AALBORG UNIVERSITET

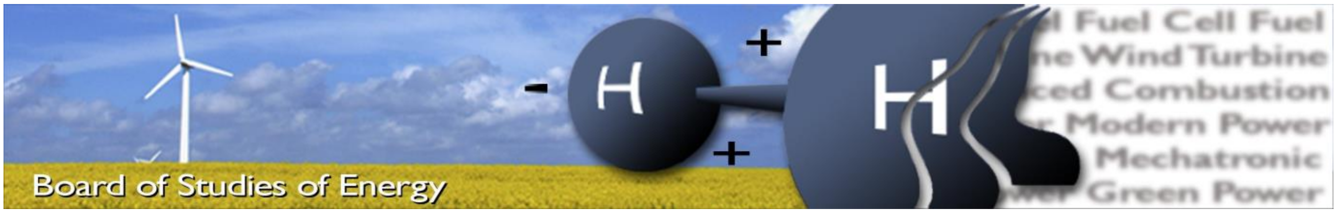
POWER TO HEAT SYSTEMS IN ACTIVE ELECTRIC DISTRIBUTION NETWORKS

MASTER THESIS

PANAGIOTIS DAMIANOS CHEILAS

DEPARTMENT OF ENERGY TECHNOLOGY

AALBORG UNIVERSITET



Title: Power to Heat Systems in Active Electric Distribution Networks
Semester: 3rd & 4th (Master)
Semester theme: Master thesis
Project period: 1/09/2018 – 31/05/2019
ECTS: 50
Supervisor: Jayakrishnan Radhakrishna Pillai
Project group: EPSH4-934

Panagiotis Damianos Cheilas

SYNOPSIS:

The increasing incorporation of renewable energy in the power system is expected to cause issues to the system operation due to the uncertainty of the renewable-based generation. In this project, the ability of power to heat units to increase the flexibility of the power system by the synergy between the electricity and heating energy sectors is investigated. For this reason, heat pumps interconnected with thermal energy storages are inserted in a power grid and the control and coordination of their operation is implemented in order to use them to provide the desired flexibility to the power grid and gain benefits in cooperation with local renewable energy generation from PVs.

Pages, total: 54
Appendix: A
Supplements: -

By accepting the request from the fellow student who uploads the study group's project report in Digital Exam System, you confirm that all group members have participated in the project work, and thereby all members are collectively liable for the contents of the report. Furthermore, all group members confirm that the report does not include plagiarism

Summary

The use of renewable energy sources in Denmark is on a continuous rise with national plans that target an energy system operating based completely on clean-energy by 2050. In this future power system, there will be a lot of uncertainty due to the renewable-based generation and as a consequence, the acquisition of flexibility is considered of high importance. The integration of different energy sectors, like electricity and heat, can provide the necessary flexibility to the electric power system and enhance the collective operation of the energy systems. In this project, power to heat systems, specifically heat pumps, are assessed on the capability to give flexibility in a low voltage residential grid with the presence of local PV systems.

Two separate studies are carried out in this project: one considers the integration of individual residential heat pumps and the other considers the integration of a large regional heat pump system in the same Danish low voltage grid where local PV generation is also available. Both systems are interconnected with thermal hot water storages and the heat pumps operate in an ON/OFF way. Control & cooperation strategies are implemented in order to enhance grid operation and reduce any arising problems as well as increase the self-consumption and efficiency of PV generation while the thermal comfort of the inhabitants is not threatened. The studies were carried out in DIgSILENT PowerFactory with the assistance of MATLAB. Daily simulations were performed to observe the operation in days of winter and summer.

The results support the capability of heat pumps with heat storages as a solution that can provide flexibility in the future power grid and cooperate with renewable energy sources, like PVs, in order to achieve beneficial operation and assist renewable energy utilization. This is managed by the use of simple local controllers that do not require the deployment of communication systems and do not involve increased complexity.

List of figures

List of tables

Contents

1 Introduction

This chapter introduces the basic background for the development of the project. Denmark's renewable energy vision and the future integration of different energy sectors are introduced, with the Power to Heat (P2H) systems being the main focus of the project. The scope and objectives are then presented along with the necessary limitations that were taken. Finally, an overview of the content of the report is given.

1.1 Background

The potential of renewable energy utilization and reduction of carbon emissions is a major goal for the future of Denmark, as well as for the rest of the EU. Particularly in Denmark, ambitious goals have been set for the upcoming years as the government's energy plan foresees at least 50% renewable-based energy along with a complete fossil fuel free electricity sector until 2030 and total fossil fuel independence in 2050. The new Danish energy proposal includes many actions to promote this transition, including the installation of Denmark's biggest offshore wind farm until now, allocation of funds to boost renewable energy capacity, reduction of taxes and alternation of the heating sector in order to make it more environmentally friendly [1].

The path of green development has already been set, with the increasing integration of renewable energy generators in the Danish system over the past years. Figure 1.1 depicts the evolution of electricity production from different sources and the total electricity consumption from 1990 to today, along with projections until 2027. As it can be seen, renewable energy generation has rapidly increased during the previous years with wind being the dominant renewable energy source, while solar witnesses a significant increase from 2012 onwards. Meanwhile, the production from central power stations and decentralized power plants has been reduced comparing to the past. The trend of increasing renewable energy generation is awaited to continue in the next years as well, while the electricity consumption is also expected to be higher in the future, mainly due to the installation of big data centers, electric cars and heat pumps. During this period, most conventional-fueled power stations are going to be deactivated or transformed to use mainly biomass [2].

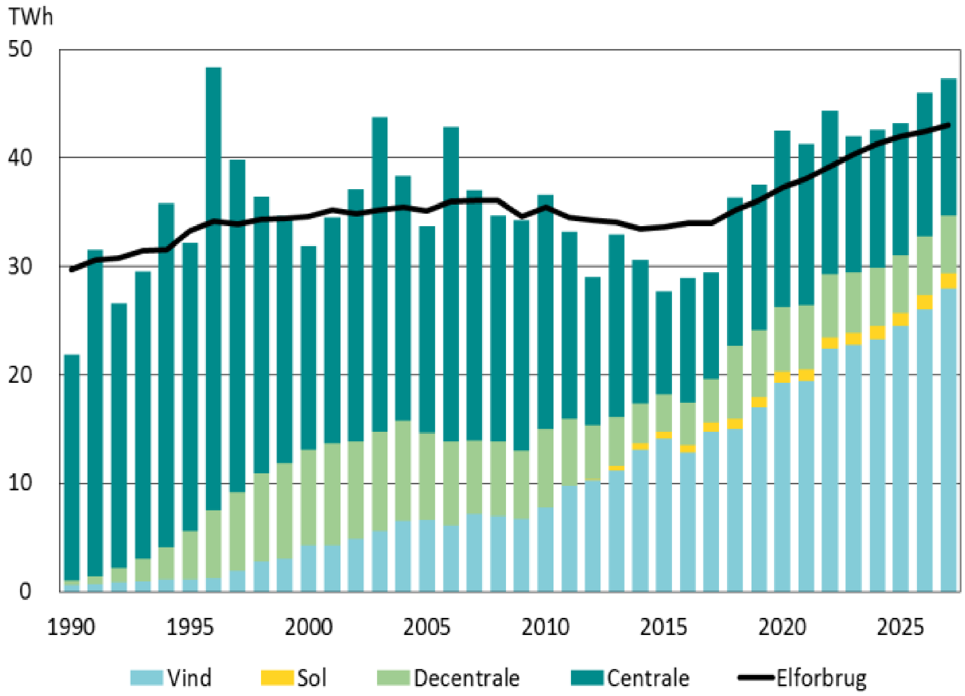


Figure 1.1: Generation & production of electricity from 1990-2027 [2]

The perception of a renewable-based energy system demands drastic changes to the current one. The uncertainty of the variable generation and the fluctuation of the demand have to be properly controlled and coordinated. In order to achieve this, the transition to a smart energy system that will offer flexibility is necessary and this future energy system has to be characterized by reliability, sustainability and cost efficiency. The flexibility in the smart system can be achieved by the application of appropriate methods like demand side management, use of storages and exchange of energy with other countries. Another inevitable measure is the integration of electricity with different energy sectors like heat and gas. The possibility to transform the electric energy and store or use in another sector can help in providing the wanted flexibility. Figure 1.2 shows the interaction between the different energy sectors in the future energy system [3].

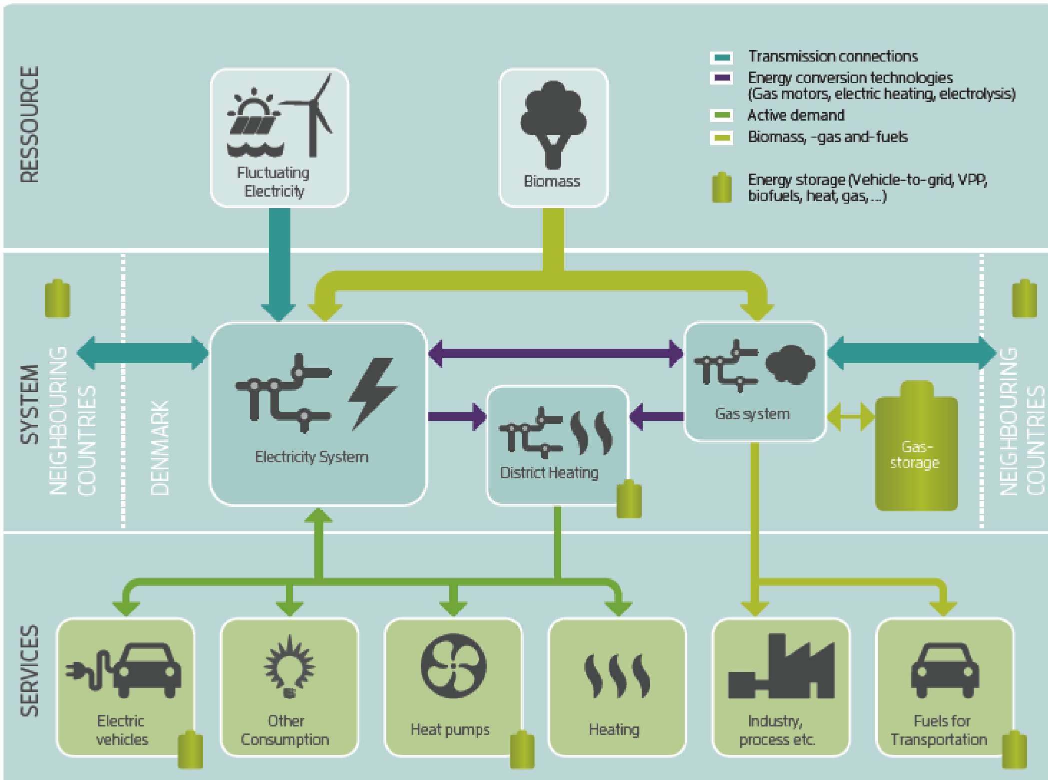


Figure 1.2: Integration of energy sectors in the future [3]

The cooperation with the heat & gas systems will assist the installation of renewable energy sources, as the excess electricity will be available to be used for other purposes. On top of that, heat & gas technologies that come with a storage can help in the conservation of energy in a cheaper way than electrical storage. Specifically, heating systems can provide support for short to medium times, while gas systems for long times [3]. When the generation is high and the electricity price low, energy can be stored in order to be used later, when the price will be high, achieving cheap operation. This is relevant for Denmark, where the high wind power generation can be utilized in this way. In the case of the gas system, there is also the capability to transform the stored energy back into electricity [4]. The district heat plants & production units can schedule their operation according to prices & system requirements to get better energy efficiency and economic benefits.

Nowadays, the majority of households in Denmark (more than 60%) cover their heating needs by the use of district heating while others use individual heating options. Today's heating sector is mainly supported by combined heat & power (CHP) plants and, to a lesser degree, by other technologies like fossil-fueled boilers, waste to energy, electric boilers (EBs) and heat pumps (HPs) [5]. In the next years, the renewable energy share in heating is expected to further increase with the use of biomass instead of coal and gas in CHP stations, the increment in solar heating and the advancement in the usage of HPs. The numbers of HPs will notice a significant rise in the following years as they will take the place of conventional boilers. Figure 1.3 shows the heat consumption in households from different means until 2030, where this change can be noticed [6].

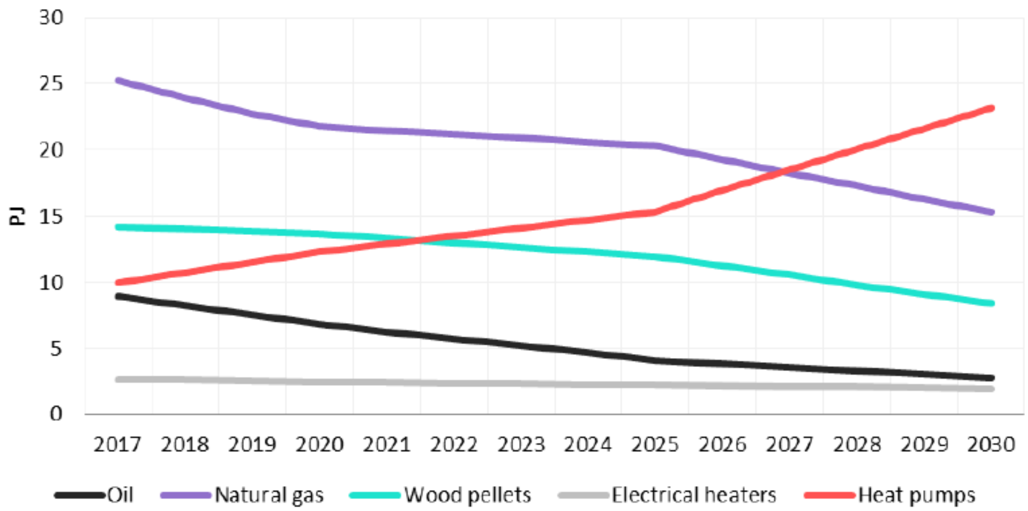


Figure 1.3: Household consumption from different heating resources until 2030 [6]

The escalating penetration of these devices can cause major problems to the electrical grid because of their fluctuating electrical demand, affecting the planning, operation and control of the network. These problems include overloading, deviation of voltage, power quality issues and voltage unbalance in the case of single-phase connection [7]. The management of these flexible loads, the control of their operation as well as the coordination between them and the varying distributed generators must be done in an effective way to avoid the appearance of issues to the system.

1.2 Problem Formulation

Due to the increasing penetration of energy from renewable sources in Denmark to minimize the usage of fossil fuels in the future, the synergy between different energy sectors is crucial. Power to heat systems, where the excess electricity from variable renewable energy sources can be utilized in the heating sector, is relevant for Denmark in order to achieve the country's clean energy goals. Therefore, the interaction between the thermal systems and the electric network must be properly assessed. The flexible electric loads that are used for heating, such as electric boilers and heat pumps, affect the electrical system and need to be operated and controlled in a proper way.

1.3 Objectives

The project aims to investigate the impact of flexible HP units on electric distribution grids for residential and large units and to develop suitable control schemes to enhance the utilization of renewable generation in local grids and the efficient operation of distribution networks and heating systems.

To achieve the above-mentioned objective, the following tasks will be conducted:

- Theoretical review of HP systems.
- Modelling of a distribution network with flexible HP units and renewable energy sources.
- Analysis of the impact of the HP loads at residential and feeder level (community-based) on the electric distribution network.
- Application of appropriate control and coordination methods to enhance the renewable energy utilization and achieve overall efficient system operation of heat and electricity sectors.

1.4 Methodology

The main tool used for the simulations in this project is DIgSILENT PowerFactory. The models for HPs and thermal storages were developed using the DSL (DIgSILENT Simulation Language) module. The solar PV production profiles inserted in PowerFactory were prepared in MATLAB. RMS simulations were performed for the daily operation. The result data from PowerFactory were plotted using MATLAB.

The methodology followed can be described as follows:

- Development of models for residential & central HP – thermal storage, control methods and gathering of data for PV production.
- Test of developed models.
- Simulations of different scenarios involving residential HPs and PVs in a Danish LV grid.
- Simulations of different scenarios involving large central HP and residential PVs in the LV grid.

1.5 Limitations

Some of the limitations taken in this project are listed as follows:

- The power system was considered to be balanced 3-phase.
- Simplified models are used for HP and storage systems.
- Short-term transient behavior is not taken into account.
- PVs are modelled as static generators producing only active power.
- One representative day in winter and one in summer have been used for the studies.

1.6 Overview

Chapter 1 – The topic of the project is introduced with the basic background, objectives, methodology & limitations.

Chapter 2 – A state of the art review of the P2H systems with HP operation and participation in smart grids as flexible loads.

Chapter 3 – A description of the models developed for this project including HP, storage and control procedure.

Chapter 4 – Analysis of a LV grid with the integration of residential HPs and PVs and the application of the control to enhance their synergy and increase the flexibility.

Chapter 5 – Analysis of LV grid with a central HP system and PVs and assessment of their synergy.

Chapter 6 – The conclusion of the project along with possible ideas for future work.

2 State of Art

This chapter touches upon the Danish electricity and heating networks and then P2H technologies with focus on HPs are described. The topic of demand side management is presented along with the applicability of HPs in smart grids. Finally, some aspects of the Danish electricity market, which will be highly relevant for the future role of heat pumps in the system are mentioned.

2.1 Electricity & Heating Network in Denmark

The electric network in Denmark consists of the transmission system, operating at 400kV, 150kV & 132kV (high voltage) and the distribution system, operating at several voltage levels below 60kV (medium and low voltage) [8]. The Danish energy system has faced major changes in the previous decades with the major integration of dispersed energy generation. The transition from a centralized system to a decentralized one can be noticed in Figure 2.1, where the state of the system at the years 1985 and 2015 is visually compared [9]. Many decentralized plants, mainly wind turbines and CHP plants, are currently incorporated in the Danish system. Distribution networks, which are traditionally not designed for the hosting of distributed generators, are now becoming active and this transition has a drastic effect on the operation and planning of these networks [10].

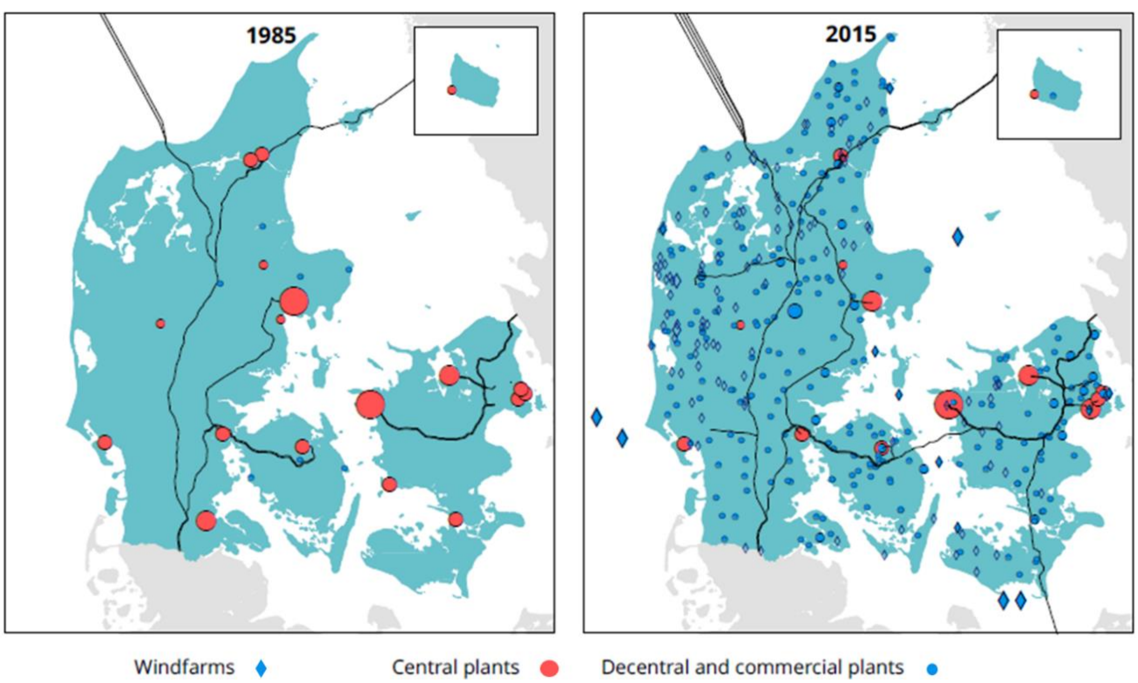


Figure 2.1: Evolution of the Danish system [9]

The Danish heating sector consists of an extent district heating network, which is supported mainly by CHP plants and also individual heating. An illustration of Denmark's heating sector is given in Figure 2.2 [9]. More than 50% of the district heating is utilizing renewable energy sources, such as solar, biomass, biogas and geothermal energy. In 2015, there were 670 centralized and decentralized CHP plants, producing heat and power at the same time, with a total power capacity of 2500MW [11]. As for district heating HPs and EBs, in 2015, there were 45 EB connected at voltage levels from 0.4kV to 150kV with a total capacity of 488MW and, at the same year, the number of installed and under plan heat pumps was 23, with total electrical power 9.3MW [12]. Meanwhile, more than 27000 domestic electric heat pumps were installed in individual houses [13]. In the future, it is expected that the numbers of large and small heat pumps, for district heating and residential use, will increase rapidly with a rate of around 7% per year reaching 8% of the total renewable energy consumption in 2030. Meanwhile, CHP plants numbers will decline and the remaining ones will be shifted to utilize renewable energy sources [6].

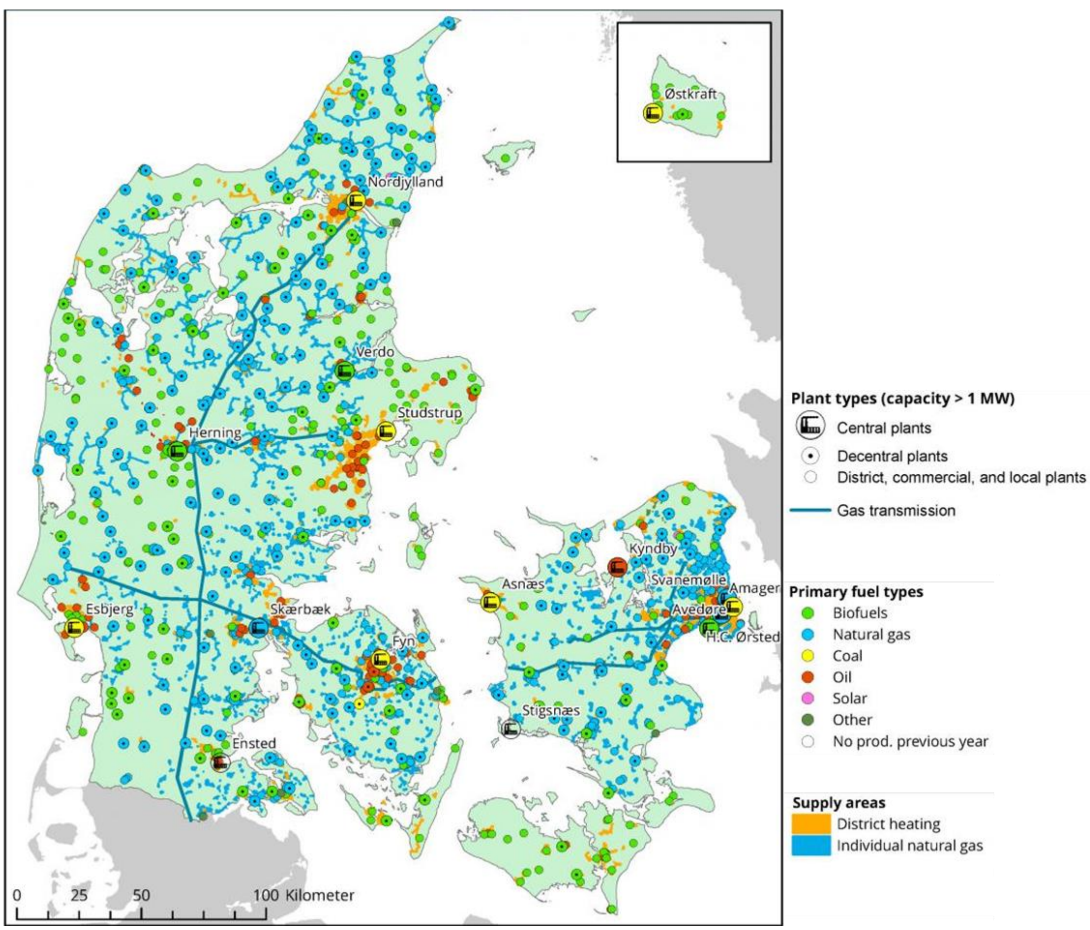


Figure 2.2: Danish heating supply in 2014 [9]

2.2 Power to Heat technologies

Power to Heat technologies, which refer to the direct conversion of electricity to heat, can be distinguished into two categories, decentralized and centralized (Figure 2.3). Centralized technologies basically describe district heating, where large heat pumps and heat boilers can be utilized in combination with energy storages. The decentralized ones, which are related to houses or small urban areas, can be divided to direct and TES (thermal energy storage) options. Direct options come without storage and include devices like radiators and heaters, while TES options come with an external or internal thermal energy storage and include individual HPs and EBs [14].

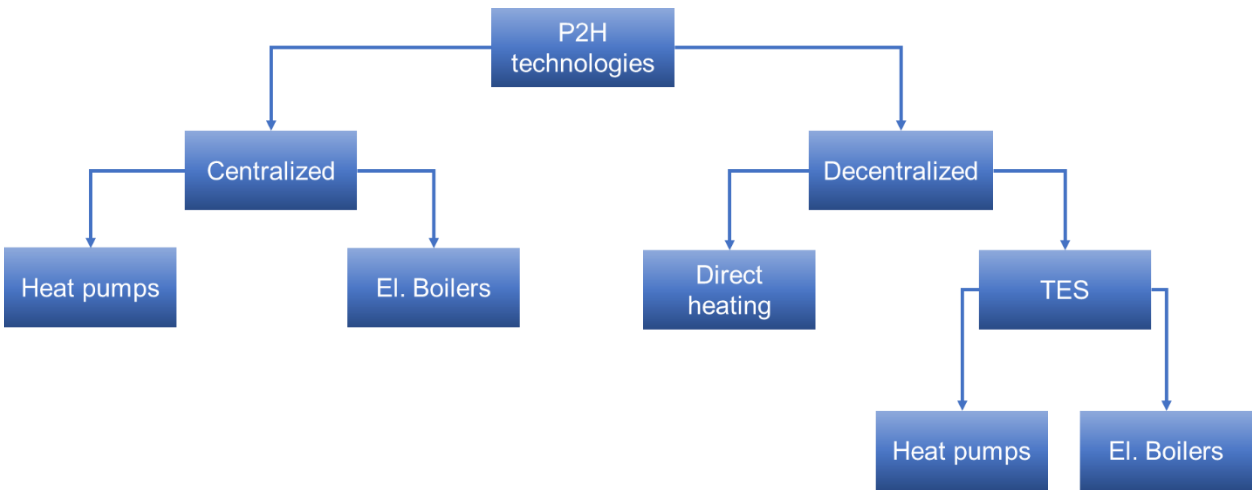


Figure 2.3: Power to Heat technologies categories [14]

EBs are devices that use electricity to warm water in a tank through an electrical resistance or directly through electrodes. They have a low initial cost and a coefficient of performance that is around 1 [15]. The coefficient of performance (COP) can be defined as the ratio of the heat power produced by the device ($\dot{q}$) to the electric power required (P) as [14]:

$$COP = \frac{\dot{q}}{P} \tag{2.1}$$

HPs move a fluid (refrigerant) through two sources, the heat source and the heat sink, as illustrated in Figure 2.4. The heat is taken from the heat source at the vaporizer, then a compressor heats the fluid more and finally the heat is released to the heat sink at the condenser before the fluid passes through an expansion valve for the cycle to start again [16]. HPs have high initial cost but they are more efficient than EBs since their COP is higher with typical values around 3-5 [15].

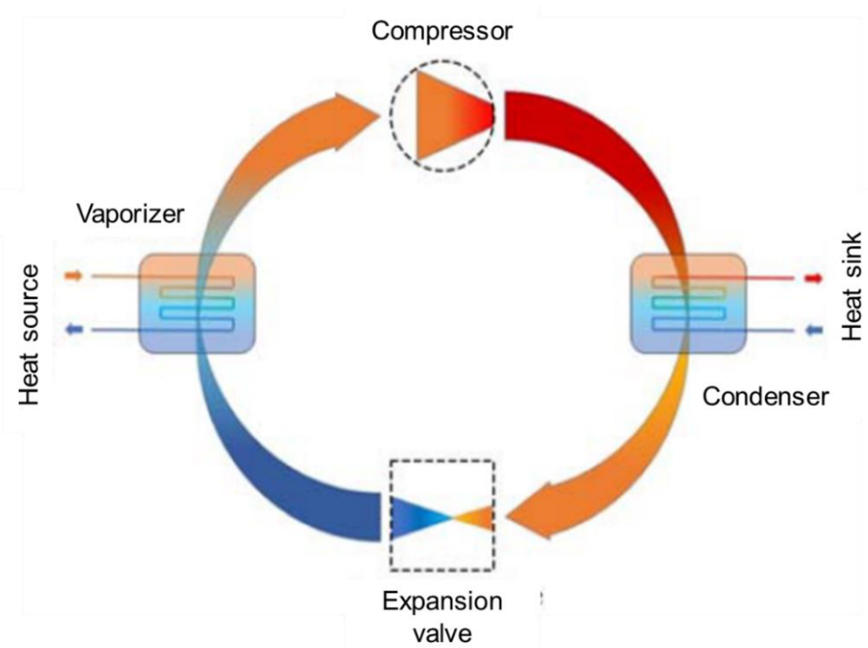


Figure 2.4: Schematic of heat pump operation [16]

One major aspect that affects the COP of a HP is the temperature difference between the source and the heat sink. Because these temperatures fluctuate throughout the year, the COP of a HP is not constant and varies. Therefore, the types of heat source and sink are very important for the performance and efficiency of the HP. The most common sources that can be used for these purposes are ground, air & water. Even though air as a source is easy to use and the most economical option, it has high temperature variations and low temperatures in the winter. Water and ground provide more stable operation without big temperature differences throughout the seasons, which makes them more efficient, but have more difficult installation and higher cost [17]. A comparison of the COP of 3 HPs that use air, underground water and ground is given in Figure 2.5 [18].

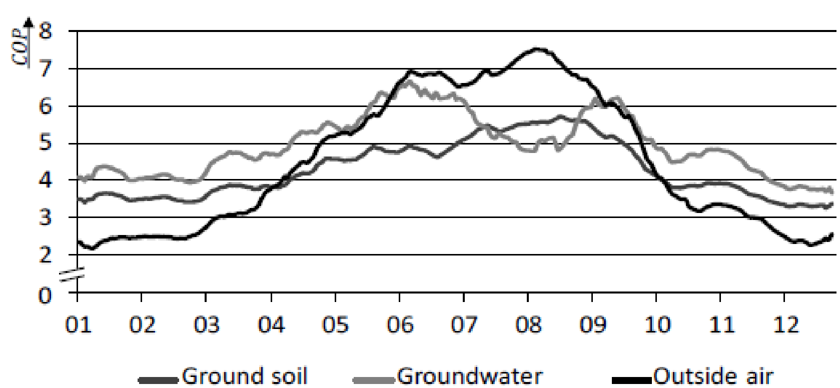


Figure 2.5: COP of heat pumps with different source in a year [18]

2.3 Connection to the electric grid and related effects

The compressor of an electrical HP is driven by an induction motor that is connected to the grid. At original HP technologies, the motors are connected directly to the grid, usually with the addition of a soft starter, as depicted in Figure 2.6. These types of HPs are controlled by an ON/OFF switch [19]. Usually, the control of the operation is done by setting a reference temperature point, and a corresponding range. When the temperature goes above the upper limit the motor is turned-off and when it goes below the lower-limit it is turned on again [20].

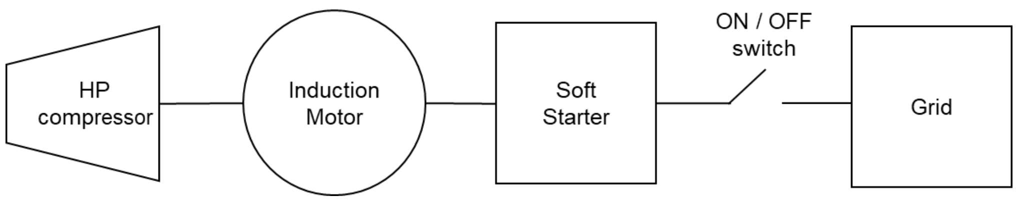


Figure 2.6: Fixed-connected heat pump configuration [19]

At more advanced HP technologies, the compressor motor is driven by an inverter providing variable-speed control. This type of configuration is depicted in Figure 2.7 where, as it can be seen, an inverter and a rectifier exist between the grid and the motor. This setup gives more benefits to the operation that include [21]:

- Variable speed control that provides better control and efficiency, as the temperature can be regulated in a continuous way
- Soft-start to reduce undesired high turn-on currents
- Capability of power factor correction to provide better power quality.

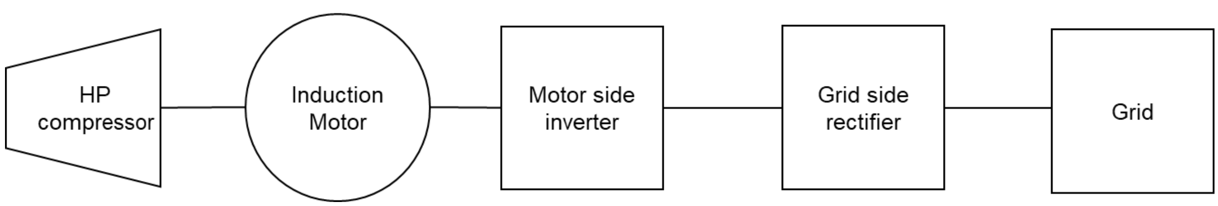


Figure 2.7: Inverter-connected heat pump configuration [19]

HPs, being flexible loads, can affect the electricity network causing operational problems to its operation due to their electrical characteristics. The induction machine of HPs can draw high starting currents that are normally 4-7 times the nominal current and, even with the use of a soft-starter, they can be reduced to 2 times the nominal value. This can create sudden voltage variations and affect the power quality of the system, including voltage dips and flickers. With a big number of these loads connected at a single feeder, this may even lead to voltage collapse [22].

Moreover, HPs that use single-phase induction motor cause voltage unbalance problems which can be critical with a big accumulation of such devices. Unbalanced loads have more effect on the loading increase than balanced ones [23]. HPs that come with a power electronic interface, can threaten the power quality more, as they are sources of harmonics for the grid [21]. Another important consequence of HPs on the system is overloading. Studies in [22] and [23] showed that even a relatively small penetration of HPs, around 20-30%, can cause overloading of the substation transformer. Also, above this level of penetration, the system faces undervoltage problems with the voltage reaching values below the typical lowest setpoint of 0.9pu. In order to tackle these problems, suitable control schemes along with demand side management techniques should be implemented.

2.4 Demand side management

Demand side management (DSM) refers to measures used to control the consumption of customers in order to increase energy efficiency and attain system balance. In Figure 2.8 some common DSM techniques are presented [24].

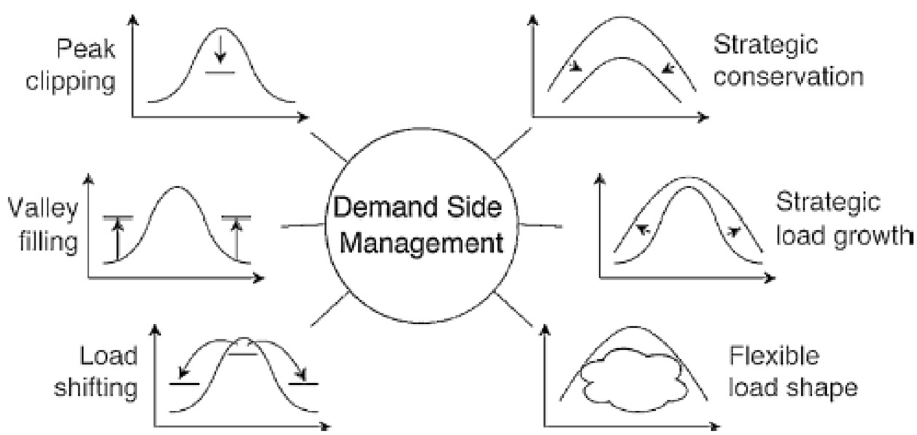


Figure 2.8: DSM schemes [24]

The term demand response (DR) describes the programs designed to give initiatives to the customers to shift their electricity use, responding to changes in electricity prices [24]. Demand response can be done by reduction of the consumption at peak times, which would create discomfort but decrease the energy cost, or by moving the consumption of flexible loads, like heat pumps, to off-peak times when electricity is cheaper. Another option would be on-site generation, which would make the customer more independent, but it would increase the complexity of the system [25]. In general, demand response methods can be distinguished into incentive-based and price-based. At price-based methods, customers get time-varying prices from the suppliers and decide to change their demand according to them. At incentive-based, the response is defined by third-parties beforehand and the customers get compensated to follow this alternation [26].

2.5 Heat pumps in the smart grid

HPs, like other distributed resources, can be utilized in the framework of smart grids as part of the demand side management in order to support the operation. The applications of HPs in the smart grid can be broadly categorized into 3 areas [18]:

- Grid focused,
- renewable energy focused and
- price focused.

Grid focused applications have to do with the management of HPs in order to provide extra services to the grid, like voltage regulation, congestion control as well as reserves and ancillary services. In these applications, the HPs can be controlled by signals as the voltage level or the transformer loading state. At renewable based applications, special care is given to the integration of renewable energy, mainly wind and solar, as well as the smoothing of residual load. In this case, wind or solar power generation signals can be used for the HPs. Finally, price-based appliances investigate the operation of HPs in different price environments. This means price signals that can be fixed, like time-of-use tariff schemes, or variable, which can be real-time of ahead-time. Of course, all the above categories are interdependent with the price always being a central aspect in the smart grid context [18]. A point that is crucial in order to achieve efficient and beneficial management for HPs, as for the other flexible loads, is the development of intelligent systems for metering, forecasting and communication between them and the associated companies in control [4].

Studies in [27], [28] have shown that HPs can be efficiently used to shift load at certain times of days, when the grid is overloaded, thereby reducing congestion problems. The use of a storage or a supporting generator is essential for this cause, to keep the appropriate comfort level. In [29], heat pumps are used to alleviate the overvoltage problems caused by PVs in residential areas, reducing the PV infeed. However, in summer this effect was limited due to the lower need for heating. [30] showed the applicability of HPs to utilize the excess electricity by renewable energy sources and relief the grid when a large penetration of renewable generators is present. At [31] HPs together with other flexible loads were used to provide frequency support in a high wind penetrated system, performing actually better than typical generator units. Also here, the reduced operational availability of HPs in summer was pointed out. [32] studied the economic benefit of using HPs inside a flexible price scheme. Using flexible price thresholds for the operation of the HPs and optimization, savings were achieved up to 25%, increasing at the same time the self-consumption ratio of PVs without dealing great loss of comfort.

2.6 Electricity market

Today's Danish electricity exchange takes place at Nordpool, which contains Elspot and Elbas. Elspot is the day-ahead market place, where electricity is traded one day before the delivery time while at Elspot, the intra-day market place, exchange of electricity happens until one hour before the delivery hour. The transmission system operator, Energinet, operates the regulating and reserve capacity markets in order to obtain balance in the system. At the regulating market, Energinet gets power from suppliers and consumers which can be used during the hour of operation to fix imbalances due to forecast errors. At the reserve capacity market, Energinet makes agreements for available reserve resources to use during the moment of operation in case of possible outages [33].

The future demands changes in the current market, mainly due to the rise of renewable energy sources which will change the generation and consumption relationship. The demand-dependent system of today will turn into a generation-dependent one and the future market has to be able to maintain high level security of supply in a cost-effective way. "Market model 2.0" notes the general need for 3 aspects: adequate capacity, increased flexibility and new ancillary services. Firstly, in order to attain sufficient capacity, which is expected to be reduced due to the shutdown of CHP plants and the dominance of fluctuating wind power, the related proposals include the development of strategic reserve, possibly in collaboration with the neighbor countries. For the flexibility, the need for the utilization of the customer's flexible loads is pointed out. Mainly heat pumps and electric vehicles are expected to play a role here, as they have the ability to give flexibility in the future system. This can be achieved by giving market roles to third-party aggregators who will correlate the flexible demand to the system needs and by adjusting prices to give initiatives for participation in the flexibility market. For the last point, the need for introduction of new reserve services exists, as the current ones will be reduced. The change of market involvement of reserve providers to make it more active and effective to increase these services is essential [34].

2.7 Summary

The interconnection of the Danish electric & heating network is prominent with the increasing participation of P2H technologies in Denmark. Heat pumps, having high efficiency, can give many possibilities for achieving flexibility in the future power system. Depending on the source and technology of heat pump the operation and the effects on the system can vary. The management of heat pumps can contribute to the smart grid context through various aspects, including the provision of support to the grid, assisting the integration of renewables and participation in the energy market. On the other hand, they can create issues to the grid and have reduced operability in summer due to less heating demand.

3 System modelling

In this chapter, the modelling procedure followed for the components used in the studies is explained. The heat pump system models are described for residential and regional operation.

3.1 Residential heat pump system

The HP system that is modelled for residential operation consists of an air-water HP connected with a hot water storage tank (HWST) in order to provide a residence with the necessary heat. In Figure 3.1 a schematic of this system can be seen. The HP takes energy from the electrical grid, produces power to heat the water in the tank and the energy from the tank is used for the residential heating demand. The house also covers its electricity demand from the grid.

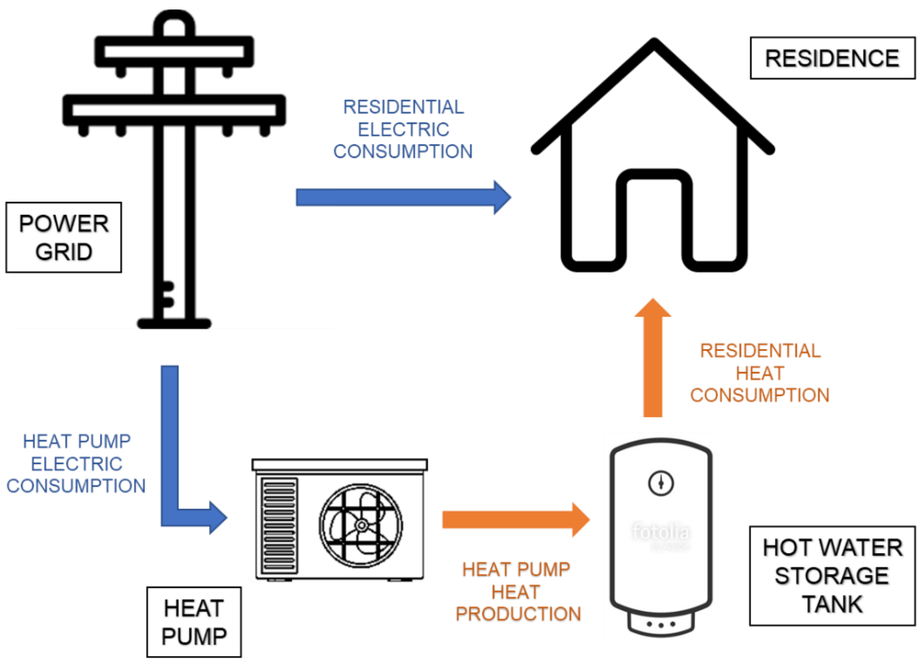


Figure 3.1: Residential system layout

3.1.1 Residential heat pump and storage model

The HP is modelled based on the COP, following equation (2.1). The data for the HP values (rated electric power) used were taken from [35]. To get a more realistic approach, the COP is taken to vary as a function of temperature. Following the formula derived in [36] by interpolation of data from the manufacturer, the COP is calculated using the atmospheric temperature (T_{atm}) as:

$$COP = -0.000016T_{atm}^3 + 0.00052T_{atm}^2 + 0.073T_{atm} + 3.4 \quad (3.1)$$

The resulting COP of the HP for a winter and a summer day is presented in Figure 3.2 with the corresponding atmospheric temperature ranges shown in Table 3.1. As it can be seen, the COP during summer is higher as expected due to the higher atmospheric temperature, which means that the HPs are more efficient during this period. Also, the COP variation in summer is bigger. The power factor of the HP was not indicated so it was assumed to be 0.98 inductive.

Table 3.1: Temperature range for winter & summer day

Winter	-1.2 ~ 2.5 [°C]
Summer	10.3 ~ 20.1 [°C]

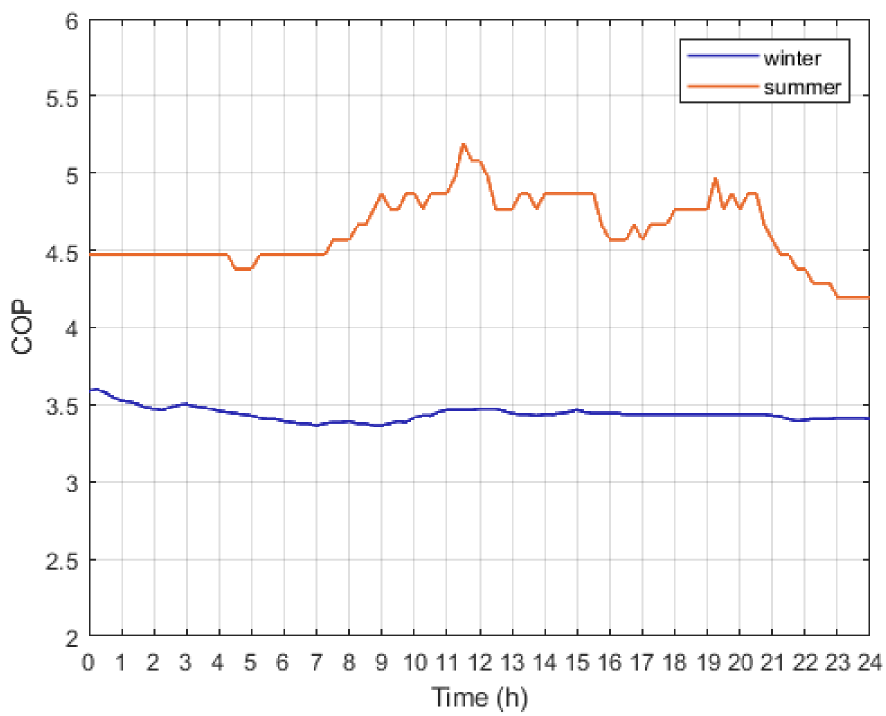


Figure 3.2: COP variation in a winter and a summer day

A heat storage is added to the HP to achieve more efficient management of the produced power. For this storage, a cylindrical HWST is considered as depicted in Figure 3.3. The storage is modelled using the average temperature of the water inside it.

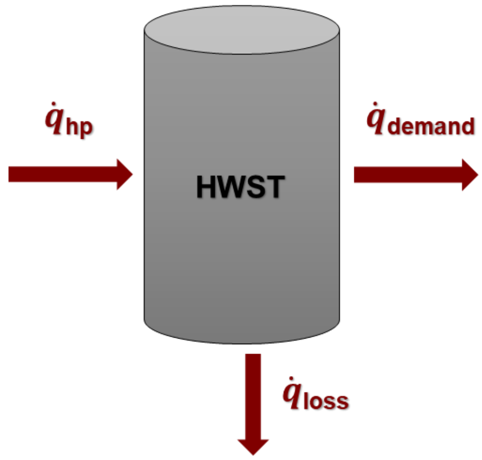


Figure 3.3: Hot water storage tank

The model was realized using the following relation of powers [37]:

$$\dot{q}_{stor} = \dot{q}_{hp} - \dot{q}_{demand} - \dot{q}_{loss} \tag{3.2}$$

Where $\dot{q}_{stor}$ the heat stored in the tank, $\dot{q}_{hp}$ the heat provided by the HP, $\dot{q}_{demand}$ the heat consumption and $\dot{q}_{loss}$ the losses of the tank (in W).

Also, the following equations apply:

$$\dot{q}_{stor} = mC\frac{dT}{dt} \tag{3.3}$$

$$\dot{q}_{loss} = UA(T - T_a) \tag{3.4}$$

Where m the mass of water, C the specific thermal capacity of water (=4190J/kg·°C), T the average temperature of water inside the tank, U the overall heat transfer coefficient of the tank (in W/m^2·°C), A the area of the tank and T_a the temperature of the environment where the tank is located.

Thus, equation (3.2) becomes:

$$mC\frac{dT}{dt} = \dot{q}_{hp} - \dot{q}_{demand} - UA(T - T_a) \tag{3.5}$$

3.1.2 Control of residential heat pump

A control for the temperature of the water in the storage is developed. The control takes into account the maximum & minimum allowed temperature in the tank within a specific comfort range.

The temperature control operates as an ON/OFF control, turning off the HP when the temperature reaches the upper limit and turning it on again when the temperature falls below the lower limit.

As a next stage, a voltage command has been added, taking into account the voltage of the bus where the HP is located to avoid undervoltage issues. Now, the control takes the specified voltage as an extra input as a combine temperature-voltage control. If the voltage falls below a selected minimum value the HP will turn off nevertheless the temperature in the tank. The HP can be set into operation again only if the system voltage reaches a set recovery value. The block diagram for the whole arrangement developed in DIgSILENT PowerFactory modelling environment DSL is shown in Figure 3.4.

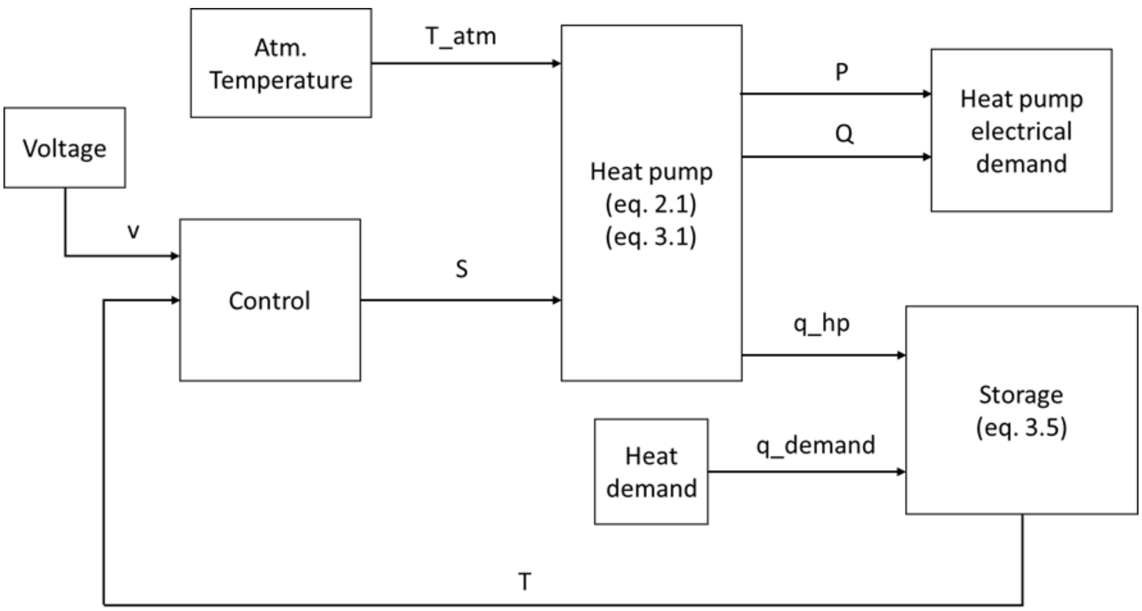


Figure 3.4: DSL frame for residential HP system

An extra layer has been added to the temperature-voltage control to avoid the temperature in the tank dropping dramatically below a set critical value. So, the HP can turn on after a voltage drop either if the voltage reaches the recover value or if the temperature reaches the lower critical temperature value.

The collective control operation is described graphically in Figure 3.5. The operation of temperature, voltage and critical control are highlighted. The maximum, minimum & critical temperature limits are symbolized as T_{max}, T_{min} & T_{cr} and the minimum & recovery voltage limits as V_{min} & V_{rec}.

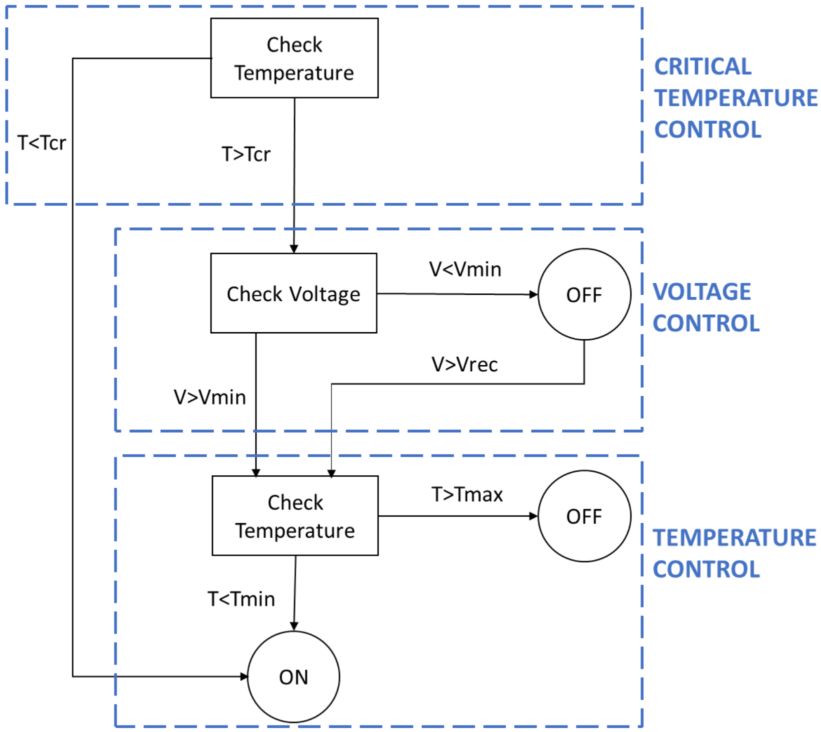


Figure 3.5: Control operation

3.1.3 Model performance

The model has been tested in a simple network that is depicted in Figure 3.6.

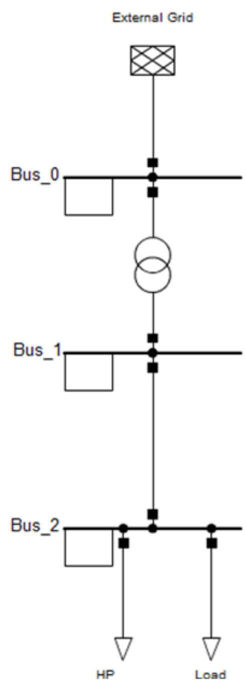


Figure 3.6: Simple grid for testing the model

At bus-2, which operates at 0.4kV, two loads are connected. One of the loads represents the heat pump's electric demand and the other one the residential electricity consumption. The system is fed by an external grid of 10kV through a 10/0.4kV transformer.

Simulation for this system was performed using typical data for the residential demand for a day in winter and one in summer. The residential heat demand consists of the combined effect of space heating (SH) and domestic water heating (DWH). The HP was selected to have rated electric power 3.25kW while the storage size was selected at 0.5m^3 [35].

The results that show the operation of the model with the temperature control in winter are shown in Figure 3.7. Here, the maximum allowed temperature is taken at 70°C with a comfort range of 15°C and a minimum temperature of 55°C. With the heat pump turned off, the temperature in the tank reduces. The control signal turns on the HP when the temperature falls to 55°C and when the maximum temperature of 70°C is reached the signal is removed and the HP turns off again. Concerning the summer case, the corresponding results are shown in Figure 3.8. It is clear that the HP operates less during this day. This is due to the higher COP of the HP in this period, giving higher heat production, in combination with the smaller heating demand. This means reduced flexibility form HPs during summer months.

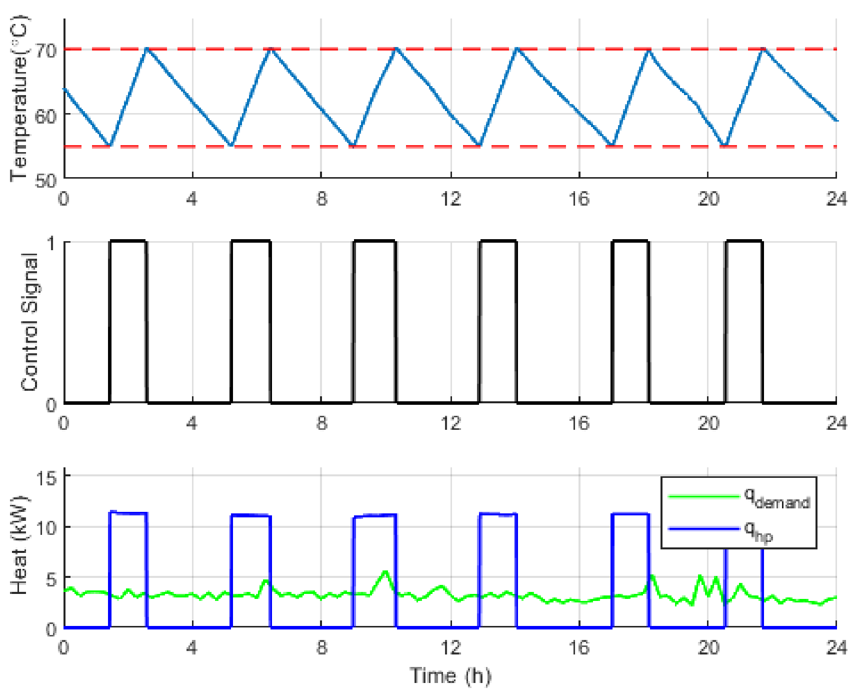


Figure 3.7: Temperature of water in tank, control signal and demand & produced heat in winter day with temperature control

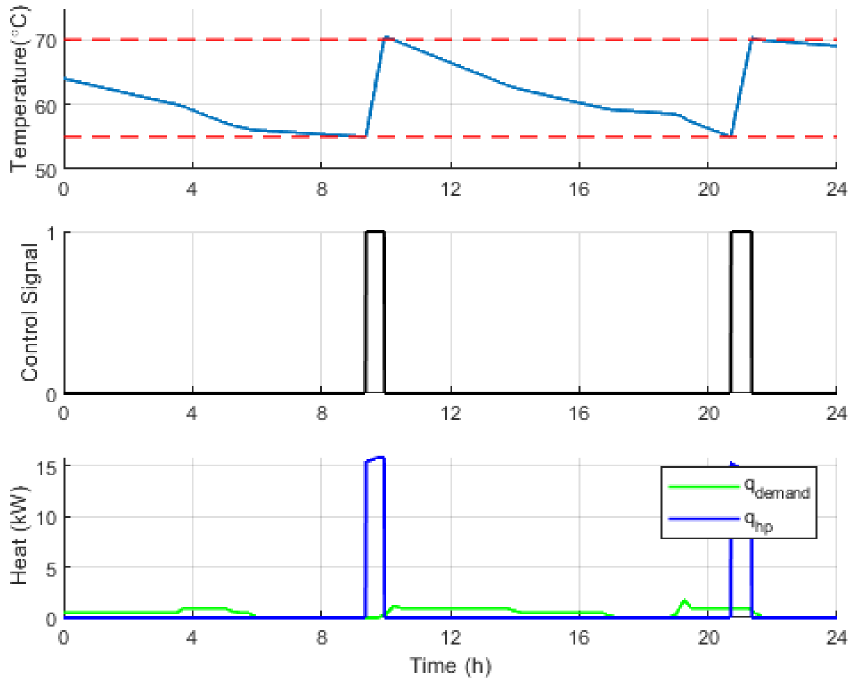


Figure 3.8: Temperature of water in tank, control signal and demand & produced heat in summer day with temperature control

The operation of the combined temperature-voltage control is shown for the winter case in Figure 3.9. Here, even though the temperature goes below 55°C at 20h the HP is not turned on because the voltage has fallen below the limit (here taken as 0.93pu). Later, when the voltage reaches the recover limit (here 0.97pu) the HP turns on. Now, the temperature has fallen below 55°C, at around 40°C.

Adding the extra layer that considers the critical temperature value (taken as 50°C), the results are shown in Figure 3.10. Now, the temperature is not allowed to fall below 50°C so the HP turns on at 21h to maintain the temperature even though the voltage has not reached the recovery voltage.

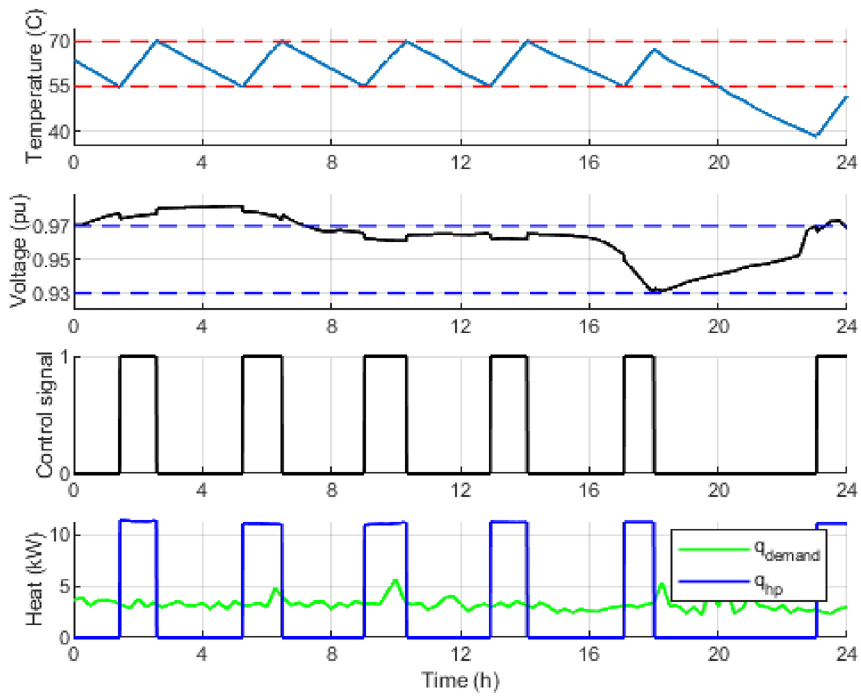


Figure 3.9: Temperature of water in tank, voltage, control signal, demand and produced heat with temperature-voltage control

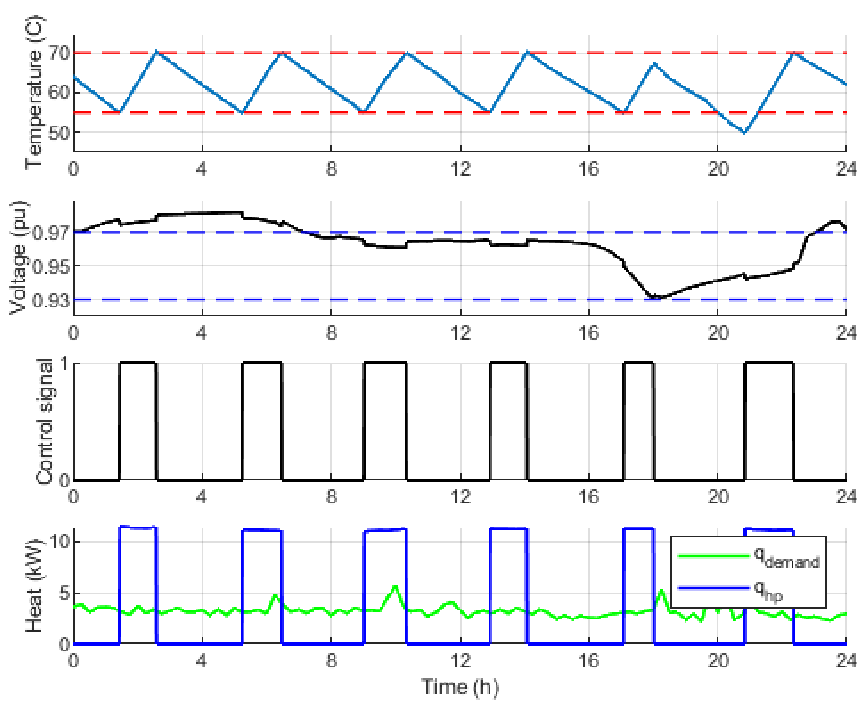


Figure 3.10: Temperature of water in tank, voltage, control signal, demand and produced heat with temperature-voltage control including critical temperature setting

3.2 Central heat pump system

A large central HP system is considered next, in order to provide the heat demand of a certain area where a number of residences are located. The system consists of a brine-water HP connected with a large HWST. The electric energy from the grid is transformed to heat by the HP which is transferred to the storage and then delivered to the community.

3.2.1 Central heat pump and storage model

The model of the big HP is based on the COP similarly to the small one as per equation (2.1). The heat source of the HP is ground which temperature does not present a big variation in a day. So, the COP of the HP is considered constant in this case. From the manufacturer's data [35] the COP is given for specific temperatures of heat source and heat sink. In order to adjust the COP for the desired operation temperatures (T_{source} & T_{sink}) equation (3.6) can be used [18].

$$COP = \frac{T_{sink}}{T_{sink} - T_{source}} \eta \tag{3.6}$$

Here, η is the quality factor of the HP and the temperature values are expressed in [K]. The quality factor can be determined by equation (3.6) using the COP value that is given by the manufacturer for the indicated T_{source} and T_{sink}. Then, the value the COP for the desired T_{source} and T_{sink} can be calculated by using equation (3.6) anew with the calculated quality factor. For a 146kW HP from [35] the COP is given at 4.55 for values of T_{source} / T_{sink}: 0 / 35°C. Using these values, the quality factor is calculated at 0.52. Then, by using the quality factor of 0.52 and temperatures of source 5°C (typical value of ground temperature for winter in Denmark [38]) and sink 70°C (typical value of district heating supply water [39]) the actual COP is calculated at 2.75.

A time shift between the turn-on of the HP and the production of heat has been considered in the model to take into account the delay of the compressor to reach full power. This was neglected for the small HP as it would be quite smaller. The value of this delay is taken to be 10min [40]. A step response is considered for this, as shown in Figure 3.11.

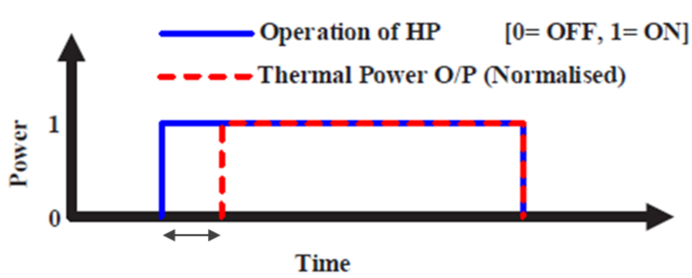


Figure 3.11: Time delay between HP tun on and heat production [40]

For the large thermal storage, the modelling is done using the amount of energy inside the tank. The state of energy (SOE) of the tank in pu can be defined as in equation (3.7) [41].

$$SOE = \frac{E_{ini} + E_{hp} - E_{demand} - E_{loss}}{E_c} \quad (3.7)$$

Where, E_{ini} the initial energy at the tank, E_{hp} the energy provided by the HP, E_{demand} the energy demand, E_{loss} the energy losses of the tank. The energy capacity of the tank can be calculated by equation (3.8).

$$E_c = mC(T_h - T_c) \quad (3.8)$$

Where T_h and T_c the temperature of the supply and return water. Typical values for these temperatures for the district heating system in Denmark are 70°C and 40°C [39].

The losses in the tank are mapped in relation to the SOE. When the tank is full of hot water, SOE is 1pu, and the losses can be calculated using equation (3.4) with T equal to T_h. When the tank has no hot water and is full of cold water, SOE is 0pu and the losses are calculated by equation (3.4) with T equal to T_c. For a storage of volume $100m^3$ [42] (area of $118m^2$) with U equal to $1W/m^2 \cdot °C$ and T_a at 10°C using linear interpolation, the following formula is derived for the heat losses power (in kW).

$$\dot{q}_{loss} = 3.56 \cdot SOE + 3.56 \quad (3.9)$$

3.2.2 Control of central HP

The control developed for the central HP is an ON/OFF control that takes into account the SOE of the storage tank. The control checks the SOE and keeps it between a minimum value SOE_{min} and a maximum value SOE_{max}. The HP turns on when the SOE falls below the minimum value and turns off when the SOE reaches the maximum value. The DSL model and the block diagram of the control operation are shown in Figure 3.12 and Figure 3.13.

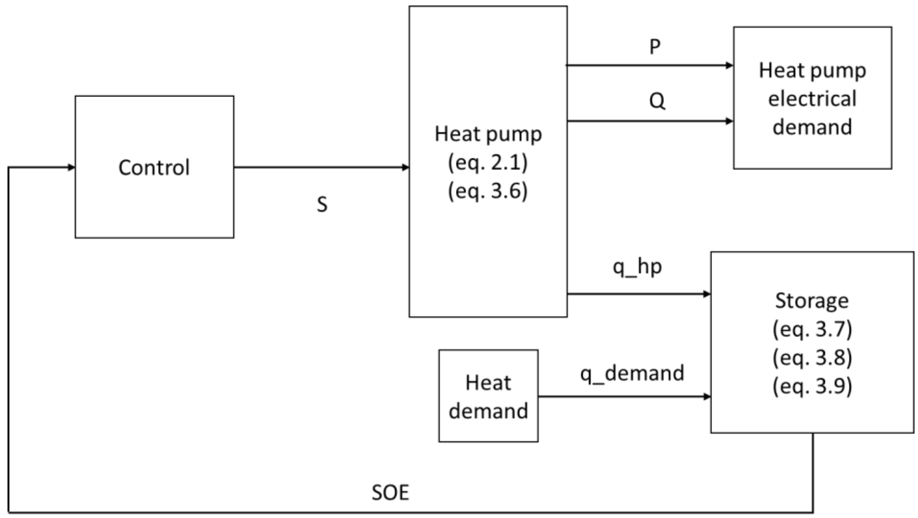


Figure 3.12: DSL model for central HP

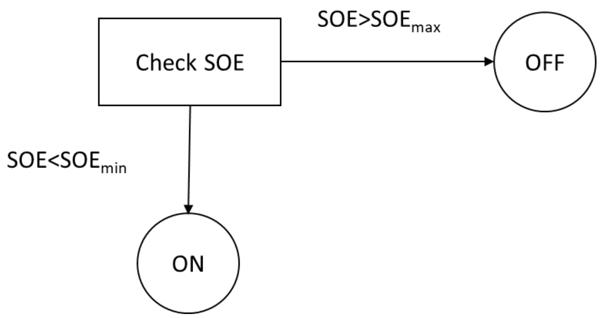


Figure 3.13: Control operation for central HP system

3.2.3 Model performance

The model for the large central HP is tested at the same test grid as before (Figure 3.6) with the HP load now located at bus-1 (low-voltage side of transformer) instead of bus-2. The results of the operation are depicted in Figure 3.14. The data used here are referring to the winter day that was used also in the residential case with the heat demand scaled. The tank initially is fully charged and its energy is used to cover the demand. At around 10h the SOE reaches 0.5pu which is the minimum control limit taken in this case. So, the HP turns on and starts producing heat after a time delay of 10min. At around 18h, when the tank is fully charged (SOE is 1pu), the HP turns off and the stored energy is used for the demand for the rest of the day.

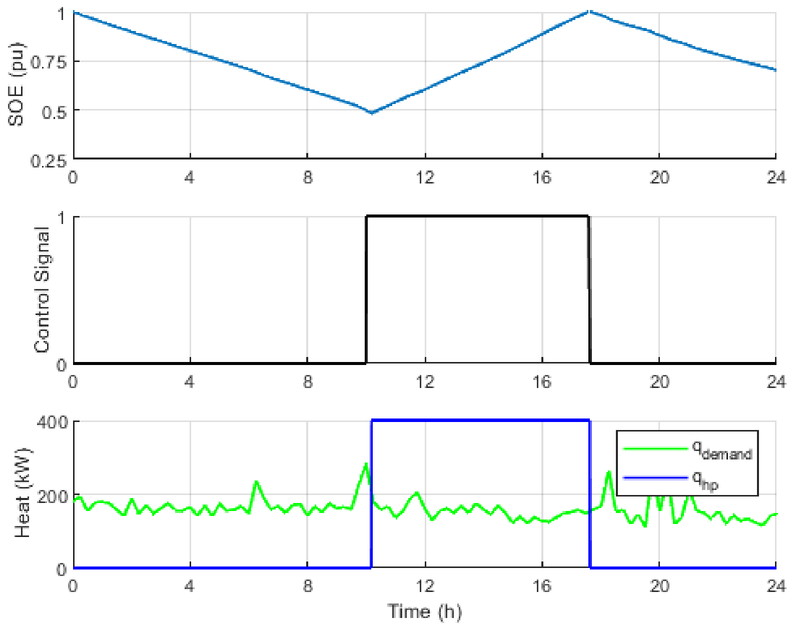


Figure 3.14: SOE of tank, control signal and heat demand & production for large system

3.3 Summary

The modeling and the control procedure are described. For the residential system, a temperature control that satisfies comfort but does not take into account the condition of the grid and a temperature-voltage control that slightly compromises comfort to avoid voltage problems are developed. In order to reduce the loss of comfort, a critical temperature limit is added to the temperature-voltage control that overrides the voltage. In the following studies, the temperature control and the temperature-voltage control with critical temperature are going to be applied. From the testing of the model the reduced applicability of HPs in summer can be observed. For the central system a control of the stored energy that takes into account the SOE of the tank is developed.

4 Analysis of LV grid with residential HPs & PVs

In this chapter, the studies and results for the operation of residential HPs and PVs in a LV grid are presented.

4.1 Grid description – Base operation

For the forthcoming analyses, a low voltage grid has been used. The grid consists of 6 feeders (F1-F6) accommodating a total of 164 residences, being fed by the medium voltage grid through a 10/0.4kV transformer. A schematic of the grid is depicted in Figure 4.1. The parameters of the grid can be found in Appendix A.

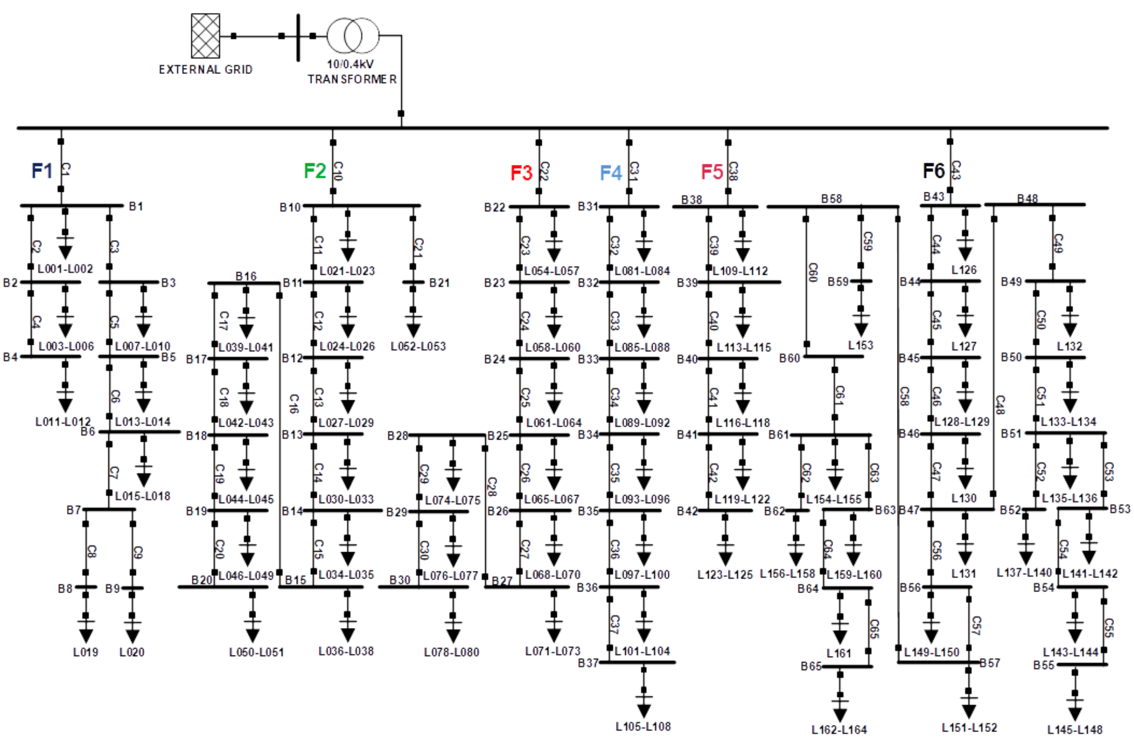


Figure 4.1: The LV grid used in the studies

In this work, it is considered that the residences have the same electrical demand profile but different magnitudes based on daily demands. Their profile is shown for a winter and a summer day, as a percentage of the total daily demand, in Figure 4.2. As it can be seen from the profile, both for winter and summer, the higher electricity demand is observed from the evening till the midnight while in the morning the demand is significantly lower and minimal after midnight. The daily consumptions of the loads range from 1.15kWh/day to 42.78kWh/day for the winter case and 0.81kWh/day to 29.95kWh/day for the summer case. At the current state, the houses do not have any electrical heating and are supplied by the district heating network.

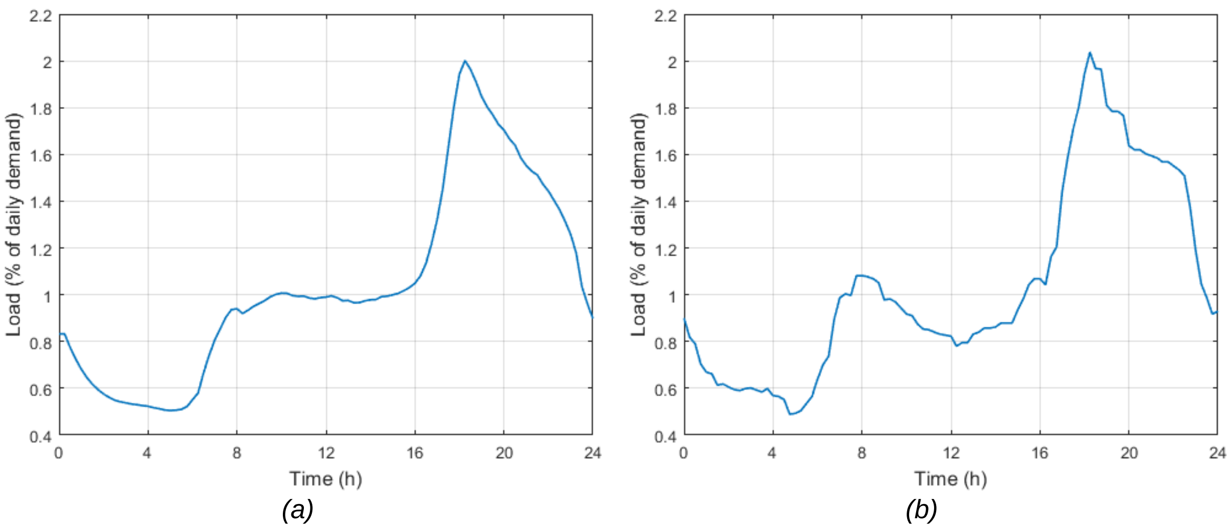


Figure 4.2: Electric load consumption profile in percentage for (a) winter day (b) summer day

As a reference case, for the grid analysis with only the base residential loads, the main results are shown in Figure 4.3. The transformer loading throughout a winter day, the maximum loading for all lines in the grid and the terminals with the lowest voltages are presented. The lowest voltage is located at terminal 163 of feeder 6, which is 0.96pu. No major overloading is observed, with the transformer maximum loading being 24% and the maximum line loading 26%. For the summer case, the results are similar due to the similar load profile but the voltage drops and loadings will be slightly lower due to reduced load magnitudes in summer.

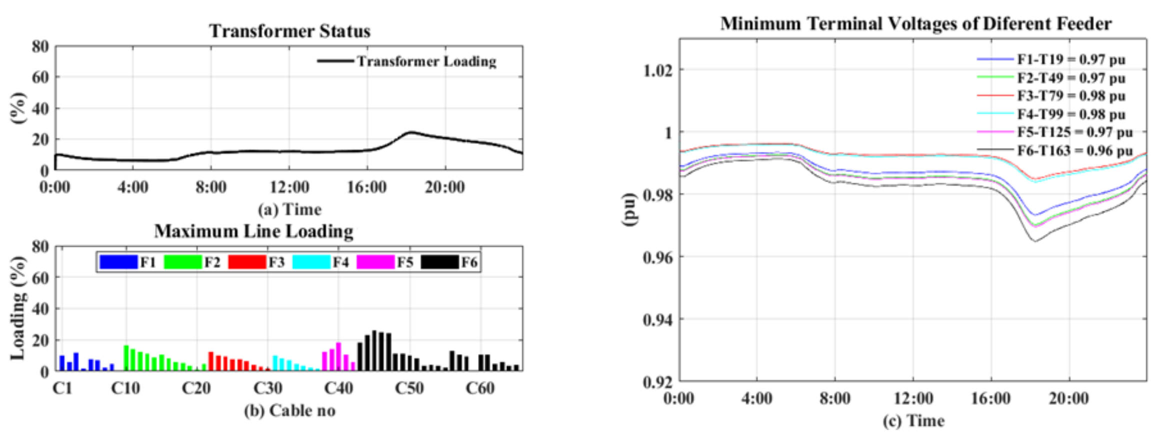


Figure 4.3: (a) Transformer loading, (b) maximum line loading, (c) minimum terminal voltages for initial operation - winter

4.2 Case Studies: Smart Integration of HPs and PVs

To analyse cases of smart integration of heat pumps to the grid and the interaction with solar PVs, five different cases are formulated. First, in Case 1, only the temperature control of HPs is taken into account. After that, in Case 2, the operation with the addition of voltage control of HPs is investigated. Then, PVs are added and study with the combined temperature-voltage control is performed in Case 3. In Case 4, Case 3 is considered but with the storage sizes reduced to half in order to see the effect of storage size on the flexible operation. Finally, in Case 5, Case 3 is repeated for the summer to notice the potential flexibility from the HPs in this period. In the temperature-voltage control used here the critical temperature setting is also taken into account. All in all, the scenarios are outlined in Table 4.1.

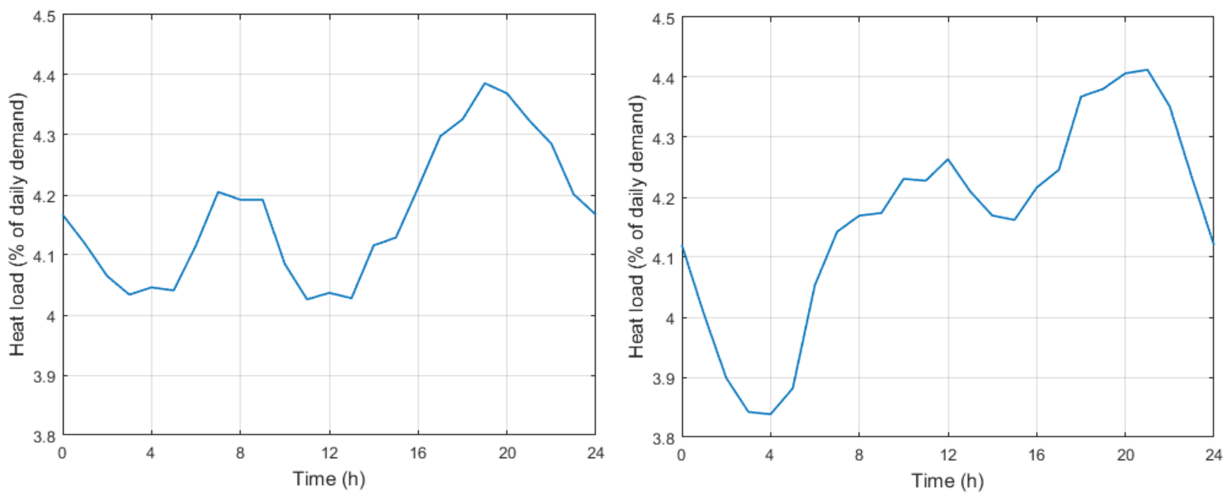
Table 4.1: Study case overview

Case	HPs	Temp. Control	Volt. Control	PVs
1	○	○		
2	○	○	○	
3	○	○	○	○
4	Case 3 with half size storages			
5	Case 3 for a summer day			

The temperature control limits are set to 55°C and 70°C for the minimum and maximum temperature, as in [43]. It is assumed that the consumer comfort is satisfied while the temperature is maintained in these limits. For the voltage control, considering a desired margin of 5% for the system voltage, the values taken are 0.95pu for the minimum voltage and 0.97pu for the recovery voltage in order for the HPs to safely turn on again. The critical temperature that will activate the HPs regardless of the voltage is 50°C to minimize loss of comfort. With the addition of PVs and to increase the self-consumption in the house, which in turn also establishes synergy with the thermal load/storage, the lower temperature limit is raised from 55°C to 60°C during the time period of considerable PV power production. So, if the PV produces power mainly from 11-15h in a winter day, the temperature limits become narrower during this time in order for the HPs to turn on more frequently and operate for an extended time. This way, the power from the PVs is utilized from the HPs for their operation and to charge the storages.

4.3 Insertion of HPs & PVs

The heat demand of the houses for a winter and a summer day follows the profiles depicted in Figure 4.4, as a percentage of the daily thermal demand. The main peaks of heating consumption are located in the morning and from late afternoon until the night. However, it can be noted that the variation of the demand is not so big and there is always need for heat, restricting the potential control of heat demand. In summer, the peaks are slightly shifted in the morning with a bigger drop after midnight. The daily demand of the individual houses ranges from 8.29kWh/day to 88.16kWh/day for the winter case and 2.1kWh/day to 22.05kWh/day for the summer case.



(a) (b)

Figure 4.4: Heat demand profile in percentage for (a) winter day (b) summer day

The loads in the area have been separated into three categories by the assumption that higher electricity demand is associated with higher heating demand, as shown in Table 4.2.

Table 4.2: Categorization of loads

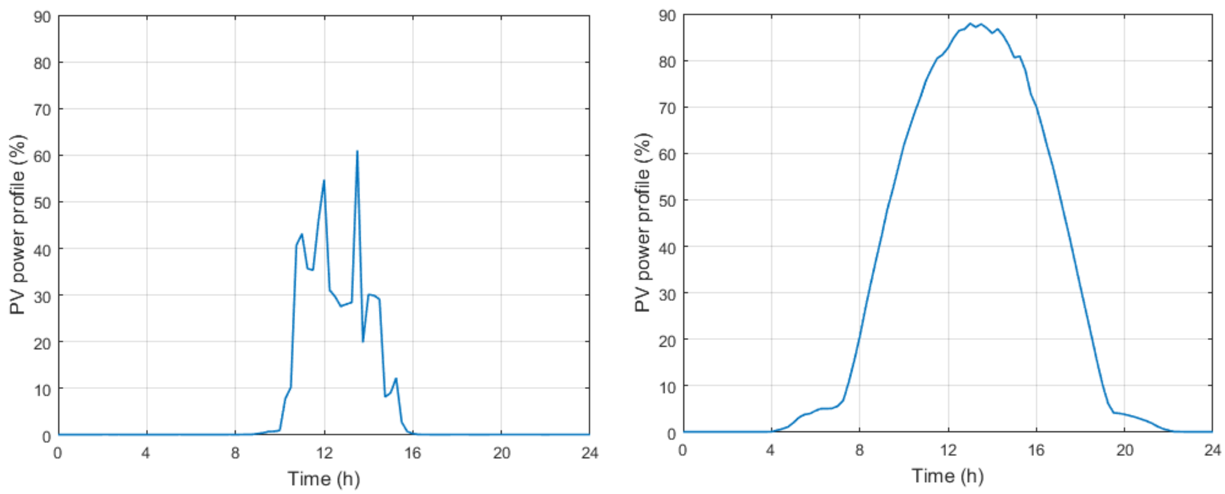
Category	**Electric demand [kWh / day]**	**Heat demand [kWh / day]**	**Number of residen-tial loads in the grid**
I	> 22	> 55	6
II	10-21	35-55	62
III	<10	< 35	96

Taking into account this categorization, heat pumps are integrated into the residences. In relation to the categories described above, heat pumps of different rated power and storages of different sizes (based on [35]) have been used as this is shown in Table 4.3. For Case 4, to investigate how storage size can affect the operation, these storage sizes are reduced to 1, 0.75 & 0.5m^3 respectively.

Table 4.3: HP & storage for each load category

Category	HP rated power [kW]	Storage size [m^3]
I	4.2	2
II	3.25	1.5
III	1.73	1

PVs will also be connected to the residences. The PV profiles that were taken for a winter and a summer day are depicted in Figure 4.5. The size of the PVs was selected and distributed considering the categorization of the houses that was described above as depicted in Table 4.4.



(a) *(b)*

Figure 4.5: PV profile for (a) winter day (b) summer day

Table 4.4: PV rated power for each load category

Category	PV rated power [kW]
I	6
II	4
III	2

4.4 Operation under different scenarios

4.4.1 Case 1 & Case 2

In these cases, the operation with only HPs is investigated. Case 1 takes into account only temperature control while in Case 2 combined temperature-voltage control with critical temperature is implemented. The results for these cases are shown in Figure 4.6, on the left side for Case 1 and on the right side for Case 2.

As in case 1, when the HPs are operating under only temperature control, the temperature at all houses is regulated between the limits of 55°C and 70°C. Now, the voltage of the system drops, with the minimum value of 0.94pu at feeders 2,4 & 6, as shown in Figure 4.6(c). In Figure 4.6(a) & Figure 4.6(b) it can be seen that the loading has increased in comparison to the base grid case, with a maximum line loading of 44% and maximum transformer loading of 38%. From here can be inferred that in order to have 100% penetration of HPs and to maintain the desired temperature comfort, problems can appear to the grid, involving undervoltage and higher loading.

With the addition of the voltage control in case 2, the lower voltage is limited at 0.95pu, as appears in Figure 4.6(c). The maximum line and transformer loadings are slightly improved to 36% and 37% respectively in relation to Case 1, as depicted in Figure 4.6(a) & Figure 4.6(b). As for the temperatures, the critical control allows them to drop up to 50°C now. As it can be seen from Figure 4.6(d), at terminal 163 of feeder 6 the temperature starts dropping below 55°C reaching 53°C at midnight due to the effect of voltage control that turns off the heat pumps then. This means a small loss of temperature comfort to restrain undervoltage with the critical control assuring that this loss is limited.

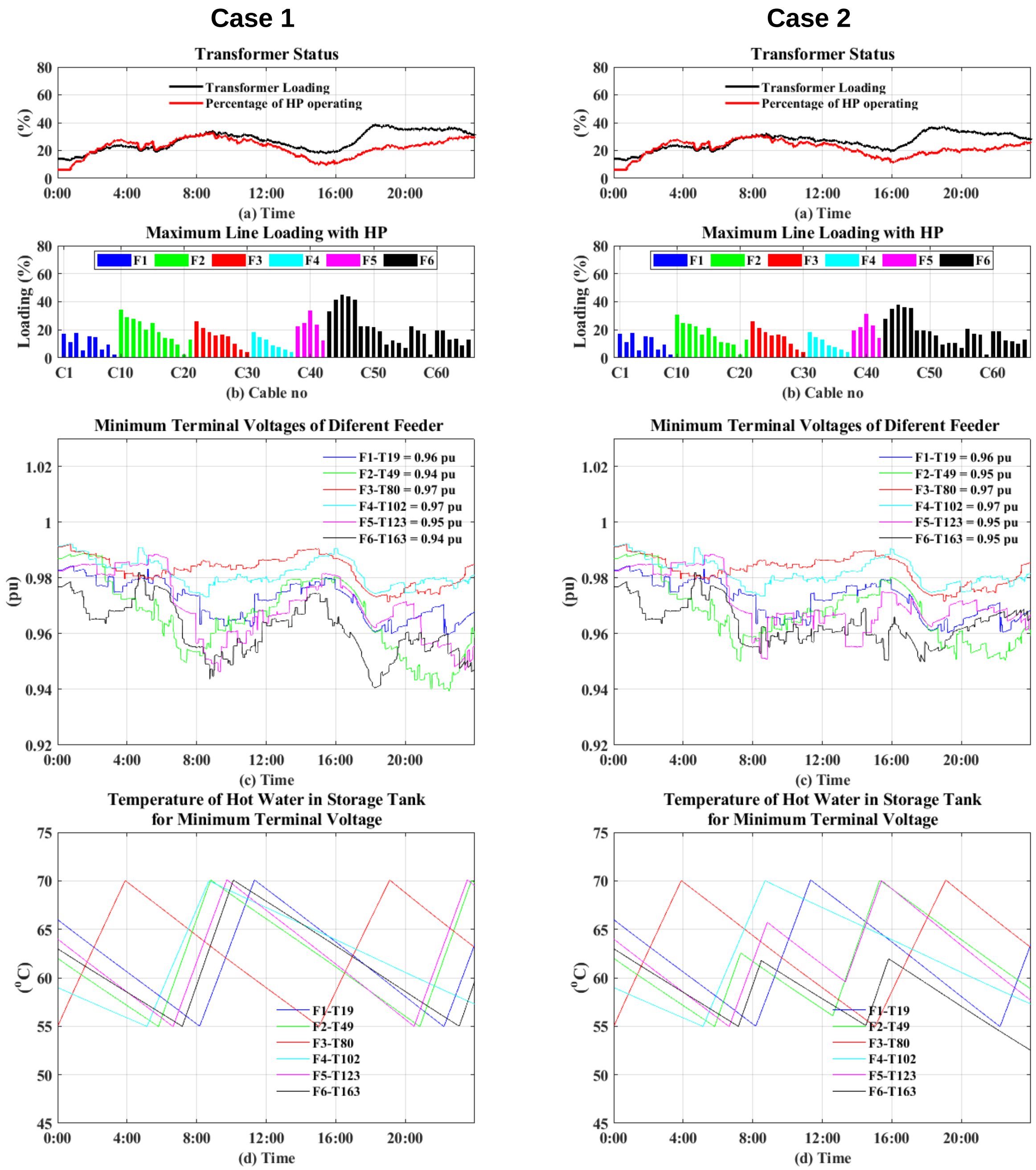


Figure 4.6: (a) Transformer loading & HP in operation, (b) maximum line loading, (c) minimum voltage at each feeder (d) temperature of minimum voltage terminals for Case 1 and Case 2

4.4.2 Case 3

In this case, the operation of HPs jointly with PVs is simulated and combined temperature-voltage control with critical temperature is applied. The corresponding results are illustrated in Figure 4.7.

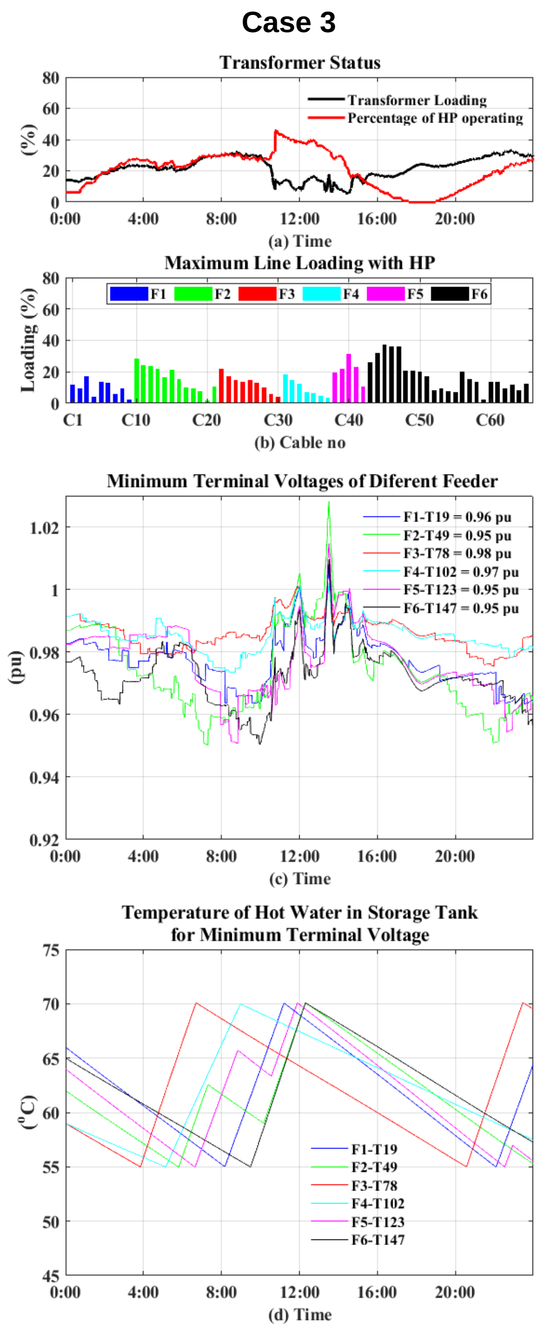


Figure 4.7: (a) Transformer loading & HP in operation, (b) maximum line loading, (c) minimum voltage at each feeder (d) temperature of minimum voltage terminals for Case 3

The PVs are added to the system and in order to maximise self-consumption, the lower temperature limit of the control is raised from 55°C to 60°C at the time period that the PVs produce significant amount of power (from 11:00 to 15:00). This leads to a sudden increase of operating HPs at 11:00, which can be seen in Figure 4.7(a), as they are turned on to supply the storages using the power from the PVs. At the same Figure can be seen that after 15:00 the number of operating HPs drops as the temperature lower limit is decreased again while the storages are fully charged and can provide the necessary demand for the following hours. So, through the PVs and storages the peak demand is regulated with the HP operation shifted from evening - where the electric demand is high - to noon. This also results in an improvement in the voltages, comparing to Cases 1 & 2, during these hours that can be witnessed in Figure 4.7(c). However, it can be seen in Figure 4.7(a) & Figure 4.7(d) that around 20:00 the HPs start operating again as the temperature of the water in the storages eventually drops. The minimum voltage is regulated to 0.95pu, because of the voltage control, while the transformer and line loading are lightly improved to 37% and 33% each. It can be noticed in Figure 4.7(d), that the lower temperature at the minimum voltage buses is maintained at 55°C and that the charging and temperature rise are interrupted at times of low voltage as the heat pumps turn off then to avoid undervoltage.

4.4.3 Case 4

The operation of HPs with temperature-voltage control and PVs but with the storages reduced to half is investigated. The results are shown in Figure 4.8.

The temperature control is again adjusted to 60°C at 11:00-15:00, the time of PV generation. With the storages reduced to half of their size, they are now not able to keep the temperature for a long time. This results in the increase of HPs in operation, loading and fall of voltage at around 18:00, as seen in Figure 4.8(a) & Figure 4.8(b). Because the temperature in many storages is lost at around the same time (20:00-21:00), a lot of HPs have to turn on simultaneously which results in crucial voltage drop and loading rise, as noted in Figure 4.8(a)-(c). As the temperature threatens to fall below the set critical value of 50°C, the voltage control is bypassed to sustain it, which results in eventual voltage drop to 0.92pu. Meanwhile, the transformer and line loadings are increased, having higher values compared to the previous case at 43% and 57% respectively. From these results, it is clear that smaller storage size can worsen the operation as it is not able to provide the required flexibility.

Case 4

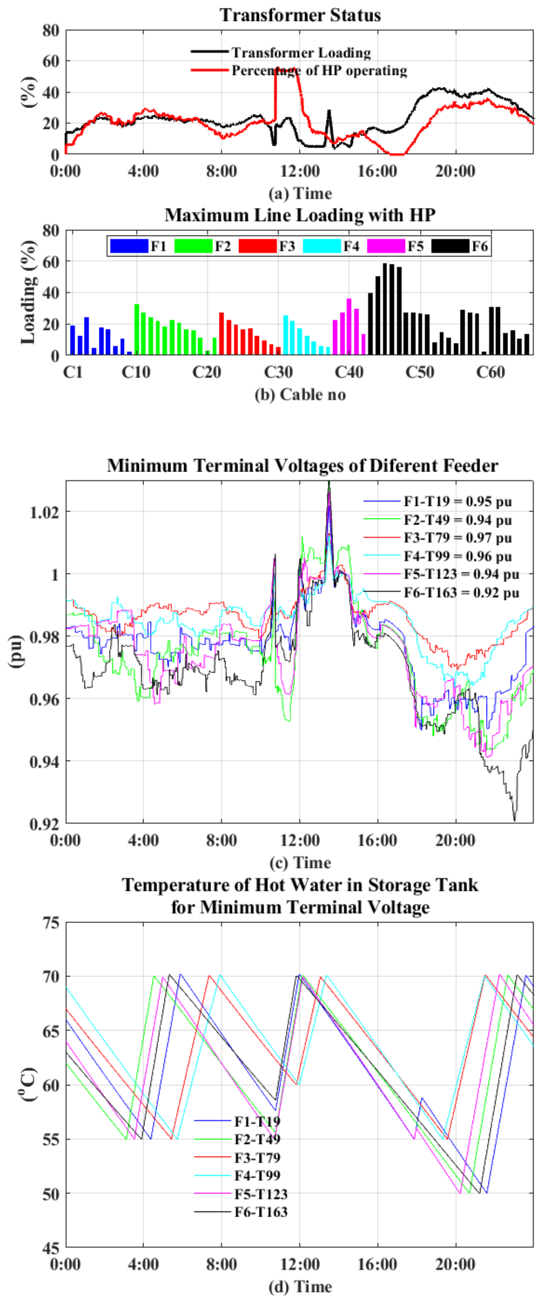


Figure 4.8: (a) Transformer loading & HP in operation, (b) maximum line loading, (c) minimum voltage at each feeder (d) temperature of minimum voltage terminals for Case 4

4.4.4 Case 5

Here, the operation of HPs with temperature-voltage control and PVs in a summer day is considered. The results are depicted in Figure 4.9.

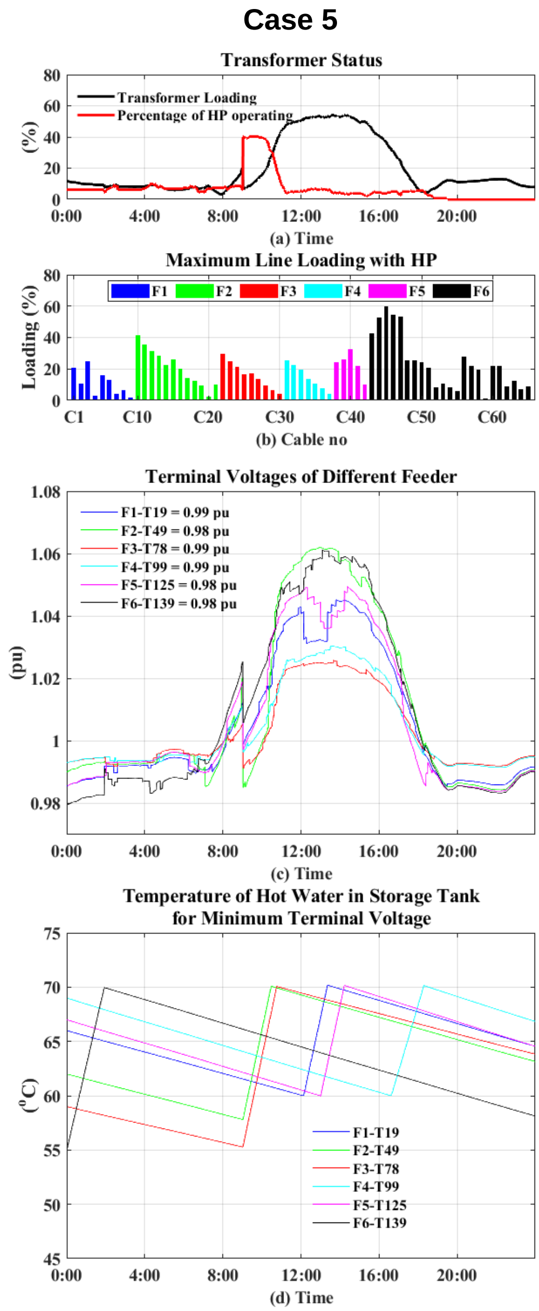


Figure 4.9: (a) Transformer loading & HP in operation, (b) maximum line loading, (c) minimum voltage at each feeder (d) temperature of minimum voltage terminals for Case 5

As the availability of solar power is longer during this day the lower temperature limit of the control is raised to 60°C from 9:00 till 18:00 to benefit from the PVs. Due to the large production of PVs in summer the main problem of the grid, as observed in Figure 4.9(c), is not undervoltage but overvoltage as the minimum terminal voltage is 0.98pu while the maximum one reaches 1.06pu. As can be seen from Figure 4.9(a) many heat pumps are turned on at 9:00, which is the time the lower temperature limit rises to utilize the PV power and provide the thermal load and storage. At the same time, the voltage drops due to many HPs turning on together, as in Figure 4.9(c). After the storages are fully charged, the HPs are turned off and the voltage rises again. After that, the HPs are not needed to operate again in the day as the heat produced was enough to provide the following demand. The big quantity of PV power results in high loadings and reverse power flow. The maximum transformer loading is 54%, in Figure 4.9(a), at the time the PV production is maximum. The maximum line loading as seen in Figure 4.9(b) is 59%. The temperature is maintained in the desired limits as in Figure 4.9(d).

4.5 Discussion of results

The results from the previous studies are summarized in Table 4.5. As it can be seen, comparing Case 1 & Case 2, loadings and voltages can be improved by the use of voltage control with a minor compromise for temperature comfort. Also, from Case 3, the PVs seem to give benefits to the operation, being able to provide flexibility for a certain period of time in cooperation with the thermal storage. Their produced power is used for the operation of HPs, increasing the self-consumption of PVs. At the same time, the storages are charged which gives the flexibility, as they support the production for the next hours alleviating the grid from overloading and undervoltage issues. This way, the synergy of PVs and HPs provides grid operational flexibility and increased utilization of solar power without threatening greatly the consumer comfort by the use of a simple local control instead of complex systems required for the management of the loads and for communication. The flexibility is greatly depended on the storage size, as can be noted from Case 4, with smaller storage providing little flexibility and resulting in the appearance of enhanced problems regarding the grid condition. Because the storage was not able to support until the night hours, when the demands are higher, the HPs have to turn on collectively which induces crucial issues to the grid operation. As for the summer, Case 5 showed that the overvoltage issues that appear due to high solar power penetration cannot be improved by the utilization of the PV power for the heating load/storage, as the heat demand is quite low, which means reduced operation of the HPs and less flexibility from them and also the PV power is quite high. However, the large quantity of PV power until the evening can provide the thermal load for the rest of the day without the need to operate the HPs.

Table 4.5: Results overview

Case	Max. transformer loading [%]	Max. line loading [%]	Min. voltage [pu]	Min. allowed temperature [°C]
1	38	44	0.94	55
2	36	37	0.95	50
3	33	37	0.95	50
4	43	57	0.95	50
5	54	59	0.98	50

4.6 Summary

The operation of a LV grid with 100% penetration of HPs under different controls and the cooperation of HPs with PVs has been investigated. By the use of the voltage control, the voltage can be restrained above a certain limit with the temperature comfort remaining above a critical value. PVs can increase self-efficiency and provide flexibility to the grid by charging the storage. The inability of small size storage to support the operation was observed as well as the limited flexibility potential of HPs in summer. In the next chapter, the operation of a central large-scale HP will be investigated for the same grid.

5 Analysis of LV grid with central HP & PVs

This chapter presents the studies and results for the central HP system and residential PVs in the LV grid.

5.1 System description

The low voltage grid now accommodates a central HP that is inserted at the bus at the low-voltage side of the substation transformer. The HP has to supply all the area with heat so the heat demand that needs to be covered is the sum of the individual heat demands of all the residences increased by a percentage of 10% to take into account the heat losses in the heating supply system. This leads to a total heat demand of 4670kWh/day to be covered. The supply and return temperatures for the water are considered 70°C and 40°C each [39]. The HP size, COP and storage size used were discussed in Chapter 3.2.1 and are shown in Table 5.1. Individual PVs are accommodated in the residences with rated power and profile as described in Chapter 4.3.

Table 5.1: Central HP and storage values

HP rated power [kW]	COP	Storage size [m^3]
146	2.75	100

5.2 Case studies

To observe the effect of the large HP on the grid and the cooperation with the individual PVs, 3 study cases are formulated. In the first case, Case 1, the operation of the grid with the central HP and the residential loads is presented to see the effect of the large HP on the grid. In Case 2, the operation without the HP but with the residential PVs is simulated to notice potential overvoltage and reverse power flow issues from the PV generation. Case 3 considers the combined operation of the large HP and the residential PVs in order to assess their cooperation in order to restrain reverse power flow and increase local consumption inside the area. The cases are outlined in Table 5.2. The HPs in all cases operate under SOE control with limits of 0.5pu and 1pu while the storage is considered to be fully charged initially. All the cases are referring to a winter day.

Table 5.2: Study cases for large HP system

Case	HP	PVs
1	○	
2		○
3	○	○

5.3 Operation under different scenarios

5.3.1 Case 1

In this case, the initial grid with the large HP installed is considered to observe its impact. The results are shown in Figure 5.1.

As the storage is initially fully charged, its power is used to cover the demand. This is possible until around 9:00 when the SOE limit of 0.5pu is reached and the HP is turned on (Figure 5.1(d)) to charge the storage. The HP stays on until the storage is fully charged again which happens at 18:00. During this period, the power flowing through the substation transformer and the transformer loading rise significantly reaching maximum values of 285kW and 47% each, as can be seen in Figure 5.1(e) & Figure 5.1(a). At the same time, a drop can be observed at the voltages, as in Figure 5.1(c). After 18:00, when the HP turns off, the loading, power flow, and voltages are improved as the demand is now covered by the fully-charged large storage. The minimum voltage observed in the system is almost 0.96pu at feeder 6 which means that the 5% voltage limit that has been assumed in the studies is not violated with the use of the central HP. The maximum line loading is observed also at feeder 6 with a value of 26%.

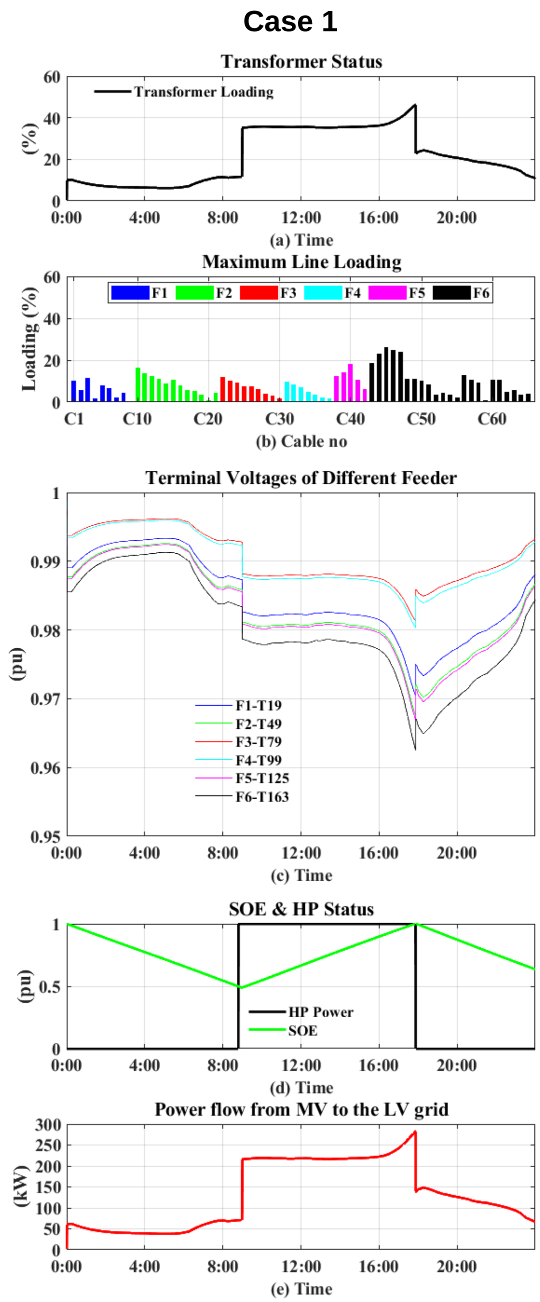


Figure 5.1: (a) Transformer loading, (b) maximum line loading, (c) minimum voltages at each feeder, (d) HP & storage state and (e) power flow through substation transformer for Case 1

5.3.2 Case 2

Here the simulation of the initial grid with the addition of residential PVs is done to clearly notice how they affect the operation. The results are illustrated in Figure 5.2.

Case 2

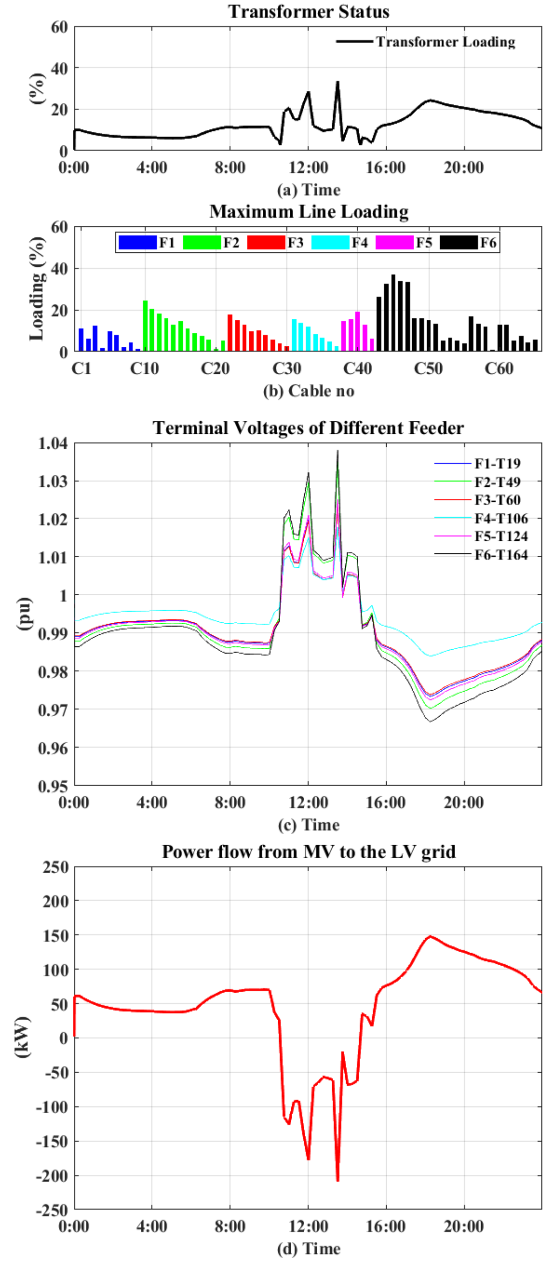


Figure 5.2: (a) Transformer loading, (b) maximum line loading, (c) minimum voltages at each feeder and (d) power flow through substation transformer for Case 2

As the PVs operate mainly from around 11:00 until 15:00, increase in voltage, loadings and reverse power flow is observed during this period. From Figure 5.2(a)-(b) it can be seen that the maximum transformer & line loadings are 34% and 37% respectively. Big reverse power flow occurs during the whole period of PV production as seen in Figure 5.1(e). The maximum amount of the reverse power flowing back to the MV is 210kW taking place between 13:00 and 14:00. As for the induced overvoltage, its maximum value reaches 1.04pu at feeder 6 while the lowest voltage on the same feeder is above 0.96pu. The biggest issue concerning the PV operation, in this case, is the reverse power flow as there is a big amount of excess energy that needs to be sent back to the MV level, which may be related to inefficiency and high cost for the utility.

5.3.3 Case 3

Here, the combined operation of the central HP and the residential PVs is analysed. The results associated with their joint performance are shown in Figure 5.3.

The combination of the HP and the PVs shows some improvement in the operation when comparing to the individual performance in Case 1 and Case 2. This improvement is present when the HP and the PVs operate together, from around 11:00 till after 15:00, as at this period the power produced from the PVs is consumed from the HP. That results in reduction of the transformer loading during this period as can be seen in Figure 5.3(a). However, after the PV production stops the HP needs to operate for few hours more so the loading increases again reaching the same maximum value as in Case 1. As seen in Figure 5.3(b), the maximum line loading is not reduced compared to Case 2 as the same PV power passes again through the lines to the HP. The overvoltage in the system is faintly improved, with a peak value of 1.035pu as seen in Figure 5.3(c) as there is still reverse power flowing in the lines of the grid causing overvoltage. However, the reverse power flow through the substation transformer is significantly decreased with a maximum value of 65kW (Figure 6.3(e)) instead of 210kW in Case 2 which means a decrease of approximately 70%. So, the utilization of the PV power and the self-consumption inside the area is highly increased while quite less power is needed to be sent back to the MV level meaning reduced cost for the utility and increased efficiency.

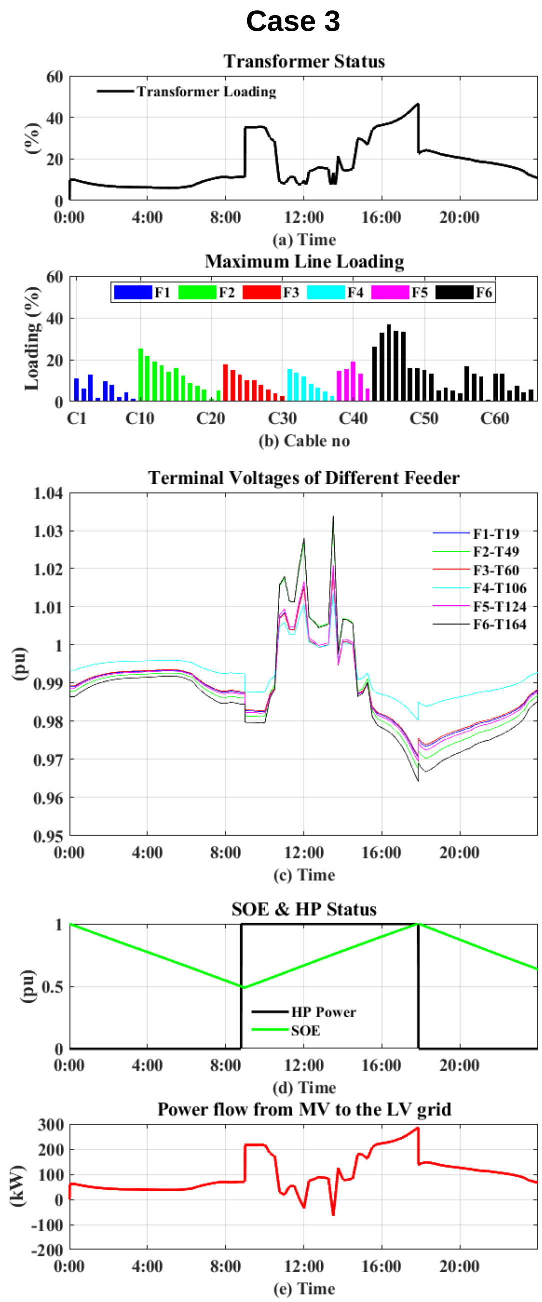


Figure 5.3: (a) Transformer loading, (b) maximum line loading, (c) minimum voltages at each feeder, (d) HP & storage state and (e) power flow through substation transformer for Case 3

5.4 Discussion of results

From Case 1 & Case 2 can be noticed that the individual operation of the HP and the PVs can have as impact the increase of the system loadings. The large HP effect on the undervoltage is not crucial even with the conservative 5% voltage limit considered and less compared to the effect of the residential HPs. This is due to the fact that the bus where the HP is located is a strong bus. The operation of the PVs is strongly related to increased overvoltage and reverse power flow issues. The reverse power flow in Case 2 was quite high which induces technical and economic problems to the grid and the associated utilities. The combination of the PVs & HP operation in Case 3, showed the potential of reducing the system loadings at the time of the PV production. The major effect of the joint operation can be noticed in the reduction of the reverse power flowing to the MV level, managing to restrain it by a percentage of 70% comparing to Case 2. This means increased self-consumption and efficiency as the PV power is effectively used for the operation of the HP to satisfy the heating demand of the area and as a result, there is reduced need for PV curtailment. On another notice, less amount of power needs to be sent to the MV level, which means reduced costs as the prices can be high when the production from renewables is large and there is excess generation available. The overvoltages in the grid were not markedly improved as there was still reverse power flowing in the lines of the grid.

5.5 Summary

The operation of a central HP with residential PVs has been assessed. The main benefit of the combined operation was the restriction of reverse power flow to the MV grid and the increase of local consumption by utilizing the PV power for the HP. During the time period of simultaneous HP & PV operation improvement was noticed in the system loadings. The voltages were not affected noticeably by the HP as it was located on a strong bus.

6 Conclusion

6.1 General conclusions & discussion

The aim of the studies in this project was to assess the effect of HPs to the electrical power system and to investigate their capability to participate in the future power grid and enhance the grid operation by providing flexibility in cooperation with local PV generation. Two different HP systems, a residential one and a central one, were inserted in a typical Danish LV grid along with residential PVs and their effect on the operation was analysed.

For the residential study, HPs of different rated power interconnected with hot water storages of different sizes were distributed to all the 164 residences along with individual PVs. An ON/OFF control was developed in order to maintain the customer comfort by keeping the water temperature above a certain limit. The control also monitored the voltage of the grid regulating it above a certain value while making sure no great loss of comfort occurs. The results showed that in order to have 100% penetration of HPs and to keep the voltage in a 5% limit the consumer comfort was slightly violated. For the cooperation of HPs with the PVs, the studies showed that the PVs can be used when their production is high to support the thermal load and charge the storage. The storage energy was used later in the day when the demand was also higher, satisfying the demand for the rest of the day and relieving the grid. In this way, increase of self-consumption and efficiency was achieved by a simple control that does not need complex systems to achieve communication between the different units which could result in cost increment. The storage size seemed to be crucial for effective operation as smaller size storages were not able to provide enough flexibility to assist the operation. For the summer case, the operational capability of HPs was reduced so their benefits in cooperation with PVs were limited.

For the large system, a large HP with a large storage was located at the LV side of the substation transformer in order to supply the whole area with heat. An ON/FF control was implemented here that takes into account the energy level of the tank and keeps it above a certain level. Results showed that the effect of the HP on the voltage was not big, as the grid did not face undervoltage issues even with the conservative 5% voltage limit. In cooperation with the PVs, the HP was successful at restraining the reverse power flow from the LV grid to the MV level. This resulted in the increase of local consumption inside the area and the reduction of necessity to send power back to the MV grid which can be related to high cost for the utility, especially at times when the renewable production is high. Also here, the power from the PVs stored in the tank could be used in the evening and night satisfying the heat demand. The induced overvoltage by PVs in the grid did not seem to reduce as reverse power flow was still present at the lines. The operation of PV in reactive power regulation could possibly be a more efficient solution in cases where this overvoltage would be a problem exceeding the grid limits.

Comparing the two different systems, it can be concluded that the effect on the voltage of the residential HPs was higher in comparison to the large one, as the latter was located at a strong bus. The application of the voltage control managed to restrain the voltage for the residential HPs causing a slight loss of comfort at some residences while in the central case there was no need for this action. In cooperation with the PVs both cases showed benefits, increasing the local consumption by utilizing more cheap clean energy. At the central system case, the reverse power flow could be limited at the substation point which reduces costs for sending the excess energy to the MV but as there will be still reverse power flow in the individual lines it would not be efficient in reducing overvoltage. For the operation in summer, residential studies showed reduced operation ability and flexibility which should also be expected for the central case as heating demand is lower and PV generation increased.

As a general conclusion, it can be said that HPs seem to aid the electric grid operation and provide the necessary flexibility when combined with storages. Local controllers that do not make necessary the employment of communication systems and large data handling can be applied to make beneficial operation possible. Other types of loads that are expected to be integrated in the future grid, like electric vehicles, can be controlled in a similar way and coordinated with HPs and renewable generation in order to potentially offer increased advantages to the grid operation. The operation of HPs together with renewables was validated that can work in a good way, managing to increase the use of renewable energy and self-consumption, supporting future clean energy goals without endangering the grid. Power to heat systems with the ability to boost the utilization of renewable energy can be considered of high importance in community-based energy projects that are quite relevant lately and can be highly beneficial to the society and for the EU energy goals. The size of the heat storage is clearly very important as provision of enough flexibility is only possible if the storage is large enough. Finally, as the heating needs are reduced in summer the flexibility provided is minimized and the employment of other measures should be considered for achieving flexible operation in summer periods.

6.2 Future work

Some ideas relevant for future work on the topic of this thesis are presented here:

- Application of converter-based HPs that can offer more operational ability. This way the power can be controlled in a continuous way and get adjusted to the current demand.
- Detailed modelling of stratified storage tanks that can offer increased efficiency.
- Modelling of PVs that includes reactive power regulation. So, the PVs can participate in the voltage control and assist the operation.
- Implementation of a central control that includes communication between different units in order to compare its performance to the local individual control.
- Taking into account the interaction of the HPs with the market. In the future smart grid, the participation of the flexible units in the energy market will be significant and will influence the control decisions.
- Addition of more types of distributed energy resources (e.g. electric vehicles, wind turbines). More flexible units are about to come in the LV grids in the future and their individual and combined effect should be properly analyzed and their operation coordinated.

BIBLIOGRAPHY

[1] Danish Ministry of Energy, Utilities and Climate, “Energy – for a green Denmark”, April 2018. [Online]. Available: https://en.efkm.dk/media/11857/energiudspillet_eng.pdf

[2] Energinet, “Environmental Report 2018”, 2018. [Online]. Available: https://en.energinet.dk/About-our-reports/Reports/Environmental-Report-2018

[3] The Partnership Smart Energy Networks, “Vision for smart energy in Denmark”, 2015. [Online]. Available: https://ens.dk/sites/ens.dk/files/Forskning_og_udvikling/vision_for_smart_energy_in_denmark_2015.pdf

[4] Danish Ministry of Climate, Energy and Building, “Smart grid strategy - the intelligent energy system of the future,” 2013. [Online]. Available: https://ens.dk/sites/ens.dk/files/Globalcooperation/smart_grid_strategy_eng.pdf

[5] Danish Energy Agency, “Regulation and planning of district heating in Denmark”, June 2017. [Online]. Available: https://ens.dk/sites/ens.dk/files/Globalcooperation/regulation_and_planning_of_district_heating_in_denmark.pdf

[6] Danish Energy Agency, “Denmark’s energy and climate outlook 2018”, 2018. [Online]. Available: https://ens.dk/sites/ens.dk/files/Basisfremskrivning/deco18.pdf

[7] I.D. De Cerio Mendaza, B. Bak-Jensen, Z. Chen, A. Jensen, "Stochastic impact assessment of the heating and transportation systems electrification on LV grids", IEEE PES Innovative Smart Grid Technologies Europe, pp. 1-6, Oct 2014.

[8] Danish Energy Regulatory Authority, “National Report Denmark 2017”. [Online]. Available:http://forsyningstilsynet.dk/fileadmin/Filer/Information/Diverse_publikationer_og_artikler/National_Report_2017_DERA.pdf

[9] https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/energy-infomaps

[10] T. Ackermann, V. Knyazkin, "Interaction of distributed generation and the distribution network: Operation aspects", Proc. PES T&D Conf. Asia Pacific, vol. 2, 2002

[11] Energinet, Distributed Generation Trends and Regulation: The Danish Experience, Presentation, June 6th 2014, Cambridge

[12] www.smartvarme.dk

[13] B. Biegel, P. Andersen, T. S. Pedersen, K. M. Nielsen, J. Stoustrup and L. H. Hansen, "Electricity market optimization of heat pump portfolio", 2013 IEEE International Conference on Control Applications (CCA), Hyderabad, 2013, pp. 294-301

[14] A. Bloess, W.P. Schill, A. Zerrahn, “Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials”, Applied Energy, Volume 212, 2018, pp. 1611-1626

[15] Fraunhofer IFAM, “Flexibility from heat for power systems – future applications for CHP and P2H”, Presentation, July 15th 2014, University of Hamburg

[16] M. Kuprat, M. Bendig and K. Pfeiffer, "Possible role of power-to-heat and power-to-gas as flexible loads in German medium voltage networks", Frontiers in Energy, vol. 11, no. 2, pp. 135-145, 2017

[17] D. Fischer, H. Madani, “On heat pumps in smart grids: A review”, Renewable and Sustainable Energy Reviews, Volume 70, 2017, pp. 342-357

[18] A. Schäfer, P. Baumanns and A. Moser, "Modelling heat pumps as combined heat and power plants in energy generation planning," 2012 IEEE Energytech, Cleveland, OH, 2012, pp. 1-6

[19] P. J. Douglass, I. Trintis and S. Munk-Nielsen, "Voltage unbalance compensation with smart three-phase loads", 2016 Power Systems Computation Conference (PSCC), Genoa, 2016, pp. 1-7

[20] Karlsson F., "Capacity control of residential heat pump heating systems, Ph.D. Dissertation", Chalmers University of Technology, Sweden, 2007.

[21] W. J. B. Heffernan, N. R. Watson, R. Buehler and J. D. Watson, "Harmonic performance of heat-pumps", The Journal of Engineering, vol. 2013, no. 9, pp. 31-44, 9 2013

[22] M. Arnold, W. Friede and J. Myrzik, "Investigations in low voltage distribution grids with a high penetration of distributed generation and heat pumps," 2013 48th International Universities' Power Engineering Conference (UPEC), Dublin, 2013, pp. 1-6

[23] M. Akmal, B. Fox, J. D. Morrow and T. Littler, "Impact of heat pump load on distribution networks," in IET Generation, Transmission & Distribution, vol. 8, no. 12, pp. 2065-2073, 12 2014

[24] L. Gelazanskas, and K. A.A. Gamage, "Demand side management in smart grid: A review and proposals for future direction", Sustainable Cities and Society, 11, pp. 22-30

[25] P. Pavani, B. Bak-Jensen and J. R. Pillai, "Impact of demand side management in active distribution networks," 2017 IEEE Power & Energy Society General Meeting, Chicago, IL, 2017, pp. 1-5

[26] Eurelectric, "Demand Response", 2015. [Online]. Available: https://www3.eurelectric.org/media/176935/demand-response-brochure-11-05-final-lr-2015-2501-0002-01-e.pdf

[27] T. Buber, S. von Roon, A. Gruber and J. Conrad, "Demand Response potential of electrical heat pumps and electric storage heaters", IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, 2013, pp. 8028-8032

[28] L. Kreuder, C. Spataru, "Assessing demand response with heat pumps for efficient grid operation in smart grids", Sustainable Cities and Society, Volume 19, 2015, pp. 136-143

[29] M. Brunner, K. Rudion, S. Tenbohlen, "Voltage support in distribution grids using heat pumps", CIRED 23th International Conference on Electricity Distribution, Lyon, 15-18 June

[30] C. Brandoni, G. Ciriachi, F. Polonara and A. Arteconi, "Heat pumps and demand side management for renewable energy integration in sustainable communities," 2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE), Pattaya, 2014, pp. 1-7

[31] U. Uslu, B. Zhang, J. R. Pillai, S. K. Chaudhary, B. Bak-Jensen and I. Diaz de Cerio Mendaza, "Participation of flexible loads in load frequency control to support high wind penetration", 2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia), Melbourne, VIC, 2016, pp. 442-447

[32] L.R. Rodríguez, J.S. Ramos, S.A, Domínguez, U. Eicker, "Contributions of heat pumps to demand response: A case study of a plus-energy dwelling", Applied Energy, Volume 214, 2018, pp. 191-204

[33] Energinet, "Regulation A: Principles for the electricity market", 2007

[34] Energinet, "Market modet 2.0, Final report", 2015

[35] Viessmann, Technical data manuals, https://www.viessmann-us.com/

[36] I. D. de Cerio Mendaza, I. G. Szczesny, J. R. Pillai and B. Bak-Jensen, "Flexible Demand Control to Enhance the Dynamic Operation of Low Voltage Networks", in IEEE Transactions on Smart Grid, vol. 6, no. 2, pp. 705-715, March 2015.

[37] R. Sinha, B. B. Jensen, J. R. Pillai, C. Bojesen and B. Moller-Jensen, "Modelling of hot water storage tank for electric grid integration and demand response control". 2017

52nd International Universities Power Engineering Conference (UPEC), Heraklion, 2017, pp. 1-6.
[38] http://systemlab.dk/smartvarme/teknologikatalog.pdf
[39] Danish Energy Agency and Energinet, “Technology data for energy plants”, 2012. [Online]. Available: https://ens.dk/sites/ens.dk/files/Analyser/c_teknologikatalog_for_individuelle_varmeanlaeg_og_energitransport_2012.pdf
[40] R. Sinha, B. Bak-Jensen and J. R. Pillai, “Autonomous Controller for Flexible Operation of Heat Pumps in Low-Voltage Distribution Network”. Energies, 12(8), p.1482, 2019
[41] B. P. Bhattarai et al., "Active control of thermostatic loads for economic and technical support to distribution grids", 2016 IEEE Power and Energy Society General Meeting (PESGM), Boston, MA, 2016, pp. 1-5
[42] European Association for Storage of Energy (EASE), “Thermal hot water storage”. [Online]. Available: http://ease-storage.eu/wpcontent/uploads/2016/03/EASE_TD_HotWater.pdf
[43] R. Sinha, B. B. Jensen, J. R. Pillai and B. Moller-Jensen, “Unleashing Flexibility from Electric Boilers and Heat Pumps in Danish Residential Distribution Network”, CIGRE 2018, Paris, France

APPENDIX A

LV GRID DATA

Transformer data				
630kVA	10/0.4kV	u_k=4.66%	$P_{loss,cu}$=6.5kW	$P_{loss,Fe}$=868W

Cable data		
Cables	Resistance (Ω/km)	Reactance (Ω/km)
C1, C10-C14, C21-C24, C30, C31-C36, C37, C42	0.208	0.086
C2-C6, C39-C41	0.642	0.087
C7	0.321	0.086
C8	0.526	0.083
C9, C59, C60, C62, C63	1.201	0.094
C15-C20, C25-C29, C38, C43	0.321	0.086
C44-C50, C52, C53, C55-C58	0.642	0.09
C51, C54, C61, C64	1.141	0.09
terminal lines	1.81	0.094