Diploma Thesis

The potential of demand flexibility provided by heat pumps to the Austrian electricity system

carried out for the purpose of obtaining the degree of
Dipl.-Ing., by

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Abstract

To achieve a sustainable and climate-friendly future today's energy systems are undergoing a major clear transformation towards decarbonization where renewable energy sources are expected to play a key role. The objective of this work is to define the technical and economical potentials of different heat pump systems with regard to the use of electricity in the heating sector combined with heat storage in times when cheap, renewable, surplus electricity is available. This shall serve to estimate the flexibility that can be provided by heat pumps for the Austrian electricity system. For this purpose, a detailed evaluation of heat pumps and their dynamic properties (=flexibility) is required. Having a huge impact on both the reduction and expansion of flexibility for different heat pump types, both technical and physical (environmental factors, e.g. temperature) constraints will be assessed. To define the term flexibility of heat pump operation, it is necessary to evaluate the working principle for different types of heat pumps.

The open-source energy system model Balmorel is used to optimize the combined dispatch of the previously discussed heat pumps in the overall Austrian electricity and district heating system concerning the specific operational properties of heat pumps; an additional focus is laid on fitting heat storages in economically profitable periods and the effect of sector coupling in the Austrian electricity system. For analyzing the role of increased sector coupling appropriately, an extension of the model appears necessary. Thus, part of this master thesis's work plan was to extend the model scope by an additional add-on "Demand-Response", including model optimization, expansion, and adjustment of heat storage to strategically and economically rational periods, incorporating key technical and economic features of heat pumps.

It is shown that the model and the additional add-on is well qualified for analyzing possibilities and system benefits of operating heat pumps flexibly. This includes prioritizing heat pump operation for hours with low marginal electricity production costs, resulting in less pollution from a lower conventional operation of gas plants and accordingly lower electricity prices over the year.

Kurzfassung

Um eine nachhaltige und klimafreundliche Zukunft zu erreichen, werden die heutigen Energiesysteme einem klaren Wandel in Richtung Dekarbonisierung unterzogen, bei dem die erneuerbare Energiequellen eine Schlüsselrolle spielen werden. Das Ziel dieser Arbeit ist es, die technischen und wirtschaftlichen Potenziale verschiedener Wärmepumpensysteme im Hinblick auf die Nutzung von Elektrizität im Heizungssektor zu evaluieren und diese in Verbindung mit dem Bedienen von Wärmespeichern in Zeiten von günstigem, erneuerbarem und überschüssigem Strom zu setzen. Dies soll dazu dienen, die Flexibilität, welche die Wärmepumpen für das österreichische Stromnetz bieten können, abzuschätzen. Folglich ist eine detaillierte Bewertung der Wärmepumpen und ihrer dynamischen Eigenschaften (= Flexibilität) erforderlich. Weiters erfolgt zusätzlich eine weitere Einschätzung technischer und physikalischer Umweltfaktoren, z. B. Temperatur, hinsichtlich der Verringerung und der Erweiterung der Flexibilität für verschiedene Wärmepumpen. Folglich wird der Begriff Flexibilität des Wärmepumpenbetriebs definiert, um das folgende Arbeitsprinzip für verschiedene Arten von Wärmepumpen zu bewerten.

Das Open-Source-Energiesystemmodell Balmorel wird verwendet, um die Verteilung der zuvor diskutierten Wärmepumpen im gesamten österreichischen Strom- und Fernwärmesystem hinsichtlich der spezifischen Betriebseigenschaften von Wärmepumpen zu optimieren. Ein weiterer Schwerpunkt liegt auf der Bedienung von Wärmespeichern in wirtschaftlich rentablen Zeiten und den Auswirkungen der Sektorkopplung im österreichischen Stromnetz. Um die Rolle einer erhöhten Sektorkopplung angemessen zu analysieren, erscheint eine Erweiterung des Modells erforderlich. Teil des Arbeitsplans war es daher, den Modellumfang um ein zusätzliches Add-On "Demand-Response" zu erweitern, einschließlich Modelloptimierung, Erweiterung und Anpassung der Wärmespeichers an strategisch und wirtschaftlich rationalen Zeiträumen unter Einbeziehung wichtiger technischer und wirtschaftlicher Aspekte von Wärmepumpen.

Es wird gezeigt, dass das Modell und das zusätzliche Add-On dafür gut qualifiziert sind, die Systemvorteile des flexiblen Betriebs von Wärmepumpen zu analysieren. Dies führt zu einer Priorisierung des Wärmepumpenbetriebs in Stunden mit geringen Kraftwerksgrenzkosten für die Stromerzeugung, was folglich zu weniger Emissionen durch einen geringeren konventionellen Betrieb von Gasanlagen und dementsprechend niedrigeren Strompreisen im Laufe des Jahres führt.

Foreword

"As human beings, we are vulnerable
to confusing the unprecedented with
the improbable. In our everyday experience,
if something has never happened before,
we are generally safe in assuming it is
not going to happen in the future,
but the exceptions can kill you
and climate change is one of those exceptions"

-Albert Arnold Gore Jr.

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Contents

1 Introduction

The transformation processes towards decarbonization in combination with a higher share of renewable energy sources are underpinned by ambitious climate, energy, and environmental targets set both on a regional- and European level[1]. However, the Austrian power system was designed as a top-down system with fossil electricity production (coal, gas, etc.) combined with hydropower, which accounts for around 2/3 of the total electricity generation, together with an extensive transmission grid that transports electricity to the final consumer, this has generally turned out to be robust and reliable[2]. On the other hand, variable renewable energy (VRE), such as wind and solar photovoltaic (PV) systems, production is intermittent and less predictable, while depending mostly on the weather conditions and affecting the electric energy sector.
To maintain the stability of the grid, the production must be equal to the consumption at any point in time. A possible gap between the flexibility needed within the energy system and the flexibility being provided would result in a blackout. So, in times with a high share of VREs, it becomes more difficult for other electricity power plants to compensate for the residual load. As a result, the system needs to be more flexible than before. A solution to provide the flexibility to the energy system is to couple the electricity and heating sector with versatile, renewable energy and energy-efficient technology such as heat pumps[3].

The Union of the Electricity Industry-Eurelectric defines the word flexibility for participants in the electricity market, as follows:

"On an individual level flexibility is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterize flexibility include the amount of power modulation, the duration, the rate of change, the response time, the location, etc." [4]

1.1 Austrian energy system

Austria has set ambitious climate policy goals that require a comprehensive transformation of the energy system towards full long-term decarbonization.

The term "sector-coupling" plays a special role in the discussion about possibilities for the concrete implementation of the climate policy goals in Austria. This leads to a stronger link between the systems ("sectors") electricity, gas, mobility, and heating infrastructure that has mostly been considered separately.

Even though the decarbonization is already well advanced in the power generation sector, the heat and transport sector is currently far behind in implementing the restructuring of the energy system. Today, renewables account for around three-quarters of domestic electricity generation. The proportion of gas on the final energy consumption, however, is still around 40 percent. The space heating sector accounts for around 27 percent of total final energy consumption or around 16 percent of greenhouse emissions. Electricity has a share of more than 11 percent in final energy consumption in space heating and hot water preparation[5].

Thus, power-to-heat capacities are determined to have strong relevance in the upcoming years. In order for the electricity and heating sectors to be more closely interlinked with further expansion of fluctuating electricity generation, power-to-heat technologies, such as heat pumps, are increasingly being used to utilize renewable electricity. In doing so, (excess) electricity is converted into heat and can either used directly or temporarily stored in a buffer storage[6].

1.2 Motivation for the research

There is a drastic difference between the electric- and heating energy system. While the electric energy system largely depends on the supply/demand structure and the stability of the grid, the heating sector intrinsically provides more flexibility, since the production does not have to be equal the consumption at every given second. This reveals the following research question:

- How can the strategic and flexible deployment of heat pumps contribute to the future energy system in Austria?

- What role has the heat storage system with its flexibility in the power system?

1.3 Method of approach for this thesis

To answer the given questions, it is crucial to understand the detailed working- and physical principle of heat pumps, as to make justifiable assumptions later.

The technical analysis of different heat pump types underpinned by various working parameters and an outlook to the thermodynamics is in the focus of chapter 2. In addition the description of the assessment energy system model Balmorel is introduced in the last section of chapter 2.

The link between the theoretical and practical analysis is described in the beginning of chapter 3, being the energy system analysis model Balmorel coupled with an additional add-on "Demand-Response". Following, chapter 3 summarizes all previously described heat pump systems in a context that can be used for the following model implementation and scenario analysis, as to answer the given research question in section 1.2.

Chapter 4 introduces the result section, thus being the flexibility potential provided by heat storage coupled up with heat pump systems.

2 Heat pumps: Theoretical background and evaluation

Learn from the past to provide solutions for the future: The history of heat pumps Speaking about the past, the principle of the heat pump system is derived from the description of the Carnot cycle, which was first published in his book “Reflections on the Motive Power of Fire and on Machines Fitted to Develop that Power” in 1824[7]. However, the prototype called the “Heat Multiplier”[8] was introduced by William Thompson in 1852 and was used to operate the refrigerator in reverse for heating purposes. According to his calculations, his invention was able to provide the required heat, by using only 3% of the energy used for direct heating.
Even for this time, Thompson already pointed out that the conventional energy sources would be limited, which was a huge asset for the “Heat Multiplier”, as it would consume less fuel than conventional furnaces.

While the Refrigerating machines advanced already at the end of the nineteenth century, the first heat pump systems had their breakthrough in the 1920s and 1930s in England. After a successful period in England, the United States and the rest of Europe were quick to put the first large heat pump in operation, which used the thermal energy of river water, a rotary compressor, and a refrigerant. The device provided heating for the city hall in Zurich, with a dual operation mode of heat accumulation with an electric heater to cover the peak load in winter, while cooling the city hall in summer at a temperature of 60°C and at a thermal power of 175 kW[9].

2.1 Heat pump fundamentals

Heat pumps generate work using a heat source of a respectively lower temperature area. To transport thermal energy from a low-temperature region called *source* to a high-temperature one known as a *sink*, a working fluid circulates in a combined sequence of thermodynamic processes. The described heat transfer would not comply with the second law of thermodynamics, thus an external energy input, work, or heat transfer, is needed, to compensate for the reverse nature of the cycle [10].

Heat pumps are more common than it might look, a refrigerator or freezer operates as a heat pump in a reversed cycle. Following, the energy flows are in the opposite direction compared with heat engines. While the refrigerator simply uses the "cold" side, the heat pump mainly uses the "hot" side [Fig.1] .

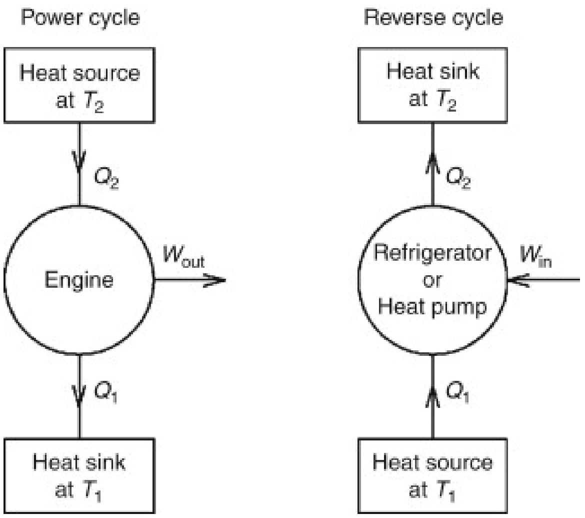

Figure 1: Concept of power cycle for a heat engine and reverse cycle for a refrigerator or a heat pump[11].

While the heat engine performs work using a heat source, the heat input Q_2 is extracted from a high-temperature level T_2 to get the energy output in the form of work W. However, the heat Q_1 must be detached to the heat sink from a lower temperature level T_1, as to obey the first law of thermodynamics. The first law of thermodynamics, also known as the Law of Conservation of Energy, states that energy cannot be destroyed nor created, but transferred from one location to another and converted to and from other forms of energy:

$$Q_2 = |W| + |Q_1| \tag{1}$$

In contrast, a heat pump moves a certain quantity of heat Q_1 from a heat source at a lower temperature level T_1 to a heat sink at a higher temperature level T_2. To obey the first law of thermodynamics, a work W must be supplied to the system to upgrade a certain amount of heat. Resulting in the exact amount of heat Q_2 applied to the heat sink. Q_2 equals the sum of heat Q_1 detached from the heat source and the amount of work W.

A small outlook to the principle of a refrigerator, reveals a conversely working principle, as the heat source Q_2 is extracted from a low-temperature level T_1, meaning a function of cooling down a determined heat source by extracting a certain quantity of heat Q_1. Practically, both cycles can be combined together for times when both heating and cooling are required simultaneously (e.g. chillers at sports centers used to both cool an ice-skating area and provide heat for hot water pools)[11].

2.2 Efficiency of heat pumps: Ideal measures of performance

The Carnot cycle describes the highest possible thermal efficiency, whereby the coefficient of performance COP, which is derived from the first law of thermodynamics, measures the efficiency of a heat pump.
In practical terms, it is described as the ratio of energy that is used for heating (heat sink) or cooling (heat source) to the performed work W to the cycle:

$$COP = \frac{Q_2}{|W|} = \frac{Q_2}{Q_2 - |Q_1|} \tag{2}$$

In addition, the diffusion of heat flow from a lower temperature level to a higher temperature level without any expenditure of energy is restricted by the second law of thermodynamics and can be derived as followed:

$$\sum \frac{Q_\mathrm{i}}{T_\mathrm{i}} \overset{[1]}{=} 0 \tag{3}$$

In practical terms, this would mean a required minimum amount of work W for the heat pump to operate in a reversed cycle. For the most common type of heat pump, the vapor compression heat pumps, the required work W is delivered in the form of mechanical energy provided by electrical energy to drive the heat pump compressor [12].
The coefficient of performance establishes the fundament for further scenario analysis in regard of the viability of the heat pumps in a district heating system [13].

2.3 Heat pump operation

In principle, to extract the thermal energy or heat from the environment, i.e., water, air, or soil, the heat pump lifts the working fluid to a higher temperature, which then delivers heat to the heating system [Fig.2]. The refrigerant circulates through the significant components: *Evaporator*, *condenser*, *compressor* and *expansion valve* in a closed circuit:

Evaporator: An evaporator is a heat exchanger in which thermal energy is absorbed by the working fluid, thereby cooling its surroundings. However, a Carnot cycle is impractical for power generation. Due to the principle of convection the thermal energy is absorbed by the working fluid, resulting in a cooling of its surrounding. Thus, an evaporator is a heat exchanger, which is traversed by a refrigerant at low pressure and near-ambient temperature. By the Second Law of Thermodynamics, the received heat from the environment must be higher than the refrigerant, resulting in evaporation of heat.

Compressor: The incoming refrigerant, in its vapor-state, is received by the compressor, which increases its pressure, and consequently its temperature. For that, external power input is required, which is usually supplied by an electrically driven motor from the power supply network. This creates a great potential for the deploying heat pumps in times with a surplus renewable electrical energy, that can be used to run the compressor.

Condenser: The now hot refrigerant vapor leaves the compressor into the condenser. Like the evaporator, the condenser is a heat exchanger for the superheated refrigerant, which extracts the heat energy to a colder area, e.g water in a heating coil, following the Second Law of Thermodynamics, the heat from the refrigerant goes to the heat carrier. Resulting in a condensation of the refrigerant and heating of the colder area, while the pressure of the refrigerant remains high.

Expansion valve: The task of the expansion valve, in practical terms also known as a throttle, is to even the high pressure created by the compressor, while renewing the cycle by reducing the temperature of the refrigerant to a level lower than the heat source. This can be referred to as the Joule-Thomson effect, as to achieve cooling of the system[14].

The optimal working condition for a mechanical heat pump is a low-temperature lift, while the heat source and heat sink are latent heat, leading to less heat loss. In multi-stage heat pump systems, higher temperature lifts can be achieved. Also, the heat pump performance decreases with the increase of temperature lift [15].

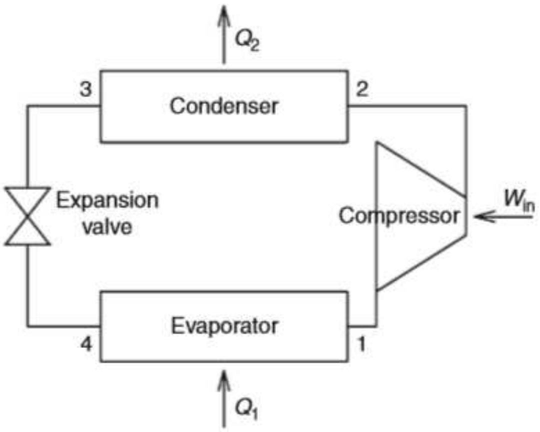

Figure 2: Schematic concept of a vapor compression heat pump[11].

2.4 Thermodynamic cycles

To achieve the reversible cycle of a heat pump, the refrigerant, which is a condensable fluid, has to fulfill a reversed Carnot cycle. By doing so, the input and output system heat Q_1 and Q_2 remain at a constant temperature through the periods of boiling and condensation. This leads to the assumption, that all heat transfer to and from the system must be reversible. Fig.3 illustrates the Carnot cycle for an ideal heat pump in a temperature-entropy T-S diagram [11][12].
The operating process can be written as such:

1-2 Isentropic compression: The isentropic process is characterized by a constant entropy of the fluid or gas, leading to no transfer of heat or matter. In practice, the refrigerant in its dual-phase liquid-gas flows from the evaporator into the electrical energy driven compressor for compression to the required level of pressure and temperature.

2-3 Condensation-Constant pressure and temperature heat rejection: Due to the high pressure the working fluid releases a vapor at high pressure and temperature flowing from the compressor to the condenser, resulting in a condensation of the working fluid at constant pressure and temperature while emitting the latent/condensation heat to the sink and a change in entropy $\triangle$s.

3-4 Isentropic expansion: The condenser releases the liquid-state of the working fluid at high pressure and temperature into the expansion device, which expands the liquid to the required lower level of pressure and temperature to close the cycle.

4-1 Evaporation- Constant pressure heat absorption: The expansion valve emits the two-phase liquid–gas working fluid at low pressure and temperature into the evaporator. Because of the temperature difference between the working fluid and the low-temperature heat source the fluid evaporates at constant pressure and temperature. The process repeats afterward.

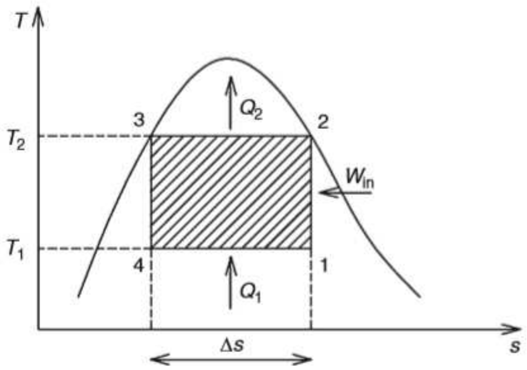

Figure 3: Carnot cycle of a heat pump[11].

2.5 Thermodynamic efficiency of ideal vapor compression heat pumps

The peak performance of an ideal heat pump, with an ideal reversed Carnot cycle, is derived from the isothermal heat transfer that occurs at both the high- and low-temperature ends of the cycle. A constant temperature of the heat source $T_1 = const$ and the heat sink $T_2 = const$ is characterized by the ideal reversed Carnot cycle, which follows an adiabatic transition process(= without transferring heat or mass between a thermodynamic system and its surroundings) based on the Second Law of Thermodynamics:

$$\frac{dQ}{T} = dS = 0 \tag{4}$$

As can be seen in Fig.3 the processes 1-2 compression and 3-4 expansion have an adiabatic nature. It is important to note, that the Eqn.4 is valid only for reversible adiabatic processes, leading to a constant entropy S. Resulting in an equity of entropy differences, S_4-S_1-S_3-S_2, with the efficiency of the Carnot cycle for a heat engine be written as such:

$$\eta = \frac{|W|}{Q_2} = 1 - \frac{|Q_1|}{Q_2} = 1 - \frac{T_1(S_4 - S_1)}{T_2(S_3 - S_2)} = 1 - \frac{T_1}{T_2} \tag{5}$$

Transforming the efficiency (i.e. COP) of a heating device operating in reversible adiabatic processes 1-2 and 3-4:

$$COP = \frac{|Q_2|}{|Q_2| - Q_1} = \frac{T_2 \triangle S}{(T_2 - T_1)\triangle S} = \frac{T_2}{(T_2 - T_1)} \tag{6}$$

As can be seen from Eqn.6 the Carnot cycle has the maximum possible COP between any two temperature levels T_2 and T_1 and is used for comparison of an ideal cycle with practical ones. Whereas the work W, which is the area limited by lines 1–2, 2–3, 3–4, and 4–1 and necessary to drive the machine, is the smallest. Leading to the fundamental understanding to keep the temperature of a heat source as close as possible to the temperature of a heat sink and the selection of heat sources and heat sinks.

Eqn.6 determines the COP of an ideal Carnot cycle heat pump. However, inserting an exemplary number for the outside air at 1°C as the heat source and the air inside a house at 25°C as the heat sink will lead to a COP of 12.41. This is practically impossible, for the COP of a real heat pump is about 3 to 4, due to environmental constraints such as temperature[19].

Fig.4 shows the ideal vapor compression cycle for heat pumping in a T-S diagram [11]. The ideal vapor compression heat pump cycle differs to the ideal carnot heat pump cycle by :

- The replacement of the throttling valve with an expansion valve, as to drop the pressure level
- The inlet of a saturated vapor, instead of a 2-phase liquid-vapor mix to the compressor
- The rejected heat from the condenser Q_2 is on a higher temperature level than at the condenser in the ideal heat pump cycle

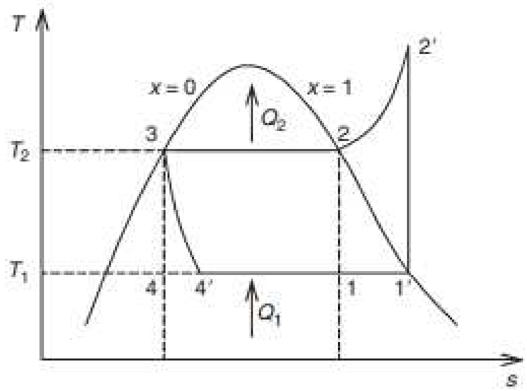

Figure 4: Basic vapour-compression cycle shown in a temperature–entropy diagram[11].

1‘-2‘ Isentropic compression: The evaporator emits low pressure saturated dry vapor inside the compressor, which processes the vapor to the required level of pressure and temperature within the superheating vapor region

2‘-2 Isobaric heat rejection: The condenser, receiving the working fluid from the compressor, forces an isobaric cooling at constant pressure due to a temperature gradient.

2-3 Isotherm–isobar condensation: Following a constant pressure and temperature level, the desuperheated vapor at high pressure flows through the condenser, resulting in a heating of the sink (in practical terms: space heating medium).

3-4‘Isenthalpic expansion: The condenser releases the saturated liquid (of the working fluid), which flows at high pressure and temperature into the throttle and is expanded to low pressure and temperature.

4‘-1‘ Isotherm–isobar evaporation: The working fluid, at low pressure and temperature in its two-phase state, leaves the throttle and traverse the evaporator. The working fluid evaporates at constant pressure and temperature and remains the heat source at a low temperature.

Real vapor compression systems: Deviations from ideal vapor compression systems Describing the physics of a real heat pump system leads to an essential description of the vapor compression cycle, also called the reversed Rankine cycle. Comparing ideal and real thermodynamic systems reveals one great difference: friction. Real vapor compression cycles are characterized by several fluid frictions with its surroundings in the piping that connects the four main processes that make up the cycle. This leads to an entropy increase-/decrease, pressure drops and heat losses to the surroundings[16].

2.6 Heat source types

This section presents a spectrum of different heat source types, which are examined through this work.
The implementation of heating devices such as heat pumps in the central and decentral systems is also complementary with further standards of the low carbon heat roadmap[17][18], such as increasing utilization of low-grade heat sources, such as heat rejected from industrial facilities and thermal power stations and potentially also nuclear power stations.

Looking at the range of possible heat source types, it is paramount to evaluate the connection and most effective integration of heat pumps and heat networks. The biggest challenge is the low efficiencies, due to high operating temperatures of conventional heat networks and relatively low temperature of available heat sources(see Sec.2.5). However, multiple innovative approaches to conquer these challenges have been developed, with the focus laid on the approach of using several heat pumps operating over small temperature ranges to improve efficiency. Another way is to focus on the seasonal use of heat pumps, to raise the temperature of water sources in the winter, while also to developing high-temperature refrigerants and the redesigning of heat networks to operate at lower temperatures.

As mentioned in Chapter 2.2 each heat pump is determined by its efficiency which is assessed at different predefined points of operation and temperature and referred to as "Coefficient of Performance".
While the *COPs* of air source heat pumps lie between 3 and 4 [19], the *COPs* of water source heat pumps are not legitimate comparable as different operating points and even the media differ significantly. Ground source heat pumps, described in Sec.2.6.5, naturally reach higher performances with mean values of 4.

Literature also mentions the term SPF (Seasonal Performance Factor), which considers all operating conditions occurring in a year and measures the operating performance of an electric heat pump heating system over a year. It is the ratio of the heat delivered to the total electrical energy supplied over the year [19]. While the COP determines the ratio of heat output (in kilowatts) over the electrical input (in kilowatts) at any one time, the Seasonal Performance Factor (SPF) is the average COP of a heat pump over the full heating season.

Due to their low investment cost and ease of installation air source heat pump show the highest market share in Europe and are expected to improve even further. Key problem for this heat pump technology is the relatively high sound emission, in particular from outside unit fans. However detailed investigations show initial results in the form of reduced emission levels and an improved understanding of the impact of installation location on sound emissions [20].

2.6.1 Sewage water

The water heat pump system operates by recovering the solar energy stored naturally in river water or open water. In simple terms, the water passes through heat pumps to yield its low-grade heat before being returned to the river with a temperature change. Wastewater is currently the most common type of heat source for large-scale heat pumps, also bearing a huge potential for future projects in most urban areas. It is regarded as a long-term stable type of heat source, with the largest capacities (>10MW) of heat pumps using is located in Scandinavia.

The most valuable aspects of the source are the availability in regions with high domestic or industrial heating demand and a desired typical temperature range from 10°C-20°C (even 30°C and more for Industrial sewage water). In contrast to surface water heat pumps, the typically small temperature spread between seasons allows a more precise deployment and consequently higher COP‘s [21].

2.6.2 Ambient water

As already mentioned the *COP* (see Sec.2.2) can be drastically limited by a lower inlet temperature. The bigger projects in Stockholm (230MW) are located in a region of a typical inlet seawater temperature of 3°C, which can be raised by the heat pump to 80°C, whilst achieving an average *COP* of 3. However, the alpine regions in Austria with their glacier-fed rivers, are characterized by reduced flow rates during the winter months, which additionally restrain the extractable amount of energy and bear a negative effect on operational flexibility[22].

2.6.3 Industrial waste heat

Today's and future ambitious climate targets focus on decreasing the carbon footprint of the industry sector. From a heat recovery and distribution perspective, heat pumps in central systems bear a viable solution for many locations in Europe, in which the recovery and recycling of low-temperature excess heat, produced by industrial or external consumers, can play a major role.

About 200 active large industrial heat pumps in Austria already provide heat for district-heat systems and local buildings. During power generation, thermal power plants have the highest level of excess heat of 70%, which can be used directly in the district heating (DH) systems [23]. It is important to note that the described heat source is heavily relying on the industry supplying it and is most directly tied into an industrial process, which restrains corresponding heat pumps from periodic use, as their application provides mandatory cooling power for the process.

2.6.4 Ambient heat

Both air-to-water and air-to-air heat pumps deriving their heat source from the atmosphere can be described as a technological- and economical "all-rounder" since air is and will be an omnipresent low-temperature energy source. The utilization of air heat pumps prospects great advantages in both small and large scale applications. Per contra, the air has a lower energy density compared to e.g. water, which leads to the demand for excessive air throughput volumes. Besides air is a very temperature volatile energy source, meaning that the territorial weather conditions lead to a significant impact on the *COP* of these systems.
For bigger central systems, the measures of the fans and evaporators have to be increased respectively, which leads to noise pollution and further restrictions in urban areas.

To sum up, despite air not being flawless as a heat source, the great availability, self- sufficiency, and geographical placement freedom form a basis for further evaluation but only for smaller systems [24].

2.6.5 Geothermal heat

The main aspect of turning geothermal heat pumps (GHP) into a dominant choice for energy supply in commercial and residential building is owned to its high Coefficient of Performance, due to lower soil temperature than the ambient air temperature in the cooling season, but higher in the heating season. Following, the GHP system utilizes the soil as a heat source in the heating season, and as a heat sink in the cooling season. Moreover, GHP shows a significant advantage over traditional heating and cooling units due to its low operating costs.

A GHP system composes of three major elements: ground heat exchanger (GHE), heat pump, and heat distribution subsystem.
As the working fluid circulates through a ground heat exchanger (GHE), the GHE system can release heat to the ground for space cooling in summer and extract heat from the ground for space heating in winter. In other terms, a GHE plays an important role in the heat transfer mechanism. The most common GHE are classified as Vertical ground heat exchangers (VGHEs) and horizontal ground heat exchangers (HGHEs).

Due to the seasonal soil temperature variation(e.g. effect of groundwater flow and higher thermal properties of the surrounding ground, such as rock) the thermal performance of the horizontal GHP system is comparatively lower than the vertical system, thereby the horizontal GHP system needs a larger area and longer pipe. However, the horizontal GHE offers a cost-effective option as the expenses of the horizontal trench is much lower than the vertical installation cost. This results in an extensive dominance of the horizontal GHE in the GHP system in several regions of the world over the past decade[Fig.5][25].

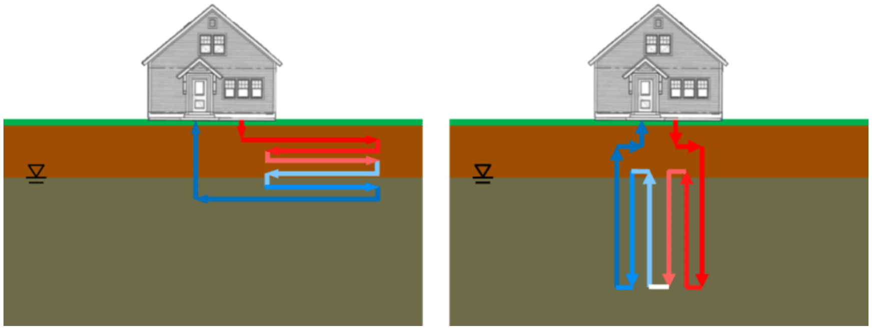

Figure 5: Closed-loop ground source heat pump system: (left) horizontal circulation loops and (right) vertical circulation loops[26].

3 Methodology

To get viable results for the 2030 Austrian energy sector and to assess its full flexible heat generation potential, two different portfolios of heat pumps and their operation were simulated by the use of the energy system model Balmorel, each differing from each other by their flexibility potential. The constructed scenarios were closely related to recent studies on the development of heat pumps and storage units for the upcoming years (see Sec.3.2.1)[5][17]. Sec. 3.3 "Methods and assumptions" deals with the resolution of the heat pump types and capacities regarding the overall heat demand in the selected area.

The inflexible scenario is characterized by the heat demand, which is predefined and has to be covered by, inter alia, heat pumps, leading to inflexible electricity demand as a result. The main goal of the heat pumps in the inflexible scenario is to cover the given heat demand in the given area, and following causes an inflexible demand for electricity to drive the heat pumps, which places the foundation for the flexible scenario: Both the heat demand and heat pump systems in the decentralized area are not set in a flexible scenario, and only the electricity demand for the decentral heat pumps, as a result of the inflexible scenario, is analyzed/implemented in the further research of the flexible scenario, as to assess its shifting potential. Meaning, that the inflexible electricity demand/electricity input of all heat pumps in the decentralized area is summed up and processed, with some restrictions, in the "Demand-Response" addon, as to cover that demand "flexibly"[Fig.6]. In order to do so, the heat demand of the heat pumps in the inflexible scenario was converted to their electricity demand. Through integration of the add-on into Balmorel, existing constraints on e.g. installed thermal(=heat) capacity, full load hours, and relation between heat output and electricity input for heat pumps are utilised[1]. The full load hours were calculated as a quotient of the heat demand, which had to be covered by heat pumps, and the installed thermal capacity.

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[1] Heat demand $= COP *$ electricity input.

Following, the inflexible scenario builds the foundation for further flexible analysis. Since the "Demand-Response" add-on is not implemented in the inflexible scenario, Balmorel optimizes the heat shifting ability of the heat storage based on the corresponding lower heating price, without any regards to realistic heat shifting time. Since the heat storage time for a PTES varies from weeks to months (see Sec.3.2.3), the heat shifting time can be approximated by an "infinite" time-frame, that is already optimized by the Balmorel engine (see Sec.3.1).
However, the heat shifting time of hot water tanks is in the range of hours. Thus, an additional model supplement is required for the decentral heat pumps in the flexible scenario. To put it in a practical context, the heat demand in the flexible scenario is 0, since no heat pumps are given in the decentralized area. Those being analyzed as an additional electricity demand [Tab.3] in the "Demand-Response" add-on. In addition, the capacity of the heat pumps in the flexible scenario is only given in the centralized area.

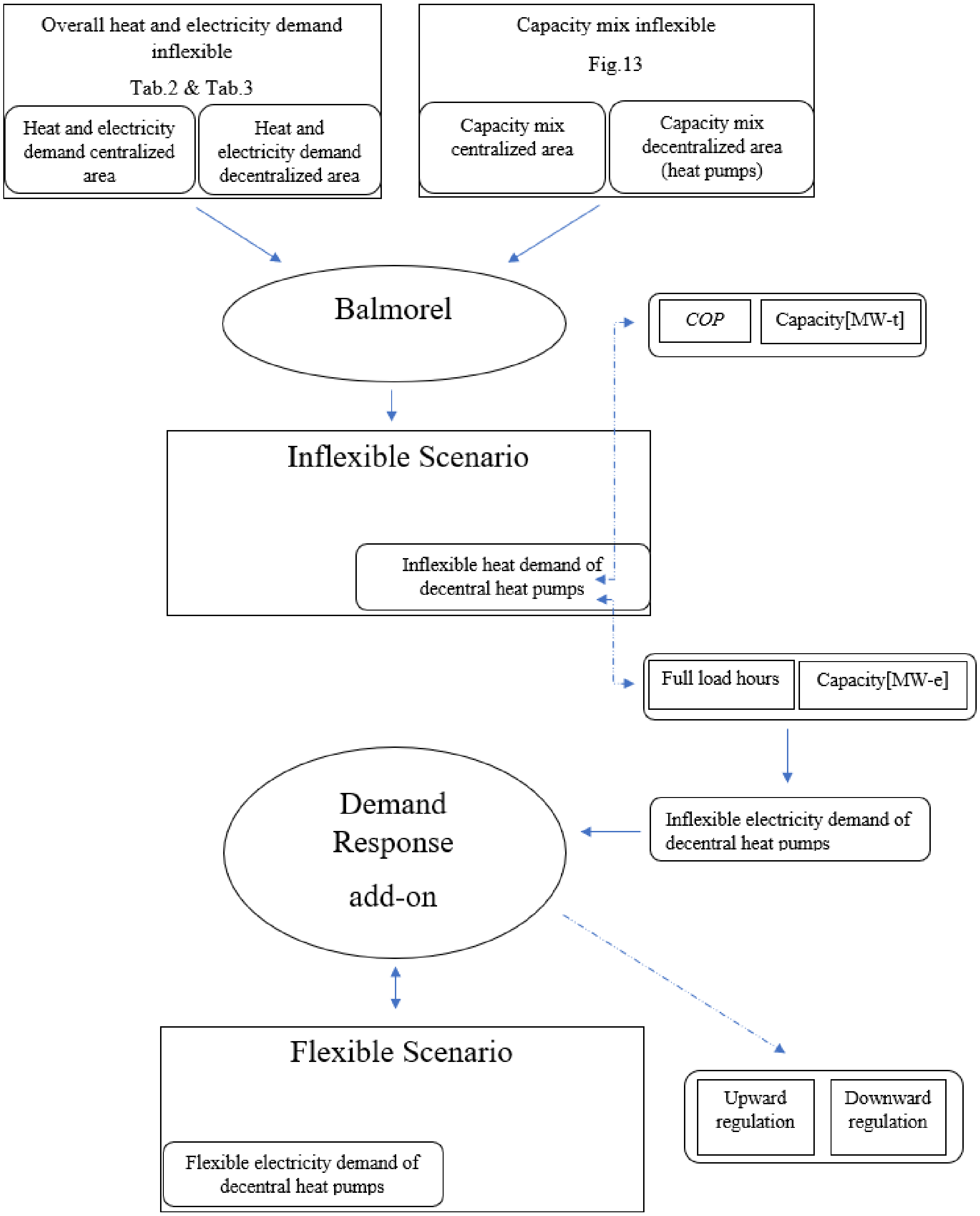

Figure 6: Structure of the methodical overall approach. The inflexible scenario defines the heat demand and results in a electricity demand that is being processed in the "Demand-Response" add-on for the flexible scenario.

3.1 Balmorel: Model description

The model used for the system analysis is Balmorel, which is an energy system analysis model, with a focus on electricity and district heat. Previously described coefficient of performance (COP) plays a crucial role as an efficiency factor in the optimization of the model. Following, the economic feasibility highly depends on the supply and the demand temperature; the higher the difference, the lower the COP, and thus the higher the required electricity share in the overall system.

The Balmorel model is based on a deterministic partial equilibrium model assuming perfect competition, i.e. monopolies or market powers, seeking only the goal of maximizing their profit, are being disregarded. The applied version of Balmorel is written as a linear optimization model in GAMS, a high-level modeling system for optimization and mathematical programming.

Balmorel optimizes the operation and investment if allowed for the power-/heat system, which renders it possible to analyse the economic competitiveness of the different flexibility measures and to investigate whether they can facilitate increased renewable production, such as heat pumps. Thus, total costs in the energy system are minimized over a determined period, usually, a year, covering annualized investment costs, operation and maintenance costs of existing and new units, and fuel and CO_2 costs. For a realistic optimization, some constraints, including satisfaction of electricity and heat demands in each period, technical unit restrictions on units in the system and fuel potentials have to be taken into account. Electricity prices are generated endogenously as a result of the specification of the electricity demand and the available technology to cover the resulting demand. A schematic representation of the system modeling structure (input/output) is in Fig.7.

Fundamental equation "The objective function in Balmorel maximises social welfare subject to technical, physical and regulatory constraints. It represents the sum of system costs which include fuel, transmission,fixed and variable O& M costs, taxes and subsidies, minus consumers' utility. In the case of running a model in myopic investment mode, annuitized investment costs are also included. Furthermore, if a rolling horizon investment mode is chosen, components of the objective function are represented by their net present value (NPV). The difference is caused by the need to value e.g. investments made in different years at the same time in rolling horizon investment mode"[27]. "The energy system model is set to represent an electricity market with perfect competition in which a set of technologies ($i \varepsilon I$) compete to satisfy the electricity demand Eqn.13, for every time step ($t \varepsilon T$) in every region ($r \varepsilon R$), at the minimum costs Eqn.11, while complying with a set of constraints imposed Eqn.12"[28] :

$$min_{e_{i,t,r}} \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{r=1}^{R} C_i(e_{i,t,r}) \tag{7}$$

$$s.t.g_i(e_{i,t,r}) \tag{8}$$

$$\sum_{t=1}^{T} \sum_{i=1}^{I} e_{i,t,r} = E_{t,r} \tag{9}$$

"Eqn.11 represents the 'objective function', providing a solution that represents the least-cost combination of operation and investments in technologies, to satisfy the electricity demand ($E_{t,r}$) considering a series of costs (C_i). The costs consider both fuel and emission taxes; investments are also included and consider the annuity of capital costs, assuming a fixed discount rate and an overall economical lifetime into account. Eqn.12 represents a set of linear relations imposed to reflect the characteristics of the units generating electricity ($e_{i,t}$), such as capacity constraints"[28].

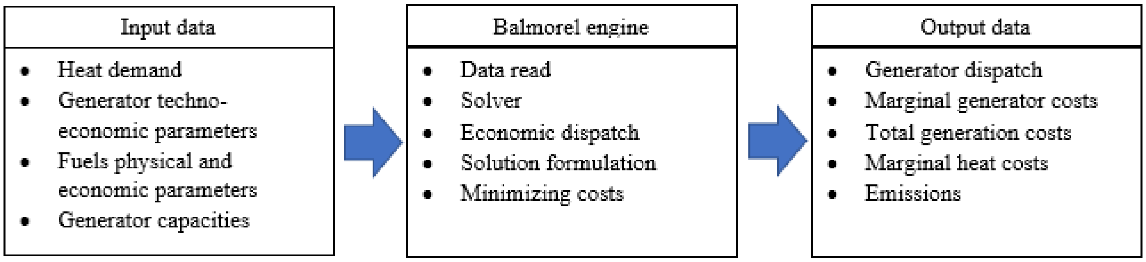

Figure 7: The system modelling structure of Balmorel specifically for this study.

3.2 Demand-Response add-on

This section provides further details without going into implementation details or algebraic formulation of the described "Demand-Response" add-on. The commented sourcecode can be found on GitHub [29].
The add-on ‘Demand-Response’ developed by Jon Gustav Kirkerud is a complement to the basic functionality of Balmorel with special energy source or function, which is applied as to shift the demand by user defined demand response technologies e.g. household appliances such as heat pumps/heat storage.

Regarding the flexibility potential of heat storage in combination with previously described heat pump systems, two different scenarios had to be developed to evaluate the overall flexibility and impact of parameter variation in the specific Balmorel add-on "Demand-Response", which is used only for the flexible scenario, as will be shown throughout the following chapter. The add-on "Demand-Response" operates by optimizing the heat storage, which is applied to a heat pump system, availability in times with favorable exogenous conditions, those being: High share of renewables in the overall energy mix and thus low electricity prices, operation and maintenance costs (both fixed and variable), possible heat shifting time, and weekly heat shifting cycles.

Figure 8 points the schematic description of the described add-on. The previously described input data (Fig.7) still remains intact with the only exception of a reduced value of specific parameters, those being explicitly simulated in the Demand-Response add-on. As can be seen new model variables are introduced in the input data, those being specific flexibility relevant variables, e.g. Technology investment costs (DRINVCOST), variable/annual operation and maintenance cost (DROMVCOST/DROMFCOST), etc. The variables DR_RATE_S and DR_RATE_T describe the energy demand profile for the specific shifting technology and forms in combination with the installed capacity DR_FX[2] and its operating full load hours the foundation for a flexible demand profile. However, the possible heat shifting time (DRSHIFTNEXT) can be seen as the most crucial add-on variable as it induces actual heat shifting operation of the chosen system. The full list of possible variation parameters,sets and variables can be seen in Tab.1. The actual simulation is still undertaken by the Balmorel engine, but the output data is evaluated by 4 additional variables. Those being upward regulation (VDR_UP), downward regulation (VDR_DWN), positive storage level VDR_Store_pos and negative storage level VDR_Store_neg (see Sec 4.2).

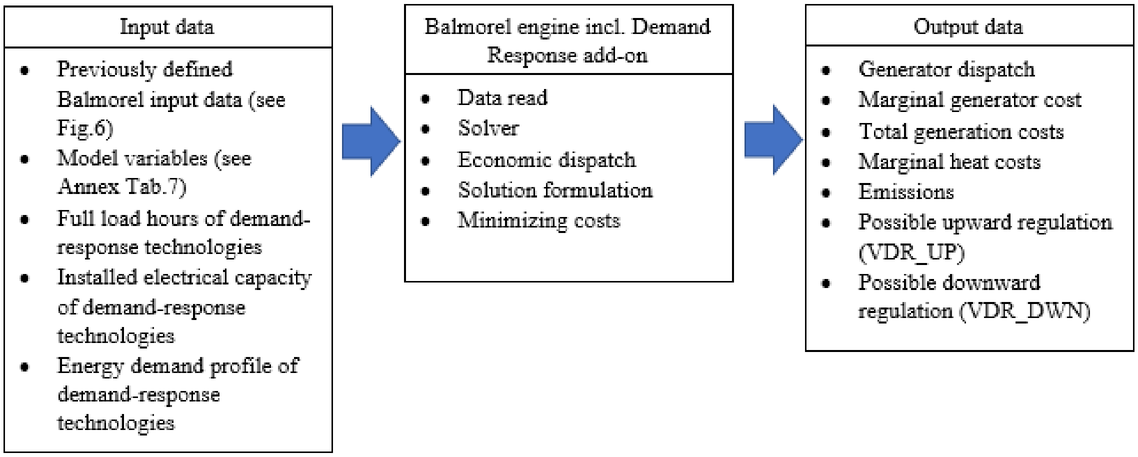

Figure 8: The system modelling structure of the "Demand-Response" add-on.

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[2] Note that the installed capacity DR_FX characterizes the "electrical capacity" of the demand-response technology and can be written as the quotient of the installed "thermal" capacity and the mean *COP*

Table 1: Definition and properties of model shortcuts in the "Deman-Response" add-on.

Add-on shortcut	Description	Unit
DRTYPE	Shifting or shedding technology type	1 = Shed; 2 = Shift
DRINVCOST	Technology investment cost	EUR/MW
DROMVCOST	Variable operation and maintenance cost	EUR/MWh
DROMFCOST	Annual operation and maintenance cost	EUR/MWh
DRLIFETIME	Economic lifetime of technology	Years
DRINTERESTRATE	Interest rate	% (decimal)
DRSHIFTNEXT	Possible shifting time	Hours
DR_FLH	Full load hours	Hours
DR_FX	Installed capacity of selected technology	MW
DR_RATE_S	Weekly energy demand profile	$\in \mathbb{R}$
DR_RATE_T	Hourly energy demand profile	$\in \mathbb{R}$
DR_ADOPTIONRATE	Availability of selected technology	0-1
VDR_UP	Upward regulation	-
VDR_DWN	Downward regulation	-
VDR_Store_neg	Negative storage level	-
VDR_Store_pos	Positive storage level	-

3.2.1 Heat storage types

Demand-side management (DSM) is classified as a sum of actions designed to efficiently manage a site's energy consumption, leading to a possible cut of the costs incurred for the supply of electrical energy, from grid charges and general system charges, including taxes. In addition, DSM contributes to the flexible operation of power systems with high renewable power penetration[30]. Following, not only heat pumps but also heat storage in combination with heat pumps, enable large reductions in excess electricity production and fuel consumption. As such, ground heat pumps and air/water heat pumps can be operated flexibly by storing heat in the central heating system, such as water pit heat storage, and in the construction itself, with the means of hot water tanks, heat accumulation tanks, and passive heat storage in the building structure.
Classifying heat storage units, the structure of decentral-/individual systems, and central-/district heating systems are suited.

Ambient water heat pumps project the greatest potential for future heat pump deployment in Austria. Because of its great availability, the ambient water is seen as a valuable heat source despite its usual low- temperature level. Austria is a great candidate, with its considerable access to both media- or large-sized rivers or lakes. But also further European countries in coastal areas or the proximity of large rivers or lakes can be equipped with this technology to provide a stable and secure source of heat throughout the year. The typical COP‘s of air/water heat pumps is between 3 and 4 with an unit size of 4kW-5MW[31].

3.2.2 Decentral-/individual systems

The potential to shift demand from hour to hour depends on the available heat storage capacity, the thermal heat storage capacity of the building, and the willingness of the habitants to adapt the demand. Focusing on the largest decentral storage potentials, heat accumulation tanks are optimized in the following scenario analysis. Typical ground heat pumps and air/water heat pump installations are combined with hot water tanks (typically around 150-200 l) and small buffer tanks (typically around 40-80 l) connected to the central heating system. The hot water tank ensures that sufficient hot water is available during the day and is loaded continuously. The buffer tank minimizes the number of heat pump start-ups, thereby enabling better-operating conditions and improving *COP* and the technical lifetime. The buffer tank is not large enough to enable shifting operations from one hour to the other. However, such flexibility can be obtained through different options, e.g. by investing in a heat accumulation tank connected to the central heating circuit or control equipment (a central controller)[32].

3.2.3 Central-/district heating system

The integration of seasonal heat storage is essential for district heating systems because they can flexibly integrate various energy sources, among others: renewable energy sources such as solar. Seasonal heat storage units, such as water pit heat storage build the foundation for future implementation of district heating in the heating system. Water pit heat storage, also known as pit thermal energy storage (PTES), underlies the concept of storing hot water in very large excavated basins with an insulated lid. The sides and bottom are typically covered by polymer liners. In the literature, pit storage are also referred to as buried tank heat storage, as the water can also be stored in artificial pits made of reinforced concrete or stainless steel constructed below ground or near the surface.

Despite its great future potential as an implementation in the district ehating system, the PTES currently show a practical relevance in combination with solar thermal energy. During the non-heating period, the sunlight reflected from the heliostat field is focused onto the receiver to heat the water from the bottom of the water pit. The hot water is then charged into the top of the water pit by a heat pump. Conversely, during the heating season, the hot water stored in the pit is used to heat cold water from the buffer tank through heat exchangers[33].

3.3 Methods and assumptions

As mentioned in Sec.2.2 "Efficiency of heat pumps: Ideal measures of performance" and also especially 2.6 "Heat source types" the *COP* determines the optimal working condition of a heat pump technology, with the main technical input parameter being temperature.
It is important to note, that the distinction between a centralized and decentralized area in the Austrian heating sector has been made to display a realistic generation portfolio.
The heat demand for a centralized and decentralized system is displayed in Tab.2. While the heat demand in the centralized system is covered by the district heating system (DH), supplied by gas, biomass and municipal waste the decentralized heating system in the model setup consists only of heat pumps and provides a sustainable, and economical, and future-proof solution for heating large spaces. The capacity mix that covers the overall heat and electricity demand is presented in Fig.13 and Fig.14. Note that natural gas and biomass can produce both electricity and heat, while solar, hydro, wind produces only electricity, leaving the heat production to the heat pumps. While heat pumps cover the heat demand only in the decentral area, the remaining overall heat demand is covered by biomass, natural gas and municipal waste. The resulting heat and electricity production is pictured in Fig.9 - Fig.12.

Furthermore, the electricity input that was generated by heat pumps was calculated and set exogenously to be deducted from the total electricity demand (see Sec.3). As to disperse as many future operational and environmental factors as possible, the assumptions on heat pump/-storage capacities regarding their *COP‘s* are pictured in Tab.6 and Tab.7.

Table 2: Model input: Overall heat demand sorted by areas and different scenarios. Note: The heat demand in the flexible scenario is 0, since no heat pumps are given in the decentralized area. Those being analyzed as an additional electricity demand [Tab.3] in the "Demand-Response" add-on. All technologies and the associated heat demand in the centralized area remain intact in all scenarios (see Sec.3).

Scenario	Overall heat demand [MWh]	Area
Inflexible scenario	20 968 691	Centralized
Flexible scenario	20 968 691	Centralized
Inflexible scenario	10 000 000	Decentralized
Flexible scenario	0	Decentralized

In physical terms, the same energy demand has to be covered in both scenarios: The heat demand is the same in both scenarios. However the heat demand in the flexible scenario is converted into and represented by an additional electricity demand in this scenario. Following, in modelling terms, the inflexible scenario is described by a heat demand, that has to be covered by heat pumps in the decentralized area, while the heat pumps in the flexible scenario are not characterized by a heat demand, which they have to cover, but by an additional electricity demand. To put it in simple terms, the exact same amount of what is missing as a heat demand in the flexible scenario is compensated by an additional heat pump electricity demand.

Table 3: Electricity demand for heat pumps in the decentralized area sorted by different scenarios. Note: The given value is a difference between the scenarios in the overall electricity demand and can allow a conclusion on the mean *COP* of all heat pump systems (see Sec.3).

Scenario	Heat pump electricity demand [MWh]	Area
Inflexible scenario	0	Decentralized
Flexible scenario	700 000	Decentralized

Table 4: Model input: Overall heat pump capacity sorted by different scenarios. Note: The capacity of the heat pumps in the flexible scenario is only given in the centralized area.

Capacity [MW-t]		
Scenario	Small Scale HP (<1 MW)	Large Scale HP (>1 MW)
Inflexible scenario	4879	2855
Flexible scenario	0	2855

Table 5: Model input: Fuel prices for all given scenarios. Note: A CO_2 price of 50 EUR/t was assumed[34].

Fuel prices [EUR/GJ]	
Natural gas	8
Municipal waste	0,1
Woodchips	6,2
Wasteheat	0,9

Table 6: Model input: Heat pump evaluation in the centralized area for both scenarios. The potential of heat shifting of heat storage units in centralized area is evaluated in the inflexible scenario (see. Sec. 4.1).

Centralized area			
Heat pump type	⊘Unit size [MW-t]	⊘COP	Capacity [MW-t]
Air to water	3,6	3,3	1440
Air to air	3,8	2,9	580
Brine to water	9,6	4,1	546
Geothermal heat	3	3,8	290

Heat storage type	⊘Capacity [MWh-t]
Pit thermal energy storage (PTES)	31 210

Table 7: Model input: Heat pump evaluation in the decentralized area for both scenarios. Note: Decentral heat pumps are only given in the inflexible scenario; The decentral heat pumps in the flexible scenario are assessed/analyzed in the "Demand-Response" add-on.

Decentralized area			
Heat pump type	⊘Unit size [kW-t]	⊘COP	Capacity [MW-t]
Air/Water	7,6	3,3	2063
Air/Air	318	3,1	1268
Water/Water	10	4	930
Geothermal heat	15	3,8	620

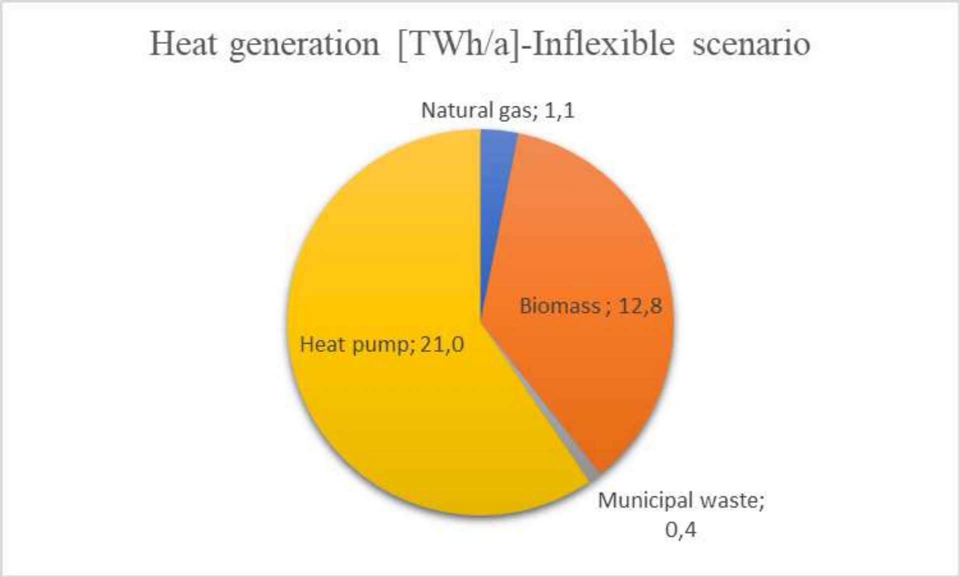

Figure 9: Heat production per year in the inflexible scenario. Note: The share of the heat produced by heat pumps is higher than in the flexible scenario, since there is an additional heat demand in the decentralized area that is set in the inflexible scenario and has to be covered by decentral heat pumps (see Tab.2).

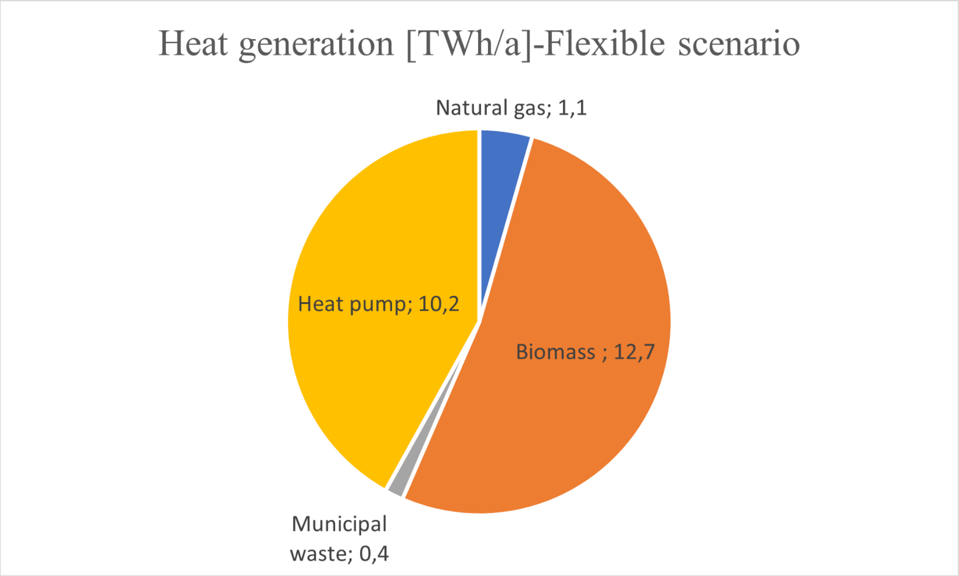

Figure 10: Heat production per year in the flexible scenario. The electricity demand of the decentral heat pumps is predefined exogenously in the flexible scenario. Following the decentral heat demand and the associated heat pumps in the flexible scenario are missing (see Tab.2 and Tab.3).

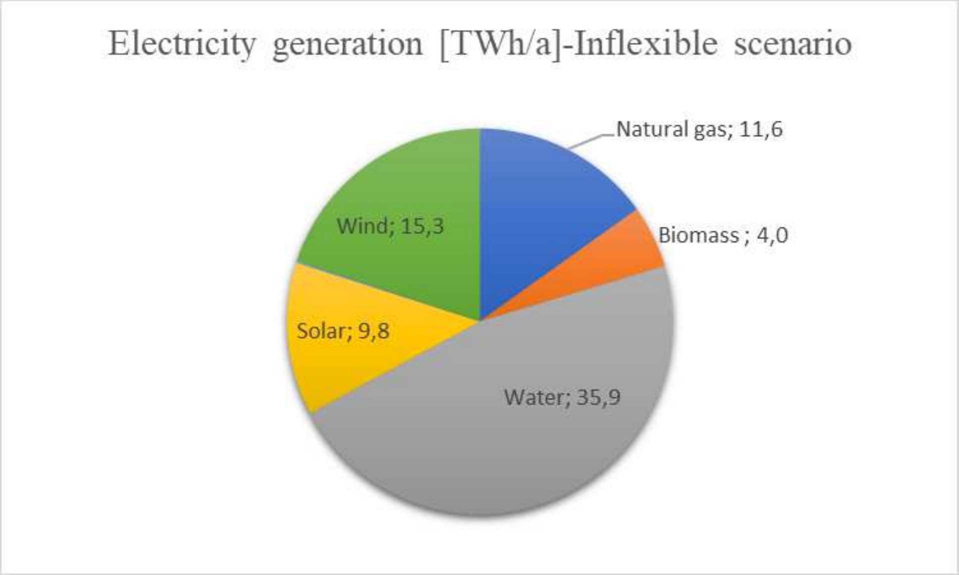

Figure 11: Electricity production per year in the inflexible scenario.

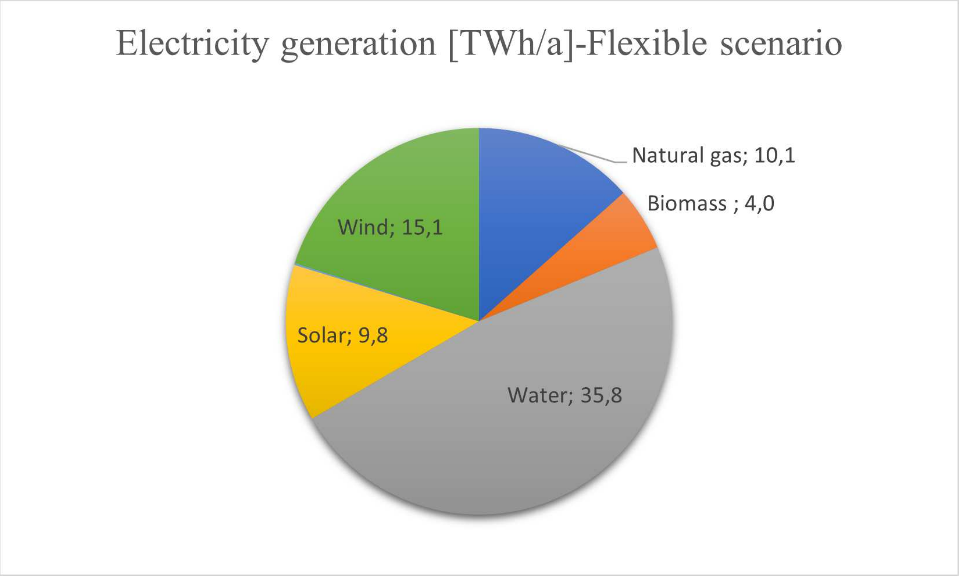

Figure 12: Electricity production per year in the flexible scenario.

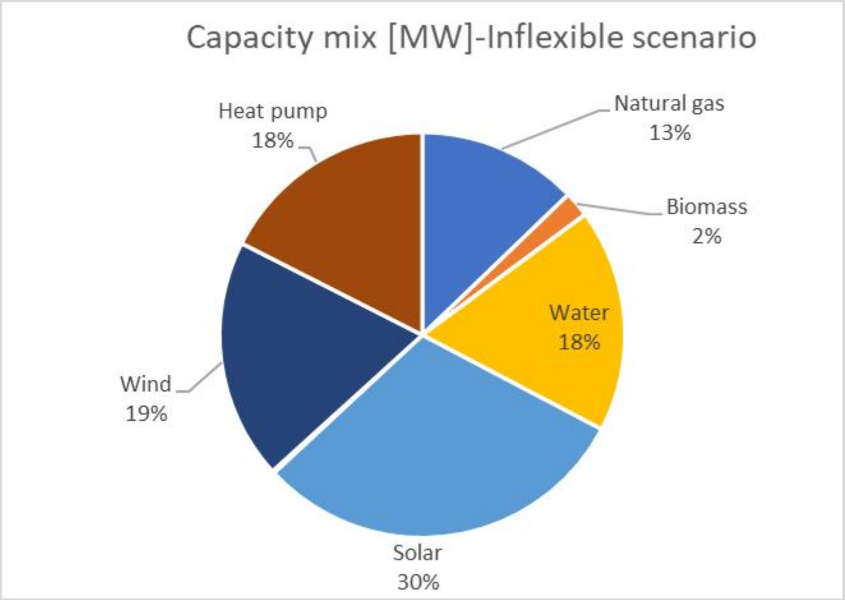

Figure 13: Cumulative installed overall energy capacity mix (%) of the inflexible scenario. Both heat- and electricity production technologies are included. Fig.13 and Fig.14 picture the pendant to the previously stated arguments in Fig. 9 - Fig.12.

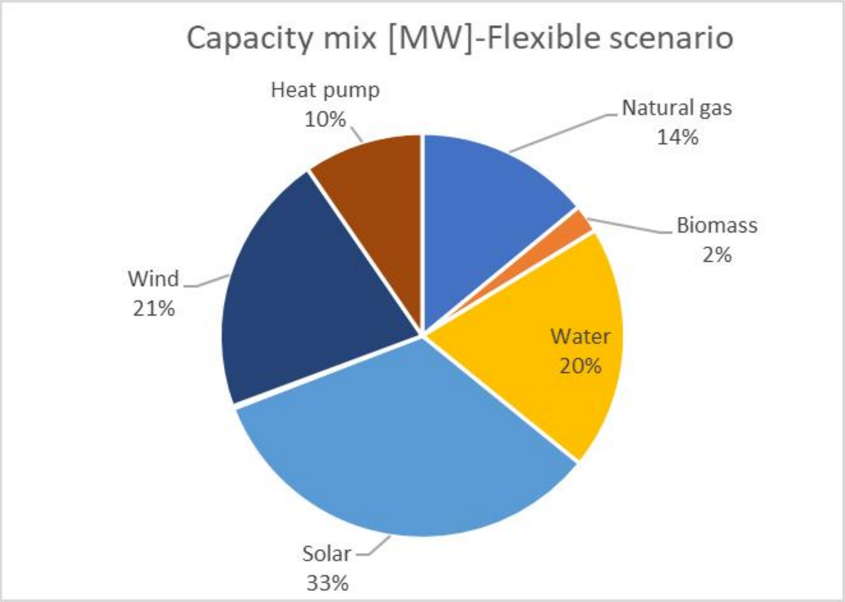

Figure 14: Cumulative installed overall energy capacity mix (%) of the flexible scenario. Both heat- and electricity production technologies are included.

4 Results

4.1 Inflexible scenario

The following section is dedicated to an "inflexible" scenario, in which the flexibility of the heat storage, meaning storing and transferring heat in times with favorable working conditions, was given only in the centralized area. The key technology in the centralized area was a pit thermal energy storage (PTES). In principle, a PTES is a large water reservoir for storing thermal energy. The storage medium of a PTES is water, which has several advantages; being non-toxic, enables stratification (layering according to different temperature levels), high capacity when charging and discharging, good heat transfer characteristics, and high specific heat capacity. Besides, water is comparably cheap. Moreover, the heat shifting time varies from weeks to months. Therefore, a relevant hourly shifting strategy is not important, as it is with water tank storage (see Sec.4.2).

However, the decentralized area is completely inflexible, meaning that no heat storage units are attached to heat pumps, so that the heat demand has to be covered by the heat pumps in the same second, it is produced. Those 2 assumptions were made to display the importance of heat storage units in the decentralized area if being operated by an external regulator, that is calibrated to operate in times with favorable working conditions, or the market design[24][33].
The developed market scenarios are based on findings from finished research projects and analysis of the historical market development [35].

Fig.15 pictures the heat generation by the PTES during several weeks of 2030. It is noteworthy that the PTES can also shift its heat generation in a short period of time. Fig.15 underlines this statement by expressing the time of unloading heat from the storage in a short time frame. The shown flexibility in the centralized area is given in both scenarios, with the only difference of an additional flexibility in the decentralized area.

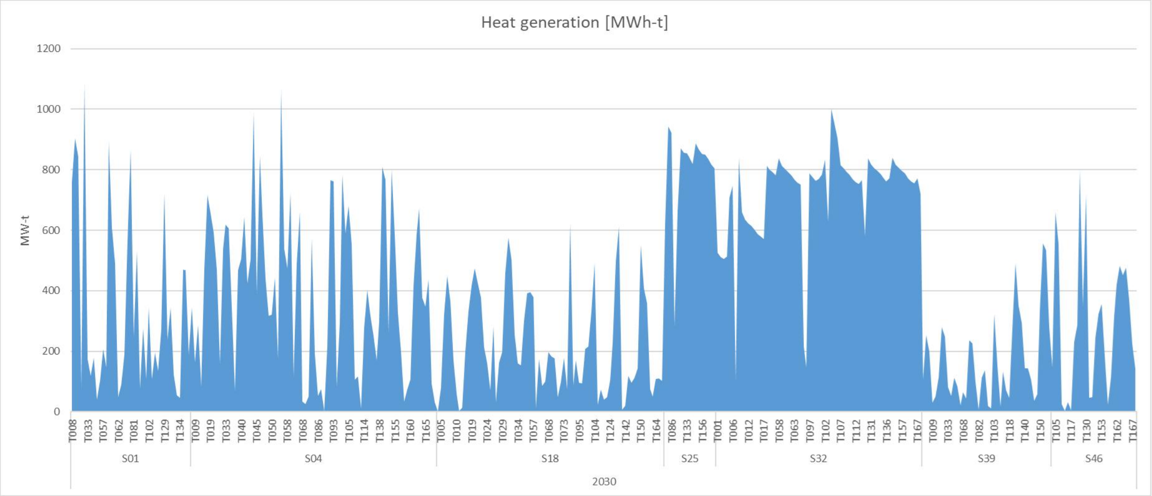

Figure 15: Heat generation by central heat storage units PTES during several weeks of 2030.

The approximated set-up is designed to highlight the relation between electricity price and the heat generation. This forms the base for further flexibility analysis. The electricity price curve for the inflexible scenario throughout the whole year is shown in Fig.17 and is a result of the marginal electricity producer's marginal costs determining the electricity price in the model.

Fig. 18 represent heat generation throughout the year. As can be seen, in times with dominating electrical heat generation, e.g the down-peaks of S.12 and S.13 in Fig.18, the electricity prices in Fig.17 turn downwards in the mean of low/non-existent marginal costs and the merit order effect.

Besides, as can be seen in Fig.17 the weeks S12-S13 are characterized by extremely low electricity prices, which leads to the assumption of a high renewable generation during this time period. Fig.16 highlights this analogue, by revealing a high generation volume of renewable energy sources, especially water for the base consumption loads in combination with sun and wind to cover up peak consumption loads.

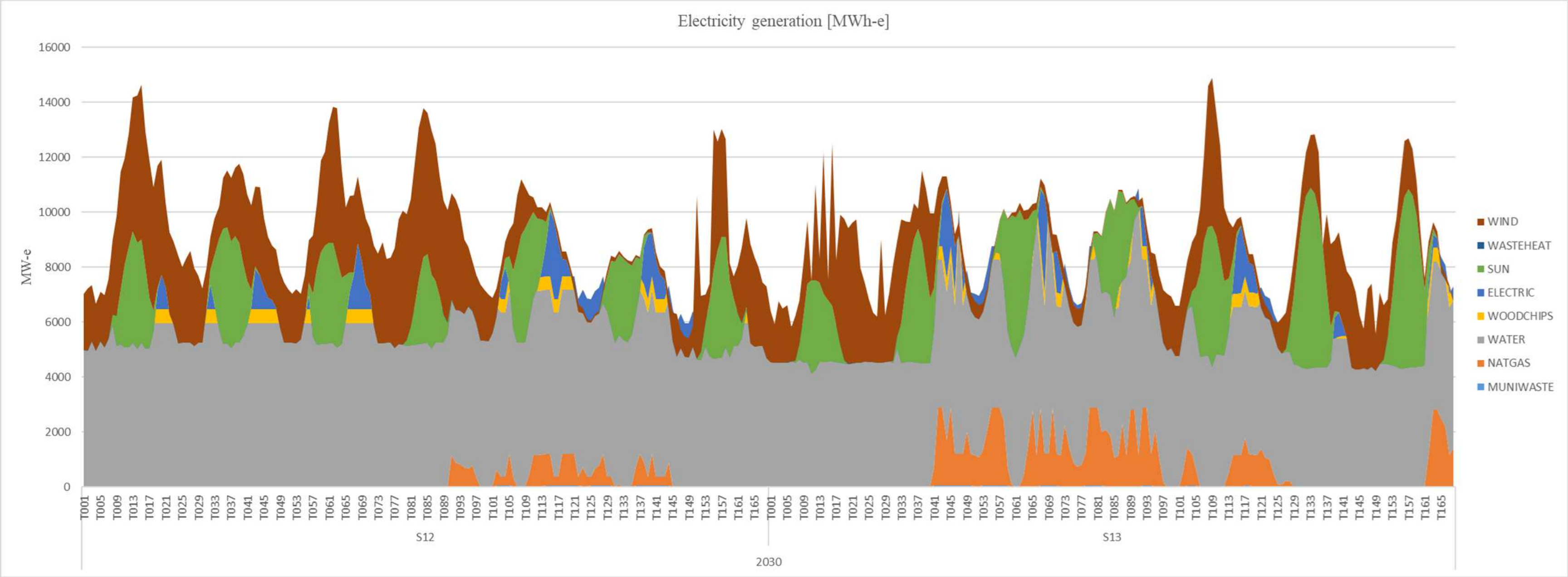

Figure 16: Electrcity generation [MWh-e] in the inflexible scenario, for a given time period (S12-S13) with a high share of renewable energy sources.

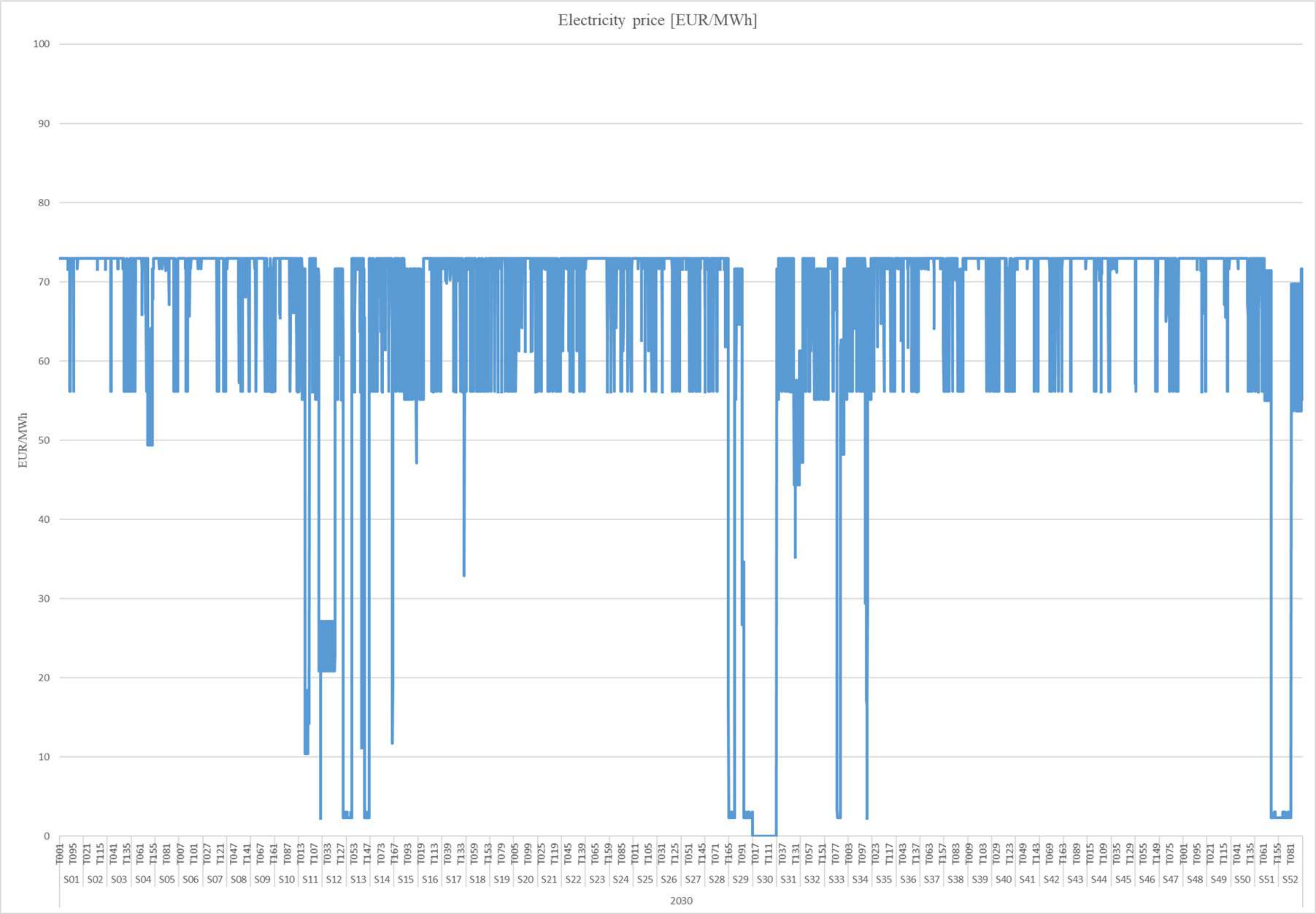

Figure 17: Electrcity prices [EUR/MWh] for the simulated inflexible scenario . "S" for weeks; "T" for hours.

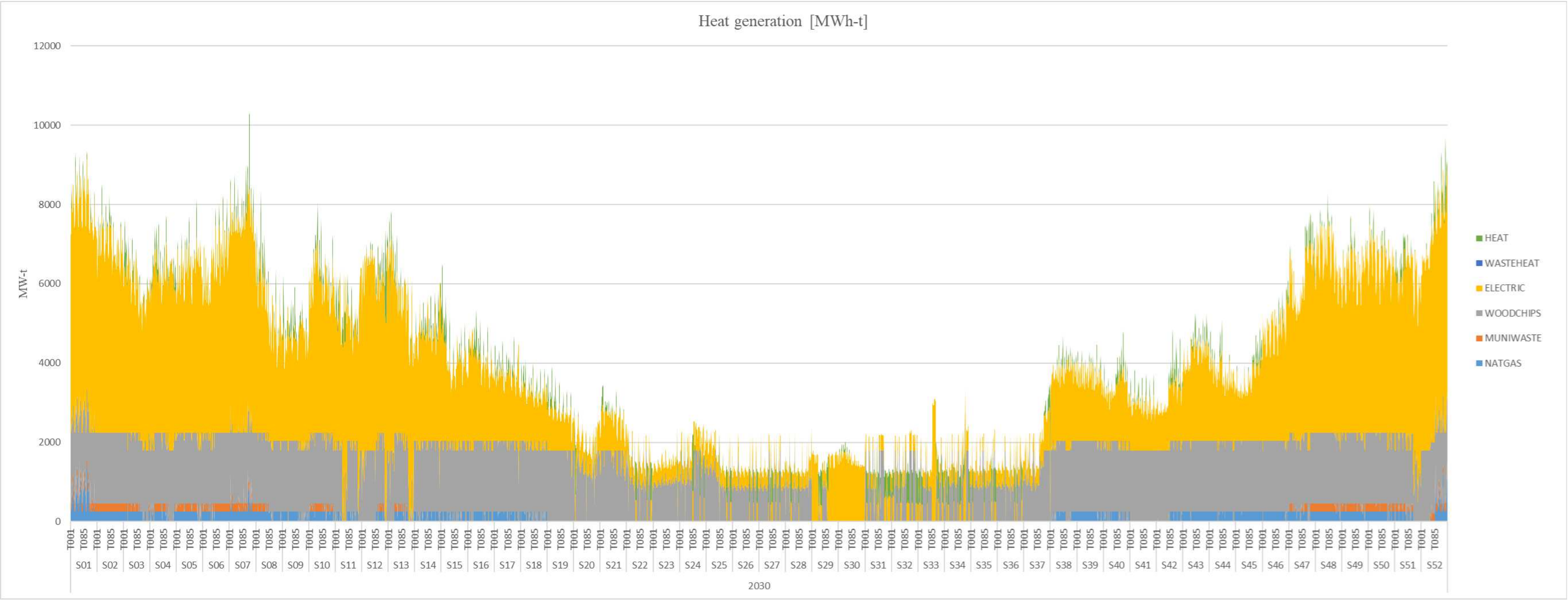

Figure 18: Heat generation [MWh-t] for the simulated inflexible scenario .

4.2 Flexible scenario

The flexible scenario portrays the ideal future heat storage deployment. The previously described flexibility is still available in a centralized area. Also, a heat shifting flexibility is provided by small-scale hot water tanks in the decentralized area. Hot water storage vessels in private flats and houses are used for different purposes, those being: ensure sufficient flow for high demands such as showers and filling bathtubs, operating as peak shavers for district heating or solar heating, and varying load storage to capture the cheaper, off-peak electricity and using it at other times, effectively shifting portions of peak load to off-peak hours. Reshaping the load curve improves the utility's capacity factor and, by extension, its financial health[36].

Following the terms "upward regulation" and "downward regulation" are introduced, to characterize the working principle of a hot water tank. While the upward regulation indicates favorable shifting conditions, such as a high renewable electricity generation followed by successively low electricity prices and thus an optimal time frame for a heat pump/-water tank operation, the downward regulation induces the opposing working setup.

A hypothetical full regulation cycle would consist of full storage at T000, which would be down-regulated, meaning a withdrawing of heat, due to high electricity price, a heat demand in the given hour, and a possible heat shifting time. This leads to a negative storage level in the hours, with the stated conditions. A change in electricity prices or an essential heat demand induces an upward regulation and the filling of the heat storage.

Fig. 19 points out a constant high upward regulation, in correlation with a high share of renewable technologies in the energy mix for the given week S52[Fig.20] and consequently low electricity prices.

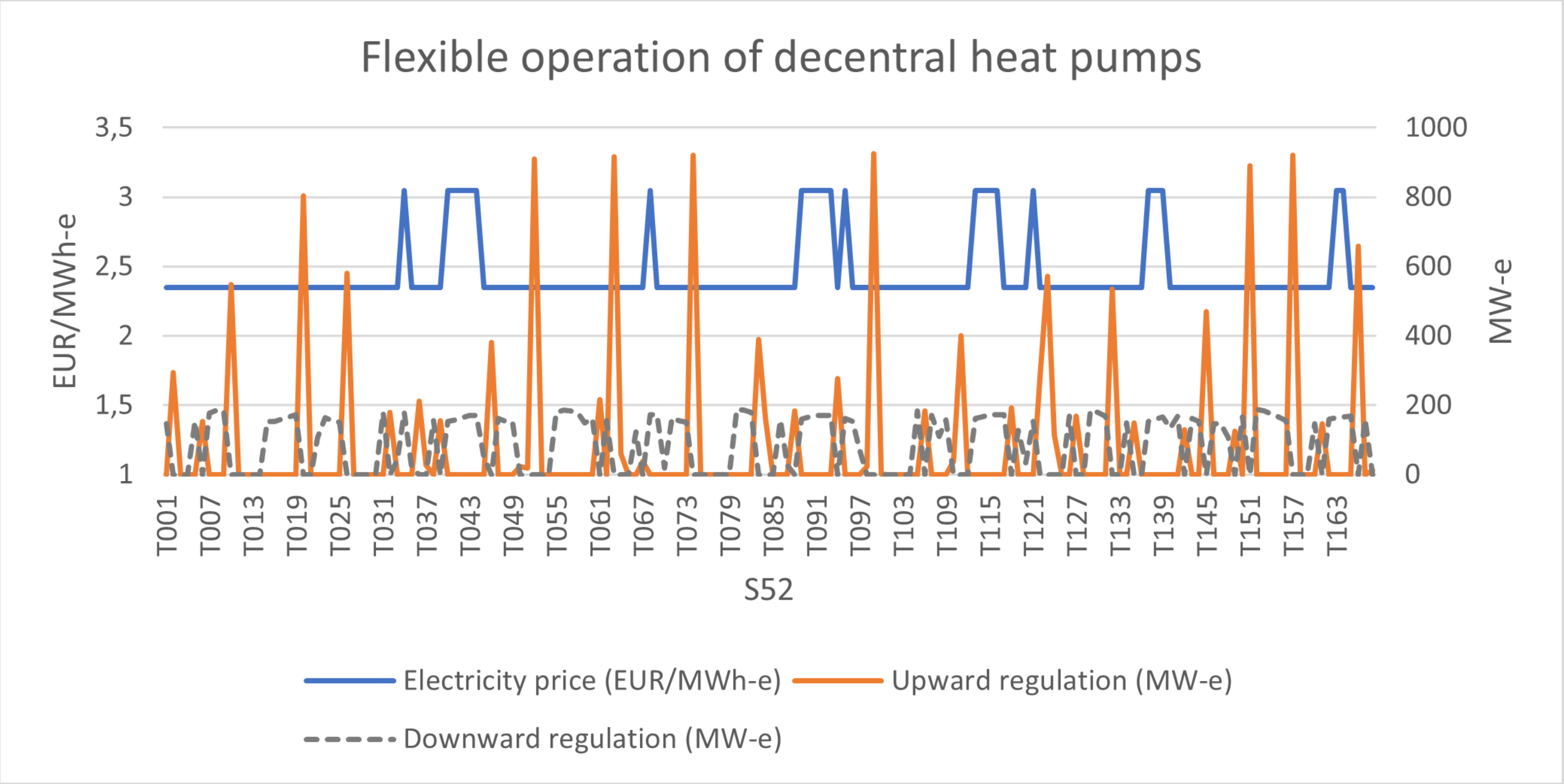

Figure 19: Flexible heat pump operation due to favourable exogenous conditions during s week with a high share of renewable technologies in the overall energy mix.

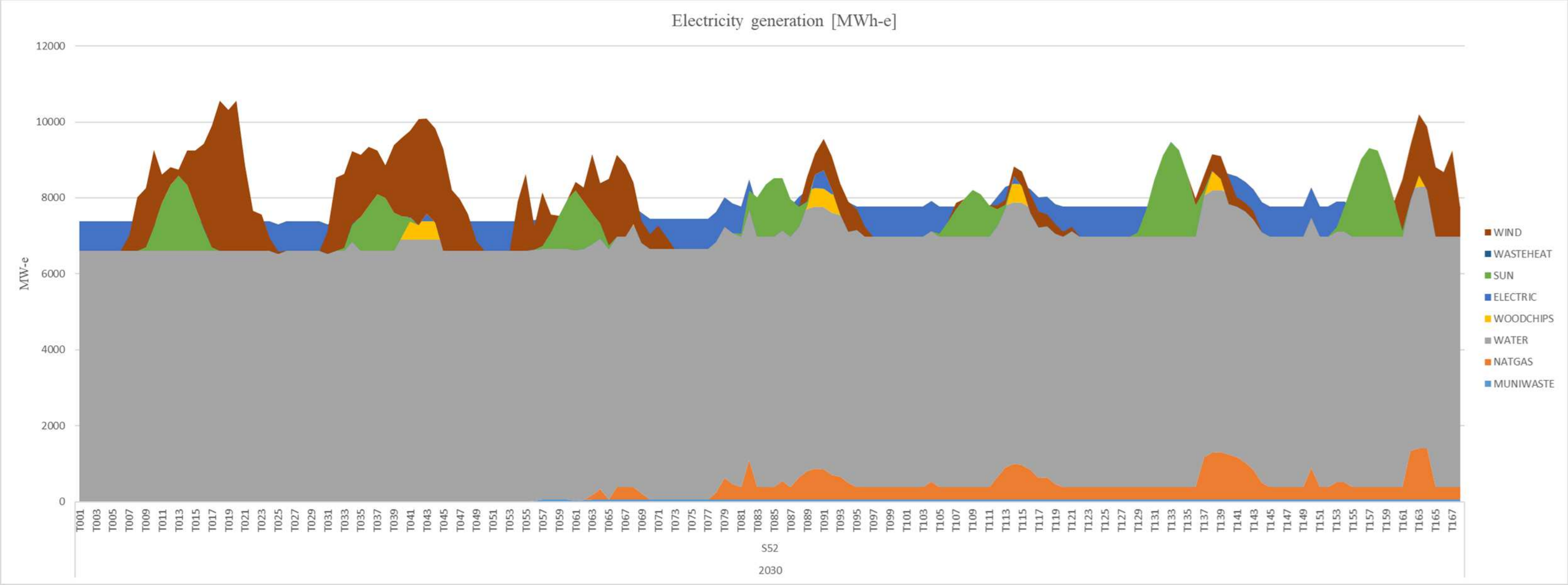

Figure 20: Electricity generation [MWh-e] in the week S52, characterized by a strong share of water in the overall energy mix.

In addition, a week with a mixed share of both conventional and renewable energy mix is analyzed. The first ∼25 hours of the third week (T001-T030) are marked by relatively high electricity prices and leaves only a little potential for cost-saving through flexible heat pump operation. However as can be seen there is a characteristic price leap in the hours 26-30, which results as a favorable condition and thus an upward regulation[Fig.21].
The hours T31-T117 show respectively high electricity prices and thus little to none need for a thermal energy shifting. Instead, those hours are determined to release the thermal energy (downward regulation), which was saved previously in the considerable upward shifting in the hours T026-T030 [Fig.22]. The last hours of the third week (T118-T168) show volatile electricity prices with a strong upward regulation in the hour T145 [Fig.23]. The volatile electricity generation of week S03 is pictured in Fig.24. An interesting aspect is the upward-and downward regulation in times with constant electricity prices, which can be explained by the assumption, that the electricity price in times of the regulation could have been lower, thus inducing an upward regulation or higher, for a downward regulation.

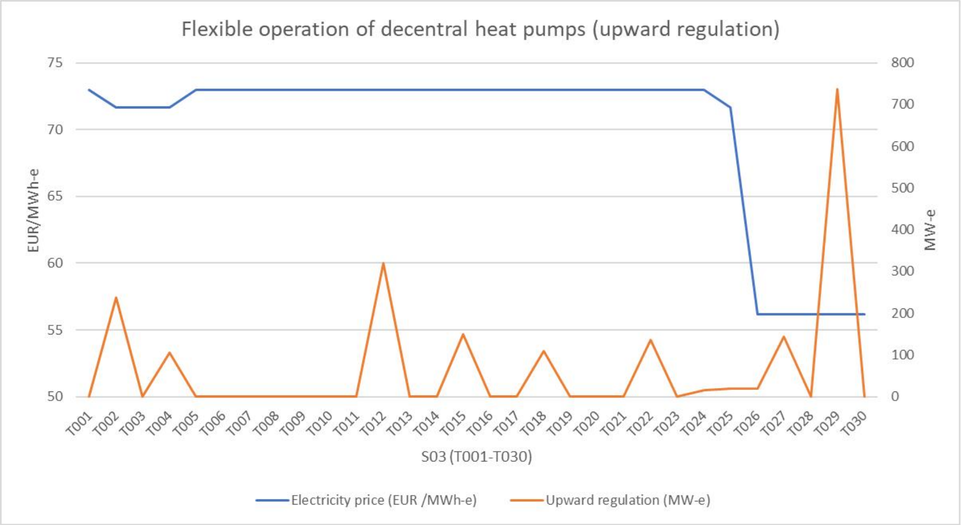

Figure 21: Flexible heat pump upward regulation in the hours T001-T030 of the third week.

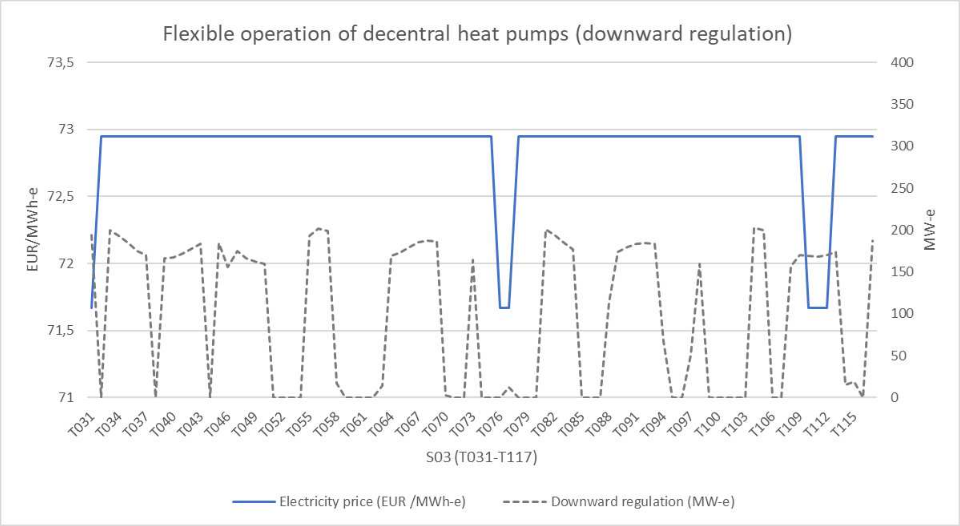

Figure 22: Flexible heat pump downward regulation in the hours T031-T117 of the third week.

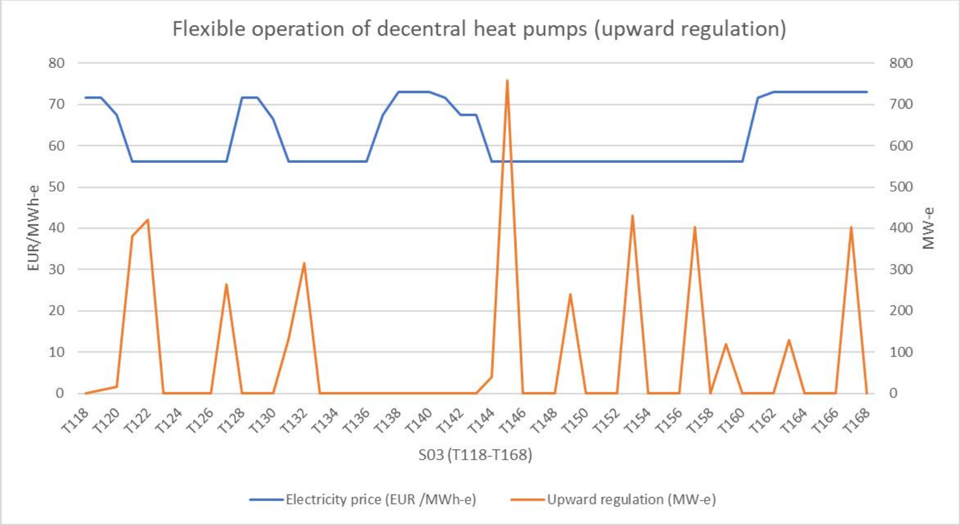

Figure 23: Flexible heat pump upward regulation in the hours T118-T168 of the third week.

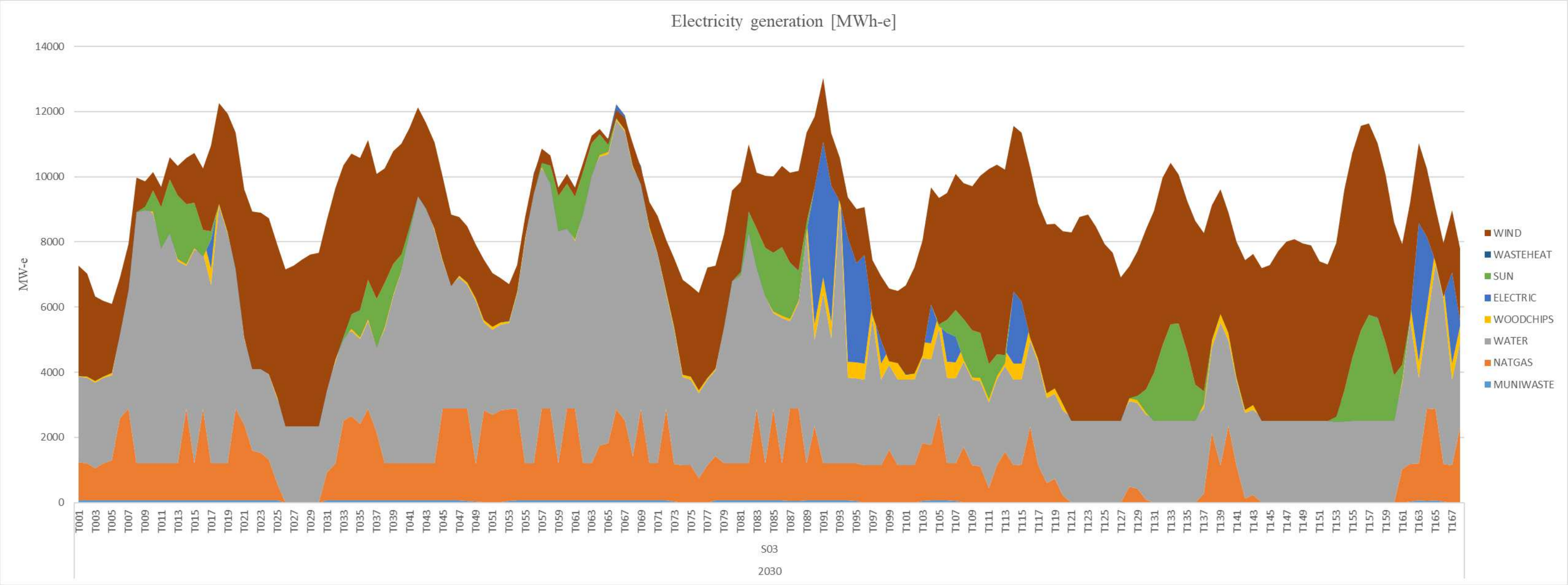

Figure 24: Electricity generation [MWh] in the week S03, characterized by a diverse overall energy mix.

4.3 Scenario comparison

The following section assess further scenario results based on the possibility of a flexible heat pump operation. The previously stated possibility to shift the operational hours of heat storages to times with a high share of renewables in the overall energy mix in the flexible scenario leads to an additional derivative of lower electricity prices [Fig.25], due to the lack of necessity to rely on costly gas energy. In addition, this is also undermined by a lower annual heat generation by natural gas [Fig.26], and consequently lower annual CO_2 emissions [Fig.27]. The overall heat shifting potential (upward- and downward regulation) of decentralized heat pumps for the course of a whole year results in 414 GWh-t. Through comparison with measured data, it is indicated that the model gives a reasonable representation of actual electricity and heat generation profiles[Fig.15-Fig.24].

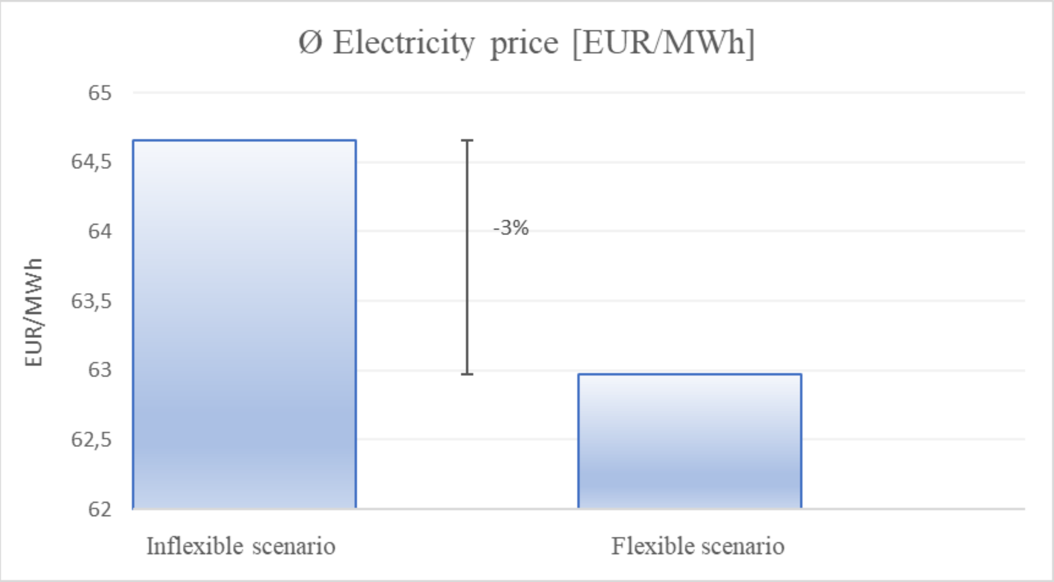

Figure 25: Comparison of the average annual electricity price in both scenarios.

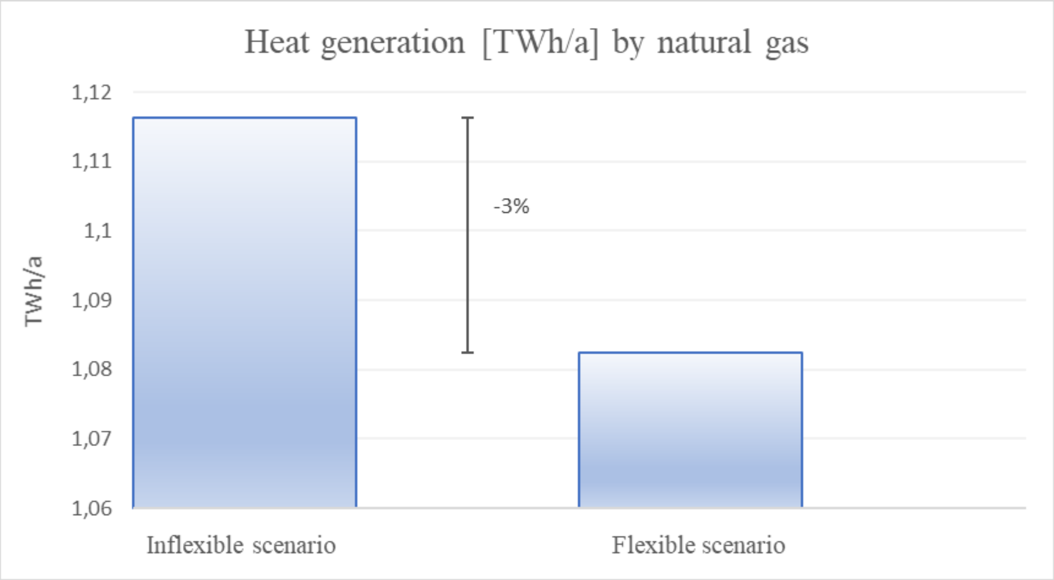

Figure 26: Comparison of the annual heat generation by natural gas [TWh] in both scenarios.

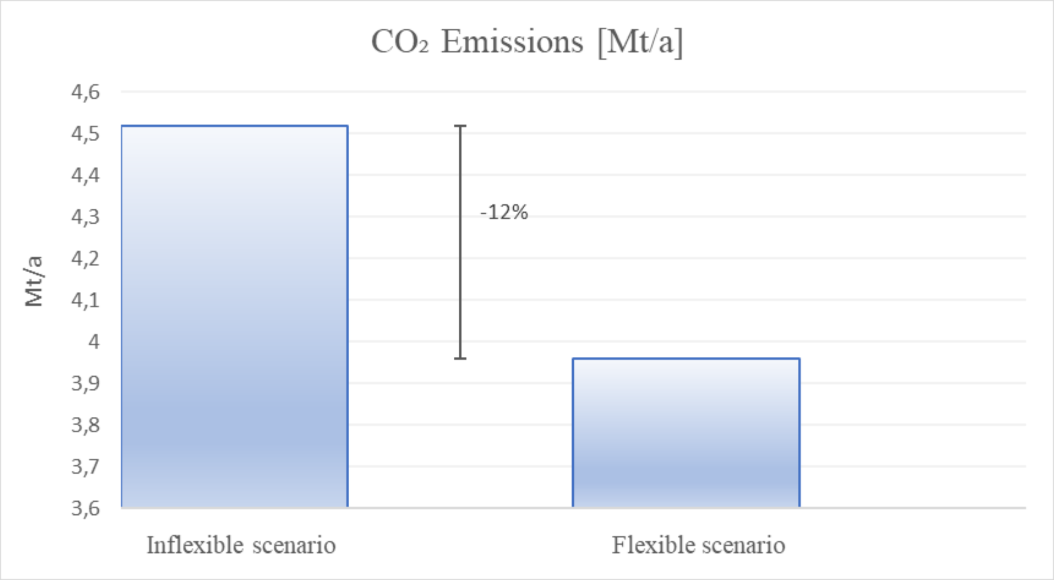

Figure 27: Comparison of the annual CO_2 emissions in both scenarios.

5 Discussion and conclusion

To mitigate the reliance on conventional energy sources, and consequently force an expansion of renewable energy sources in the future Austrian energy mix a flexible heat shifting operation of heat pump systems was introduced in this work. The Austrian energy system in 2030 has been used as a case, representing a system with a very important, also historical, reliance on renewable energy sources, district heating, and gas plants. Nevertheless, the described advantages of a flexible heat shifting operation of heat pumps can only be fulfilled, in terms of reducing overall fuel consumption of the system and consequent installation of heat pumps in the upcoming years.

This work presents a model that renders it possible to analyze individual heat pumps and complementing heat storage units in integration with the energy system when optimizing operation. It was shown that the model is well qualified for analysing the possibilities and system benefits of operating individual heat pumps intelligently.

Compression heat pumps in a household (individual heat pumps), combined with heat accumulation tanks have been analyzed in terms of their deployment potential in times with favorable conditions. The described thermal storage tanks can also contribute to passive heat storage in the building structure via space heating and hot water availability. As mentioned before, the overall heat shifting potential (upward- and downward regulation) of decentralized heat pumps for the course of a whole year results in 414 GWh-t.

The model also covers the implementation of centralized large scale heat pumps, combined with water pit heat storage (PTES), bearing a great potential in the decarbonization of district heating system, by having a big timeframe to shift heat. It was shown that the centralized heat storage results in over 1 TWh of heat shifting per year, which is a strong opposition to its climate unfriendly counterpart natural gas and bears a great potential in the mitigation of climate change.

All in all, the strategic and flexible deployment of heat pumps in the future energy system in Austria results were as follows: The previously stated possibility to shift the operational hours of heat pumps to times with a high share of renewable in the overall energy mix in the flexible scenario leads to an additional derivative of a 3% reduction of the electricity prices [Fig.25], due to the lack of necessity to rely on costly natural gas and other dispatchable electricity technologies. In addition, it is found that the flexible operation of heat pumps is undermined by a 3% lower heat generation with natural gas [Fig.26], which results in a CO_2 emission saving amounting to 12% [Fig.27]. This undermines a significant role in decarbonising the Austrian heating sector and in achieving climate targets.

However, as mentioned in Sec.3 the linear structure of the model does not include minimum load requirements, additional start-up costs, or the impact of a partial storage load on the overall efficiency of the system. In addition, the model portrays perfect foresight, which leaves no room for power balancing responding to errors in forecasts of volatile renewable energies such as wind and load. Ref.[37]shows a drastic influence of the start-up costs and minimum load requirements for thermal power plants on the operation cost savings obtained when using individual heat pumps for demand side management.
However, the performed study represents the heat pumps by a yearly average *COP*. A possible subject for further research could be the evaluation of hourly *COP* variations in the model caused by variations in the heat source- and output temperature of the heat pump. It would also be of interest to model how flexible operation of the heat pumps influences required enhancements in the distribution grids.

Nevertheless, the shown model development build the foundation in providing the structure needed for evaluating centralized-and decentralized heat pumps and heat storage in an energy system context.

6 Annex

Table 8: Definition of relevant thermodynamic properties

Variable	Description	Unit
Q_1	Heat from a heat source	J
Q_2	Heat from a heat sink	J
T_1	Lower temperature level	K
T_2	Higher temperature level	K
T	Absolute temperature	K
W_{in}	Input Work	J
W_{out}	Output work	J
W	Work done by the system	J
$COP_{Refr.}$	Coefficient of performance (refrigeration cycle)	$\in \mathbb{R}$
COP_{HP}	Coefficient of performance (heat pump cycle)	$\in \mathbb{R}$
η	Efficiency	%
dQ	Heat supplied to the system	J
dS	Differential of entropy	J/K
$\triangle$ S	Change in entropy	$\in \mathbb{R}$

Table 9: List of large scale heat pumps in the centralized area.

Large Scale HP (>1 MW)			
Heat pump type	*COP*	Unit size[MW]	Capacity[MW-t]
Air/Water	3,1	4	380
Air/Water	3,2	4	581
Air/Water	3,6	3	480
Air/Air	2,8	1	35
Air/Air	3	2,5	53
Air/Air	4,8	3	88
Air/Air	5,2	3	123
Air/Air	2,9	6	176
Air/Air	3,6	6	70
Air/Air	4,1	4	18
Air/Air	3,7	5	18
Brine/Water	4,4	12	141
Brine/Water	4,5	10	141
Brine/Water	4,5	7	41
Brine/Water	3,7	12	91
Brine/Water	3,3	10	41
Brine/Water	3,5	7	91
Geothermal heat	3,6	2	123
Geothermal heat	3,8	4	114
Geothermal heat	4,1	3	53

Table 10: List of small scale heat pumps in the decentralized area.

Small Scale HP (<1 MW)			
Heat pump type	*COP*	Unit size[kW]	Capacity[MW-t]
Air/Water	3,1	10	621
Air/Water	3,2	3	921
Air/Water	3,6	10	521
Air/Air	2,7	340	69
Air/Air	3,5	800	496
Air/Air	4	200	138
Air/Air	4,6	150	542
Air/Air	2,8	100	23
Brine/Water	4,6	12	138
Brine/Water	4,4	5	238
Brine/Water	4,6	13	138
Brine/Water	3,5	12	138
Brine/Water	3,9	5	238
Brine/Water	3,1	13	38
Geothermal heat	3,7	20	138
Geothermal heat	3,8	10	161
Geothermal heat	4	15	321

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I confirm that this work is original and has not been submitted elsewhere for any examination, nor is it currently under consideration for a thesis elsewhere.

Danijel Katsman 28.10.2020

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