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Characterization of technologies for district scale optimization of multi-energy systems

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Abstract

The energy transition relies on the integration of renewable energy sources in the electricity mix. However, the traditional energy system is based on few large power plants which power many small consumers. The conventional top-to-bottom energy paradigm is shifting towards a more inclusive and active approach. Many small power producers will thrive. The residential sector will be one of the protagonist of this revolution. Therefore, it is essential to examine how future cities will develop. In this project, a MILP formulation is proposed with the purpose of investigating the decentralisation level of power production and understanding the optimal energy system configuration. The modelling framework was therefore applied to Geneva residential district, Florissant, to find the potential of a decentralised strategy. Self-consumption is also driven by the integration of district energy system, such as district heating networks. Their role is studied and investigated as a technology able to satisfy building thermal demand.

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CHAPTER 1

INTRODUCTION

The energy transition is one of the global challenges of the 21^{st} century. The world is facing difficulties in reaching the Paris agreement goals set in 2015. The direction to follow is the development of new technological solutions, which involve sustainable and renewable energy systems to the detriment of current energy system based on fossil fuels [1] [2]. Renewable energies are seen as the driving force leading this transition to reduce green house gas emission, deriving from the combustion of fossil fuels.

As of 2016, hydropower has been the major source of green energy across the world, accounting for up to 71% of this supply. However, negative social and environmental externalities highlight the unsustainability of current practice [3]. On the other hand, solar energy is the fastest growing among renewable energies, peaking at up to 40% Compound Annual Growth Rate in the last decade [4]. With the reduction of the cost, the local generation of electricity from photo-voltaic panels is rapidly increasing.

The building sector should be one of the primary target for GHG emission mitigation effort as it accounts for 30% of final energy use and 28% of energy- and process-related emissions in 2018. Global final energy consumption has a growing trend in the last few years [5]. Smart energy system is an essential concept to aspire for 100% renewable energy system exploiting low-value heat resources and energy across subsectors. Smart energy system differs from the smart grid concept, which takes into consideration only the electrical sector. The former has a broader spectrum including the entire energy system when it comes to identify operational strategies and proper infrastructural design. The most efficient and cost-effective solutions are to be found when electricity sector is combined with district heating network, transport sector and/or IT sector, in terms of decentralized data centers [6].

This project concerns the identification of an optimal energy mix at district level through the exploration of a wide range of scenarios. The aim is to give a better understanding of the direction cities in the future should follow in order to reduce green house gas emission, but also the dependency from energy supply coming from foreign countries.

Results show the importance of sharing information and resources within the district itself. The advantages are clear as a greater percentage of the district energy mix is represented by renewable energies, which require a higher degree of coordination rather than base load oriented fossil fuel energy sources.

Furthermore, an analysis of a district heating network installation is carried out to comprehend the economical and environmental benefits this technology could be bring within the district. However, the first step to reduce energy consumption and heat losses is the renovation of existing building alongside a careful design of new ones.

CHAPTER 2

LITERATURE REVIEW

The energy transition revolves around the exploitation of renewable energy resources at the expenses of traditional fossil fuel based technologies. However, in last decade a new paradigm is developing. A new way of producing and supplying energy is studied and analyzed.

Traditional energy distribution is based on a large-scale production plant where electricity is produced and one-way power flow is established. It is transmitted through the network and then distributed by local grids to the final consumers. Nevertheless, losses account for up to 6.5% of all generated electricity is lost as it is transported to end-consumers: 1.5% in high voltage transmission and 5% in low voltage distribution [7]. In order to reduce these losses on-site production and consumption is preferred. A shift from a pyramidal top-to-bottom energy production to a self-consumption, decentralised and two-way energy flow one is wished.

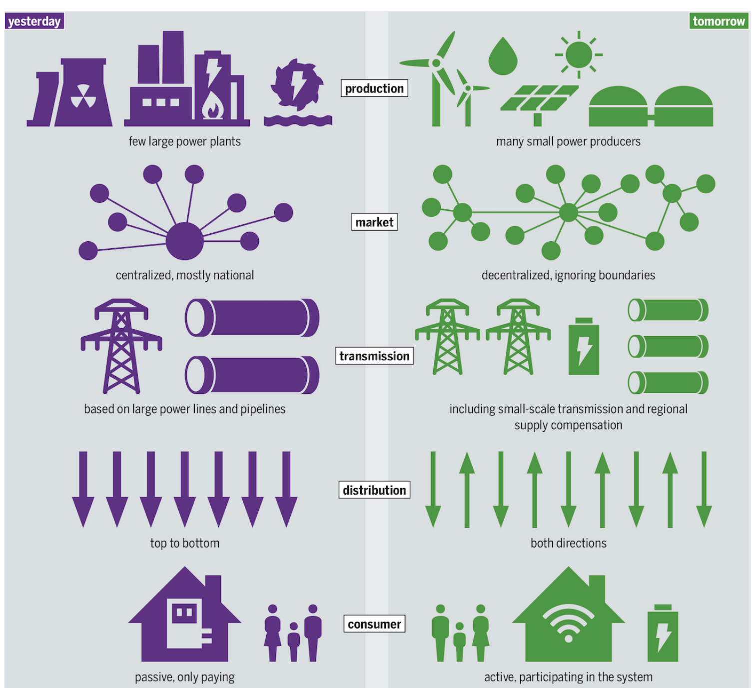

Figure 2.1: Characteristics of a traditional system versus the smart grid [8]

2.1 Decentralised energy system

Distributed energy harvesting is becoming increasingly important in the current challenging energy transition, pushing towards a more decentralised approach [9]. Distributed energy system encompasses a broad spectrum of usually low-carbon or renewable technologies, which are small-scale compared to conventional generation. The main feature of new approach to energy harvesting is their proximity to the end user, which give rise to numerous advantages in terms of distribution and transmission efficiency [10].

Decentralised energy system characteristics are the size and autarky level. On one hand, size defines the scale of optimisation, which can span from a single house to a district. On the other hand, the autarky level states if the system is connected to the transmission grid, capable of supplying excess produced energy and demanding when needed. Energy systems where all energy is harvest and used on-site also exist, called isolated or fully autarkic [9].

		Autarky level	
		Grid connected	Fully autarkic/isolated
Scale of optimisation	Single house	**Prosumers**	**Autarkic prosumers**
	District (multiple houses)	**Microgrid**	**Autarkic microgrid**

Figure 2.2: Categorisation of distributed harvest concepts [9]

2.1.1 Decentralisation challenges

Decentralisation is steadily gaining in popularity. It is considered to be the path to follow in order to reach sustainable energy target [11]. However, many challenges will be faced in the future both at technological and regulatory level.

Technological problem

Increased use of decentralised energy will change the size and even direction of the power flows in networks, becoming less predictable than in the centralised model. This creates the need for more active network management, flexible voltage control and sophisticated fault detection and safety procedures [11]. The intermittent nature of renewable energy technologies, rather than base load traditional ones, such as nuclear power, needs to be addressed. Energy surplus and deficit must be coped with both from daily and yearly perspective. Energy storage technology should be developed accordingly, as of today electricity storage in decentralised systems currently depends mainly on traditional batteries [11].

Regulatory policy

Policy and regulation will influence the deployment of decentralised energy at least as much as technological factors. In the UK, current policies provide fewer incentives for decentralised systems than for centralised renewables under the Renewables Obligation. An increase in decentralised energy harvesting will require changes to the way in which the energy sector is regulated, and its prices controlled, by the regulator. Regulation might be necessary to extend to new areas, such as heating networks. Furthermore, energy companies will shift their business from supply-focused to a service-focused one [11].

2.1.2 Decentralised versus centralised energy harvesting

In the past, large scale centralised energy plant flourished thanks to their high reliability and economy of scale. The level of penetration of decentralised energy harvesting systems in the portfolio of generation techniques will be highly dependant of its benefits and cost compared to the current and traditional centralised energy system [10].

By connecting energy harvesting system closer to the end user, the scale of the transmission grid as well as the related infrastructure to transport electricity, for example, is reduced [12]. Furthermore, it may be able to offer transmission and distribution cost savings by reducing or, in some situations, avoiding completely the costs incurred in reinforcing these networks. However, distributed energy harvest has a positive impact on network reinforcement and losses only when it supplies local consumers reducing supplies from remote centralised plant. Therefore, higher losses are expected when decentralised harvest considerably exceeds local demand. In this scenario, the output surplus flows in the transmission grid resulting in a less efficient condition with respect to traditional transmission-grid connected centralised plant [7] and it should be avoided.

In most of the case, power generated from decentralised energy system costs more than that from conventional technologies [10]. Distributed system are usually renewable energy sources or low-carbon such as combined heat and power, relative new technologies which are starting to benefit from technological advancements in the last few years. Furthermore, it is well known that new technologies generally begin with high unit costs, which tend to fall with cumulative capacity installed. This so-called learning effect may be measured in terms of a reduction in the unit cost of a product as a function of experience gained from an increase in its cumulative capacity or output [13].

Emission considerations have to be made as well. Decentralised energy system usually exploits renewable resources: micro-wind turbines, photo-voltaic panels and solar panels to name a few. Nonetheless, the true benefit from an economical perspective is not highlighted by market analysis, therefore emission savings are not reflected in technologies price even though are value in the society as a whole [10]. Some attempts have been made in this direction. The European Union Emissions Trading Scheme (ETS) issued allowances to industrial operator, which can be traded from companies having a carbon emission deficit with respect to the regulated caps. The overall policy imperative is simply to ensure that overall emissions caps are sufficiently tight [14].

2.2 District Heating Network

District Heating Network (DHN) comprises a network of pipes connecting the various building of a neighborhood, or even a whole town with the aim to be served by a centralised heat plant or many distributed heating production unit [15]. This chapter provides an overview on DHN technologies and their development throughout history. The benefits arising from their installation are assessed, both from an environmental and economical point of view. The improvements accomplished are highlighted as well as the increasing heating system integration into already operating services, such as industries.

2.2.1 Environmental impact

District energy systems have the potential to decrease the CO_2 emissions linked to energy services, thanks to the implementation of large multi-energy conversion technologies, connected to a group of buildings over a network [16]. A paper, investigating a 100% renewable energy system in Macedonia, states that it is possible to achieve this goal, however high share of biomass, wind power and solar power as well as different storage technologies are needed [17]. Nowadays, due to the intermittent nature of renewable energy sources the 50% renewable energy system seems much more likely than the 100% renewable energy system, but with energy efficiency measures alongside a reduced power consumption and development of greater storage capacities, the goal is easily achievable [17].

Furthermore, a study conducted by Möller and Lund [18] presents a integrated geographical and energy systems analyses underlines to potential environmental benefits of a gradual expansion of district heating with the replacement of most individual natural gas around cities and towns, and individual heat pumps in the more rural and remote areas. This transition will not only further reduced the green house gas emissions, but has the potential to foster technologies that use geothermal heating, biogas production, and solar heating.

Advantages of district heating network over single-house heating systems in densely populated areas are beneficial for population well-being. Indeed, the study conducted by Petrov, Bi, and Lau [19] presents results and scenarios on the effect of district heating on health and breathing rates. Incremental air quality is observed on the immediately surrounding community where population density varies significantly during day. In addition to environmental impact, economical assessment should be understood and quantified [20].

2.2.2 Economical assessment

Design of district heating network, and district energy system in general, should be conducted with an economic aspect in mind. Selecting solutions which show a large environmental benefit and green house emission reduction, may in fact end up being economically feasible, while the most economical solution usually provided little to none or even negative environmental effect. Studies have shown that district thermal system are particularly economically viable when considering high-density building as well as densely populated urban areas [20].

Following this conclusion, a paper by Guo, Huang, and Wei [21] analyzes the North-South debate on district heating in China on whether South China should supply heat through a district heating system, as it is widely used in North China. The major concern is that it may further accelerate China's energy demand. Based on China Residential Energy Consumption Survey (CRECS), the results presented state that energy consumption in southern cities is lower than northern ones served by a district heating system. However, when accounting for heating area southern cities consume more energy and paid more per unit area. The conclusion is that district heating system should be installed in specific areas in South China, but there should be the willingness to introduce regulation policies and subsidies.

District heating market regulation

Natural monopolies arising as a consequence of the development of district heating network, which may lead to new challenges to be addressed. Regulation of DH market is a tricky task to tackle, as a change in the paradigma in Sweden led to protests and much national media debate [22]. Worldwide, there are two main types of DH market, namely the regulated and deregulated [23]. In the paper by Zhang, Ge, and Xu [24], it has been proven that either a fully regulated market nor a deregulated market can provide an optimal solution. Both markets have various advantages and weakness between producers and consumers.

In regulated markets, the price of DH is regulated by the government and profits made by DH companies are dictated by the imposed price. This was the case of Sweden before January 1st 1996, where DH companies where owned by the municipalities [25]. In regulated markets, the price for

DH is equal to the sum of costs to be recovered and reasonable profits for DH companies as in Equation 2.1:

$$Price_{DH} = OA + AD + PP \tag{2.1}$$

where OA is operating cost, AD is annual depreciation, and PP is permitted profit. This method is called the cost-plus pricing method [23]. In deregulated market the most common method to price district heating is marginal cost [26]. A marginal cost is the cost of one more unit of product, which is the cost of producing one more unit of heat through DH. According to economic theory, the market price is obtained at the equilibrium point where the total amount of heat supply is equal to the total heat demand. Facing the exogenous market price, a DH supplier can take a larger market share and gain more profits by setting its price at a lower level than the market price. As the DH price is based on the supplier's marginal cost, every supplier is motivated to reduce costs, promote efficiency, and invest in infrastructure and equipment. Consequently, pricing DH according to marginal costs will benefit not only DH producers, but also the environment in terms of reduction in CO_2 emissions and other pollutants [23]. From a mathematical point of view, the total cost is divided into a fixed and variable cost. The marginal is the derivative of these costs over one more unit of produced DH Q, as Equation 2.2:

$$Marginal\ Cost = \frac{\mathrm{d}VC}{\mathrm{d}Q} + \frac{\mathrm{d}FC}{\mathrm{d}Q} \tag{2.2}$$

2.2.3 Performance analysis

When analyzing a thermal system, consideration on efficiency and key components understanding are necessary, regardless of the heat sources under investigation. Furthermore, proper examination of energy and exergy balances must be carried out. Anyhow, all district heating networks may be depicted as in Figure 2.3, where the energy rate balance for the cycle is presented in Equation 2.3. An exergy rate balance equation is presented in Equation 2.4. Exergy is considered to be the maximum work or quality of an energy source and is used to account for inputs, losses and wastes within a process and offers potential as a measure for environmental impact.

$$\dot{Q}_i + \dot{W}_p = \dot{Q}_{loss} + \dot{Q}_c \tag{2.3}$$

$$\dot{E}_{x,i} + \dot{E}_{x,w} = \dot{E}_{x,loss,r} + \dot{E}_{x,loss,s} + \dot{E}_{x,c} \tag{2.4}$$

where [27]:

$\dot{Q}_i$ is the heat added to the working fluid by the heating plant

$\dot{W}_p$ is the pump work for circulation of the working fluid

$\dot{Q}_{loss}$ is the heat loss associated with the pipe network

$\dot{Q}_c$ is the heat available for the consumer

$\dot{E}_{x,i}$ is exergy added to the working fluid from the heating plant

$\dot{E}_{x,w}$ is the exergy for the pump circulation of the working fluid

$\dot{E}_{x,loss,r}$ is the exergy losses associated with the returning fluid

$\dot{E}_{x,loss,s}$ is the exergy losses associated with the supply fluid

$\dot{E}_{x,c}$ is the exergy losses associated with the heat transfer to the consumer

$T_{c,s}$ is the temperature of the fluid provided to the consumer

$T_{c,r}$ is the temperature of the fluid returning from the consumer

To improve the efficiency of DHN, distribution losses should be reduced. In the research conducted by Çomaklı, Yüksel, and Çomaklı [27], heat losses in the pipe network account for up to 9% of heat produced in the heating plant. In addition, the major factor affecting exergy losses is supply and return temperatures in pipes. These heat losses should be kept at minimum resorting to insulation and to a lower temperature in pipes.

However, in the last decade as the knowledge and awareness of environmental problems (e.g. climate change and air pollution) grows, there has been a change in the approach [28]. The process of transitioning from large-scale conventional production units owned by energy companies to single-building prosumers is being studied. A prosumer is a customer who both produces and consumes energy, such as electricity or district heat [28]. This new approach goes in net zero energy buildings (NZEBs) direction. A NZEB is typically a grid connected building with very high energy performance. NZEB balances its primary energy use so that the primary energy feed-in to the grid or other energy network equals to the primary energy delivered to NZEB from energy networks [29]. By this definition, NZEBs are not self-sufficient and autonomous system able to satisfy occupants at all times during the year. Instead, they are buildings connected to existing infrastructure, with a greatly reduced demand and renewable energy system integrated which can supply and demand energy. Thus, NZEBs can reach the net zero energy balance [30].

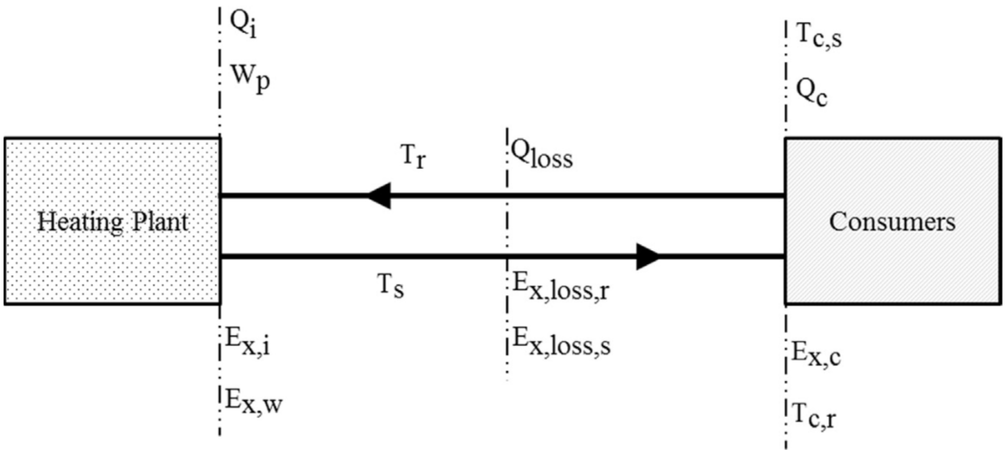

Figure 2.3: Common district heating cycle [20]

2.3 Historical background

2.3.1 The first three generations of District Heating

The first generation of district heating network was installed during 1880s in USA. These systems exploited steam as the heat carrier and the technology was supported by concrete ducts, steam traps, and compensators [31]. Their introduction was driven by the danger of boiler explosion inside apartments. However, today such technology is to be considered outdate since it leads to considerable heat losses and very low energy efficiency. Steam is still used in some major cities around the world, such as old New York and Paris, meanwhile it has been successfully replaced in Munich and Hamburg just to name a few [31].

The second generation used pressurized hot water usually over 100 °C. These systems first appearance was in the 1930s and dominated up until 1970s. Typical components were water pipes in concrete ducts, large tube-and-shell heat exchangers, and material-intensive, large, and heavy valves [31]. The development of such technology was mainly motivated by the will to exploit combined heat and power in urban areas.

The third generation of district heating network still uses pressurized hot water as the heat carrier, but the temperature is mostly below 100 °C. These systems is usually referred to as "Scandinavian district heating technology", since most of the component are manufactured in Scandinavian countries [31]. The first installations of this technology date back to 1970s and it is still the dominant one around the world, in Europe, China and Canada. Typical components are prefabricated, pre-insulated pipes directly buried into the ground, compact substations using plate stainless steel heat exchangers, and material lean components [31].

Throughout the three generation of DH, common trends are towards lower distribution temperatures and prefabrication of components. The former is linked with distribution heat losses and the possibility to have access to different heat generation systems, which are not feasible for a single-house application, including geothermal plant, excess heat from the industries and waste incineration [32]. In third generation system heat losses account up to 20 %, the reduction in temperature will lead to a increased efficiency. Likewise, it will be possible to integrate renewable energy sources (RES) in the heat distribution which would have been otherwise excluded in previous generation district heating networks.

2.3.2 4$^{\text{th}}$ generation of District Heating

The future 4$^{\text{th}}$ Generation District Heating (4GDH) must follow the common trend and be further developed to reduce the supply temperature decreasing grid losses, exploiting synergies thereby increase efficiency of low-temperature production units, such as heat pumps [31].

These reductions and the integration of renewable energy sources in 4GDH are achievable by a sustainable reduction in space heating demand, in order to have similar energy level of domestic hot water. Consequently, the difference in heating demand of each building throughout the year is smoother, easing the integration process of RES. Future energy systems will mostly rely on renewable energy. These resources do not contain large amount of stored energy, but it must be captured and consumed immediately. Future systems must be able to cope with these characteristics in an efficient manner [15].

However, in older buildings, where space heating is fulfilled with a traditional radiator system, a substantial retrofitting might be needed both in terms of residential domestic hot water temperature booster technology, due to sanitary issues, as well as a potentially installing floor heating [32]. On the other hand, moving towards lower supply temperature can result in seasonal HP performance factor above 5.5 for optimal scenarios [32] [33].

Studies on 4GDH evaluate their feasibily and advantages in terms of energy efficiency and renewable energy system integration, but also from policymaker and investor perspective. In Abokersh, Saikia, Cabeza, *et al.* [33], the possibility of integrating heat pump into solar assisted district heating system (SDHS) with seasonal thermal energy storage is explored. Outstanding results have been found in such case study, an extensive environmental improvement alongside a strong economical motivation for stakeholders to pursue towards this path is discussed.

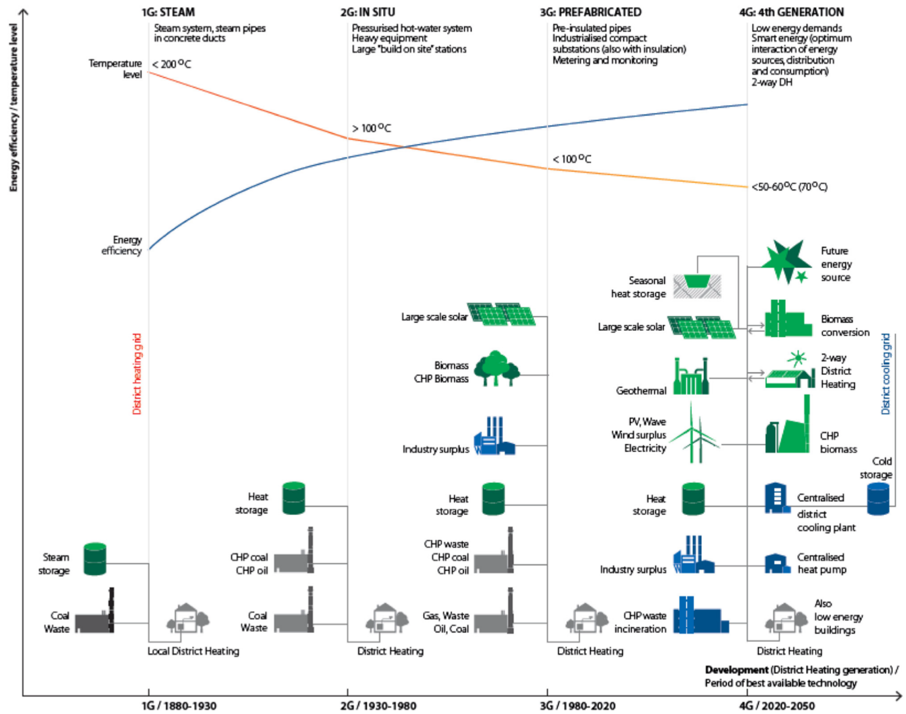

Figure 2.4: Illustration of the concept of 4th Generation District Heating in comparison to the previous three generations [31]

2.4 Goals and Contributions

Previous researches have highlighted the key importance of decentralisation of energy system and the growing role of district heating network integration in future smart cities. This project aims at providing a deeper understanding of how communities should make their decision regarding energy systems. Furthermore, an investigation of district heating network within a multi-energy system district is performed, both from an economical and environmental perspective. Understanding its potential in a competitive model helps when designing future neighbourhoods.

The study is carried out and focused to explore these concept and to answer the following research questions.

- What is the level of decentralisation energy system should be installed at the district scale?
- How does coordination affect energy system results at district scale?
- What are the benefit arising from this optimum configuration, both from an economical and environmental perspective?
- How does district heating network integrate in the multi-energy system scenario?

- What is the potential of a district heating network?
- What are the supply and feed-in tariff to be expected for such system in the future?

CHAPTER 3

MULTI-ENERGY SYSTEM

This section aims at introducing Renewable Energy Hub Optimizer (REHO) on which the optimization problem is based on.

3.1 REHO Overview

The building energy system (BES) and the district energy system (DES) are modelled and optimized following the work done by Middelhauve [34], Girardin [35], Stadler [36] and Terrier [37]. A district heating network modelling framework is then integrated in the main optimization problem formulation. A mixed-integer linear programming (MILP) is used to identify the decision space of BESs and DES. Each building energy system has three different types of energy demand: space heating (SH), domestic hot water (DHW) and uncontrollable electricity (such as for lightning or appliances). Space heating is modelled with the framework itself, taking into consideration conductive heat losses, heat capacity of the building, solar irradiation, appliances and heat gains from occupants. On the other had, domestic hot water and uncontrollable electricity are direct inputs from standardized profiles. The energy demand is fulfilled by two utility grids (electricity and natural gas) and competing energy conversion technologies (Figure 3.1).

The optimization objective is to minimize the total cost of the energy system, identifying the optimal type, size and usage of the energy technologies at disposal. The two decision variables considered in the optimization are the binary decision variable to install the unit and the continuous variable defining the size of the technology installed. The optimization time frame spans over many years, therefore a data clustering is performed. The k-medoids method has been employed aggregating based on global irradiation and external temperature.

3.2 Building energy system

Every energy conversion technology has a thermodynamic modelling framework. Additionally, each technology cost function has been linearized to identify fixed and variable costs, respectively

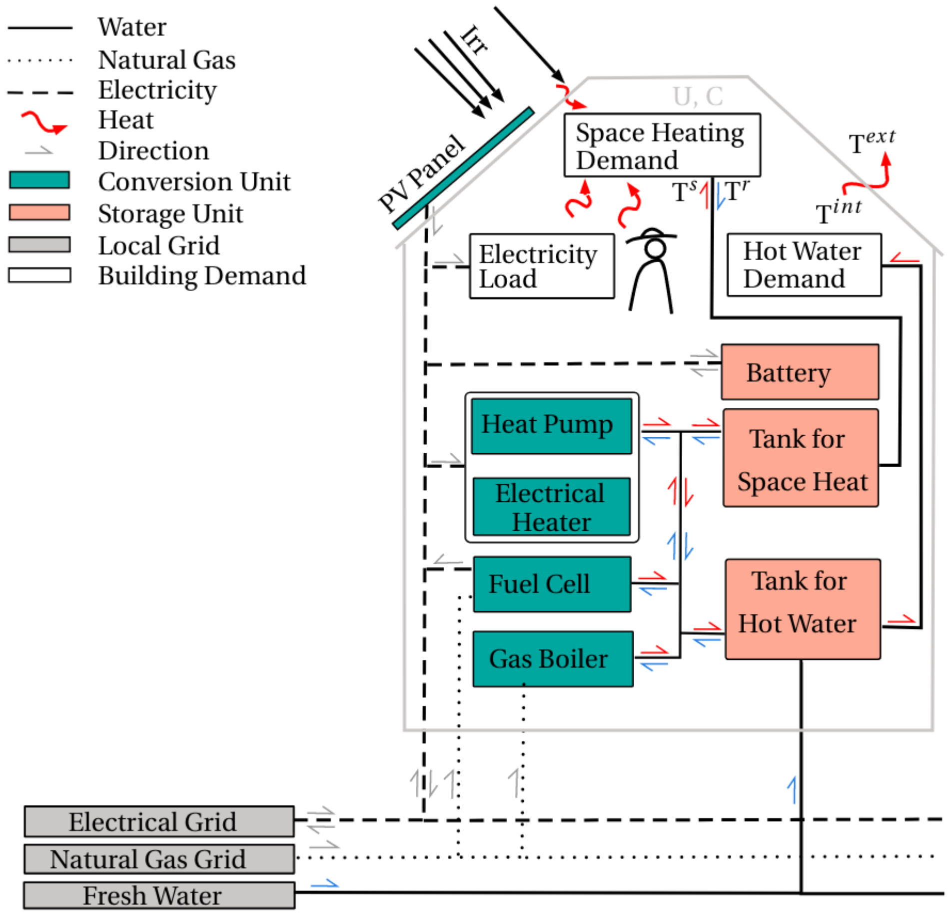

Figure 3.1: Schematic overview of a building energy system, which is also considered as a decentralized energy system [34]

linked to the unit installation variable and to sizing variable. The conversion units are an electrical heater, a natural gas boiler, an air-water heat pump; PV panels are exploited to harvest solar energy; meanwhile as storage units a stationary lithium-ion battery is employed, alongside a DHW and SH hot water tank.

The decision space of the optimization problem is delineated by constraints which mark out its boundaries. Constraints ensure the physical meaning and the convergence of the problem. The main constraints are the unit sizing, mass and energy balances, as well as heat cascade. They force the energy system to match the demand with the supplies from the utilities and the conversion units [37]. The main problem set are: the building set B, the set of available storage, conversion technologies U; time-wise the days of the year are represented by set P, meanwhile the hourly time step are contained in set T.

Sizing constraints

The main equation for sizing and scheduling problem units are described by Equation 3.1. The decision to purchase a unit is identified by the binary variable y, while the continuous variable f represent the unit size of the installed technology. The lower and upper bound (F_u^{min}, F_u^{max}) for unit installations border the validity range for the linearization of the cost function.

$$
\begin{aligned}
y_{b,u} \cdot F_u^{min} \leq f_{b,u} \leq y_{b,u} \cdot F_u^{max} \quad &(3.1a)\\
f_{b,u,p,t} \leq f_{b,u} \quad &(3.1b)\\
y_{b,u,p,t} \leq y_{b,u} \quad &(3.1c)\\
\forall b \in B \quad \forall u \in U \quad \forall p \in P \quad \forall t \in T &
\end{aligned}
$$

Energy balances

Energy balance equations are set to ensure the building energy demand is fulfilled by energy conversion technologies and by importing resources from the grid. Energy can be exchanged with the electricity grid $\dot{E}_{b,p,t}^{gr}$ in both ways (Equation 3.2a), meanwhile water and gas grids $\dot{H}_{b,p,t}^{gr}$ can only supply (Equation 3.2b). The supply (+) and feed-in (-) are accordingly distinguished. More detailed information can be found here [34].

$$
\begin{aligned}
\dot{E}_{b,p,t}^{gr,+} + \sum_{u \in U} \dot{E}_{b,u,p,t}^{+} = \dot{E}_{b,p,t}^{gr,-} + \sum_{u \in U} \dot{E}_{b,u,p,t}^{-} + \dot{E}_{b,p,t}^{B,-} \quad &(3.2a)\\
\dot{H}_{b,p,t}^{gr,+} = \sum_{u \in U} \dot{H}_{b,u,p,t}^{-} \quad &(3.2b)\\
\forall b \in B \quad \forall p \in P \quad \forall t \in T &
\end{aligned}
$$

3.2.1 Objective functions

Annual expenses

The optimization of a district energy system can pursue a broad spectrum of perspective. In this case, the main focus is on economical indicator. The principal optimization is the minimization of the total cost (TOTEX or C_b^{tot}, Equation 3.3e). Furthermore, multi-objective optimization (MOO) can be carried out focusing on operational expenses (OPEX or C_b^{op}) and capital expenses (CAPEX or C_b^{cap}).

$$C_b^{op} = \sum_{p \in P} \sum_{t \in T} (c_{p,t}^{el,+} \cdot E_{b,p,t}^{gr,+} - c_{p,t}^{el,-} \cdot E_{b,p,t}^{gr,-} + c_{p,t}^{ng,+} \cdot H_{b,p,t}^{gr,+}) \tag{3.3a}$$

$$C_b^{cap} = \frac{i(1+i)}{(1+i)^n - 1} \cdot (C_b^{inv} + C_b^{rep}) \tag{3.3b}$$

$$C_b^{inv} = \sum_{u \in U} b_u \cdot (i_u^{c1} \cdot y_{b,u} + i_u^{c2} \cdot f_{b,u}) \tag{3.3c}$$

$$C_b^{rep} = \sum_{u \in U} \sum_{r \in R} \frac{1}{(1+i)^{r \cdot l_u}} \cdot (i_u^{c1} \cdot y_{b,u} + i_u^{c2} \cdot f_{b,u}) \tag{3.3d}$$

$$C_b^{tot} = C_b^{op} + C_b^{cap} \tag{3.3e}$$

$$\forall b \in B$$

In Equation 3.3a, $c_{p,t}^{el,+}$, $c_{p,t}^{el,-}$ and $c_{p,t}^{ng,+}$ represent the electricity supply and feed-in tariff, and the natural gas supply price respectively. In Equation 3.3b, the annualization factor is present: an interest rate i of 2% over n years lifetime of the unit is considered. Investment cost takes into account the bare module factor b_u, as well as the fixed i_u^{c1} and variable i_u^{c2} costs of the linearization. Replacement costs (Equation 3.3d) are considered if a unit lifetime l_u does not reach the project time horizon. Number of replacement R is equal to zero if units lifetime is greater or equal than the time horizon.

Parameter	**Value** [CHF/kWh]	**Reference**
$c_{p,t}^{el,+}$	0.20	[38]
$c_{p,t}^{el,-}$	0.13	[38]
$c_{p,t}^{ng,+}$	0.18	[38]
$c_{p,t}^{ng,+}$	/	

Table 3.1: Resource parameters as Febraury 2022.

Global warming potential

According to the Intergovernmental Panel on Climate Change (IPCC), emissions are measured through their CO_2 equivalence [39]. The greenhouse gas emissions per unit of final energy (e.g. g_{CO_2}/kWh produced electricity) are commonly considered. GWP is divided into the share coming from the operation G^{op} (Equation 3.4a) and the construction of the building energy system G^{bes}

(Equation 3.4b) to derive the total annual global warming potential G^{tot} (Equation 3.4c) [34].

$$G_b^{op} = \sum_{p \in P} \sum_{t \in T} (g_{p,t}^{el} \cdot E_{b,p,t}^{gr,+} - g_{p,t}^{el} \cdot E_{b,p,t}^{gr,-} + g_{p,t}^{ng} \cdot H_{b,p,t}^{gr,+}) \tag{3.4a}$$

$$G_b^{BES} = \sum_{u \in U} \frac{1}{l_u} \cdot (i_u^{g1} \cdot y_{b,u} + i_u^{g2} \cdot f_{b,u}) \tag{3.4b}$$

$$G_b^{tot} = G_b^{op} + G_b^{BES} \tag{3.4c}$$

$$\forall b \in B$$

Equation 3.4 detail GWP in $CO_{2,eq}$, meanwhile the parameters $g_{p,t}$ account for the emissions per kWh consumed electricity E or gas H. The parameters i_u^{g1} and i_u^{g2} represent the linear unit cost function in terms of GWP [34].

3.2.2 Key performance indicators

Several indicators have been used to assess the performance of the energy system. Apart from the economical ones mentioned above, security and environmental indicators have been employed. Self-sufficiency (SS) represents the fraction of electricity demand satisfied by PVs (Equation 3.5b). Self-consumption (SC) represents the share of onsite generated electricity (Equation 3.5b). Then, photo-voltaic penetration (PVP) expresses how much electricity is generated by PVs over the total electricity demand. Its importance lies in the information about the renewable energy installed capacity within the DES (Equation 3.5c).

$$SC = \frac{E^{PV,+} - E^{gr,-}}{E^{PV,+}} \tag{3.5a}$$

$$SS = \frac{E^{PV,+} - E^{gr,-}}{E^{PV,+} - E^{gr,-} + E^{gr,+}} \tag{3.5b}$$

$$PVP = \frac{E^{PV,+}}{E^{PV,+} - E^{gr,-} + E^{gr,+}} \tag{3.5c}$$

3.3 District energy system

Single building energy systems are therefore connected to the same local grid. Furthermore, this grid is connected to the transmission network, which is considered to be a source of electricity and natural gas. Under these assumptions, the district electricity grid is connected to a single low voltage transformer. This consideration will be fundamental in the selection of a proper case study for the model. A visualization of these assumptions is proposed in Figure 5.1.

Energy balances

Energy balances equations at district scale serve an analogous function as building scale ones. They ensure the energy balance between the local grid and the outside world network is satisfied. The superscript TR in Equation 3.6a refers to the electricity exchanged from the transformer perspective. In Equation 3.6b, the single direction flow of the natural gas is defined.

$$\dot{E}^{TR,+}_{p,t} + \sum_{b \in B} \dot{E}^{gr,-}_{b,p,t} = \dot{E}^{TR,-}_{p,t} + \sum_{b \in B} \dot{E}^{gr,+}_{b,p,t} \tag{3.6a}$$

$$\dot{H}^{+}_{p,t} = \sum_{b \in B} \dot{H}^{gr,+}_{b,p,t} \tag{3.6b}$$

$$\forall p \in P \quad \forall t \in T$$

3.3.1 Objective functions

Annual expenses

The MILP optimization search in the decision space the minimum of the objective function at district-scale. In Equation 3.7b, capital annual expenses are defined as a sum over the b building of the district. Meanwhile, in Equation 3.6a annual operational expenses are addressed. Electricity exchanges between buildings within the district are not considered; the focus is on exchanges between the community and the outside world [34]. Fees for using the local grid both for electricity and natural gas are not considered.

$$C^{op}_{D} = \sum_{p \in P} \sum_{t \in T} (c^{el,+}_{p,t} \cdot E^{TR,+}_{b,p,t} - c^{el,-}_{p,t} \cdot E^{TR,-}_{b,p,t} + c^{ng,+}_{p,t} \cdot H^{TR,+}_{b,p,t}) \tag{3.7a}$$

$$C^{cap}_{D} = \sum_{b \in B} C^{cap}_{b} \tag{3.7b}$$

$$C^{tot}_{D} = C^{op}_{D} + C^{cap}_{D} \tag{3.7c}$$

Global warming potential

Global warming potential of the district is computed in an analogous way as the annual expenses. Therefore, operational GWP (Equation 3.8a) is defined at the boundaries of the community, which can be considered the local low voltage transformer.

$$G_D^{op} = \sum_{p \in P} \sum_{t \in T} (g_{p,t}^{el} \cdot E_{b,p,t}^{TR,+} - g_{p,t}^{el} \cdot E_{b,p,t}^{TR,-} + g_{p,t}^{ng} \cdot H_{b,p,t}^{+}) \tag{3.8a}$$

$$G_D^{BES} = \sum_{b \in B} G_b^{BES} \tag{3.8b}$$

$$G_D^{tot} = G_D^{BES} + G_D^{op} \tag{3.8c}$$

CHAPTER 4

POTENTIAL OF CENTRALISED STRATEGY

In this chapter, the exploration of different perspective to the district energy system are carried out, examined and compared: decentralised and centralised approach. However, in chapter 2, decentralised and centralised had a different meaning, which may lead to a problem of nomenclature. In Table 4.1, a brief recapitulation is proposed.

Decentralised design strategy

In the decentralised approach, the building energy systems are considered as a group of renewable energy hubs. This approach is generally applied considering a city district as a collection of building, rather than an aggregation of them. The district itself is to be considered the sum of the single buildings belonging to it. Furthermore, information are not shared among the building stock, so interaction between them does not occur. Decision are taken independently by each building, without taking into account neighbors' choices. Building energy hubs are optimized one by one without a central coordination.

Centralised design strategy

On the other hand in the centralised approach, buildings share information and decisions. The optimization is carried out considering the district as one single energy hub at district scale. This design strategy involves a higher coordination between buildings within the community, but it requires more computational power. The high fraction of renewable energy source usage within the district is maximized when interactions between buildings and a superior network occur [34].

Chapter	Decentralised	Centralised
Literature review	Few large power plants $[MW]$	Numerous small power producers $[kW]$
Chapter 4	No interaction	Interaction

Table 4.1: Nomenclature clarification

4.1 Computational CPU time

The optimal design and scheduling of a high share renewable energy system is a computational demanding task. Computational time of both approaches have to be investigated with increasing complexity of the district (i.e. increasing number of buildings). Furthermore, the modelling framework developed is able to guide decision-making both at building and district scale.

The centralised design strategy is not suitable to run optimization problem of district with a size greater than $n_{Building} = 7$ as it is depicted in Figure 4.1. The trend of the method with respect to the number of buildings is exponential, easily reaching the CPU time limit $t_{limit} = 3000\,\mathrm{s}$.

The linear tendency manifested by the decentralised approach is promising, but this method lacks synergy between buildings. Interactions have a great impact on final results, particularly in districts where the penetration of renewable energy is high. However, the key role of building size should be further analyzed.

4.1.1 Dantzig Wolfe Decomposition

The Dantzig Wolfe Decomposition (**DWD**) is implemented by Terrier [37] to overcome the computational run time issue of the optimization problem. The DWD method is integrated in the already existing MILP formulation. The original optimization problem is decomposed into sub-problems (**SP**) and master problem (**MP**).

SPs deal with individual BESs optimization, meanwhile the MP manages the grid energy balance. In addition, the feasible solutions calculated by the SPs include the costs and grid exchanges of each BES [37]. Dual variable are introduced to link SPs to MP. The initiation of the MP is carried out by a MILP optimization on each BES with the same objective function of the MP: TOTEX minimization. A first set of feasible solution is found where interactions between buildings are absent. The role of the MP is to maximise building synergy. An iteration loop between the SPs and the MP is established until termination criteria are met.

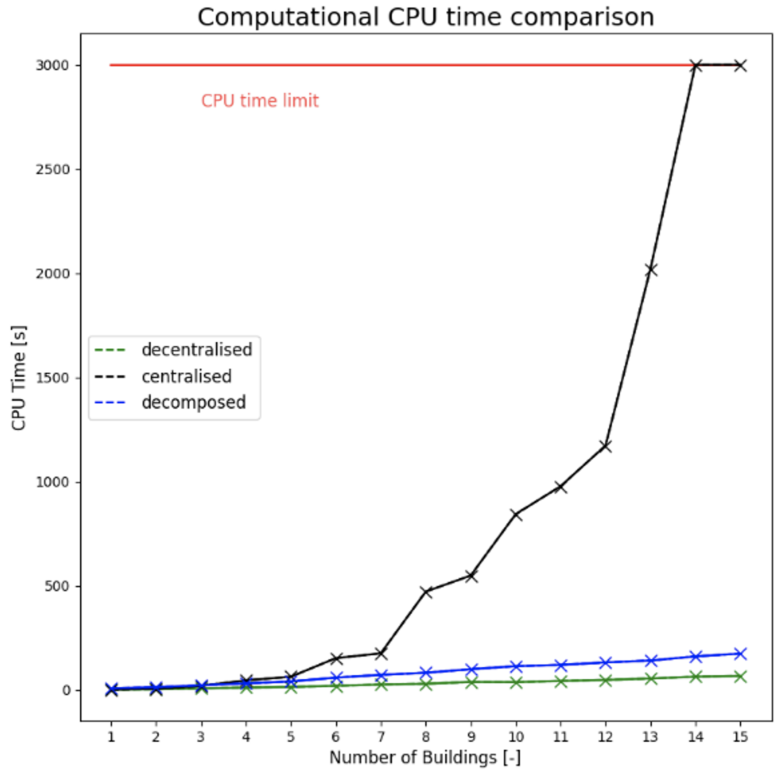

Figure 4.1: Computational CPU time comparison between three different methods

The benefit of the DWD method are plotted alongside the two previous strategy in Figure 4.1. The algorithm provides a linear trend with increasing district size, sharing the synergistic advantage of the centralised formulation. This method is suited for district where $n_{Building} \geq 8$: computational time is reduced significantly compared to the centralised approach whereas the root mean square error is less than 1% [37].

4.2 Potential of centralised approach

The purpose of this analysis is understanding the potential of using a centralised approach rather than a decentralised one. The benefits that may arise treating a district as a community when decisions have to be made. It is key to investigate when a district during its energy transition will not have the straightforward installation of additional producers the optimal solution. When and if this threshold exists it will depend on the specific case study. However, the model should be able to guide decision-makers.

During the analysis the Dantzing Wolfe decomposition was used instead of the centralised one, as explained in subsection 4.1.1. A proper case study was selected ensuring it respected the assumptions made in chapter 3.

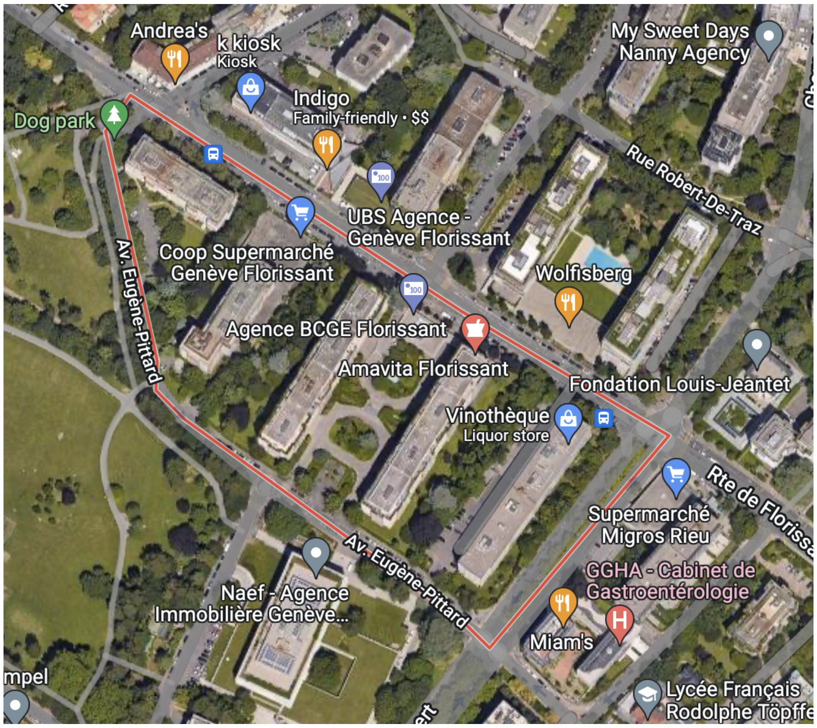

Figure 4.2: Aerial view of Florissant district in Geneva

4.2.1 Case study

The focus area of this case study was Florissant district (Figure 4.2), a residential neighborhood in Geneva. This district was chosen in part due to the location in Geneva, where measured data of temperature and irradiation are available and in part due to its connection to only one low voltage transformer, which is one of the assumption of the model described in section 3.3. Florissant is an area for a range of building size and construction period, which spans from as early as 1919 up to the twenty-first century. The Florissant area involves 38 buildings.

4.3 Multi–objective optimization

Pareto front

Multi-objective optimization, or Pareto optimization, deals with the simultaneous optimisation of multiple objectives (for example, trying to minimise at the same time the capital and operating costs of a new energy system). These objectives may be conflicting, therefore the objective functions are in a trade-off to each other. There exists a (possibly infinite) number of "Pareto-optimal" solutions that present this trade-off, as shown in Figure 4.3. A solution is called "Pareto-optimal" if none of the objective functions can be improved in value without degrading some of the other objective values.

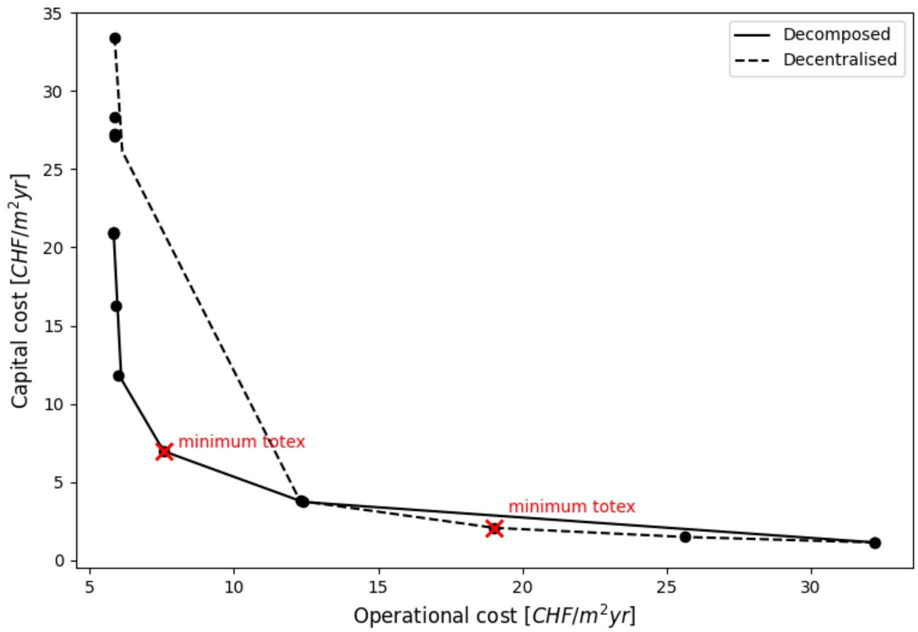

Figure 4.3: Comparison of the CAPEX–OPEX pareto curve resulting from the decentralized and centralized optimization strategies. Minimum total expenses (TOTEX) marked on both curves

As shown in Figure 4.3, the multi–objective optimization using both optimization strategies lead to a minimum of annual capital expenses (CAPEX) per energy reference area (ERA) of approximately 1.14. The reason is that there are no interaction between buildings in the lowest CAPEX scenario. Therefore, the cheapest capital expense for each building is also the cheapest capital expense for the whole district. As it is shown in Figure 4.4, units heavily rely on importing electricity and natural gas to feed low-investment cost natural gas boilers and electrical heaters. No investment is made photo-voltaic panels or heat pumps, due to their high capital costs.

An initial reduction in OPEX is experienced when high-investment cost units, (i.e. air-to-water heat pumps), start to be employed as energy conversion units instead of natural gas boilers: a switch from natural gas to electricity. Operational expenses are reduced even more when photo-voltaic panels are installed within the district. Self-consumption and self-sufficiency increase but degrading initial costs. The potential of a centralised strategy is enhanced when a high share of electricity is harvested on site: buildings share their own demand and they install the optimal amount of photo-voltaic panels for the community. Meanwhile, following the decentralised approach each building installs the optimal size of photo-voltaic panels for its demand, not taking into account neighbours.

In order to further decrease the OPEX installation of electricity storage systems (i.e. batter-

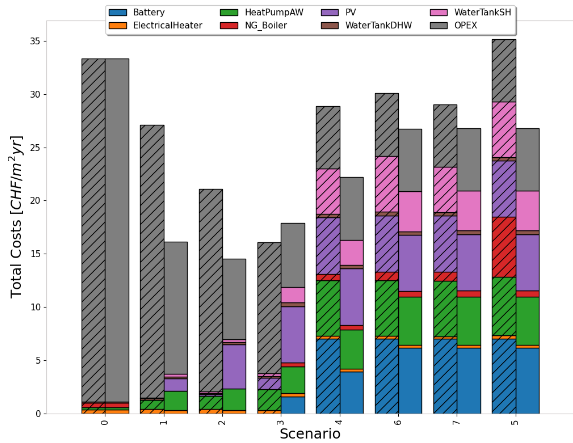

Figure 4.4: Cost breakdown for each pareto scenario

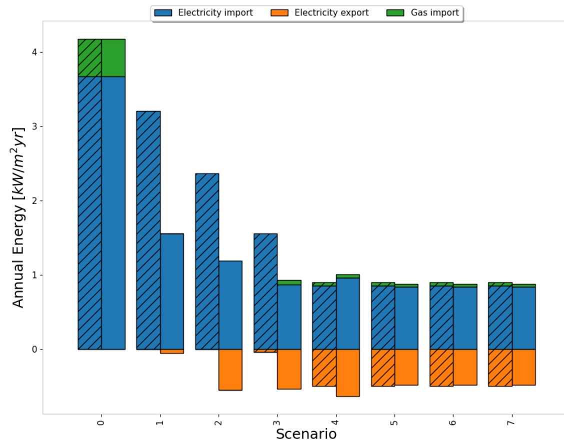

Figure 4.5: Energy flows for each pareto scenario

ies) is needed. The centralised design strategy produces results with a high share of re-imports, electricity which has been harvested in a building unit and consumed by another one within the district.

The difference which can be seen after the initial point of the pareto front is due to a low number of pareto points. The choice was made based on a trade-off between accuracy and computational time. Following this reasoning, as shown in Figure 4.3, up to an OPEX of approximately 12.4 CHF/m^{2}yr the two curves are superposed. However, a big difference is highlighted when coordination within the district is considered. Using the centralised strategy, with the same reduction in operational cost the decentralised approach experiences a 56 % capital cost increase with respect to the decomposed approach.

It is worth mentioning the minimum total expenses the district pays under these different strategies. Without coordination within the community, where autarkic decisions are made $TOTEX_{min} =$ 21.10 CHF/m^{2}yr, whereas allowing buildings to share information $TOTEX_{min} = 14.54$ CHF/m^{2}yr. A 31 % total cost reduction is experienced in the same neighbourhood.

4.4 Single-objective optimization

4.4.1 TOTEX minimization

Single-objective optimization resulted in similar objective values when performing a TOTEX minimization, as shown in Figure 4.6. The centralised approach lead to an annual TOTEX reduction of 0.75 % with respect to the decentralised approach, focused in the vast majority in the reduction

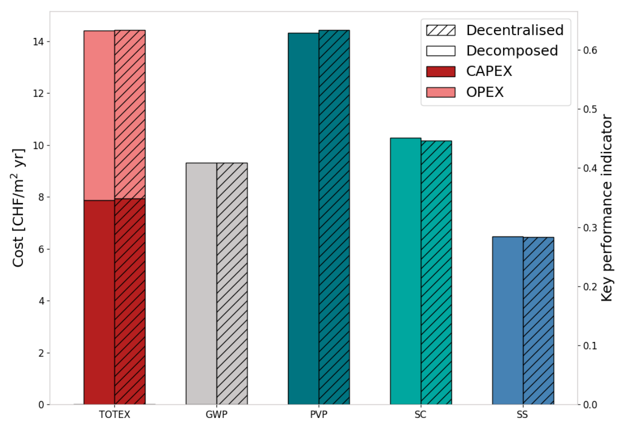

Figure 4.6: Comparison of centralized and decentralized design strategy

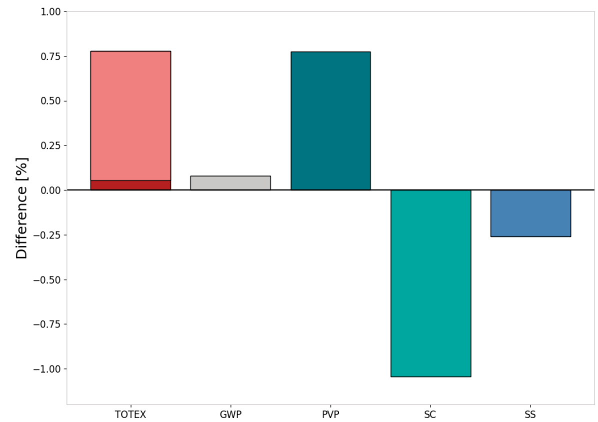

Figure 4.7: Relative difference between the decentralized and centralized methods

of OPEX.

The use of a centralised strategy led to a slight difference for KPIs too. An higher photo-voltaic penetration is shown in Figure 4.7 as expected: re-imports reduced the use of renewable energy sources in the district. Self-sufficiency and self-consumption have similar values, but confirm the more optimal solution produced by the centralised design strategy.

In Figure 4.8, the installed technologies configuration of the optimized building energy system confirm the analysis on economical and key performance indicators. Whereas for the majority of the 38 buildings unit size are identical, one extra building installed photo-voltaic panels in the decentralised design strategy. The decentralised strategy was performed from a building scale perspective not taking into account the community, thus the total size of the renewable energy source installed might be sub-optimal. This investment decision resulted in higher annual total expense.

An analysis on electricity exchange and allocated OPEX both from the buildings and transformer perspective was carried out. Results are shown in Figure 4.9 and Figure 4.10.

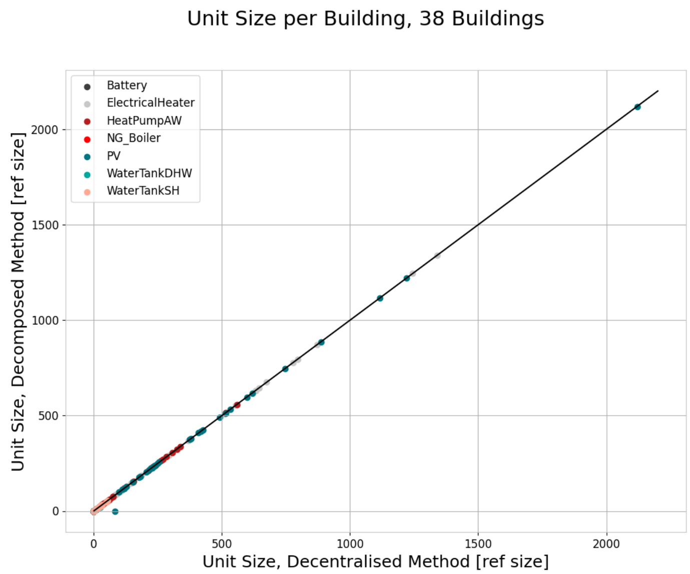

Figure 4.8: Installed unit size

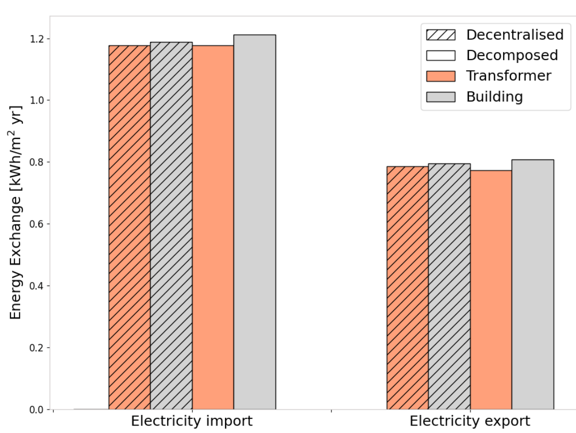

Figure 4.9: Absolute electricity exchange values from building and transformer perspective

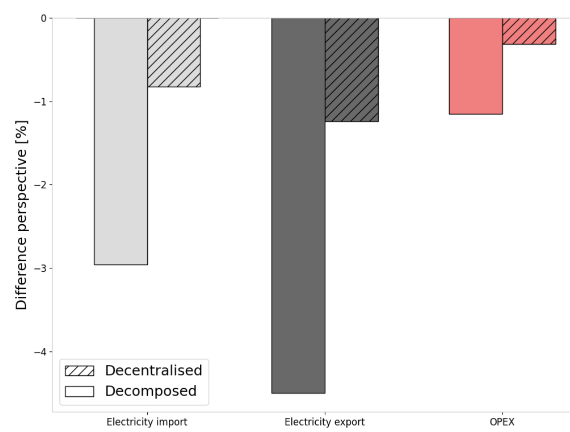

Figure 4.10: Relative difference between perspective and OPEX allocation between strategies

The difference between the two design strategy is present. However, it is much larger for the centralised strategy. Figure 4.10 shows that over 4 % of the electricity remained within the district and it is not exported at the transformation level. Meanwhile, almost 3 % of the electricity imported to satisfy the demand is coming from single energy hubs within the district. These differences in electricity exchange led to a difference in the value of the OPEX. The difference is 1 %. This benefit has to be accounted to the centralised design strategy. This comparison is possible since the feed-in and demand tariff where assumed to be the same both at building and transformer level.

4.4.2 TOTEX minimization with GWP constraint

A single-objective optimization when performing a TOTEX minimization led to similar values in KPIs. Thus, in order to understand and explore the potential of the centralised design strategy an optimization was run introducing a constraint on the global warming potential indicator (Equation 4.1). Therefore, the design strategies from both perspective had to satisfy a constraint which was set to be a little smaller than what was produced in the previous optimization (subsection 4.4.1). Results produced of economical and performance indicators are shown in Figure 4.11 and Figure 4.12.

$$G^{tot}_{D,cstr} \leq 9\,\frac{\mathrm{kg}_{\mathrm{CO_2,eq}}}{\mathrm{yr}} < G^{tot}_{D} \tag{4.1}$$

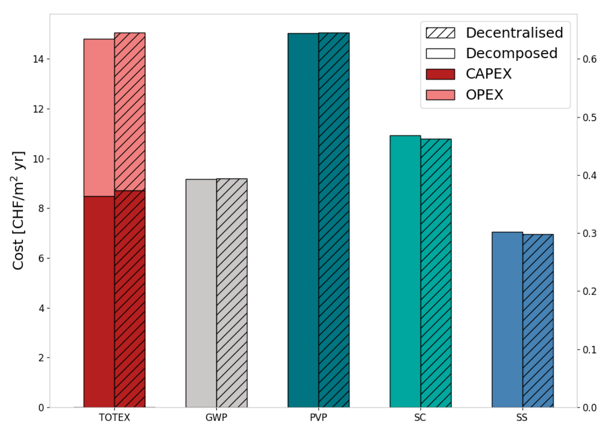

Figure 4.11: Comparison of centralized and decentralized design strategy

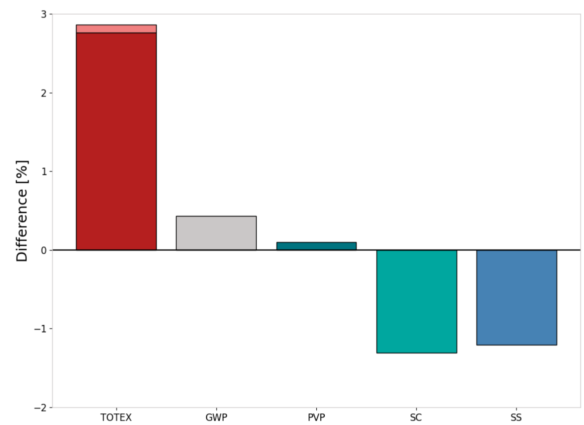

Figure 4.12: Relative difference between the decentralized and centralized methods

All key performance indicators resulted in similar values, but the smaller relative differences with respect with the previous optimization mantained the same trend: lower global warming potential and photo-voltaic penetration, as well as higher self-consumption and self-sufficiency. However, the use of the centralised strategy significantly changed annual total expenses, resulting in almost a 3 % difference. Most of this monetary benefit is attributed to a lower CAPEX (Figure 4.12).

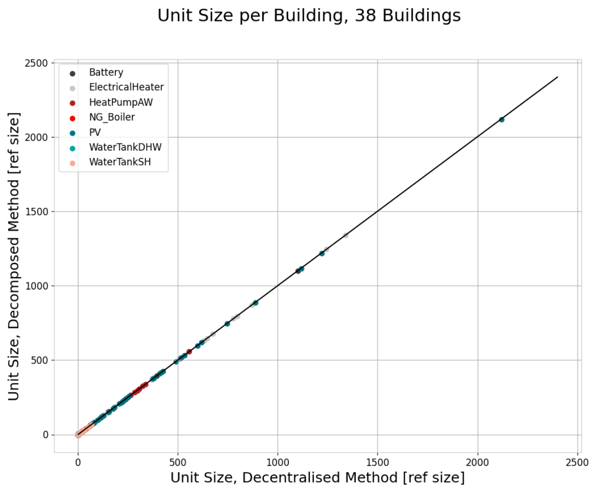

Figure 4.13: Installed unit size $\forall y_{b,u}$

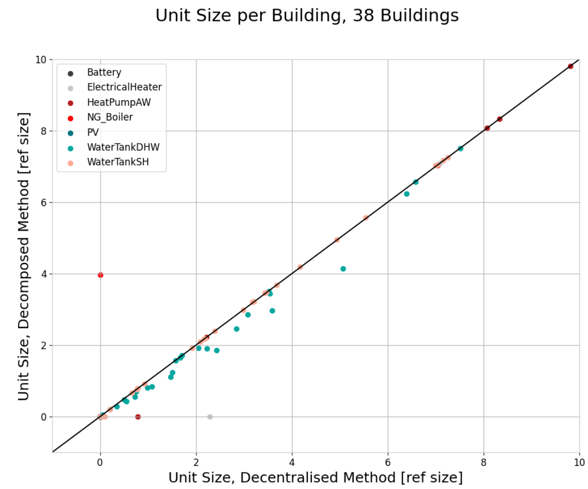

Figure 4.14: Blow-up ($0 \leq y_{b,u} \leq 10$)

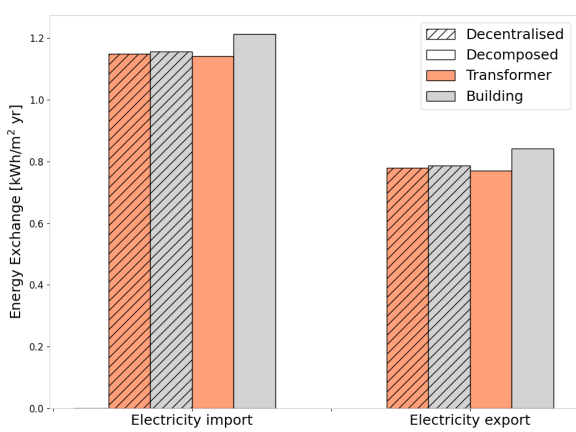

Figure 4.15: Absolute electricity exchange values from building and transformer perspective

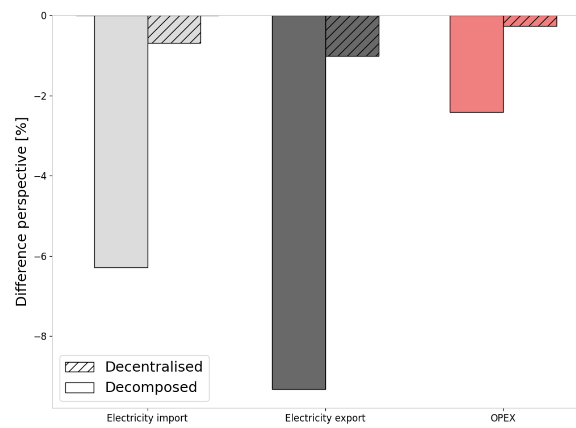

Figure 4.16: Relative difference between perspective and OPEX allocation between strategies

This difference in initial investment expenses is due to the different installed units for each building. In Figure 4.14, a comparison of the configurations of the optimized renewable energy hubs gives an insight and confirms results shown in Figure 4.12. Most of the domestic hot water tanks in the decentralised design strategy are of a sub-optimal size, leading to increasing capital cost as well as global warming potential to produce them. This small contributions add up for each building in the district. Thus, one energy hub has a major difference when it comes to energy conversion unit configuration: in the decentralised design strategy, an electrical heater and an air-to-water heat pump is installed to avoid exceeding the global warming potential cap. Whereas, in the centralised design strategy, global warming potential "savings" allowed a building to install a much cheaper, but much more polluting natural gas boiler to satisfy residents demand.

Major improvements using the centralised design strategy are shown in Figure 4.16. Almost 10 % of the electricity exported stays within the district and it is not exported at the transformer level. This electricity satisfy more than 6 % of the total electricity demand of the community, thereby reducing the operational cost associated with the import of resources from the outside world by over 2 %.

A community-based approach is less sensitive to an external perturbation. Thus, it is able to adapt better thanks to a greater energy efficiency. Meanwhile, a decentralised strategy suffers limitations, which could come from the outside world, significantly.

4.5 Conclusion

The aim of this chapter was investigating the potential of a community-based design strategy of a multi-energy system compared to autonomy-driven configurations. To address this question various steps were performed.

- Computational time comparison: running simulation with the decentralised strategy did not cause any issue. However, the centralised approach when the district is made up of 14 buildings or more reaches the CPU time limit. To solve this problem the Dantzig Wolfe decomposition was used.

- A multi-objective optimization of a Geneva district, Florissant, was carried out. The centralised design strategy outperformed the decentralised strategy. This improvement was particularly significant when high-investment scenarios where analysed. Lack of coordination within the district led it to take sub-optimal decision.

- The centralised design strategy led to better results when it was applied to a single-objective optimization with TOTEX minimization. Reduced total annual expenses and global warming potential was achieved. An ideal single energy hub configuration was designed alongside an improved share of electricity harvested on site by renewable energy source.

- A second single-objective optimization was run. The aim was to understand how both strategies were affected by a constraint on global warming potential. The centralised design strategy provided even better results: total annuals cost difference were greater, technology configuration was more optimized and coordination led to a more efficient use of on site produced electricity.

The optimization of building energy system at district level increases the energy efficiency of the residential sector. Furthermore, it contributes to minimize its impact on global warming potential as well as reducing annual expenses for the community. However, the centralised design strategy is not only more complex from a computational perspective, but also from a decision-making point of view.

CHAPTER 5

DISTRICT HEATING NETWORK

The purpose of this chapter is to investigate the capabilities of a district heating network integration within a multi-energy system modelling framework. How this technology would affect the energy efficiency of the community and what would be its benefits. The analysis aims at understanding what contribution could have a district heating network for the residential sector from an economical and environmental point of view.

In order to seek these goals a proper modelling framework has to be developed and integrated with the already existing multi-energy system model. Furthermore, new energy hubs must be introduced and modelled to be integrated within the district heating network model.

5.1 District heating network model

Single buildings throughout the year undergo a variable heating demand. A base demand is due to the domestic hot water which can experience small seasonal variations during a year. However, most of the heating demand is due to space heating. Space heating has its peak during the winter period, meanwhile it is negligible during summer.

The optimal configuration design of the energy conversion technologies is sized in order to satisfy the building demand even for extreme periods. Thus, during period where the demand is lower the installed units are oversized and could produce more than what it is need for the single energy hub. The excess heat produced could be used to satisfy, some or all of the demand of another building within the district, connected to the same heating network.

Alongside the heat exchange between building, a new energy hub type is introduced: centralised district heating unit. District heating unit is a centralised energy conversion technology which is installed and modelled at district scale, rather than at building scale as it is executed for conventional technologies, described in section 3.2. These types of unit are able to convert energy sources, such as natural gas and electricity into heat, which can be exported in the heating grid to be at disposal of buildings. The advantage lies in the economy of scale.

Many analysis could be carried out when investigating the potential of these energy systems and how they will behave within a competitive model. The model aims at providing a clear understanding about the following questions.

- What are the economical and environmental benefit of a district heating network?
- What are the potentials of a centralised district heating unit?
- How do feed-in and supply tariffs affect the configuration of the heating system?

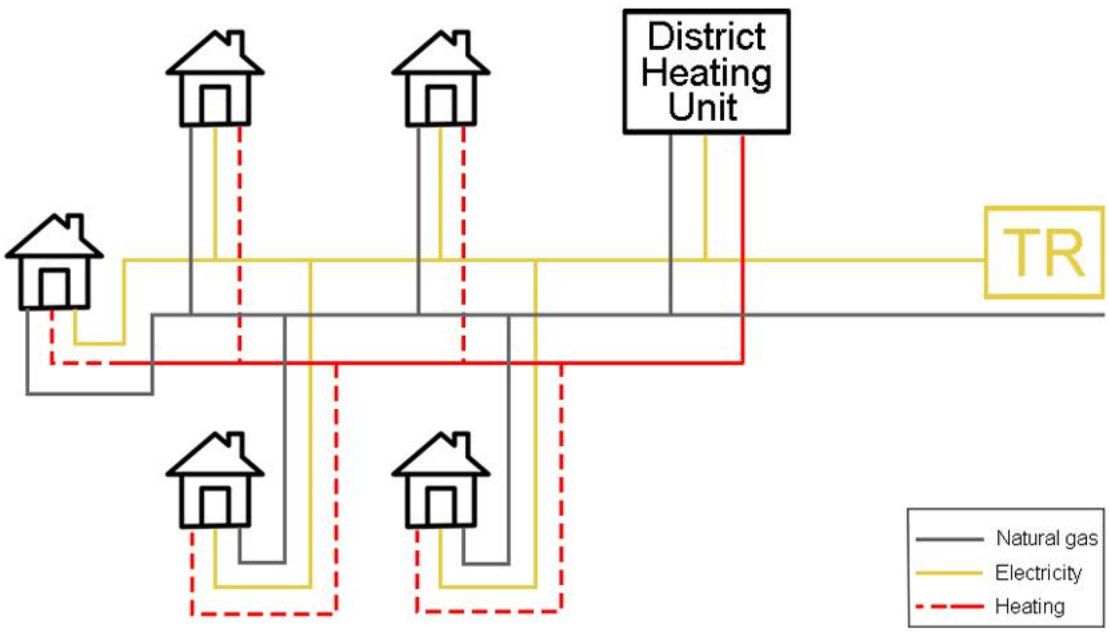

Figure 5.1: District heating network vision

5.2 Heating grid

The integration of a district heating grid, alongside with the already existing for natural gas and electricity, is the first step to be accomplished. The use of the grid by the community is not taxed. However, the connection between the building and the local heating grid is not established a priori, but it must be installed as a competitive energy conversion technology such as electrical heater and natural gas boiler.

Thus, a new energy conversion technologies is introduced: district heating connection. The installation and size of this unit are linked to the same constraint as other technologies, described in section 3.2. In this heating modelling framework distances between the main grid and buildings are not taken into account, thus energy hubs configurations are only based on thermodynamic constraints and on economic and performance indicators. Objective function presented in Equation 3.3 are still valid with two extra addenda in Equation 3.3a. The added terms are made explicit in Equation 5.1.

$$C_b^{op} = \sum_{p \in P} \sum_{t \in T} (c_{p,t}^{el,+} \cdot E_{b,p,t}^{gr,+} - c_{p,t}^{el,-} \cdot E_{b,p,t}^{gr,-} + c_{p,t}^{ng,+} \cdot H_{b,p,t}^{gr,+} + c_{p,t}^{ht,+} \cdot T_{b,p,t}^{gr,+} - c_{p,t}^{ht,-} \cdot T_{b,p,t}^{gr,-}) \tag{5.1}$$

where:

- $c_{p,t}^{ht,+} = 0.065\,\mathrm{CHF/kWh}$: heating retail tariff.
- $c_{p,t}^{ht,-} = 0.05\,\mathrm{CHF/kWh}$: heating feed-in tariff.

District heating connection

The goal of this technology is to understand which optimal configuration each building would design to minimize the objective function, without assuming the existence of the connection as it is not the case in most of the circumstances. Furthermore, implementing this model buildings have the option to export the excess heat produced, but an initial investment has to be made. This is the reason why dashed lines appear in Figure 5.1 from the local heating grid up to buildings.

District heating connection is divided into two separate technologies: inward and outward. The former demands heat from the heating grid which will be supplied to the building energy system to provide space heating and domestic hot water. Meanwhile, the latter allows building energy hubs to supply surplus of heat to the local grid. The sale of heat is possible thanks to the introduction of one additional service: heat exchange (HEX) along ones explained in section 3.2. The unit installation decision, size and scheduling are constrained by Equation 3.1 and Equation 5.2. Parameters used throughout the simulations are summarized in Table 5.1. **VALORI GWP**

$$\dot{T}_{b,p,t}^{gr,+} + \sum_{u \in U} \dot{T}_{b,u,p,t}^{+} = \dot{T}_{b,p,t}^{gr,-} + \sum_{u \in U} \dot{T}_{b,u,p,t}^{-} \tag{5.2}$$

$$\forall b \in B \quad \forall p \in P \quad \forall t \in T$$

Parameter	Value	Reference
η_{max}	0.9	
i_u^{c1}	2000 CHF	[40]
i_u^{c2}	0.051 CHF/kW	[40]
b_u	1	
n	50	[41]

Table 5.1: District heating connection modelling parameter

Transmission constraint

The heating grid has also a transmission constraint. The heat resources is produced and consumed within the district (Equation 5.3). The heat can not be exported outside the district. Thus, this constraint is imposed to cope with the intrinsic characteristic of district heating network. In subsection 2.2.3, main energy and exergy losses are depicted, which will reduce the advantages of the system economically in long transmission pipelines. Moreover, heat losses in heat distribution network were computed and accounted for up to 8–10% with a study carried out by Poredoš and Kitanovski [42].

$$\dot{T}_{b,p,t}^{NT,\pm} = 0 \tag{5.3}$$

$$\forall p \in P \quad \forall t \in T$$

5.3 Centralised district units

The centralised design strategy enables the optimal sizing and scheduling of centralised district units. They are able to provide heat to the community at a cheaper price than single-building conversion technology. However, their use and installation is limited by their minimum size, which is larger than units installed within single-building energy systems.

Centralised district units are thermodynamically modelled according to their building energy system unit counterpart. Thus, they demand resources (i.e. electricity and natural gas) as import and then covert it into useful heat for the community. District units are allocated at district scale, as building energy hubs. Operational costs of these units are also allocated at community level. Installation, sizing and scheduling of these units are constrained by Equation 3.1 as building scale energy conversion technologies. However, their contribution to the energy balance is not accounted at the building level, rather at the district level.

District Energy Balances

Equation 5.4 ensure import and export of resources at district level taking into account centralised district units alongside building energy system and outside world network. The new set U_d contains all district units. Equation 5.4c regulates the heating layer at district level and ensures the constraint assumed in Equation 5.3 is fulfilled.

$$\dot{E}^{TR,+}_{p,t} + \sum_{u \in U_d} \dot{E}^{+}_{u,p,t} + \sum_{b \in B} \dot{E}^{gr,-}_{b,p,t} = \dot{E}^{TR,-}_{p,t} + \sum_{u \in U_d} \dot{E}^{-}_{u,p,t} + \sum_{b \in B} \dot{E}^{gr,+}_{b,p,t} \tag{5.4a}$$

$$\dot{H}^{NT,+}_{p,t} = \sum_{u \in U_d} \dot{H}^{-}_{u,p,t} + \sum_{b \in B} \dot{H}^{gr,+}_{b,p,t} \tag{5.4b}$$

$$\sum_{u \in U_d} \dot{T}^{+}_{u,p,t} + \sum_{b \in B} \dot{T}^{gr,-}_{b,p,t} = \sum_{u \in U_d} \dot{T}^{-}_{u,p,t} + \sum_{b \in B} \dot{T}^{gr,+}_{b,p,t} \tag{5.4c}$$

$$\forall p \in P \quad \forall t \in T$$

5.4 District heat pump

The energy conversion technology which is taken into account for the supply of heat for the district is an industrial heat pump. The choice is driven by higher energy efficiency and performance compared to an industrial natural gas boiler or an electrical heater. Alongside these considerations, the use of heat pump goes in the same direction as the district heating network technology. As it is described in section 2.3, heat supply at lower temperature has multiple advantages: less grid losses, increased energy efficiency as well as the possibility to integrate high performance low temperature sources such as waste heat.

5.4.1 Heat pump thermodynamic analysis

The performance of the heat pump are limited by the 2$^{\text{nd}}$ law of thermodynamics, fixed by the temperature of the system. The input of the cycle is the electricity used to run a compressor. This work is able to move heat from a source (i.e. ground, water, waste heat) to a sink like a building [43]. The amount of heat moved in relation to the electrical input is a function of the coefficient of performance. The COP is the ratio of the heat provided Q over the electricity

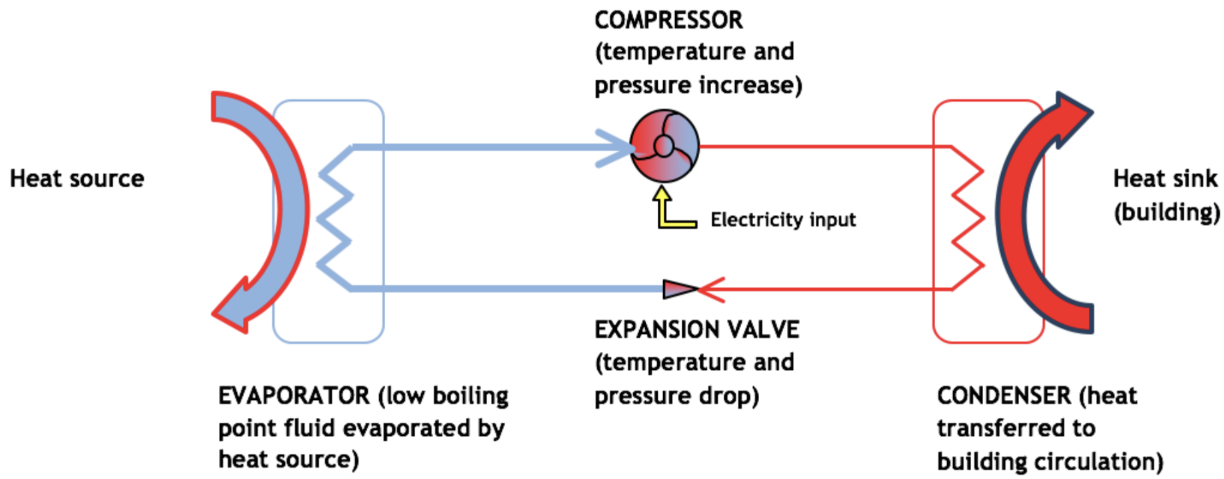

Figure 5.2: Heat pump cycle [44]

input W. The maximum value COP_{ideal} is defined as the ratio of heating temperature T_H over the difference in temperature between the sink and the source $T_H - T_C$ (Equation 5.5a). The real performance COP_{real} is stated using a Carnot factor that is defined as the ratio between the maximum performance and the real performance (Equation 5.5b).

As it is well described by Meggers, Leibundgut, and Mast [43], COP_{ideal} is very independent from the machine itself, but it is rather dependent on the temperature the system is working with. Meanwhile, the Carnot factor is directly function of the machine performance. A heat pump cycle model is presented in Figure 5.2.

$$COP_{ideal} = \frac{T_H}{T_H - T_C} \tag{5.5a}$$

$$COP_{real} = \eta_{Carnot} \frac{T_H}{T_H - T_C} = \frac{Q}{W} \tag{5.5b}$$

Heat pump source

Supplying hot water at the maximum temperature destroys a large amount of exergy in storage and distribution. Meanwhile the reduction in the supply temperature helps in the reduce the exergy destroyed, the temperature of the sources plays an important role in optimization of performances. The studies carried out by Meggers, Leibundgut, and Mast [43] highlights how the warm wastewater can be exploited to reduce the temperature lift of the heat pump, hence enhancing its performance.

A recovery heat system is used to exploit the wastewater in an optimal point of its flow, taking advantage of the high heat capacity of water and minimizing the mixing with the cold wastewater.

The source temperature is assumed to be $T_C = 30\,^{\circ}\mathrm{C}$ [43]. The cost for the recovery heat system is not taken into account.

Heat pump sink

The district heat pump is responsible to supply heat in order to satisfy both the space heating and the domestic hot water demand. In modern building space heating needs are fulfilled using underfloor heating systems which operate at lower water temperatures with respect to traditional radiator systems, minimizing losses and leading to a homogeneous heat distribution. Common water operating temperatures in these systems are around $50\,^{\circ}\mathrm{C}$ [45].

Meanwhile, domestic hot water is usually used by people at $< 40\,^{\circ}\mathrm{C}$ in practice. However, due to Legionella risk, hot water is stored at $> 60\,^{\circ}\mathrm{C}$. Legionnaires' disease, a type of severe pneumonia, is caused by breathing in small droplets of water that contain Legionella. According to HSE [46], hot water should be distributed at $50\,^{\circ}\mathrm{C}$ or higher as a primary method to control the risk from Legionella. Furthermore, more control method are investigated such as copper and silver ionisation and biocide treatments, but also mechanical methods can be implemented: filters or decentralised substation just to name a few [47].

Following those considerations, a trade-off has to be found when assuming the sink temperature between the performance of the heat pump and the number of control method that might be implemented. The cost for Legionella control are not considered in this modelling framework. The source temperature is assumed to be $T_H = 57\,^{\circ}\mathrm{C}$. In Table 5.2, thermodynamic parameters are summarized.

Parameter	Value	Reference
T_H	$57\,^{\circ}\mathrm{C}$	
T_C	$30\,^{\circ}\mathrm{C}$	[43]
η_{Carnot}	0.6	[48]
COP_{ideal}	12.22	Equation 5.5a
COP_{real}	7.34	Equation 5.5b

Table 5.2: Heat pump thermodynamic model parameter

5.4.2 Heat pump economic analysis

The size of the heat pump has to be constraint accordingly. The cost function linear regression which was performed for the single building heat pump is no longer valid in the capacity range for a district heating heat pump.

A linear cost function is a mathematical method used by stakeholders to determine the total costs associated with a specific amount of installed heat capacity. This method of cost estimation is implemented to ease calculation associated with a non-linear cost function. The linear cost function can be calculated by adding the variable cost, which is the cost per kW multiplied by the unit's kW installed, to the fixed costs of installing such technology. Performing this equation will give the total cost for a production order [49].

However, the linear regression of the cost function is less accurate as the range where such linearization occurs increases. It is crucial to define such range in order to obtain the optimal trade-off between available heat capacity that can be installed and precision in cost evaluation.

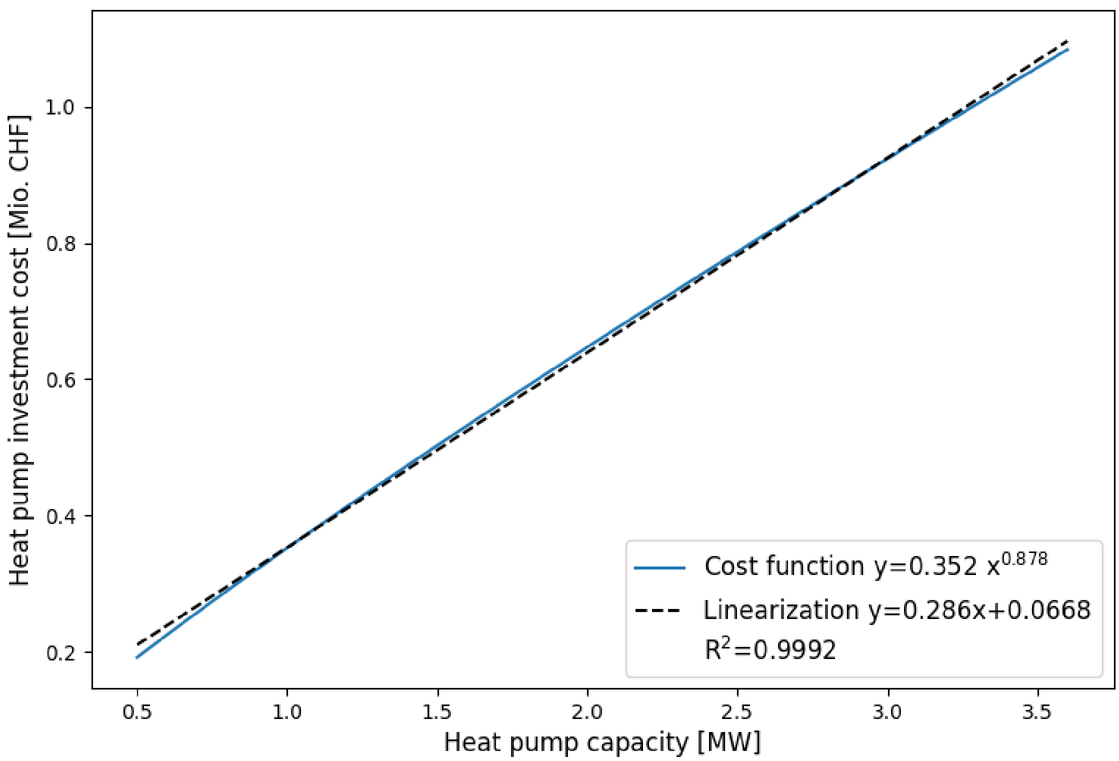

Figure 5.3: Heat pump cost function and linear regression line

In Figure 5.2 the cost function developed by Pieper, Ommen, Buhler, *et al.* [50] and the linear regression are displayed. Meanwhile, Equation 5.6 reports thier numerical values. The statistical tool R^2 is used to investigate how accurate the linear regression model is. It is the proportion of the variation in the dependent variable that is predictable from the independent variable [51]. It measures the strength of the relationship between your model and the dependent variable on a convenient 0 - 1 scale [52].

$$
\begin{aligned}
f_{ref} &= 0.352x^{0.878} && (5.6a)\\
f_{lin} &= 0.286x + 0.0668 && (5.6b)\\
R^2 &= 0.9992 && (5.6c)
\end{aligned}
$$

In Equation 5.6b, fixed and variable cost of linearization are found. These values are exploited to calculate the investment cost of the district heat pump. On the other hand, operational cost are driven by Equation 5.4. Heat pump cost is calculated as it is performed for other energy conversion technology. However, its cost is not attributed to one specific building, rather is added to the balance of the entire district. Parameters presented in Equation 5.7 are detailed explained in subsection 3.2.1. In Table 5.3 their values are summarized.

$$
\begin{aligned}
C_{HP}^{op} &= \sum_{p \in P} \sum_{t \in T} (c_{p,t}^{el,+} \cdot \dot{E}_{p,t}^{+}) && (5.7a)\\
C_{HP}^{cap} &= \frac{i(1+i)}{(1+i)^n - 1} \cdot (C_{HP}^{inv} + C_{HP}^{rep}) && (5.7b)\\
C_{HP}^{inv} &= b_u \cdot (i_{HP}^{c1} \cdot y_{HP} + i_{HP}^{c2} \cdot f_{HP}) && (5.7c)\\
C_{HP}^{rep} &= \sum_{r \in R} \frac{1}{(1+i)^{r \cdot l}} \cdot (i_u^{c1} \cdot y_{HP} + i_u^{c2} \cdot f_{HP}) && (5.7d)\\
C_{HP}^{tot} &= C_{HP}^{op} + C_{HP}^{cap} && (5.7e)
\end{aligned}
$$

Parameter	Value	Reference
i_{HP}^{c1}	0.0668 Mio CHF	Equation 5.6b
i_{HP}^{c2}	0.286 Mio CHF/kW	Equation 5.6b
i	2 %	
b	1	
l	20 years	
F_{min}	0.5 MW	Figure 5.3
F_{max}	3.5 MW	Figure 5.3

Table 5.3: Heat pump economic model parameter

5.5 Results

This section aims at presenting the main findings and results achieved applying the modelling framework to the same case study residential neighborhood, which was previously introduced in subsection 4.2.1.

First, the model is exploited to give an insight on different energy system scenarios. Then, a single-objective optimization comparison is carried out to understand the benefit of the introduction of a district heating network. At the end, an investigation on heat tariffs is executed.

5.5.1 Scenario analysis

In Figure 5.4, a comparison between different scenarios is presented both from an economical and environmental perspective. Each energy system scenario configuration is developed by a single objective optimization where the objective function is the total cost of the system (TOTEX).

The left column stands for the annualized capital investment for the system (CAPEX), meanwhile the right column represents operational cost associated with such system. Total cost and global warming potential are also shown. The scenarios investigated are:

- **Fossil-fuel**
  In this scenario natural gas boilers are used to supply domestic hot water and space heating for buildings. Investment cost are only associated to water tank purchase, since it is assumed boilers are already installed within the units. Under this assumption, most of the total cost comes from operational expenses, natural gas and electricity. Global warming potential is around 45 $\mathrm{kg_{CO_{2,eq}}/m^2yr}$ due to the extensive use of fossil fuels.

- **Renewable energy source integration**

  Renewable energy sources and heat pumps are integrated within the district, replacing natural gas boilers. CAPEX is mainly driven by high initial cost units, such as heat pumps and photo-voltaic panels. However, the installation of high performance technologies drastically reduces expenses. A 74 % in OPEX is experienced, indeed. Furthermore, the total expenses per year per square meter are reduced by 43 %. Benefits are not limited by the economical perspective, but touch even the environmental one with a 89 % decrease in global warming potential.

- **District heating**

  In the third scenario the possibility to connect to the local district heating network is available. Single building energy hubs can supply the heat surplus to the grid or buy the heat deficit to satisfy their demand. Nevertheless, this heat exchange is not possible unless a district heating connection is installed (section 5.2). However, from a first simulation buildings did not installed the connection. Instead the configuration, which was selected, is the same as in the previous scenario. Therefore, it is able to safisfy the district demand still being more cost efficient. The results presented in Figure 5.4 are obtained forcing energy hubs to install such technology, thus they are expected to be less valuable from a stakeholder point of view. Slightly worst results are produced in both total costs and global warming potential, indeed.

- **District heat pump**

  The last scenario features the integration of the district heat pump in the model alongside the district heating network. First of all, not all the heat demand of the district is satisfied resorting to the district heating network, since some buildings decided to install single heat pumps rather than connecting to the heating network. Nonetheless, the photo-voltaic penetration within the neighborhood remains constant. Economic-wise, investment cost experience a 7 % reduction when using the district heat pump compared to the renewable energy source integration scenario. This difference lies in the economic of scale. Then again, operational cost are reduced by 3 % with the integration of the district heat pump. The difference has to be accounted to the higher performance of the district heat pump compared to single heat pumps for single unit, thanks to a better heat recovery system and higher efficiency. Accounting for both expenses, TOTEX undergoes a 5 % reduction within the same residential neighborhood. Global warming potential is reduced by 16 %.

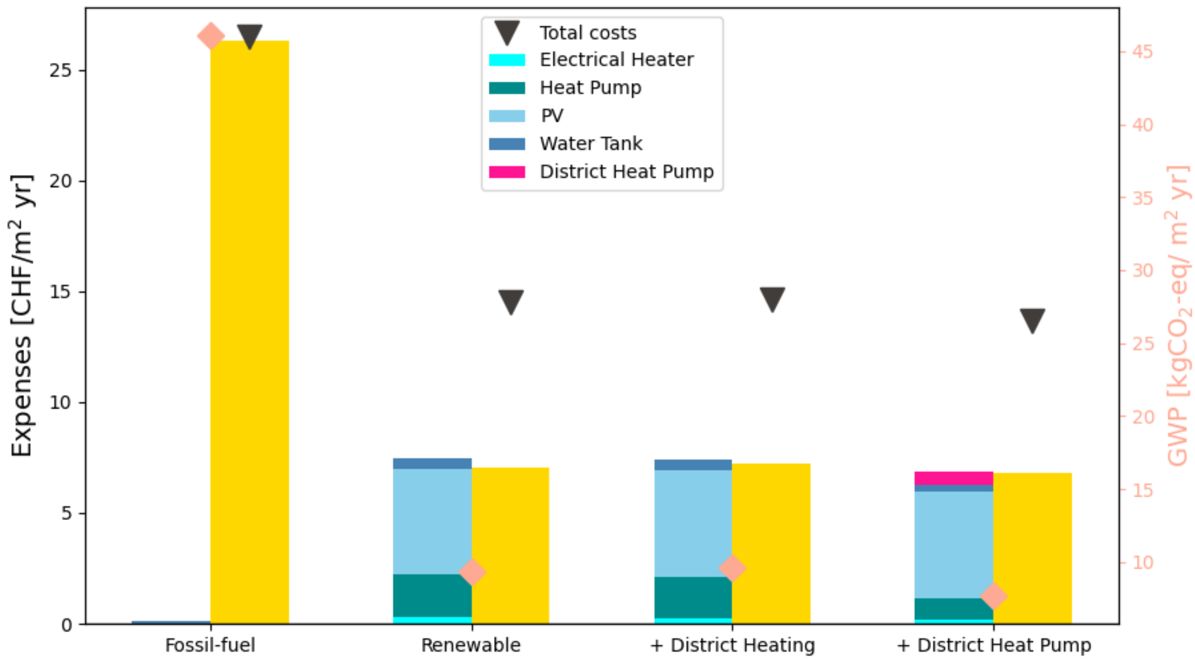

Figure 5.4: Scenario with different energy system configurations comparison

Figure 5.4 shows the benefits of shifting from obsolete natural gas boilers to more efficient heat pumps. Still, the main obstacle to overcome is the high initial investment cost which is required to install such technologies. Furthermore, the benefits arising from the construction of a district heating network powered by a centralised heat pump are even clearer. However, apart from the high initial investment cost mentioned before, the decision regarding the installation of such facilities for the community have to be made local policymaking bodies.

5.5.2 Single-objective optimization

In subsection 5.5.1, it is clear the advantages brought by the installation of a district heating network in Florissant residential neighborhood. The goal of this study is to investigate where these benefits lie resorting to both economical, environmental and key performance indicators.

A single-objective optimization with TOTEX as objective function is then performed. The district without the district heating network is compared with one with the possibility to install it alongside a district heat pump.

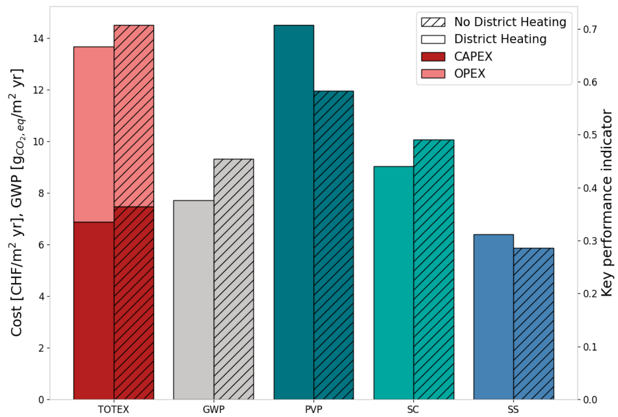

Figure 5.5: District heating network role in key performance indicators

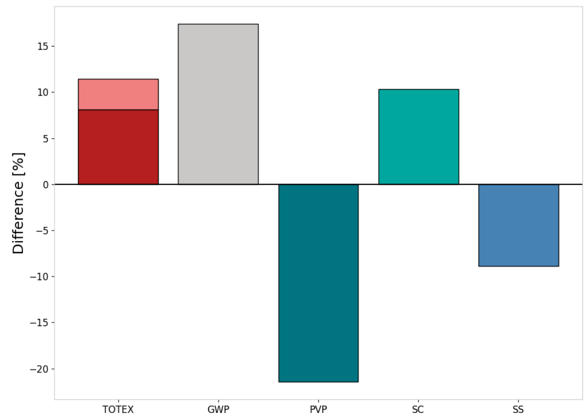

Figure 5.6: Relative difference between two scenarios

The installation of a district heating network is beneficial from a economical and environmental perspective. In Figure 5.6, a 11 % difference in TOTEX is experienced. Most of this difference is due to a better budget allocation for the initial investment. The district heat pump provides the building heat demand at a lower cost per kW rather than multiple smaller heat pumps. The OPEX is reduced by 3 %: the reason behind this drop has to be accounted to the higher efficiency of the district heat pump. Economy of scale plays a key role when it comes to economical indicators.

More than 15 % is the relative difference in emission. It is the result of a different design strategy: the district heat pump is run by electricity, so the neighborhood is stimulated to install a higher share of photo-voltaic panels to satisfy its demand. The photo-voltaic penetration is approximately 20 % more in the district with the heat pump installed, indeed. Additional PV panel installation increases the global warming potential due to their production, but it enables the district to satisfy a share of the heat pump electricity demand with green energy. The higher efficiency of the district heat pump reduces emissions compared to single-building heat pumps.

Key performance indicators give a further insight to the two solutions and confirms the analysis above. Self-consumption (subsection 3.2.2) is reduced, more electricity is exported outside the single energy hub towards the local electric grid in the district heating scenario. Self-sufficient increases as the higher share of photo-voltaic panels installed within the district, the higher fraction of electricity demand satisfied by them.

In Figure 5.7 and Figure 5.8, the analysis is deepened at the transformer level. The results presented in Figure 5.7 are a further proof of the district behaviour when a heating network is installed. Electricity import both at building and transformer level is less when the district heat pump is present, due to a lower photo-voltaic penetration. Furthermore, building export a larger

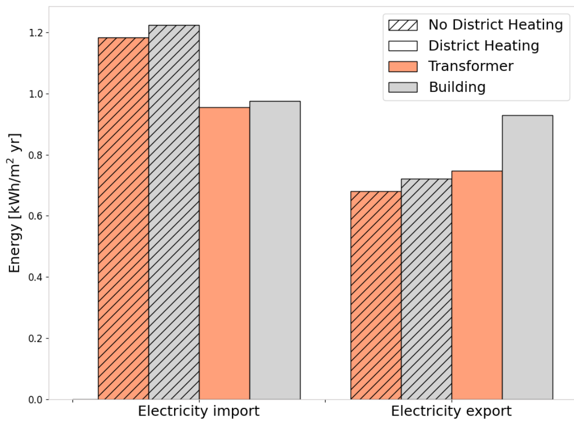

Figure 5.7: District heating network role in electricity import and export

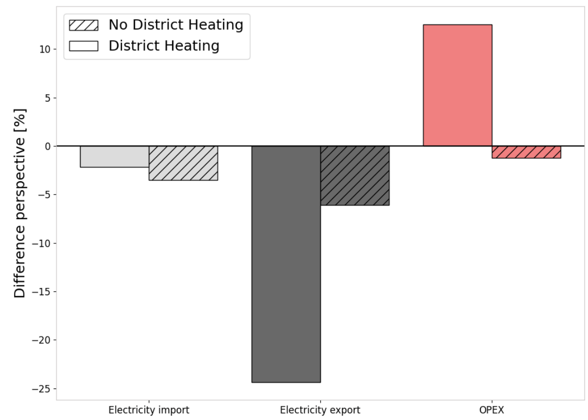

Figure 5.8: Relative difference between two scenarios

amount of electricity in the same scenario. It states how single energy hub are also the electricity provider of the district heat pump. The mutual assistance between these hubs has a positive impact on the entire district from many different perspective, as highlighted in Figure 5.5.

5.5.3 Influence of heating tariffs

The district heating is a service which is provided for the local community. Assumption made in section 5.2 are still valid. However, a supply and feed-in tariff are necessary to regulate both the model and the district energy system.

The aim of this section is to investigate what is the influence of heating tariff on the district energy system configuration. Furthermore, a simple economic assessment is performed to understand how profit of a hyphotetical heating company would be tuning tariffs. Results are presented in Figure 5.9. Profits are calculated according to Equation 5.8.

$$Profit = E^{+}_{HP} * c^{heat,-}_{p,t} - C^{cap}_{HP} \tag{5.8}$$

where:

- E^{+}_{HP} is the heating output expressed in kWh.
- $c^{heat,-}_{p,t}$ is the heating feed-in tariff.
- C^{cap}_{HP} is the capital investment for the district heat pump (Equation 5.7b).

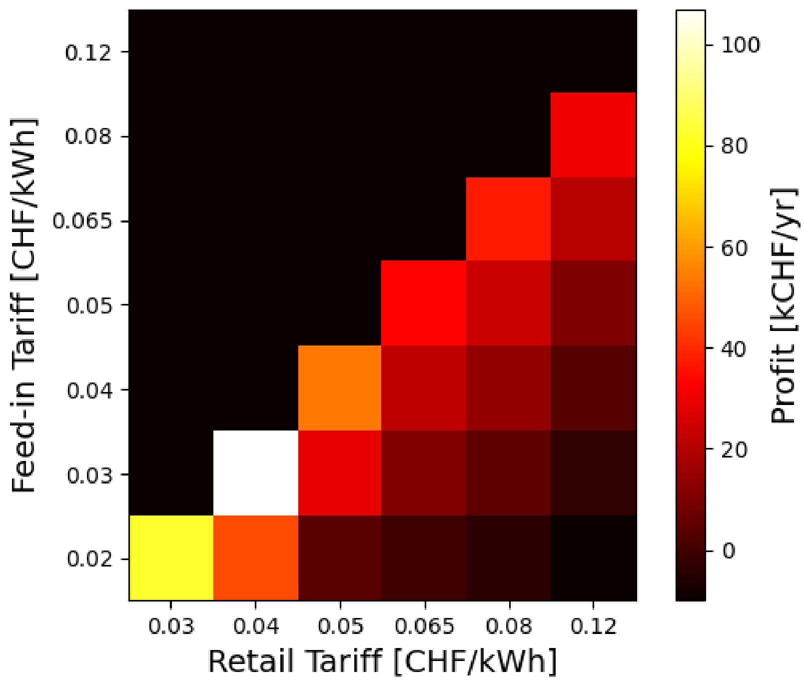

Figure 5.9: District heating tariff heat map. The influence of feed-in and supply tariff on district heat pump profit

The black upper region is excluded from calculation since it is unfeasible. The feed-in tariff can not be larger than the supply one. From the heatmap in Figure 5.9, it is clear that better results from an economical perspective are obtained when the difference between the two tariff is reduced. The reason behind this behaviour is evident from Equation 5.8, where increasing $c_{p,t}^{heat,-}$ profit are increased as well.

The model behaviour changing the retail tariff is presented in Figure 5.10: when lower retail tariff are imposed the dimension of the district heat pump increases. As a consequence C_{HP}^{cap} in Equation 5.8 increases alongside E_{HP}^{+}. The optimal trade-off between feed-in price, heating output and initial investment is found for a 0.04 CHF/kWh retail and 0.03 CHF/kWh feed-in tariffs.

Figure 5.10 gives a further insight in the mutual exclusion of the district heat pump and the decentralised heating production. The latter is not economically viable for retail tariffs lower than 0.04 CHF/kWh, reaching a peak plateau after 0.06 CHF/kWh. However, the district heat pump shows an opposite behaviour. Lower retail tariffs promote its use and installation, meanwhile for heat price higher than 0.06 CHF/kWh, just a baseload power is provided to the community.

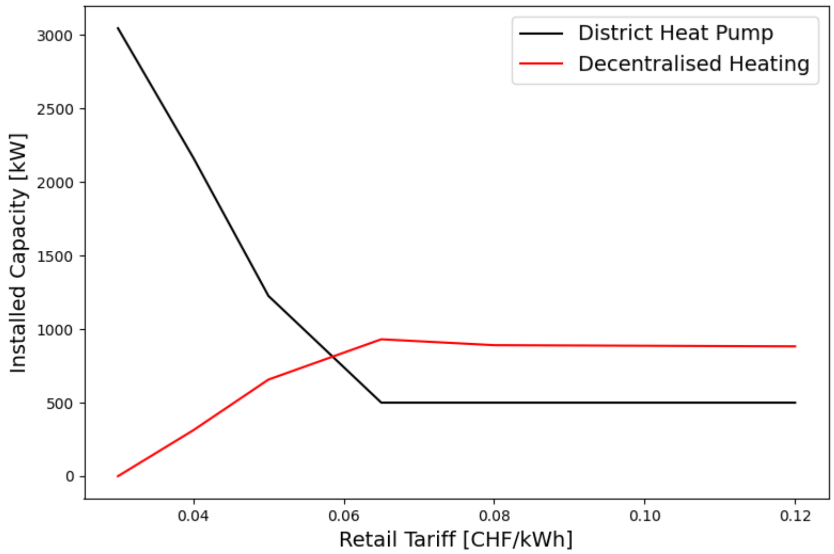

Figure 5.10: Installed capacity of district heat pump and decentralised heating production for increasing retail tariffs.

5.6 Conclusion

The aim of this chapter was investigating the capability of district heating network integration within the modelling framework, which was presented in chapter 4. Furthermore, an analysis was carried out to understand how the model would behave with the introduction of a centralised district unit. To answer these questions multiple steps were taken.

- First of all, a district heating grid was modelled and assumptions were made, both from a thermodynamic and an economical point of view. A constraint was introduced to avoid heating export outside of the district. Furthermore, a new single-building unit is modelled to enable energy hubs to connect to the main heating grid.
- Centralised district units are introduced. District energy balances are updated. Then, the district heat pump model is presented. The unit assumptions and parameters are displayed thermodynamically and economically.
- Results are presented comparing four different scenario where the district population demand is satisfied resorting to different energy system configuration. The benefits of using a renewable based approach are clear with respect to traditional fossil-fuel based one. However, a further improvement is achieved when district heating network alongside a centralised heat pump is installed in the neighborhood.

- Then, a single-objective optimization with TOTEX as objective function is carried out. The goal of this study is to confirm the advantages of a district heating network and to give further insights on where these benefits come from. The economy of scale of a centralised heat pump with the residential decentralised electricity contribution from photo-voltaic panels is beneficial for the district itself.

- In the end, a brief investigation on the influence of heating tariff was performed. Profit was implemented as the parameter to judge optimal tariffs to be used by policymakers.

The heating demand driven by the residential sector will always be a challenge to address. Reductions in global warming potential and expenses can be marginally found in a reduction of the demand. The main contribution must come from the technological advances implemented within buildings. First of all, more insulating building envelope should be built to avoid unnecessary thermal dispersion and leakages. Then, the installation of more energy efficient technologies, such as heat pumps. The results go in this direction: a district which is able to provide for its heating demand mostly resorting to on site resource production.

CHAPTER 6

CONCLUSION AND FINAL CONSIDERATIONS

To conclude, the methodology which has been developed solves many questioning about decentralisation levels and integration of district heating network. The decentralised design strategy outperforms the centralised strategy where each building energy system is optimized without any coordination within the district. The introduction of a district heat pump brings many advantages to the neighborhood enhancing energy and efficiency performance of the district. The project highlighted the numerous benefits of cooperation when the final goal is an optimal energy configuration for a residential district. The main conclusions are listed below.

- The modelling framework has its foundation in the building energy hub. The hub has electricity, water and heating demands and it is able to satisfy them either by buying them from the grid or installing competing energy conversion technologies. Sizing constraints and energy balances are set to ensure the physical meaning and the convergence of the problem. Objective function are introduced alongside key performance indicators to understand the performance of each energy configuration.

- A multi-objective optimization is exploited to investigate the difference between coordinated and cooperative district against a community where buildings take decision without considering neighbors. The results show the importance of decision-making at distrct level when operating costs are minimized, which implies a reduce demand of resources from the outside world.

- The decentralised design approach outperforms the centralised strategy in many scenarios. Total cost are decreased ($-0.75\,\%$). However, when stricter constraint are imposed on global warming potential, the decentralised strategy is able to adapt better to external perturbation, since it relies less on the outside world.

- The modelling framework of the district heat pump alongside the district heating connection and the heating grid enables buildings to demand heat as a resources. A scenario analysis is presented to highlight the advantages brought by the use of renewable energy sources and technologies compared to traditional fossil-fuel based energy system. A large increase in investment costs is justified by a massive decreases in operational costs (−74 %). The comparison is extended also to centralised heating production plant.

- The integration of a centralised heating plant both decreases the fixed (−8 %) and operating costs (−3 %). Furthermore, a greater photo-voltaic penetration (70 %) is experienced which leads to a high self-sufficiency (30 %).
- Heating tariffs have a considerable impact on the share of heat production within the district. High retail tariff enhances the installation of decentralised production unit, meanwhile as it decreases the centralised heat pump becomes the predominant mean of heat production.

The project highlights the key importance of renewable energy sources and high efficiency energy conversion technologies. High initial cost is the main drawback. However, they enable single building to be more resilient to external changes, becoming more stable and reducing operational cost. The autarkic energy transition is just a first step towards a more active participation of communities in the energy mix. Afterwards, synergism will be the key to allow the residential sector to thrive. The installation of low temperature heating network goes in this direction: energy systems designed for the community and powered by the community.

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