supply, one week in winter

## A.2. Photovoltaic and heat pump system




(a)

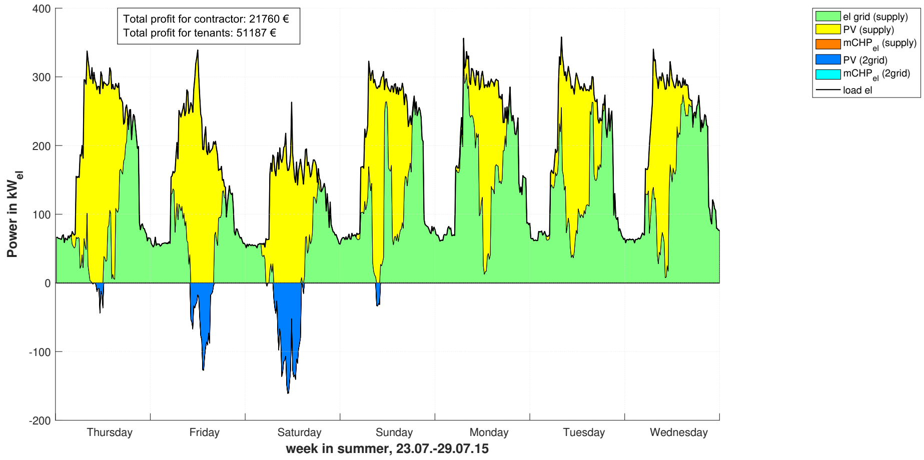



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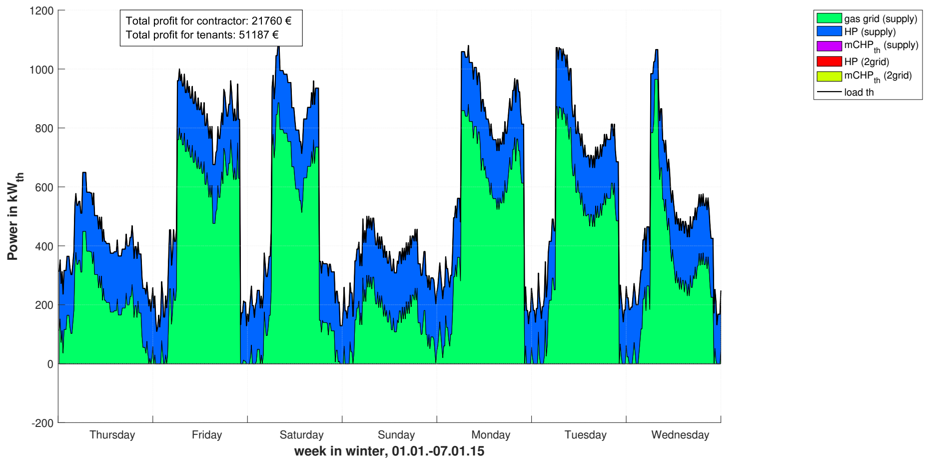
Figure A.3.: (a) Thermal and (b) electric load and supply, one week in summer

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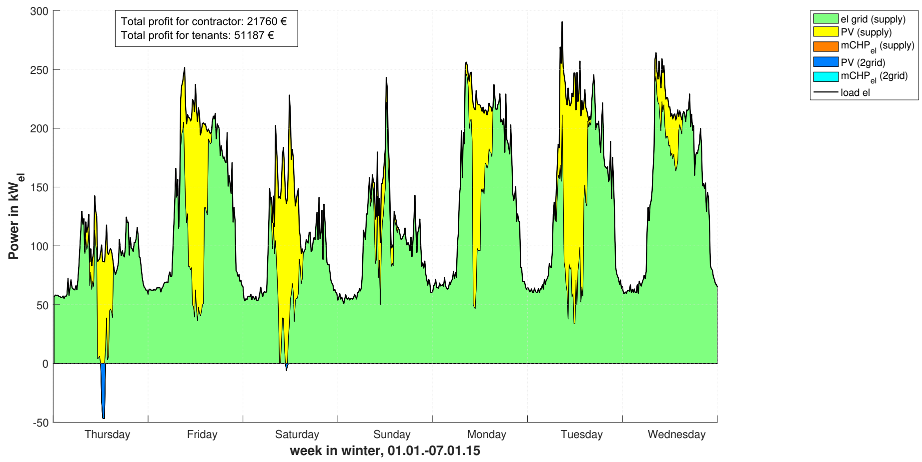
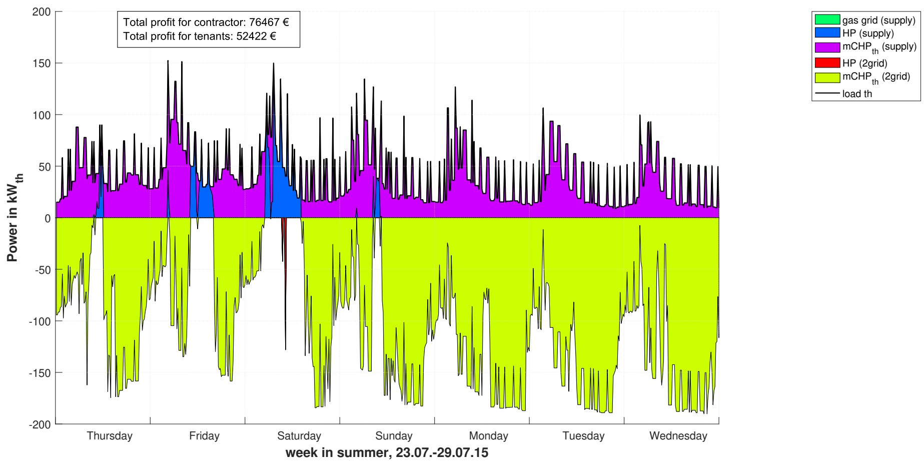



(b)

Figure A.4.: (a) Thermal and (b) electric load and supply, one week in winter

## A.3. Photovoltaic, heat pump and mini combined heat and power system

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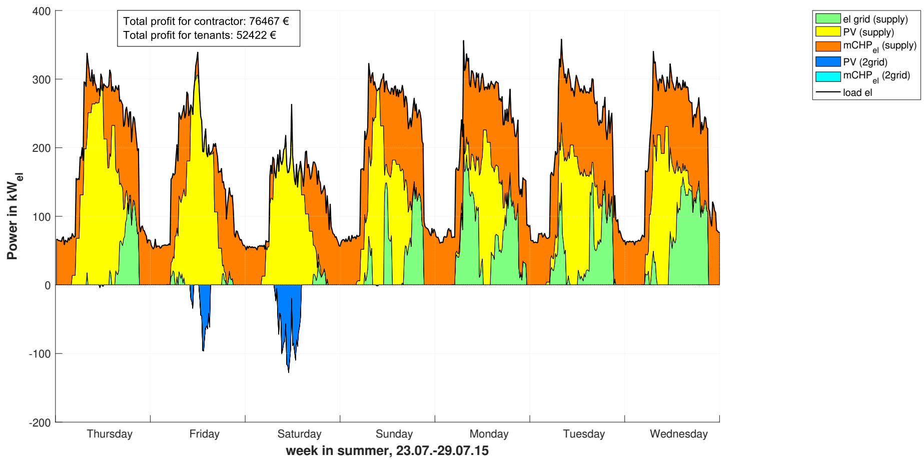


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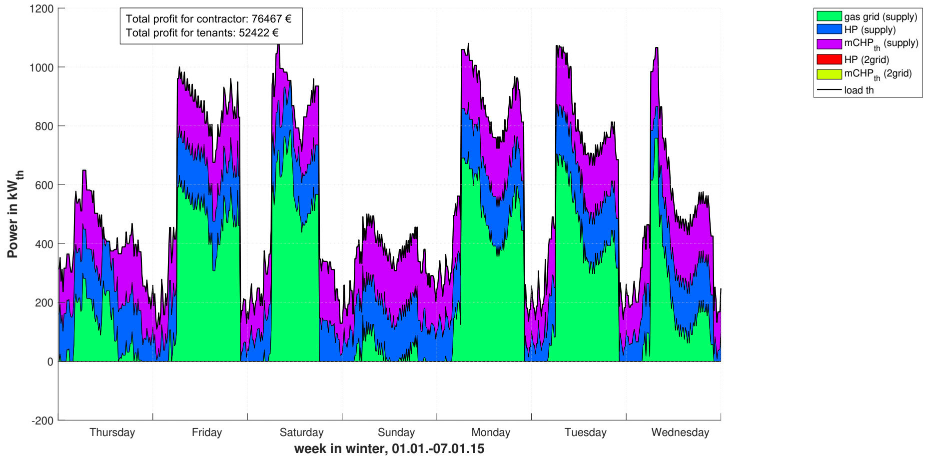
Figure A.5.: (a) Thermal and (b) electric load and supply, one week in summer

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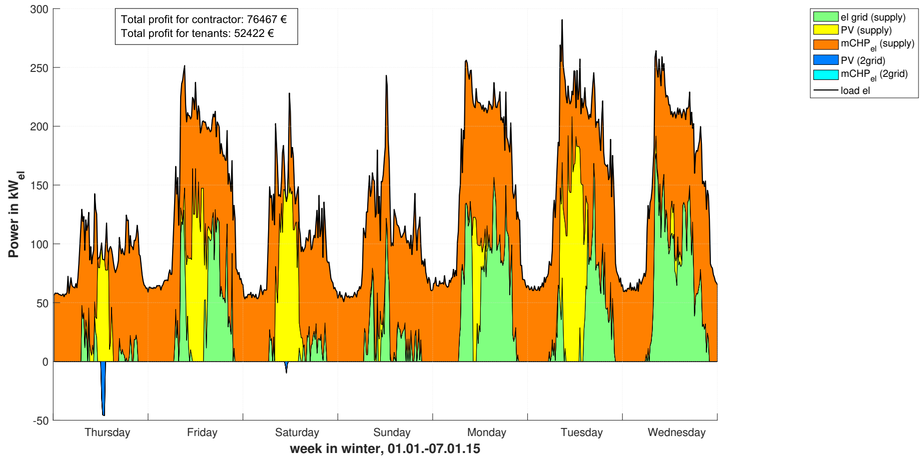
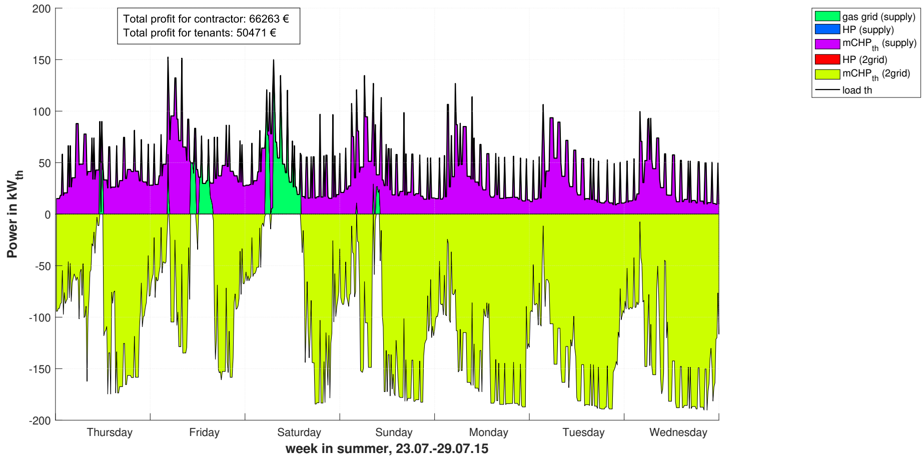



(b)

Figure A.6.: (a) Thermal and (b) electric load and supply, one week in winter

## A.4. Photovoltaic and mini combined heat and power system

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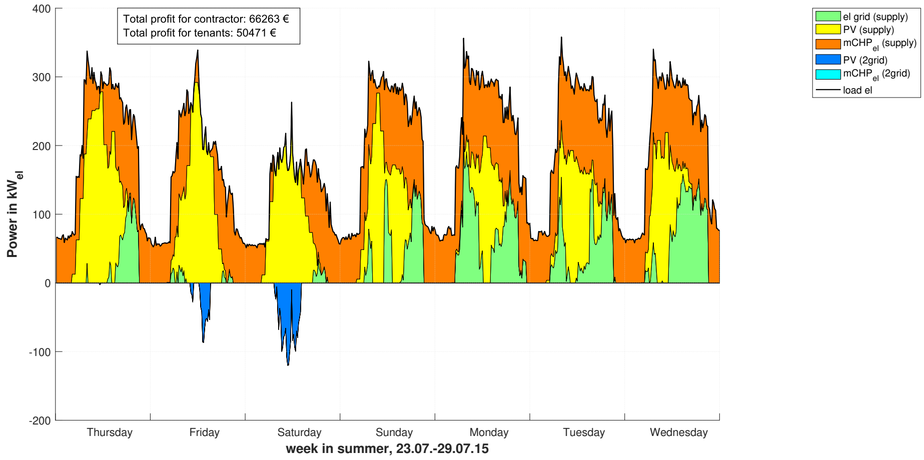


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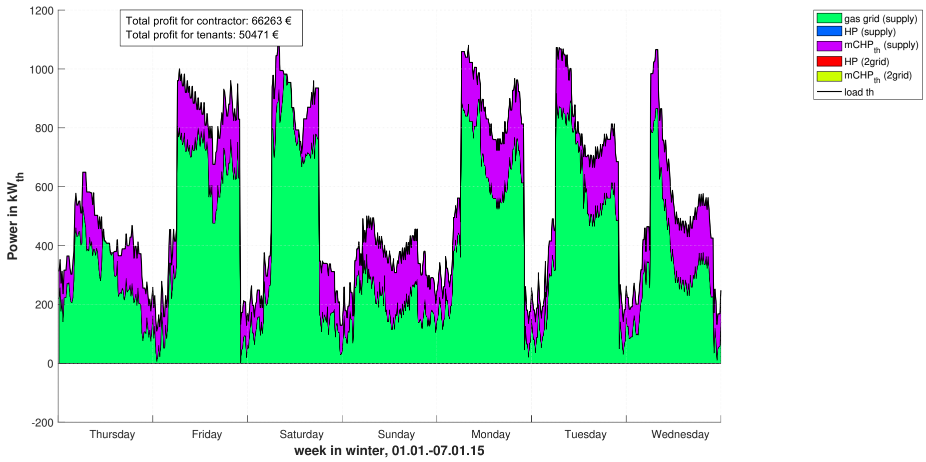
Figure A.7.: (a) Thermal and (b) electric load and supply, one week in summer

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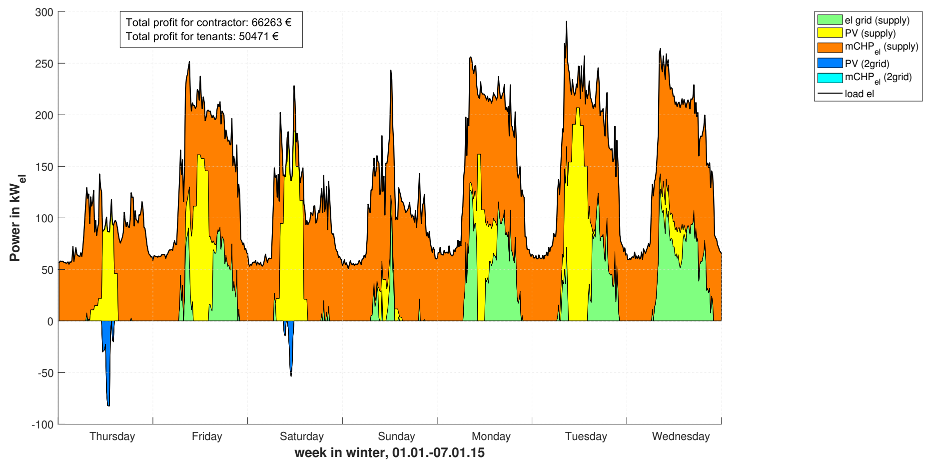
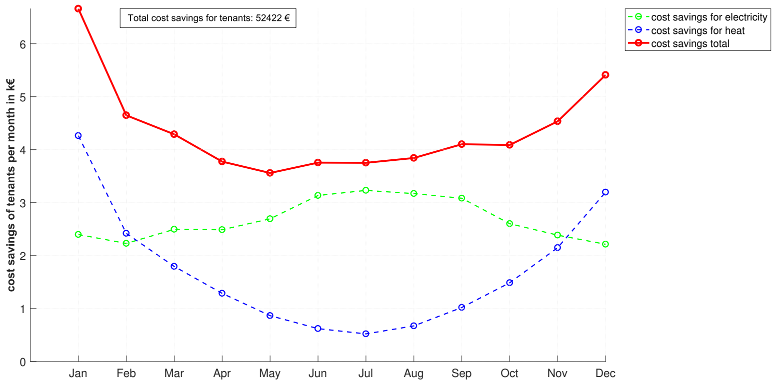



(b)

Figure A.8.: (a) Thermal and (b) electric load and supply, one week in winter

## A.5. Comparison of default heating systems

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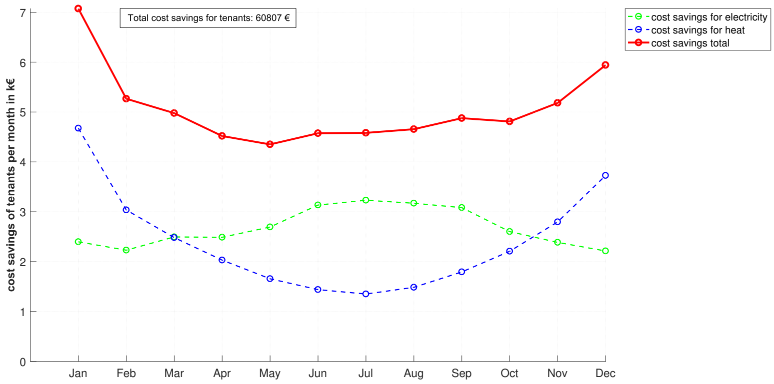


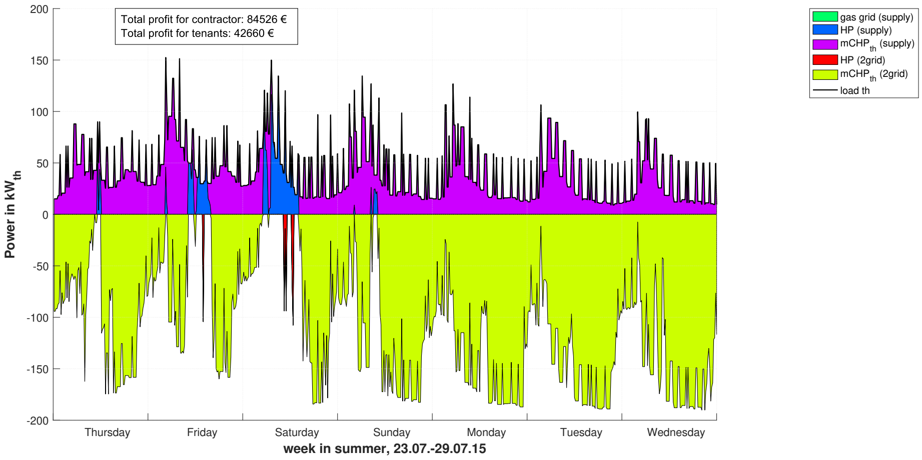

(b)

Figure A.9.: cost savings for tenants for (a) a gas (floor) heating and (b) a district heating system per month and in total

## A.6. Contracting business cases

### A.6.1. Housing association/private investor

#### Full Contracting

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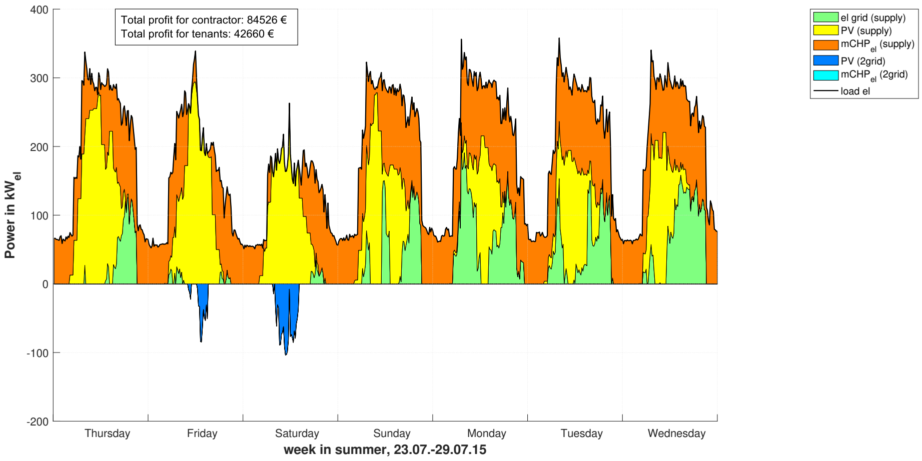
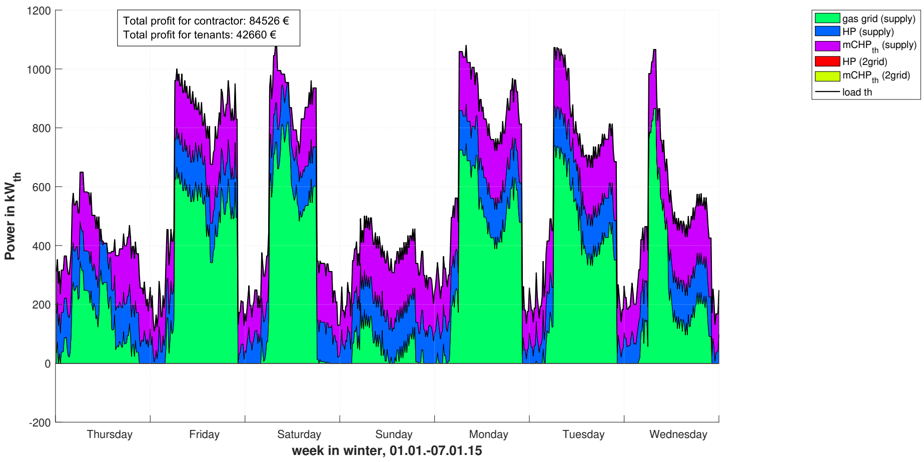



(b)

Figure A.10.: (a) Thermal and (b) electric load and supply, one week in summer

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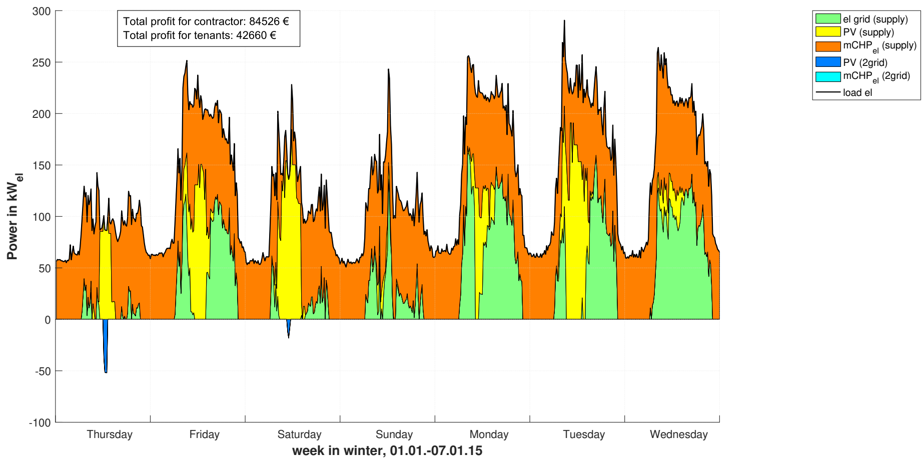
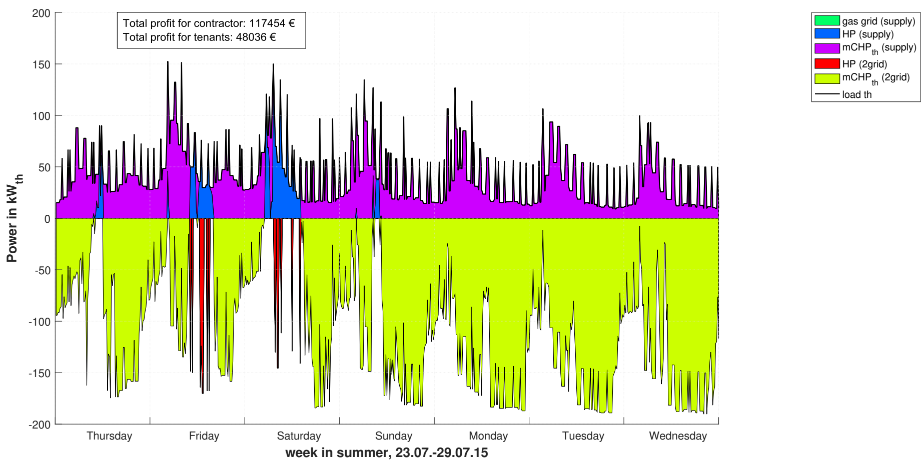



(b)

Figure A.11.: (a) Thermal and (b) electric load and supply, one week in winter

## Rent Model

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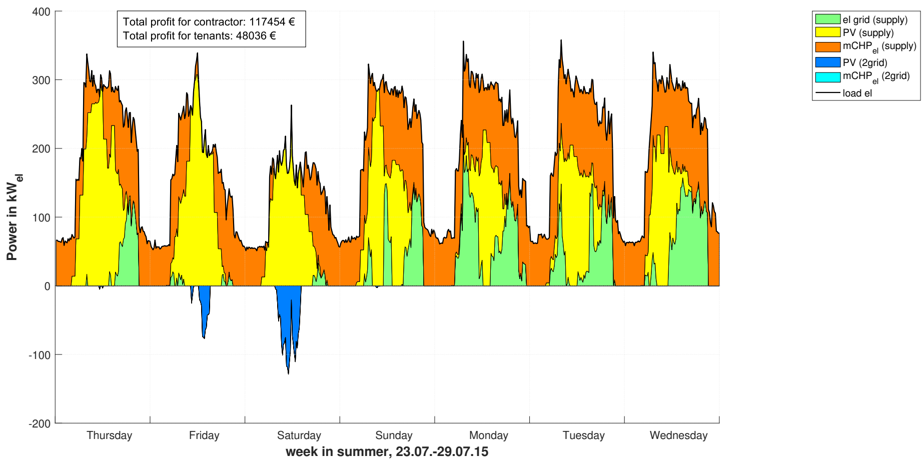
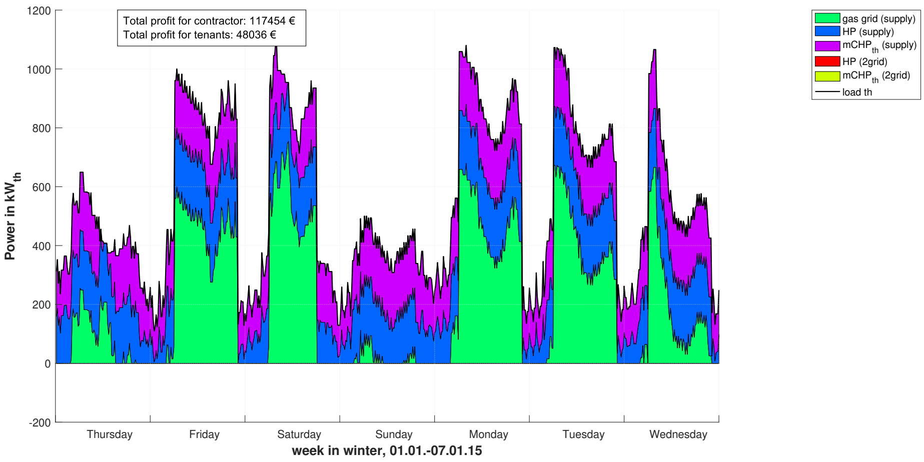



(b)

Figure A.12.: (a) Thermal and (b) electric load and supply, one week in summer

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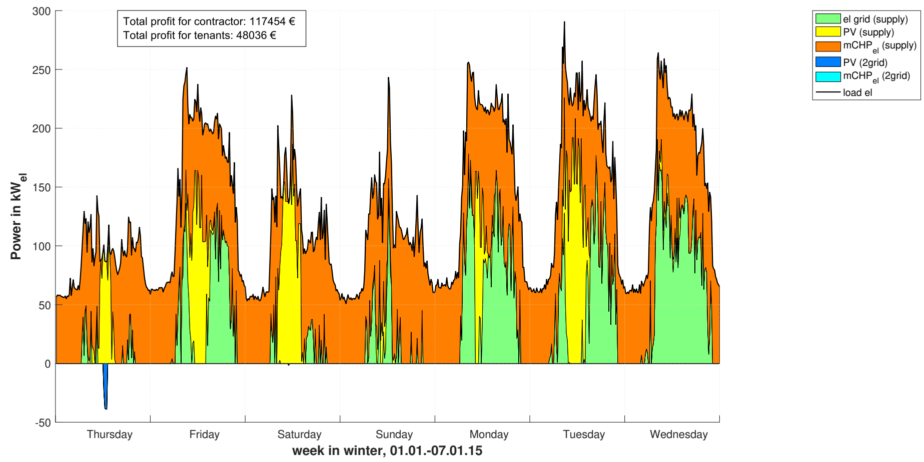
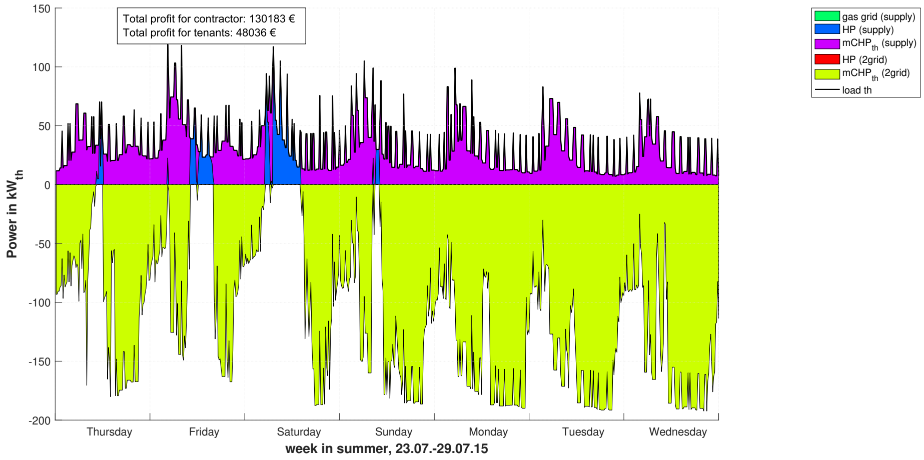


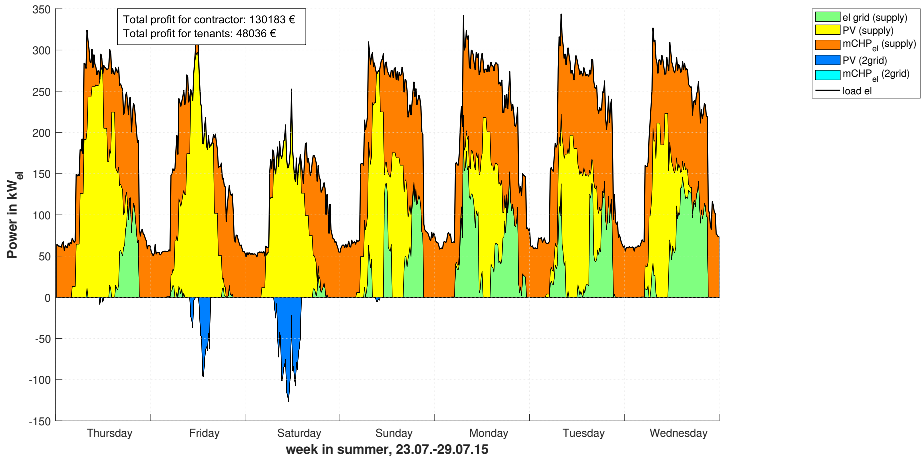

(b)

Figure A.13.: (a) Thermal and (b) electric load and supply, one week in winter

**Full Contracting with energy efficiency measures**

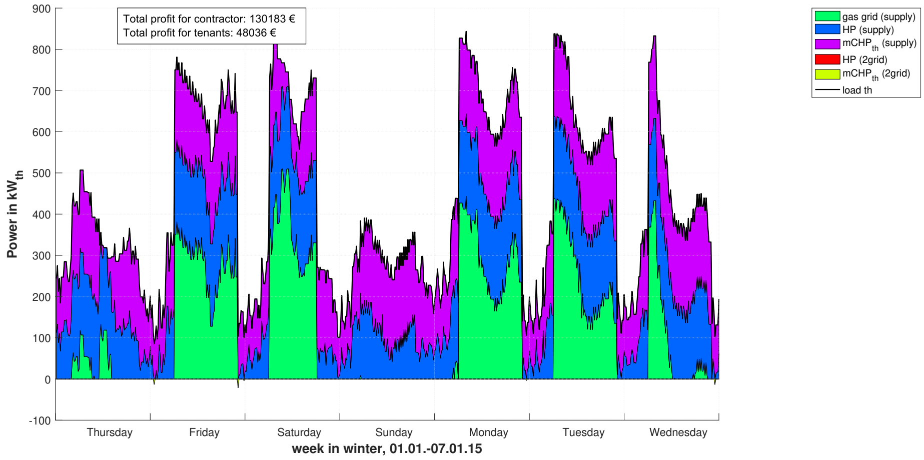



(a)

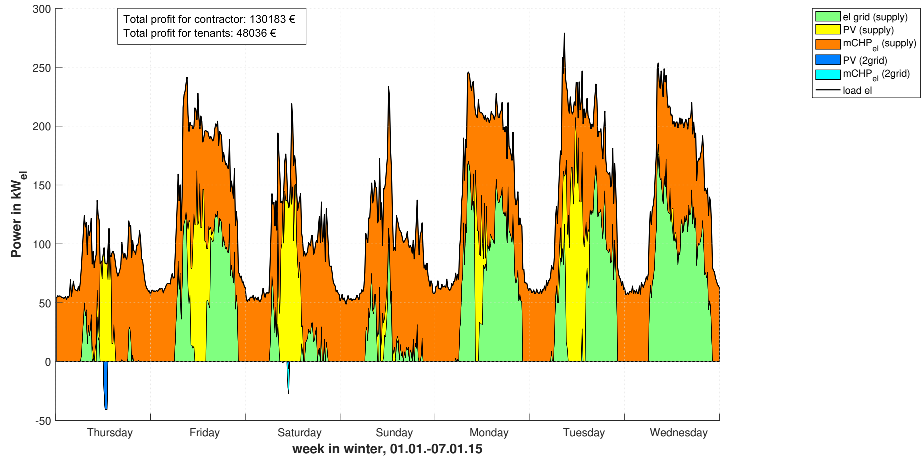



(b)

Figure A.14.: (a) Thermal and (b) electric load and supply, one week in summer




(a)

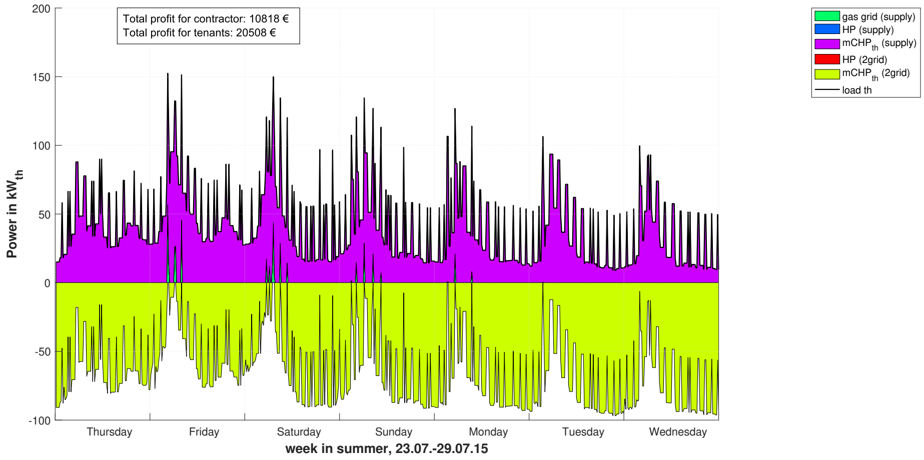



(b)

Figure A.15.: (a) Thermal and (b) electric load and supply, one week in winter

## A.6.2. Other external provider

### Full Contracting

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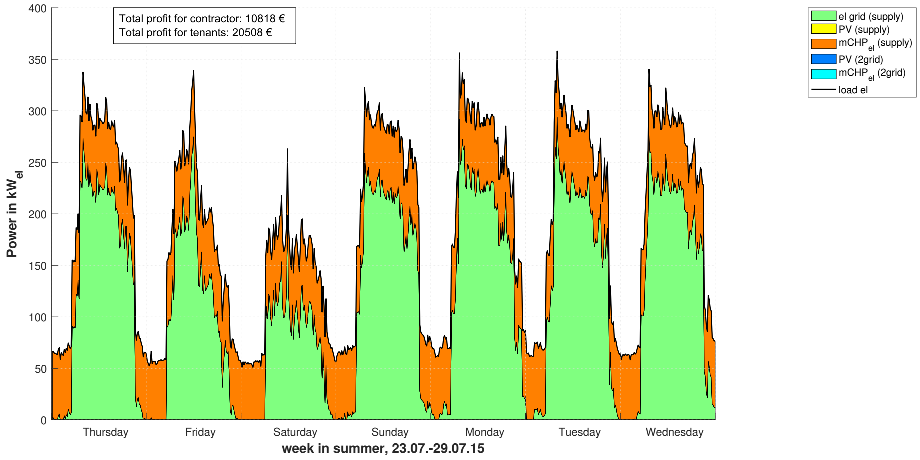
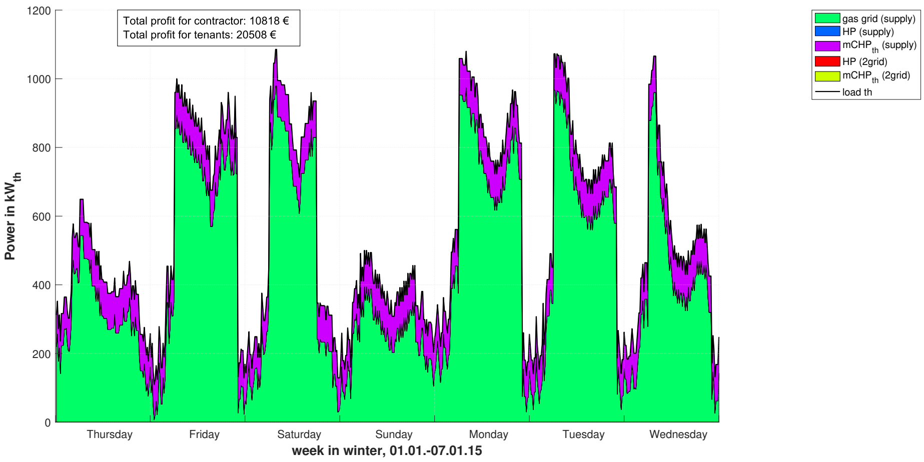



(b)

Figure A.16.: (a) Thermal and (b) electric load and supply, one week in summer

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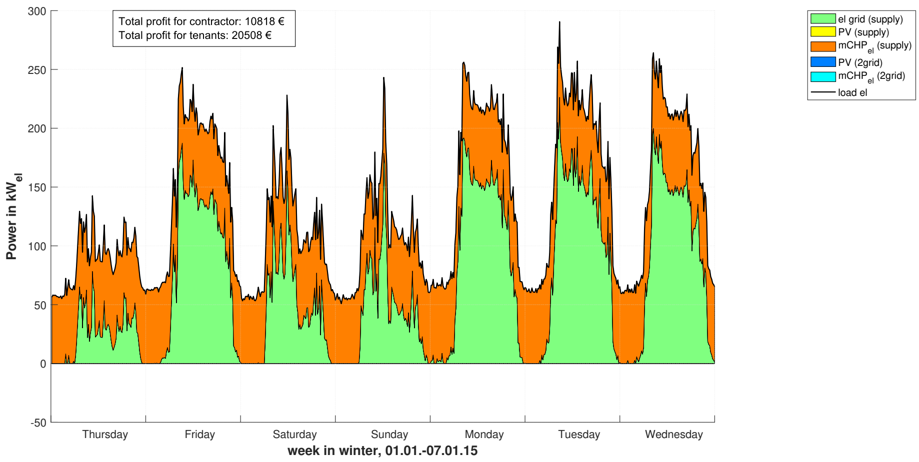
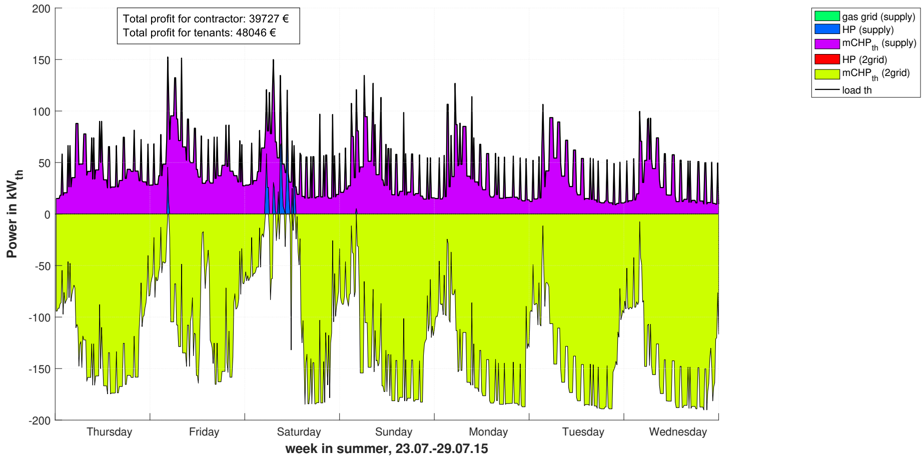



(b)

Figure A.17.: (a) Thermal and (b) electric load and supply, one week in winter

### A.6.3. Energy industry (ESCo, municipal utility)

#### Full Contracting

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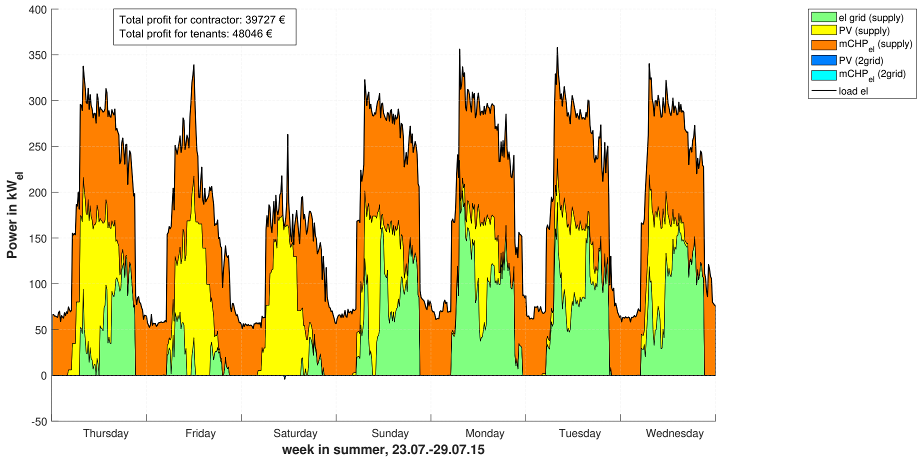
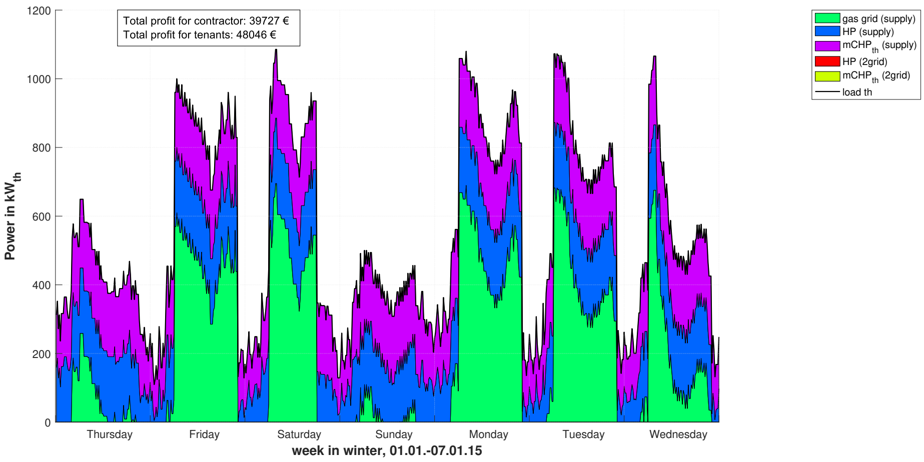
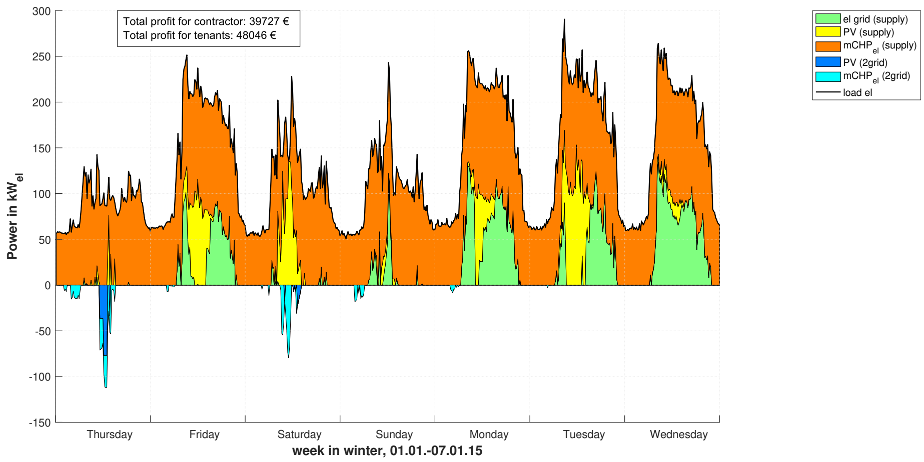



(b)

Figure A.18.: (a) Thermal and (b) electric load and supply, one week in summer




(a)

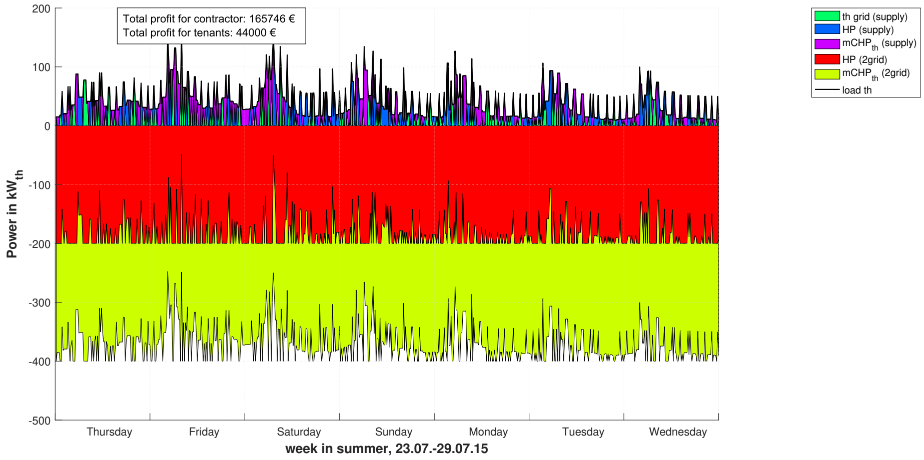



(b)

Figure A.19.: (a) Thermal and (b) electric load and supply, one week in winter

## A.6.4. Housing association and ESCo

### Enabling Model

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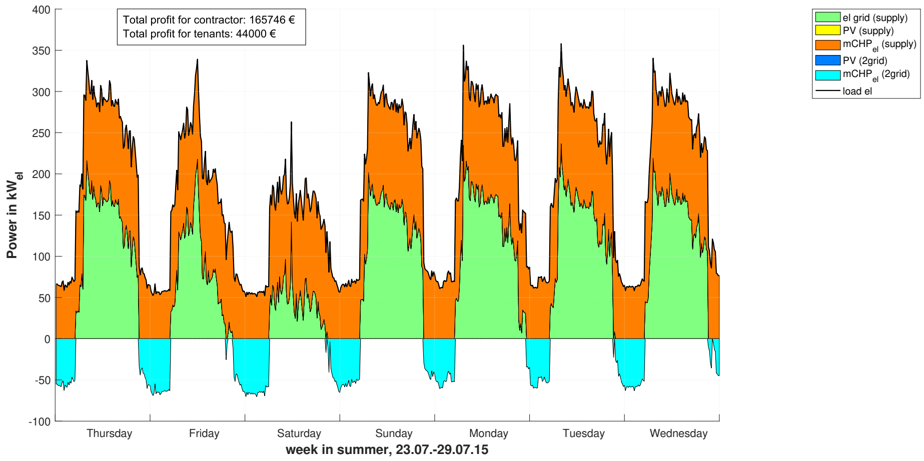
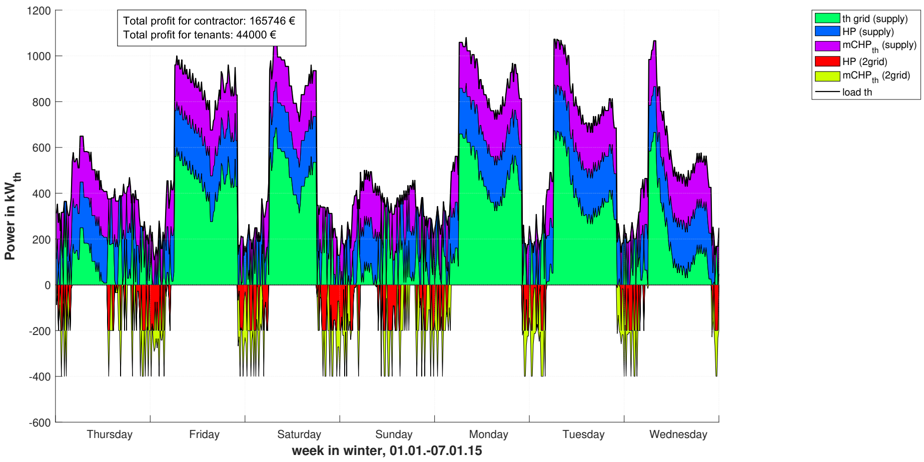
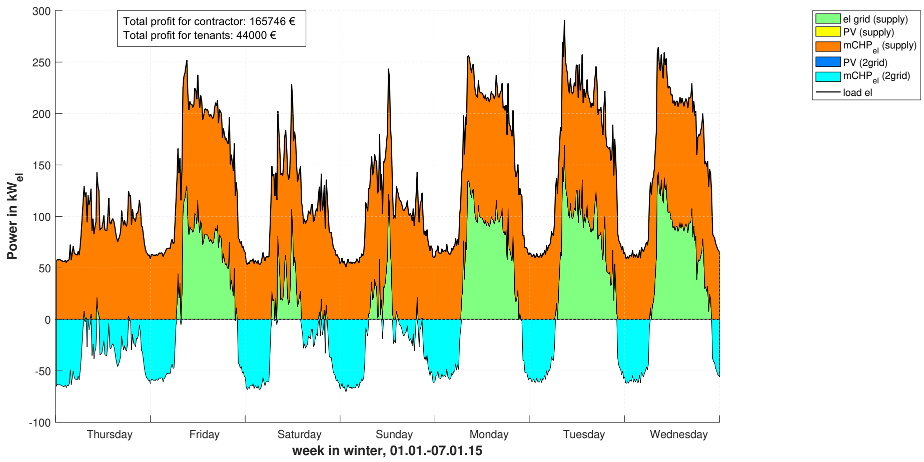



(b)

Figure A.20.: (a) Thermal and (b) electric load and supply, one week in summer




(a)

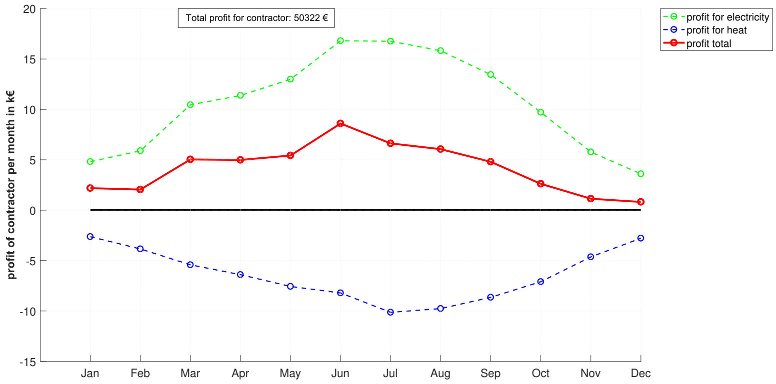



(b)

Figure A.21.: (a) Thermal and (b) electric load and supply, one week in winter

### A.6.5. (Citizen) energy cooperative

#### Full Contracting

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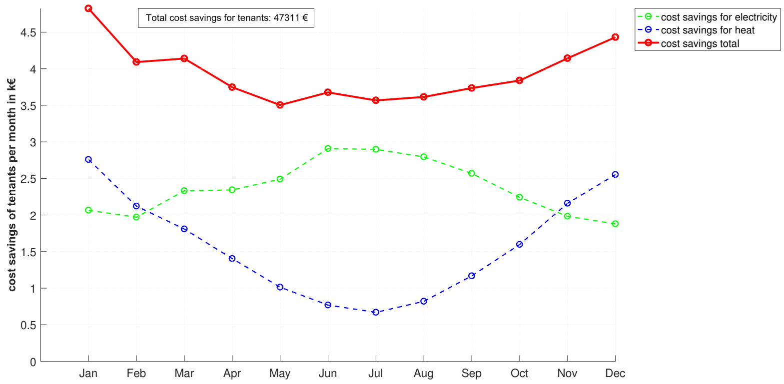
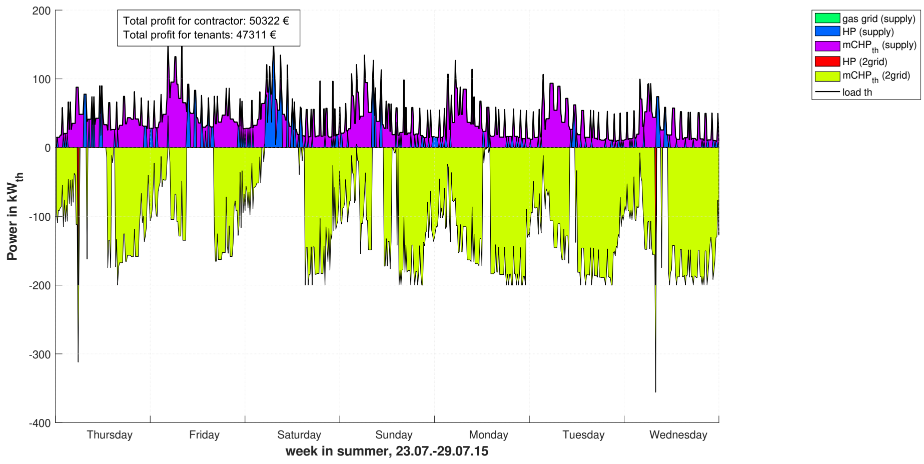
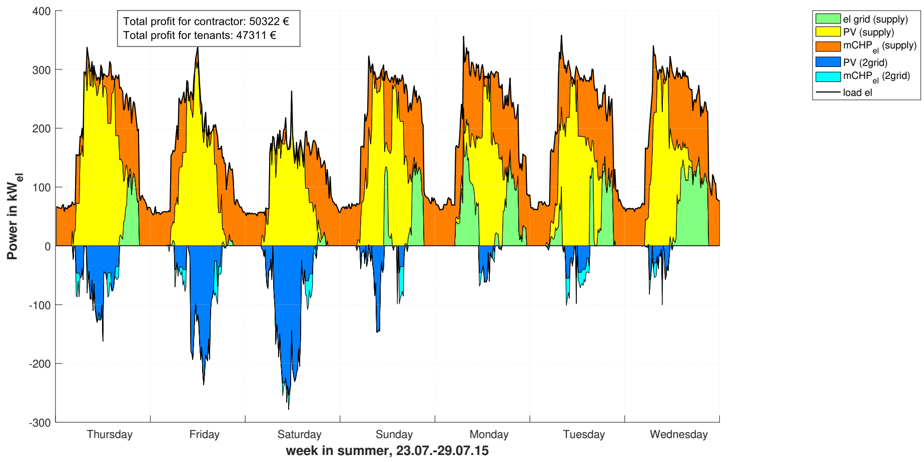



(b)

Figure A.22.: (a) Profit for contractor and (b) cost savings for tenants per month and in total

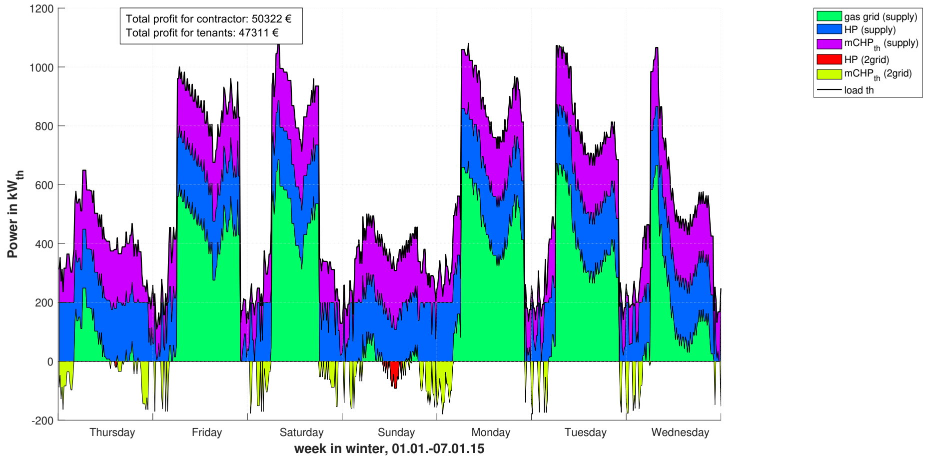



(a)

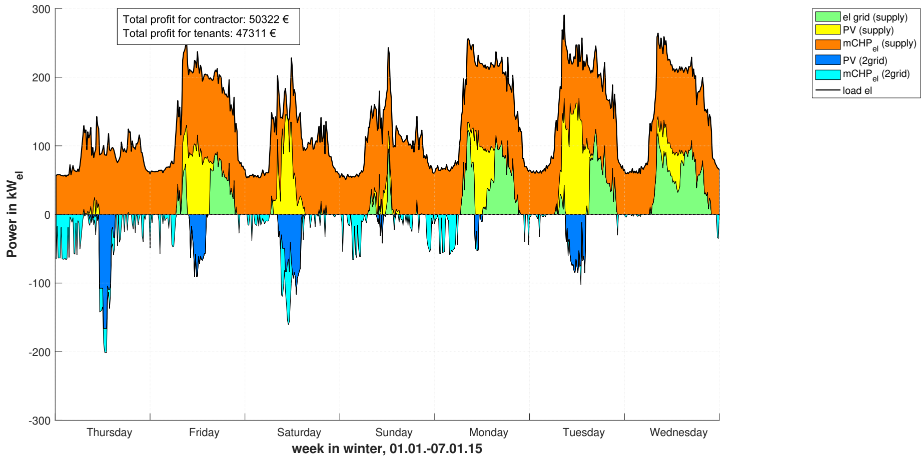



(b)

Figure A.23.: (a) Thermal and (b) electric load and supply, one week in summer



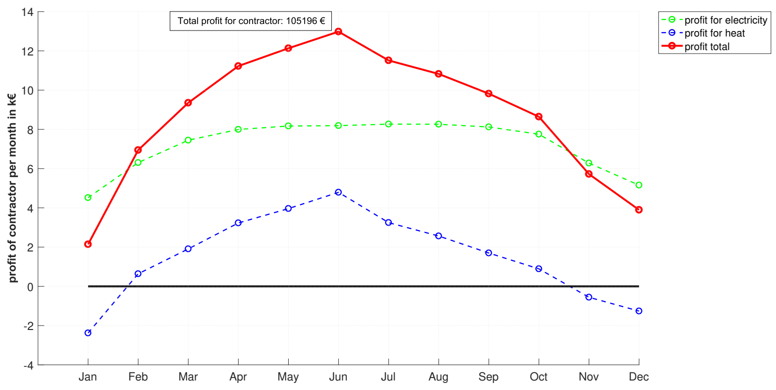

(a)



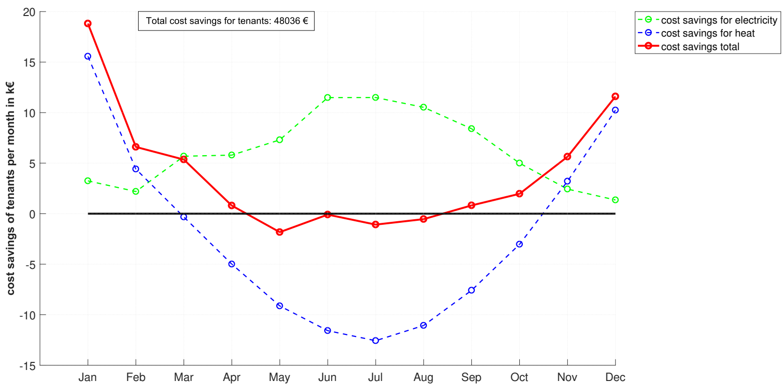

(b)

Figure A.24.: (a) Thermal and (b) electric load and supply, one week in winter

## Full Contracting with energy efficiency measures

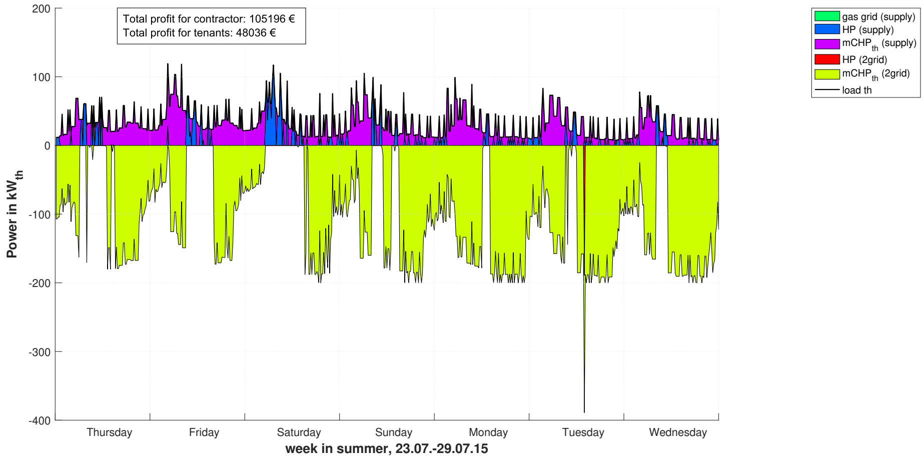



(a)




(b)

Figure A.25.: (a) Profit for contractor and (b) cost savings for tenants per month and in total

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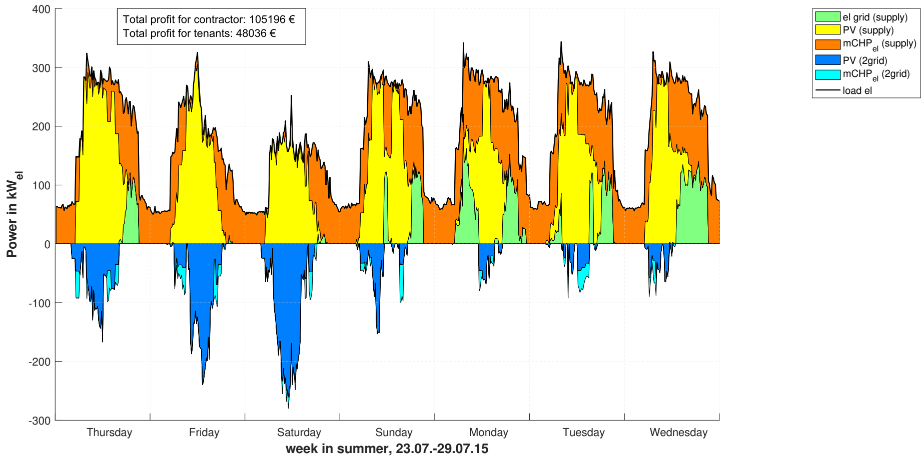
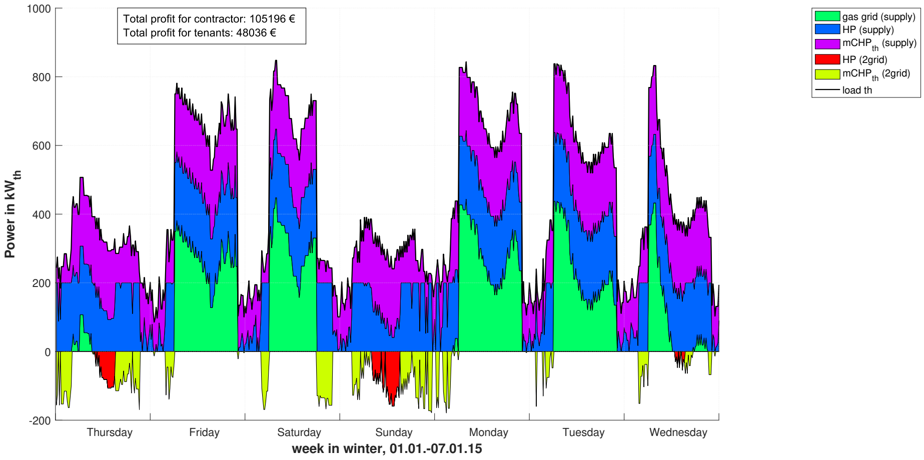



(b)

Figure A.26.: (a) Thermal and (b) electric load and supply, one week in summer

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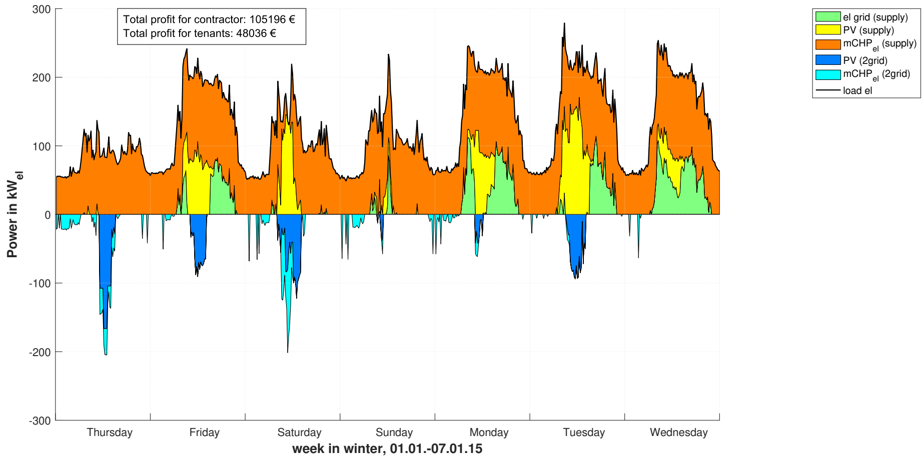


(b)

Figure A.27.: (a) Thermal and (b) electric load and supply, one week in winter

## A.7. Sensitivity analysis: Increasing $CO_2$ price

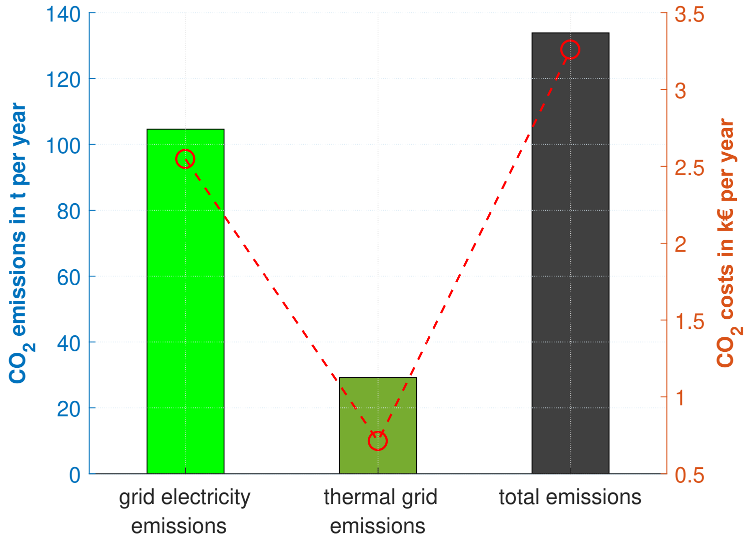


Figure A.28.: Resulting $CO_2$ emissions and costs per year for a DH system

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