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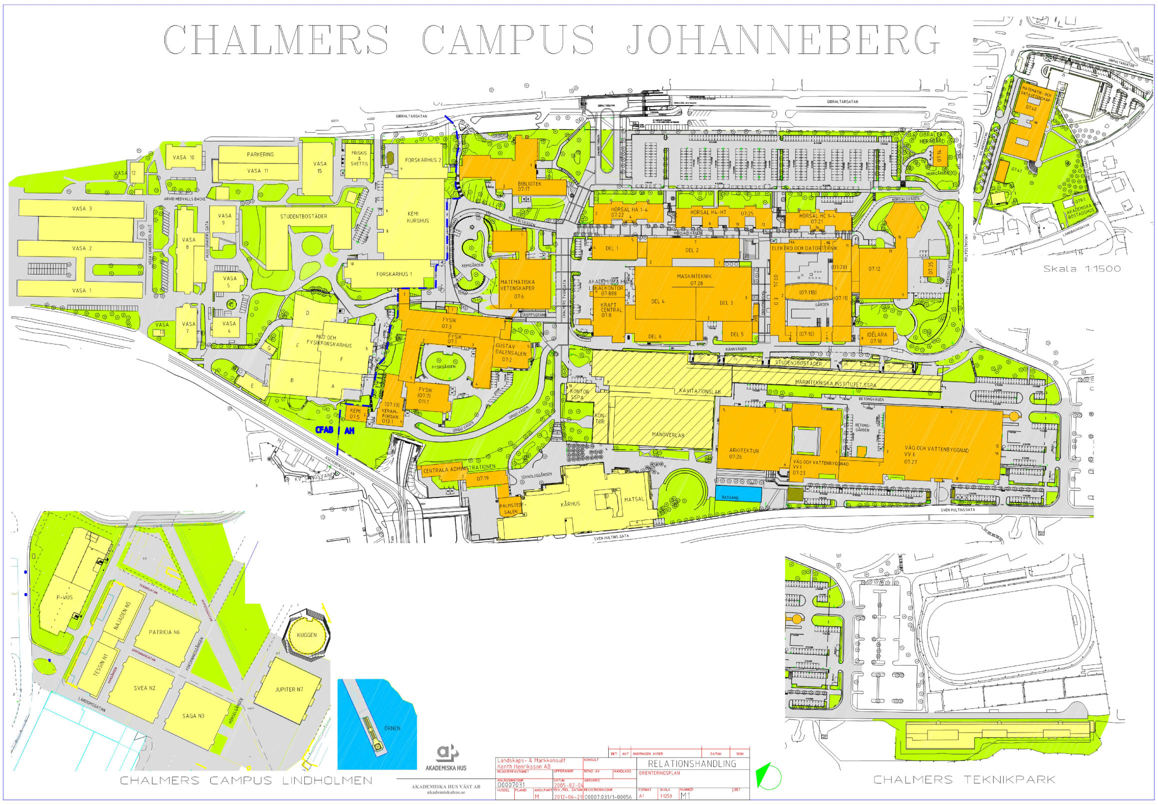

Evaluation of potential benefits and investment strategies of the integrated heating-and-electricity supply systems: The case of Chalmers campus

Master's thesis in Electric Power Division

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Department of Electrical Engineering
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Abstract

The aim of the thesis is analysis of Chalmers' district energy systems i.e. heating and electrical network with the possibility to invest in different energy alternatives with the goal of developing an integrated simulation model of electrical and heating systems to obtain possible synergies between different energy carriers. Possibilities of installation of Heat Pump (HP), Thermal Energy Storage (TES), Combined Heat and Power (CHP) plant, battery and solar PV were analyzed simultaneously and synergy between them was established. HP and CHP provided the opportunity to integrate the heating system with the electricity distribution network. Determination of the maximum capacity of energy alternatives based on their annualized investment cost is part of investigation. An optimization and modeling tool, General Algebraic Modeling System (GAMS) was used to develop a linear programming model to optimize the investments in different energy alternatives with the objective being minimization of total system cost. Sensitivity analysis with different parameters was made in terms of peak energy and energy reduction potential from grid and total cost savings potential on an annual basis.

Results from the modeling shows reduction potential in heat peaks and heat energy in the range of 82-87% and 95-97% respectively for almost all of cases considered when energy alternatives are present in Chalmers campus as compared to present situation. Exception was found in the case of high investment cost of 10% and initial investment limitation of 5 million SEK case, where reduction potential of heat peak were 74% and 49% respectively and corresponding reduction potential in heat energy over the year were 89% and 42% respectively. Electricity peak and electrical energy consumed over the year are increased in majority of the cases, but the percentage increase on the electricity side is much less than percentage decrease on the heat side. There is a net decrease in total annual cost in the range of 13-28% with inclusion of energy alternatives i.e. sum of running cost and annualized investment cost is less in presence of energy alternatives under all set of simulation conditions in the present thesis than running cost without the energy alternatives in the present situation. In addition to the above, HPs were recommended investments in all scenarios and sensitivities compared in this analysis. TESs and CHPs were present in most of the scenarios in the same order. Solar PVs make contribution when their prices were reduced by 90% as compared to the price considered in the project. Batteries make negligible contribution when they are available at 10% of present pricing in the presence of solar PVs in the model.

Keywords: heat pump, thermal energy storage, combined heat and power, energy alternative, energy carriers, investment model, total system cost minimization, annualized investment cost, sensitivity analysis, total cost savings potential.

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A.1 Demand response I

Nomenclature

Abbreviations	
A	Annualized investment cost
BITES	Building inertia thermal energy storage
CHP	Combined heat and power
COP	Co-efficient of performance
CRF	Capital recovery factor
DER-CAM	Distributed energy resources customer adoption model
DER	Distributed energy resources
DH	District heating
EES	Electrical energy storage
EU	European union
EV	Electric vehicle
FED	Fossil free energy districts
GAMS	General algebraic modelling system
HP	Heat pump
HWT	Hot water tank
LP	Linear programming
MILP	Mixed integer linear programming
PV	Photovoltaic
TC	Total cost over the year
TES	Thermal energy storage
UPS	Uninterruptible power source
Symbols	
α_{CHP}	ratio between electricity and heat produced from CHP
η_{CHP}	total efficiency of CHP
η_{eh}	efficiency of electric heater
$\eta_{el,CHP}$	electrical efficiency of CHP plant
$\eta_{heat,CHP}$	heat efficiency of CHP plant
cap	capacity of energy alternative (MW/MWh)
$capa_{battery}$	capacity of battery (MWh)
$capa_{CHP}$	capacity of CHP (MW)
$capa_{HP}$	capacity of HP (MW)
$capa_{PV}$	capacity of solar PV (MW)
$capa_{TES}$	capacity of TES (MWh)
chr_{TES}	charging efficiency of TES
$cost$	cost of energy alternative (SEK/MW or SEK/MWh)
dis_{TES}	discharging efficiency of TES

$E_{battery}$	energy available in battery at any instance (MWh)
E_{TES}	energy available in TES at any instance (MWh)
El_{out}	electricity output from CHP
$elec_{price}$	electricity price per MW electricity consumed from grid (SEK/MW)
$fuel_{price}$	price of fuel used in CHP (SEK/MW)
$heat_{demand}$	heat demand from buildings (MW)
$heat_{price}$	heat price per MW heat consumed from grid (SEK/MW)
$Investment_{initial}$	sum total of initial investment in all energy alternatives (SEK)
$limit_{peak}$	limit on heat/electric power imported from grid (MW)
$losses$	amount of power available after losses consideration in transmission lines (MW)
$maxchrrate_{battery}$	maximum charge rate of battery (MWh/h)
$maxchrrate_{TES}$	maximum charge rate of TES
$maxdisrate_{battery}$	maximum discharge rate of battery (MWh/h)
$maxdisrate_{TES}$	maximum discharge rate of TES
P_{CHP}	power input by CHP fuel (MW)
$P_{DH_{max}}$	maximum value DH power from grid in a month (MW)
P_{DH}	heat power consumed from grid (MW)
$P_{elec_{max}}$	maximum value of electric power from grid in a month (MW)
P_{elec}	electrical power consumed from grid (MW)
P_{HP}	electricity consumed by HP (MWh)
P_{PV}	power contribution from PV (MW)
$P_{tariff_{DH}}$	tariff for maximum DH power from grid in a month (SEK/MW)
$P_{tariff_{elec}}$	tariff for maximum electric power from grid in a month (SEK/MW)
$Pchr_{battery}$	charging power of battery (MW)
$Pchr_{TES}$	charging power to TES at any instance (MW)
$Pdis_{batery}$	discharging power of battery (MW)
$Pdis_{TES}$	discharging power from TES at any instance (MW)
$PeakDH_{grid}$	peak heat power from the grid over the year (MW)
$Peakelec_{grid}$	peak electric power from the grid over the year (MW)
$Price$	initial investment cost in energy alternative (SEK)
PV_{elec}	electrical power output from 1 MW capacity solar PV (MW)
Q_H	heat generated by HP
$trans_{elec}$	actual electrical transmission over a line (MW)
$trans_{heat}$	actual heat transmission over a line (MW)
$transcapa_{elec}$	electrical transmission capacity of a particular line in the network(MW)
$transcapa_{heat}$	heat transmission capacity of a particular line in the network (MW)
$transmission_{limit}$	transmission limit from local distribution grid (MW)
$Useful_{heat,out}$	heat output from CHP
W	work done on HP/electric power consumed by HP
Units	
GWh	Gigawatt hour
kW	Kilowatt
MWh	Megawatt hour
MW	Megawatt
TJ	terajoule

TWh	Terawatt hour
W	Watt
Notations	
'm'	number of months of the year i.e. 12
'n'	number of hours of the year i.e. 8784
'o'	number of buildings analyzed i.e. 12
'tech'	number of energy alternatives analyzed i.e. HP, CHP. TES, battery and solar PV

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A.1 Inherent physical property of the buildings III

1

Background and motivations

As per the Intergovernmental Panel on Climate Change-"Scientific evidence for warming of climate system is unequivocal". Rapid climate change is both evident and compelling [1]. For example: Global sea level rise in last century was 17 centimeters. But, the rate of rise in last decade is double that of last century [2]. Similarly, global temperature is on the rise. The year 2015 experienced more than 1°C higher than 1880-1899 average [3]. Climate change and energy use are highly inter-related. Increase in temperature shall lead to increase in energy use in most countries. In US, if temperature rises by 2.5 °C by the end of the century, net expenditure on cooling and heating would increase by 10% as compared to 1990 level [4]. At European level, gross electricity production in the EU-28 increased from 2595 TWh in 1990 to 3387 TWh in 2008 [5]. But, the good news is, electricity production is on a decreasing trend since 2010 with steep rise in production from renewable sources, a 48% increase by 2014 compared to 5 years before [5]. 2014 also experienced least heat production in EU-28 as compared to 24 years before i.e. 2.3 million TJ [5]. Production of heat from coal and oil is on a decreasing trend with 56% and 77% respective decrease in 2014 production as compared to 1990 level [5]. Sweden has an electricity consumption of 149 TWh in 2013 with 48% coming from renewable sources like hydropower and wind power, a decrease of 8% as compared to previous year [6]. District heating in 2013 utilized 58% of the total energy use in dwelling and residential premises [6]. Due to improved technology, there is a continuous decreasing trend of distribution and conversion losses over the years [6].

The electricity grid is in balance at all the time i.e production has to meet the demand. This implies that the system is synchronous and becomes unstable if demand doesn't exactly equals production. To reduce energy consumption, instantaneous energy i.e. power consumed should be associated with price. Also, the system would be made such that during high price hours, unnecessary loads can be curtailed or it should immediately switch to local production. Heat and electricity interaction should allow the future energy system to determine the optimum combination between the two to minimize total energy. For example, instantaneous price of heat and electricity will decide how much of which energy source is consumed so that present energy requirement is not compromised but energy cost is minimum. The same principle can also be applied to total energy consumption. If at a certain instance, electricity requirement is high with all loads of utmost importance then, the system should look for curtailing heating loads instead, so that energy consumption in aggregate becomes optimum. Similarly priority can be given to reduction of total primary energy use or CO_2 emission.

Göteborg Energi is mainly responsible for supply of heat and electricity within Gothenburg. It has created forums on a local level where customers focus on price dialogues, best practices in energy efficiency and interplay between heating, cooling and power supply system. The present research work is part of EU-project called Fossil Free Energy Districts or FED. The aim of Göteborg Energi within this project is integrating electricity, heating, cooling and a local energy market and trading system functioning in symbiosis with the existing energy market. It will also look to create cost effective energy improvement solutions, thus avoiding high rental cost for economically disadvantaged citizens [7].

The primary property owners of the buildings that make up the Chalmers campus i.e. Akademiska Hus and Chalmers Fastigheter have plans to make long term investment as part of FED project to achieve the objective of local energy market and trading system. Chalmers university campus has an extensive network of District Heating (DH) directly connected to almost every building alongwith distributed electrical network. There is a strong potential for energy savings if energy from the hot stream can be utilized in the cold stream and vice-versa. For example: exhaust heat from cooling system can serve as a source of waste heat for heating systems like HPs. But analysis of cooling system is beyond the scope of the present research work. Chalmers also has heat only boilers, a CHP plant (currently non-operational), HPs and solar photovoltaics (installed on roofs and facade of some buildings) for supplying heat and electricity to Chalmers.

Within the purview of FED project, there are plans for investment in hot water TES, HPs, CHPs, batteries and solar PVs. Thermal Energy Storage (TES) is planned to be installed, which will allow the system to shift load within a certain time frame. This will also reduce the heating system running cost annually by reducing heat demand from grid during peak price hours. HP will provide a cheap source of upgrading low grade waste heat to high grade useful heat. They will mainly utilize the difference in pricing between heat and electricity at different hours, the greater the difference, the larger their utility. CHP shall consume fuel in form of wood pellets and produce heat and electricity. Their utility largely depends upon difference between the combined pricing of heat and electricity from grid and fuel price. Batteries are similar to TES, but work on the electrical side, utilizing difference in nord pool spot pricing at difference instance. But the round cycle efficiency of both TES and battery being less than 1, makes them net consumer of heat and electricity respectively. Solar PVs are solely dependent strength of solar irradiance on the photovoltaic panel. It has nothing to do with electricity or heat pricing or availability of other energy alternatives. Other, energy alternatives have to adjust their production according to solar PV output as they have almost zero running cost. Its utility may be affected if there is price difference between electricity bought and sold to the grid. Hence, optimum sizing is important. The aim of the project is to develop a model to analyze the energy saving potential and to find out the possibilities for making profitable investment in the above mentioned energy alternatives. The present research work has been subdivided into sections: Objectives, specific tasks and scope, explained exactly in the same order.

1.1 Objectives

The present research work is carried out with following objectives in mind:

1. Determination of optimum capacity of energy alternatives: Finding the optimum capacity of HP, CHP, TES, batteries and solar PVs taking into consideration investment cost with the target to reduce the total system cost i.e. sum of running and annualized investment cost.
2. Investigation of interaction between heat and electrical system: Finding possible synergies between District Heating (DH) system at one end and electrical system at the other to determine optimum investment for improvement of overall efficiency.
3. Determine the peak reduction potential: Peak energy, in general, mostly comes from non-renewable sources which are not environment friendly. In presence of energy alternatives there are opportunities for reduction of peak energy consumption from the local distribution grid. Combination of different criteria can reduce the peak to different amount. It is therefore interesting to analyze the energy peaks under different set of simulation condition.
4. Competition between different technologies: Allowing both heating and electrical energy alternatives to compare and compete amongst themselves under different set of conditions to decide the best technology both under different situations.
5. Effort to meet objective of the FED project: The FED project has the objective of making local production free from fossils and certain limitations on the amount of peak energy imported. These objectives are aimed to be fulfilled as part of this project.

1.2 Specific tasks

In order to achieve the objective mentioned above, the overall task is segregated to following specific tasks:

1. Data collection: Collecting data for heat and electricity imported from grid on an annual basis with hourly resolution from Göteborg Energi (and other companies providing energy to Chalmers distribution grid) and creating a database for further model development.
2. Chalmers campus overall model development: Individual building optimum operation condition might be different from entire campus model. It is important to analyze the overall system energy profile. In this phase, interconnection between buildings in terms of district heating network for heating side and electrical distribution network for electrical side within Chalmers campus allows for examination of important parameters like peak power, total energy, total cost, etc.
3. Analysis of possible improvements of the energy system at the campus: Determination of the probable synergy instances between the electrical and heating system. By utilizing the integrated models, a simulation study shall be performed to improve the operation of the energy system and to determine

profitable investments that could improve the efficiency of the system.
4. Dimensioning of the energy alternatives: Under different set of conditions, different energy alternatives will have different capacity depending upon technology's investment cost. This shall help Akademiska Hus in knowing optimal investment in each technology.

1.3 Scope

To provide information to owners of Chalmers campus buildings i.e. Akademiska Hus and Chalmers Fastigheter regarding recommended capacity investment and possible benefits of different energy alternatives option e.g. TES, CHP and HP as heating alternatives and CHP, solar PVs and batteries as electrical alternatives under different sets of simulation conditions. The results from present simulations also tells about the peak reduction potential and total annual cost in each scenario. Comparison between different scenario on different yardsticks shall help the owners to quickly decide on the capacity of different alternatives and corresponding investment required. They are also made aware that the investment choice from this research reflects the minimum cost with present heat and electricity price tariff and cost of energy alternatives. The investment choice in the present scenario can be radically different from the future scenario, where average yearly price is expected to vary more rapidly than present. Chalmers buildings owners have to also keep in mind that, proper execution is required from their end as different energy alternatives have different installation time. Price used for calculation now, will be thus differ from the price of the technology during actual implementation in the future. Nevertheless, the goal is to achieve the objectives decided as part of FED project at minimum cost.

1.4 Thesis Outline

The thesis work is subdivided into six chapters including the present background and motivation chapter. The other chapters are divided in following way:

- Chapter 2 deals with introduction to different energy alternatives used in the present thesis and few literature review from which inspiration was drawn to carry out the work.
- Chapter 3 is dedicated to formulation of total cost minimization linear model using optimization tool called general algebraic modelling system (GAMS).
- Chapter 4 discusses results from the model under different set of simulation conditions and interprets the results.
- Chapter 5 presents discussion on strength and weaknesses with network constraints applied to the model explaining explicitly for all energy alternatives considered.
- Chapter 6 presents conclusion to the present work and possible future work using the existing model as base case.

2
Introduction and Literature review

This chapter deals with background and introduction to different energy alternatives used in the present thesis and few literature review from which inspiration was drawn to carry on this project.

2.1 Introduction

We live in a highly energy intensive society. Energy is required both for heating during cold outdoor temperature and cooling during high ambient temperature. In addition to this, energy is also needed for lighting, appliance and transport. Swedish energy system is partly based on renewables such as water, wind and bio-fuel available domestically. A large proportion of energy supplied in Sweden is mainly due to import of nuclear fuel for electricity production and oil and natural gas for transportation system. Apart from nuclear, hydro-power also makes a significant contribution to Swedish electricity system. Share of wind power is steadily increasing and bio-fuel is coming to fore both for electricity and heat production. Energy use in residential and service sector in short term is primarily affected by outdoor temperature and a large proportion of this comes from heating. Energy used for space heating and hot water in households and non-residential buildings in 2013 totalled 80 TWh, which represents 55% of total energy use within the sector. This huge market is further subdivided into DH, electric heating, heat pumps and bio-fuel boilers. Electricity is the most common form of space and water heating in one and two dwelling buildings, totalling 15 TWh in 2013, followed by biomass with 11 TWh. In non-residential premises, DH represents the most common form of used energy for space and water heating, contributing 18 TWh in 2013, followed by electricity with only 3.3 TWh [6].

Heating market is both energy and resource efficient, because of the high value of overall efficiency associated with conversion of fuel to heat. This make DH more environmental friendly as compared to electricity production. Existing buildings have high potential for energy consumption reduction. Energy demand for heating of existing buildings can be slashed to half by 2050 as compared to 1995 level, if the potential is fully realized. Factors like policy instruments, capital investments and new business models, have an influence on how much and how fast of this reduction will actually happen. New buildings are energy efficient as compared to existing buildings, shall represent only 10-15% of total energy demand by 2050. Since this is a comparatively smaller part, there is far more importance of existing buildings as compared to new ones in a long term for heating market development [8].

Part of the focus of this thesis is on district heating. Before analyzing the present DH network, it is important to realize what led to the formulation of present scenario for district heating. The historical development of DH system within Sweden is discussed in this paragraph, but the scenario was almost the same for most countries within Europe. Around 100 years ago, single-family houses used to have a lot of fireplaces, mainly stoves. This was followed by central heating with only one fireplace as heating source. After 1970s crisis, oil was replaced by nuclear power and electric heating. State subsidies helped smooth transition from oil to electricity. When the climate change issue came to fore, alternative energy sources were evaluated and increased in use as a way to conserve electricity. Sweden had an expansion of bio-fuels, heat pumps and district heating. The situation of multifamily houses was almost the same till 1960s. DH expansion after that, was mainly due to the need to replace oil-fired boilers with a production system having few boilers. This led to replacement of more expensive heavy oil with light fuel oil. After 1970s oil crisis, DH continued to grow and new types of energy sources were introduced. Initially coal and electricity was followed by bio-fuels and waste. Policy instruments played a crucial role in this development. As of 2013, 90% of multifamily houses and 70% of the premises were connected to DH network [8].

The other part of the thesis focuses on the electrical system. Hydro-power and nuclear power mainly contribute to Swedish electricity supply. Since 2000s contribution from renewables mainly wind is increasing. But, actual energy supply from these sources is still low even though there is lot of capacity addition. Total electricity production in Sweden amounted to 143 TWh in 2013, 8% less than the year before. It was composed of 41% hydro-power, 43% nuclear power, 7% wind power and the remaining 10% from combustion-based production, which mainly takes place in CHP plants and within industry. This production trend sector-wise is in stark contrast with production trend in 1970s, where 69% of electricity came from hydro-power and 20% from oil-fired condensing power plants. This shows that electricity consumption has increased a lot over the years and the hydropower production has reached almost its full utlilization potential long back, so the extra energy requirement is covered by other sources. Electricity produced from solar PV still accounts for very small proportion of total energy supply. For example: the total energy coming from solar in 2014 was 57 GWh, which is 0.04% of Sweden's total electricity production [6].

2020 climate and energy package is a binding legislation to ensure the EU meets its climate and energy targets for the year 2020. The package mainly has three key targets: 20% reduction in greenhouse gas emissions (as compared to 1990 levels), 20% of EU energy from renewables and 20% in energy efficiency [9]. Similarly, EU countries have agreed on a new 2030 framework for climate and energy, including EU-wide targets and policy objectives for the period between 2020 and 2030. These targets aim to achieve a more competitive, secure and sustainable energy system for EU and help to meet its long-term 2050 greenhouse gas emission reduction target. The targets are: 40% cut in greenhouse gas emissions compared to 1990 levels, at least 27% share of renewable energy consumption and at least 27 % energy savings compared with the business-as-usual scenario [10].

The wider stakeholders involved in the preparation and design of the Fossil Energy free Districts (FED) are: Göteborg Energi, Chalmers University of Technology, Johanneberg Science Park, Business Region Göteborg, Ericsson, Chalmers Fastigheter and Akademiska Hus. The aim of the local energy utility, Göteborg Energi within is project is to develop city wide district heating network with focus on price dialogues, best practices in energy efficiency and the interplay between heating, cooling and power supply innovation [7]. The project aims to deliver:

1. A grid-connected local energy system with demand and supply in balance, integrating electricity, heating and cooling.
2. A local energy market and trading system functioning in symbiosis with the existing energy markets.

This project has ambitions to achieve following environmental improvements:

1. local energy production 100% fossil free.
2. 80% less fossil energy peaks exported (i.e. energy peaks from the microgrid causing external use of fossil energy).
3. 30% less energy imported from the overlying system (as an effect of increased internal use of recycled energy, efficiency, and local generation).

In line with the above steep targets, the aim of this thesis within the ambit of EU project is to make efforts to develop a smart district energy system combining heat and electrical distribution network of Chalmers with optimal investment in HP, TES, CHP, solar PV and batteries. On a wider scale there is also possibility to investigate impact of demand response from buildings, solar shading, adding connection to the existing DH network and utilization of buildings as agents for energy interaction, but these are beyond the scope of present thesis work.

The following sections describes each energy alternatives in details alongwith energy distribution network.

2.2 Distributed energy generation

There are several methods to generate energy within a district heating and electricity network. For investigation of the possibility of utilization of energy network as a micro grid, it is necessary to have the right combination of different distributed energy generation sources, so as to have minimization of total cost while determining the optimum investment in each of them. This is also part of present research work. At Chalmers, there is currently two source of heat generation i.e. heat only boiler and HP and one source of electricity generation i.e. solar PV. Akademiska hus is planning to make investment in some of the below mentioned sources with the following objective in mind:

1. Reduce dependency on Göteborg Energi for supply of heat on an annual basis. There could be energy interaction both ways during different parts of the year. Effort is to make the net consumption from grid zero on an yearly scale.
2. The carbon dioxide peaks resulting from the operation of the energy system (including import/export) is planned to reduced.[7].

2.2.1 Heat Pumps

Heat can only be transferred from a region of higher potential to lower potential i.e. higher temperature to a lower temperature region just as electric current. When work is done on a thermodynamic cycle, it can transfer heat in opposite direction. A system which has the capability to transfer heat from a low temperature region to a higher temperature region is called a Heat Pump [11]. HP raises heat from a low-temperature level (low-grade heat source) to a higher temperature level (heat sink). It has the ability to transform low temperature waste heat (generally drawn from ground or air) to high temperature useful heat with the help of electricity (or heat), thus upgrading its quality. The efficiency or 'η' of a heat pump is measured by coefficient of performance (COP). It is defined as useful heat delivered by heat pump to driving energy consumption. COP equation is as follows:

$$COP = \frac{Q_H}{W} \tag{2.1}$$

where, Q_H is heat generated by HP, W is work done on the system or useful energy consumed by HP

Since, the COP depends principally on the working temperature, they are most efficient when operated over a narrow temperature range. The figure 2.1 below represents a simple schematics of a HP. Work is done on the system through compressor. Desired work output is warm indoor temperature.

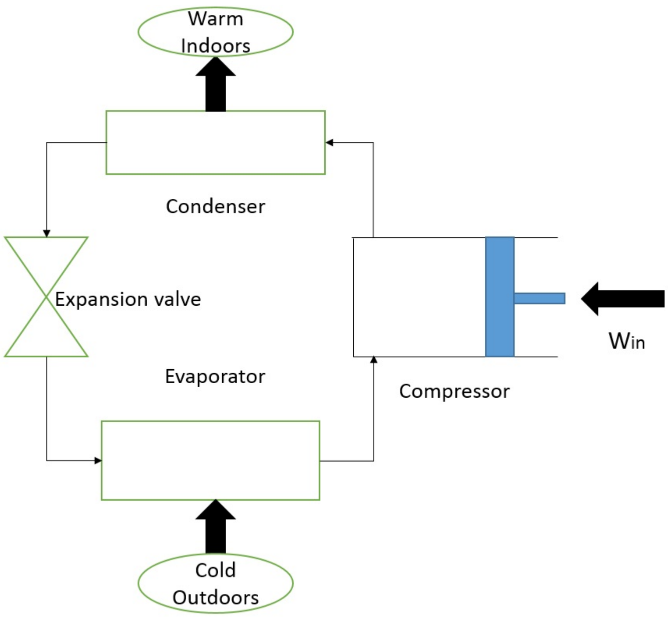

Figure 2.1: Simplified energy flow diagram for a HP unit

The primary reason for gain in importance of HP especially in single family houses is the high value efficiency as compared to electric heaters. Improvement of COP over the years has led to further decline of electricity use in heating. As of 2014, there were more than one million heat pumps installed in Sweden, mainly in single-family houses [8]. COP of HP can be improved by more efficient heat exchangers and compressors. Also, the heating system can be modified to utilize lower temperature on the warm side, improving the COP even further. Theoretically COP of 6 or more is achievable, but lot depend on improvement of technology along with energy prices. High energy price can stimulate rapid development of advanced HP systems [8].

There are primarily three types of heat pumps based on source of low quality heat: air-to-air, water source, geothermal. Air-source heat pump transferring heat between our house and outside air is the most common type of heat pump Geothermal (ground-source or water source) heat pumps achieve higher efficiencies by transferring heat between our house and the ground or nearby water source. These heat pumps are costly to install, but have fairly low operating cost because they use relatively constant ground or water temperatures. Geothermal (or ground source) heat pumps can reduce energy use by 30-60%, control humidity, sturdy operation and reliable. But they are highly dependent upon size of heating space, the subsoil and the landscape. Ground source or water source heat pumps can be used in more extreme climates than air-source heat pumps [12].

2.2.2 Thermal Energy Storage

Thermal Energy Storage (TES) refers to technology that allows the transfer or storage of heat energy. How much energy can be stored in TES depends on the medium used for storage and its size. The amount of energy stored in TES at any instant is defined by a term called State Of Charge or SOC.

TES has the advantage of load shifting both on short term of single day to long term of seasons, which helps to remove peaks in energy consumption and reduce the average price on an annual basis. Charging and discharging of TES is associated with charging efficiency and discharging efficiency respectively. Thus, from a round cycle point of view there is loss of energy. So, TES is useful in cases where there is large variation between high price and low price of a heat network, so as to overcome losses associated with overall cycle.

2.2.3 Combined Heat and Power Plant

Combined Heat and Power (CHP) utilizes fuel to produce both heat and electricity in one single, highly efficient process. In contrast to normal steam based electric power plant, exhaust heat from turbine in CHP is utilized as heat source for some other process. This helps CHP plant to achieve higher efficiency as compared to conventional power plant.

The figure 2.2 represents a simplified schematics of CHP unit.

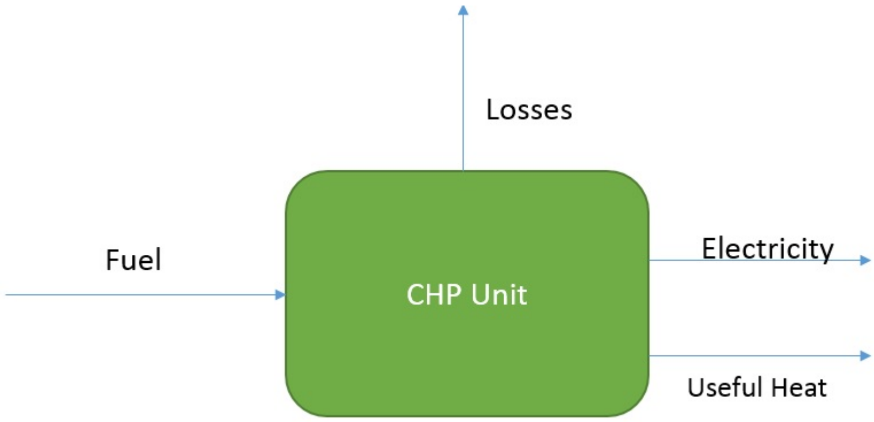

Figure 2.2: Simplified energy flow diagram for a CHP unit

The performance of a CHP unit can be characterized by its heat efficiency $\eta_{heat,CHP}$ and electrical efficiency $\eta_{el,CHP}$, defined by following equations:

$$\eta_{el,CHP} = \frac{El_{out}}{P_{CHP}} \tag{2.2}$$

$$\eta_{heat,CHP} = \frac{Useful_{heat,out}}{P_{CHP}} \tag{2.3}$$

where, El_{out} is the electrical power output and P_{CHP} is the fuel energy input to the plant before efficiency is considered. $Useful_{heat,out}$ is the useful heat extracted from CHP plant for different processes. Apart from above two efficiency there is total efficiency of the whole system defined by following equation:

$$\eta_{CHP} = \frac{El_{out} + Useful_{heat,out}}{P_{CHP}} \tag{2.4}$$

It is also common to define power-to-heat ratio, α_{CHP}:

$$\alpha_{CHP} = \frac{El_{out}}{Useful_{heat,out}} = \frac{\eta_{el,CHP}}{\eta_{CHP} - \eta_{el,CHP}} \tag{2.5}$$

2.2.4 Batteries

Batteries stores electric energy in chemical form. They should be small, light and eco-friendly. For years, advances in rechargeable battery technology proceeded slowly from lead acid to NiCd materials. In the recent past, there are other battery types that have advanced significantly. For example: NiMH, Li-ion and Li-polymer. Li-ion batteries are can be compared with supercapacitors. The power density of supercapacitor is relatively high (of the order of 5 KW/kg), but energy density is low (usually below 6 Wh/kg). Li-ion batteries on the other hand, have an energy density of typically 50-200 Wh/kg and power density of 100-3000 W/kg.

During off-peak periods when peak power sources are not utilized, prices are quite low. From the utilities' perspective there is a huge potential to reduce generation cost through storage of electricity generated by low cost plants thus eliminating costlier methods. From consumers' perspective, battery can lower the electricity cost since it can store electricity bought at off-peak prices and they can use it during peak periods in place of expensive power from grid. Consumers also have the opportunity to sell electricity to other consumers during peak hours [13].

Batteries or electrical energy storage (EES) devices have the capability to compensate such difficulties with a KW function and frequency control function. Stationary batteries are also utilized to support renewable energy output due their quick response capability. Network failures due to natural disasters or artificial causes electricity supply to stop, affecting potentially wide areas. EES assists users by continuing to supply power even when the network failure had taken place. A UPS system for example, can keep supplying electricity to critical loads even when voltage sag occurs in distribution lines. A portable battery may also serve as an emergency resource to provide power to electrical appliances [13].

2.2.5 Solar Photovoltaics

Solar cells or photovoltaic (PV) convert sunlight directly into electricity. PV derived its name from the process of converting light (photons) to electricity (voltage), which is called the PV effect. Scientists at Bell Telephone in 1954 first discovered PV effect when they found that silicon created an electric charge when exposed to sunlight. Traditional solar cells are made from silicon, are usually flat plate and generally very efficient. Second generation solar cell are thin-film solar cells as they are made from amorphous silicon or nonsilicon material like cadmium telluride. They use layers of semi conductor materials, are few micrometers thick and are flexible, thus used as rooftop shingles and tiles, building facades or the glazing for skylights. Third generation solar cells are being made from variety of new materials like solar absorbing inks, solar dyes and conductive plastics. Some new solar cells use plastic lenses or mirrors to concentrate sunlight onto a very small piece of high efficiency PV material. The material is very expensive, but since so little is needed, these systems are becoming cost effective. However, the use of concentrating collectors is limited to the sunniest parts of the country because the lenses must always be pointed at the sun [14].

A single PV is usually small, producing around 1-2 W of power [15]. But higher power is achieved by connecting them in chains to form larger units known as modules or panels. Modules can be used individually or several can be connected to form arrays. One or more arrays are then connected to the electrical grid to complete a PV system. PV cells come in many sizes and shapes, from size less than size of postage stamps to several inches long. Their thickness is same as four human hair combined. So, to withstand outdoor conditions for many years they are sandwiched between protective materials in combination of glass and/or plastics to make a PV module. But, PV modules are just a single part of the PV system. It can also include structures pointing to sun, alongwith the components which take the direct-current (DC) electricity produced by modules and convert it to alternating-current

(AC) electricity [15]. Following advantages are associated with solar PV installation and use:

1. Energy Payback (Input vs. Output) - It is considered that PV module pays for itself in terms of energy in a few years (1-5 years) [16]. With a life expectancy of 30 years, 87-97% of the energy produced by a PV system will be free of pollution and greenhouse gas emissions [16].
2. Greenhouse gas mitigation - Life cycle greenhouse emissions range from about 25-32 g/KWh and are expected to decrease to 15 g/KWh in the future. Using renewable power for manufacturing and transportation, emissions could nearly drop to zero.
3. Clean and easy installation technology - Solar PV provide clean and reliable power. They are easy to build as compared to conventional power plants and boosts national economy by creating new jobs.

Apart from the above mentioned advantages, solar PV have the advantages of being available in any sizes and capacities. This makes their application flexible ranging from small calculators to large satellites [16].

2.3 Technical Background

Romanchenko et. al (Feb, 2017) studied DH system of Gothenburg with an aim to develop an optimization model. They evaluated the interaction between heat and electricity generation in the DH system, using present and future electricity price profile obtained from modelling of the European electricity supply system using mixed integer linear programming (MILP) unit commitment model to minimize heat generation costs in the DH systems. Results from the model showed significant changes in the operation of the DH system when the future electricity price profile is applied compared to today's price. For example: 20% decrease in heat generation from HP and upto 25% increase in heat generation from CHP plants due to switch of merit order of these two technologies [17]. Steen et. al (2015) studied TES and distributed generation technologies, such as CHP and PV, which can be used to reduce energy costs and decrease CO_2 emissions from buildings by shifting energy consumption to times with less emissions and/or low energy prices. To determine the feasibility of investing in TES in combination with other distributed energy resources (DER), mixed integer programming tool called Distributed Energy Resources Customer Adoption Model (DER-CAM) was used. This model allowed improved tracking of losses based on ambient and storage temperature as compared to previous versions. They concluded that previous models overestimated the attractiveness of TES investment for cases where there is no possibility to invest in HP and underestimated it for some locations when HPs were allowed to be used. Even though there was variation in optimal technology selection between two models, the objective function was quite stable depicting the complexity of optimal DER sizing problems in buildings and microgrids [18].

Romanchenko et. al (Apr, 2017) investigated the benefits of having a TES in DH systems as a means to decrease heat load variations. Comparison and competition between two types of TES i.e. TES in centralized hot water tank (HWT) and TES in buildings was done. Building inertia thermal energy storage (BITES) is the mode of heat storage in buildings. They based their investigation on a techno-economic optimization model with an effort to minimize total operation cost of a DH system and this model was applied to DH system of Göteborg, Sweden. The results from the model showed that both the HWT and BITES can provide benefits to the operation, even though there are differences in the utilization patterns. HWT can store more than double the amount of heat over the modelled year than BITES, due to lower energy losses and they can store heat over the time period higher than few days, making them more effective for smoothening weekly heat load variations than the BITES. Also, HWT is fully available for charging and discharging at any time step, where as BITES is limited by the heat transfer between core and the indoor environment. They also observed that total system operation cost reduced by 1% when BITES and by 2% when HWT was added to the DH system, as compared to scenario without any TES [19].

Thilo et. al (2011) presented a general framework for modeling of energy systems comprising multiple-energy carriers, such as electricity, heat, gas, biomass etc. The main idea of energy hub, defining conversion matrix capable of describing the interactions between production, delivery and consumption in multiple-energy carrier systems was used in this paper. They presented a framework for comprehensive modeling of energy systems using multiple-energy carriers, such as electricity, heat, cooling etc. The approach is called hub-approach. Due to generic formulation in using this approach, it can be used in multiple-energy carrier optimal power flow, risk management and investment analysis tools, agent-based control schemes for decentralized generation units alongwith a possibility to follow top-down or bottom-up modeling strategies [20].

Sanna and Niko (2015) presented the concept for an open district heating market for cities with hourly marginal cost based pricing. They created a model with an hourly resolution, where the power plants were dispatched in the cost optimal order according to representative fuel prices and electricity spot market prices. They concluded that open heat market could be beneficial for all parties i.e. producers and consumers, and that significant cost and fuel savings are possible with mutually beneficial business models [21].

3

Model Development

This chapter is dedicated to formulation of total cost minimization linear model using optimization tool, General Algebraic Modelling System (GAMS).

3.1 Model formulation

The model development started with data collection phase. Electricity and heat demand data of 12 buildings of Chalmers campus analyzed in this project was collected and stored in excel (for information on buildings analyzed refer to figure 3.2). They were then read in MATLAB and graphs of energy demand were plotted. This was followed by creation of .gdx files. This files act as input/output mode to optimization tool, general algebraic modelling system (GAMS). Flowchart below represents the working between the different tools and programming language used in the current thesis.

Figure 3.1: Flowchart of data flow between interfaces in the model

The sets, parameters, variables were declared in GAMS. Values to be imported from MATLAB were incorporated through *gdxin* command in GAMS (used in conjunction with $load command) with the help of gdx files created in MATLAB via wgdx command. Then equations were declared and defined in GAMS. 'Solve' command was used to solve the objective function taking all the constraints (or requisite number of constraints) into consideration. Then the results were downloaded and displayed in MATLAB with help of rgdx command. Following subsections defines the equations used in GAMS model in more details.

3.1.1 Objective Function

The objective function defines the primary aim of the model formulation which in the present thesis work is total cost minimization of an economic dispatch and/or investment model. When only running cost is considered, then the model is a simple dispatch model. When investment cost (in terms of annualized investment cost) of energy alternatives are considered in addition to running cost, then the model is called investment model. In these models the capacity determination of energy alternatives becomes important, as prices are charged for per unit power or energy purchase alongwith installation charges. The standard total cost minimization objective function used in all simulations is as follows:

$$
\begin{aligned}
TC = \sum_{o=1}^{12}\sum_{n=1}^{8784}&(P_{DH}(o,n) * heat_{price}(n) \\
&+P_{elec}(o,n) * (elec_{price}(n) + 31) \\
&+P_{CHP}(o,n) * fuel_{price}) \\
+\sum_{o=1}^{12}\sum_{m=1}^{12}&(P_{DH_{max}}(o,m) * P_{tariff_{DH}} \\
&+P_{elec_{max}}(o,m) * P_{tariff_{elec}}) \\
+\sum_{o=1}^{12}\sum_{tech}& cap(o,tech) * cost(tech)
\end{aligned}
\tag{3.1}
$$

where, 'o' represents the number of buildings analyzed i.e. 12, 'n' represents the number of hours of a year i.e. 8784 (the year considered for the whole analysis is 2016), 'm' represents the number of months in a year i.e. 12, '$tech$' represents technologies available i.e. HP, CHP, TES, batteries and solar PVs.

Before understanding the terms used in the equation (3.1), it is important to understand the tariff structure of nord pool. Electricity price is the sum of nord pool spot price (charged per MW usage), energy transmission price (also charged per MW), power tariff (charged per KW per month, based on peak power consumption of the month), fixed cost (fixed amount charged on monthly basis irrespective of consumption) and reactive power (charged per KVAr per month). In the present thesis, the first three tariffs has been only considered. The fourth tariff i.e. fixed cost of 808.33 SEK/month is not taken into consideration in the objective function because they just add to the total cost and do not perform any role in optimization. The fifth tariff is not considered because only active power is considered in the current thesis. The same set of tariff is also used for DH system even though in reality there is only charge per MW of heat consumed from grid. The terms within the summations are further explained in the following paragraphs.

The first set of summation encapsulate the following terms:

$P_{DH}(o,n)$ represents heating intake for every building for every hour from the district heating grid. $P_{elec}(o,n)$ represents electrical power intake from the electrical distribution grid. Similarly, $heat_{price}(n)$ and $elec_{price}(n)$ corresponds to heat price and electrical price from the grid on an hourly basis. The price 31 is added to represent energy transmission charges for every MW electricity imported from grid. $P_{CHP}(o,n)$ is the amount of fuel utilized in the CHP plant (in terms of power i.e. MW) and $fuel_{price}$ is the price of the fuel used (taken scalar assuming that price remains fixed throughout the year). The general price of CHP fuel is taken 325 SEK/MWh (refer table 3.3) for all simulation except the case where sensitivity analysis is done around CHP fuel price.

The second summation represents the following set of terms:

$P_{tariff_{elec}}$ and $P_{tariff_{DH}}$ are the value power tariff charged for highest peak monthwise for electricity and heat intake from grid respectively. This value is fixed at 35400 SEK/MW for both electricity and DH systems for every month. $P_{DH_{max}}(o,m)$ and $P_{elec_{max}}(o,m)$ represents the highest peak of heat and electricity respectively from distribution grid (represented by MW) for every month.

The third set of summation represents the following terms:

$cap(o,tech)$ represents the optimum capacity of different technologies for different buildings. Similarly, $cost(tech)$ denotes the cost of the technology per unit energy or power (depending upon technology).

3.1.2 Transmission network description

A transmission network was created for both district heating and electricity distribution system, taking DH system as reference i.e. same connection was made for both heat and electricity w.r.t. actual DH network within Chalmers campus, so that grid does not have to supply heat or electricity independently to all buildings. Another advantage of transmission network is, it allows interaction between buildings with a possibility of micro grid both for heat and electricity or differentiated amount energy alternatives present in different buildings will allow each building as market player bidding independently in a competitive market like nordpool spot market. The network connection made is represented by the fig.3.2 below.

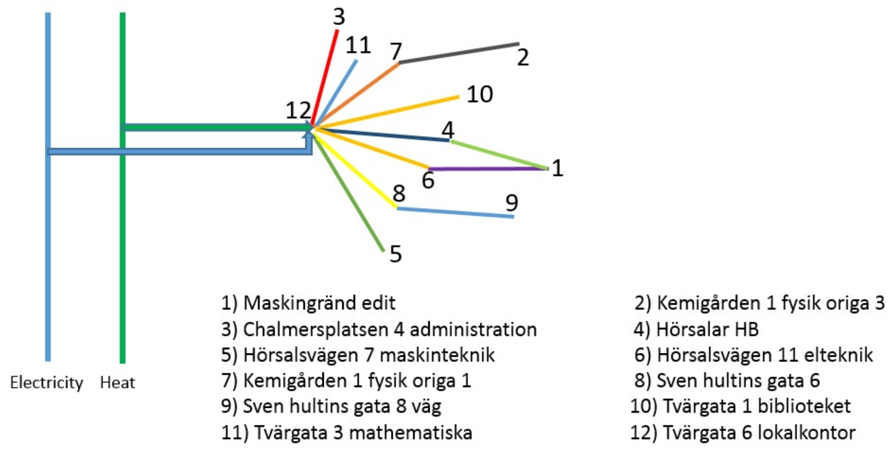

Figure 3.2: Transmission network for transfer of heat and electricity

Electrical or heat distribution network do not have unlimited transmission capacity. For the heating side, it is highly dependent upon flow and temperature. For example: on the heating side, velocity of water circulating in the pipeline is below 2 m/s. Similarly nominal pressure levels is typically around 16 bar. Water temperature ranges from 80-120°C for supply side and 30-70°C for the return side. Also, heat losses in the modern network has to be in the range of 5-10% of the total produced heat [22]. In the present thesis, neither DH network nor electricity grid has not been modelled in a detailed way i.e. above constraints have not been taken into consideration. Capacity of every transmission line was decided to be 15-20% higher than maximum value of power or heat required for each and every building for the whole year. The reason behind that are:

- To take care of the transmission losses.
- To make sure that the model does not become infeasible due to capacity limits at any hour.

In reality also, the whole transmission network for heat and electricity are over-dimensioned and same thing was done when determining the maximum capacity of different transmission lines. Since, this is a transmission network, one building within Chalmers campus is made a central node (i.e. Tvärgata 6 lokalkontor represented by node 12, refer fig.3.2) which receives both heat and electricity from the local distribution grid. As every building, do not receive energy directly from grid, there was a need to constrain objective function 3.1 to make single node in place of multiple nodes. This was done in following manner:

$$P_{DH}.fx(o,n), P_{elec}.fx(o,n) = 0; \tag{3.2}$$

Transmission from grid at every instance for every node is made 0 with the help of above eq.(3.2). This equation forces no interconnection between Chalmers internal grid and outside distribution network.

$$0 \leqslant P_{DH}('12', n), P_{elec}('12', n) \leqslant transmission_{limit} \tag{3.3}$$

Then, the eq.(3.3) allows the 12^{th} node to have connection with the local distribution grid. Lower limits make sure that there is non-negative energy transmission from grid at every hour and do not allow transmission to grid. The upper limit is subjected to $transmission_{limit}$, whose value was determined by the sum of maximum transmission of all buildings over the whole year, explicitly calculated both for heat and electricity.

Table was made each for district heating system and electricity system to define capacity of the transmission through the network.

Table 3.1: Transmission capacity for heating systems to other areas (in MW)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	1.2	0	0	0	0	0	0
2	0	0	0	0	0	0	0.40	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0.20
4	0	0	0	0	0	0	0	0	0	0	0	1.40
5	0	0	0	0	0	0	0	0	0	0	0	1.75
6	1.2	0	0	0	0	0	0	0	0	0	0	1.60
7	0	0.40	0	0	0	0	0	0	0	0	0	0.60
8	0	0	0	0	0	0	0	0	1.2	0	0	1.75
9	0	0	0	0	0	0	0	1.2	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0.30
11	0	0	0	0	0	0	0	0	0	0	0	0.32
12	0	0	0.20	1.40	1.75	1.60	0.60	1.75	0	0.30	0.32	0

Table 3.2: Transmission capacity for electrical systems to other areas (in MW)

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0.60	0	0	0	0	0	0
2	0	0	0	0	0	0	0.20	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0.15
4	0	0	0	0	0	0	0	0	0	0	0	0.75
5	0	0	0	0	0	0	0	0	0	0	0	0.80
6	0.60	0	0	0	0	0	0	0	0	0	0	0.75
7	0	0.2	0	0	0	0	0	0	0	0	0	0.30
8	0	0	0	0	0	0	0	0	0.50	0	0	0.85
9	0	0	0	0	0	0	0	0.50	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0.25
11	0	0	0	0	0	0	0	0	0	0	0	0.40
12	0	0	0.15	0.75	0.80	0.75	0.30	0.85	0	0.25	0.40	0

In both the above tables tables rows corresponds to transfer from, and column corresponds to, transfer to. Constraint equations for transmission network is as follows:

$$-\,transcapa_{heat}(o,p) \leqslant trans_{heat}(o,p,n) \leqslant transcapa_{heat}(o,p) \tag{3.4}$$

$$-\,transcapa_{elec}(o,p) \leqslant trans_{elec}(o,p,n) \leqslant transcapa_{elec}(o,p) \tag{3.5}$$

Where, 'transcapa' corresponds to transmission capacity from point 'o' to 'p' (where 'o' corresponds to transfer from, 'p' corresponds to transfer to) both for heat and electrical side (determined from the table 3.1 and 3.2). 'trans' corresponds to actual transmission based on requirement of the network on an hourly basis. As real transmission is bi-directional, '-' sign in the above equation denotes that transmission in a direction can range from negative capacity to positive capacity. Negative capacity in general means, capacity in other direction. Equations defining directions of energy flows are defined in following equations.

$$trans_{heat}(o, p, n) = -trans_{heat}(p, o, n) \tag{3.6}$$

$$trans_{elec}(o, p, n) = -trans_{elec}(p, o, n) \tag{3.7}$$

The above equations denotes that, transmission in one direction is negative of transmission in other direction with same magnitude.

It is assumed that losses is the transmission line is 5% [23] of total transmission through distribution grid. These are taken care in heating and electrical constraints equations, described in sections 3.1.4.1 and 3.1.4.2.

Transmission network is a methodological attempt to show the real energy flow in Chalmers campus. Since, the network is always over-constrained, they do not affect the result in any of the cases.

3.1.3 Formulation of constraint equations for different energy alternatives

Different energy alternatives are guided by different set of equations depending upon their technical features and sometimes relationship with other available technologies.

3.1.3.1 Heat Pump constraint equations

Heat pump mainly utilizes waste heat to upgrade its quality to high temperature which is requisite for radiator system in the buildings. Generally heat pump takes exhaust heat from some part of the system through evaporator, gets compressed in the compressor (here it is assumed that work is done on the system by electrical load). The compressed fluid releases heat to the radiator system through condenser load due to difference in temperature (amount of load delivered is called condenser load). Fluid after delivering heat return to evaporator through expansion valve. In the current thesis the source of waste heat is not explicitly defined. Also temperature difference required for transfer of heat both in evaporator and condenser is not separately declared. The heat pump constraints equations are as follows:

$$P_{HP}(o, n) \leqslant capa_{HP}(o); \tag{3.8}$$

The equation (3.8) are pretty straightforward. It states that, electricity load supplied to the HP at any instance is limited by its capacity. This equation helps in dimensioning of heat pumps for every buildings. The heat side equation of HP is represented in the heat balance equation (3.21). The COP of HP was taken to be a fixed quantity of 2.5 (standard value of HP at Kraftcentralen within Chalmers campus, refer table 3.3), except the case where sensitivity analysis was done around the parameter.

3.1.3.2 Thermal energy storage constraint equations

Thermal energy storage shift heat load from one instance to next depending on capacity. It can also shift heat load from one building to next if transmission network for heating system is place. Thus it plays a major role in cutting peaks in demand. But this happens at the expense of heat loss during round cycle efficiency. They are also limited by the maximum amount of power that can be delivered at any instance. Due to efficiency being less than 1, charging and discharging to and from a building cannot take place at the same instance (in reality, there is just one heat exchanger) and in GAMS the results would not be optimal. Following equations governs modelling of the TES in optimization tool.

$$E_{TES}(o,n+1) = E_{TES}(o,n) + Pchr_{TES}(o,n+1) - Pdis_{TES}(o,n+1); \tag{3.9}$$

where, $E_{TES}(o,n+1)$ and $E_{TES}(o,n)$ corresponds to energy available at any instance and previous instance respectively. $Pchr_{TES}(o,n+1)$ and $Pdis_{TES}(o,n+1)$ are charging and discharging to and from the TES at any instance respectively. The above equation (3.9) states that energy available in storage at any instance is sum of energy available at previous instance and amount of charge at present instance subtracted from amount of discharge at present instance.

$$E_{TES}(o,'1') = E_{TES}(o,'lasthour'); \tag{3.10}$$

where, $E_{TES}(o,'1')$ is the amount of energy available in TES at first hour and $E_{TES}(o,'lasthour')$ is the energy avaiable in TES in last hour. The equation (3.10) is used to initialize the amount of energy in storage tank at the beginning of the year for every building. Here, it is assumed that initial amount of energy in storage tank is same as amount of energy available at the last hour signifying no net loss or gain of energy by TES over the year.

$$Pdis_{TES}(o,n) \leqslant maxdisrate_{TES} * capa_{TES}(o); \tag{3.11}$$

$$Pchr_{TES}(o,n) \leqslant maxchrrate_{TES} * capa_{TES}(o); \tag{3.12}$$

where, $maxdisrate_{TES}$ and $maxchrrate_{TES}$ corresponds to maximum charge and discharge rate of TES, which is taken to be 0.20 for all further simulations (refer table 3.3). $capa_{TES}(o)$ refers to capacity of TES in each and every building. The above two equations denotes that amount of charge/discharge at any instance is limited by the maximum charge/discharge rate and the energy capacity of the tank.

$$E_{TES}(o,n) \leqslant capa_{TES}(o); \tag{3.13}$$

Equation (3.13) limits the amount of energy available in the storage tank by its capacity. Putting capacity of TES as variable allows dimensioning of it by optimizing over the year for every building. Efficiency of TES also affects the model formulation, but they are considered in the heat balance equation considered in the section 3.1.4.1.

3.1.3.3 Combined Heat and Power plant constraint equations

CHP utilizes biomass in form of wood for steam driven turbine or gas turbine for electrical power and heat generation. In the present context, woods chips is considered as source of fuel (as CHP plant in Kraftcentralen within Chalmers is operated by wood chips). CHP equation is as follows:

$$P_{CHP}(o,n) \leqslant capa_{CHP}(o); \tag{3.14}$$

where, $P_{CHP}(o,n)$ is the amount of power available or provided by fuel at any instance before efficiency consideration of a CHP plant. $capa_{CHP}(o)$ is the fuel capacity of CHP for each and every building. Power available from wood chips is subjected to capacity of CHP plant in the above equation (3.14). Generally, capacity of CHP plants are mentioned in terms of capacity of electrical power or heat power produced or both. But, in the present model capacity corresponds to capacity of fuel intake in terms of power i.e. MW.

3.1.3.4 Batteries constraint equations

All the equations for batteries were formulated similar to formulation of TES equations. But the difference is, this is on electrical side.

$$E_{battery}(o,n+1) = E_{battery}(o,n) + Pchr_{battery}(o,n+1) - Pdis_{battery}(o,n+1); \tag{3.15}$$

$$E_{battery}(o,'1') = E_{battery}(o,'lasthour'); \tag{3.16}$$

$$Pdis_{battery}(o,n) \leqslant maxdisrate_{battery} * capa_{battery}(o); \tag{3.17}$$

$$Pchr_{battery}(o,n) \leqslant maxchrrate_{battery} * capa_{battery}(o); \tag{3.18}$$

$$E_{battery}(o,n) \leqslant capa_{battery}(o); \tag{3.19}$$

All the above equations are intuitive and analogous to TES, hence needs no further explanation. The maximum charge and discharge rate of battery were taken to fixed value of 0.95 (refer table 3.3).

3.1.3.5 Solar PV constraint equations

Solar PV utilizes solar energy to produce electricity. Amount of solar energy converted to electricity is dependent upon Sun's position and solar panel's position with respect to Sun. For example, In Gothenburg, in winter when Sun is at the horizon, then its better to have solar panel perpendicular to the flat surface or in other words 90°orientation. Similarly, in summer when the solar position is above horizon, either 45°, 35°or 60°might be better. Rotating axis solar panel are better suited for utilizing maximum solar energy. But it is too costly to install on buildings, at present. Hence Akademiska Hus has plans to invest in fixed panels. On an annual basis, angle of inclination of solar panels w.r.t. surface has impact on the output, but in the present thesis one orientation angle is taken into consideration. Similarly, the direction of placement is crucial. In general, a south facing orientation is preferable in northern hemisphere. Following parameters were used for calculation of electricity output from solar PVs:

1. ALBEDO representing surface albedo
2. SWTDN representing top of the atmosphere incoming shortwave flux
3. SWGDN representing surface incoming shortwave flux
4. The outdoor temperature i.e. temperature recorded by sensors located nearer to Chalmers

The above mentioned parameters were obtained from NASA website using coordinates of Gothenburg [24] and temperatur.nu site (for outdoor temperature). The electricity from solar panels and the orientation used for the present thesis i.e. 35°were calculated using equations from the article [25]. Once the electricity was obtained in MW for every hour over the year, it was used as input for the equation 3.20.

$$P_{PV}(o,n) = PV_{elec}(n) * capa_{PV}(o); \tag{3.20}$$

where $PV_{elec}(n)$ represents electrical output from solar panel for every hour obtained from combination of parameters mentioned above and $capa_{PV}(o)$ capacity of solar PV for each and every building. The second term is used for dimensioning solar PV.

3.1.4 Demand-Supply Balance equations

Following subsections describe the demand-supply balance equations for heat and electricity system in more details.

3.1.4.1 Heating system balance

The heat demand of the building at any instance is the sum of heat intake from the grid and energy alternatives. It is represented by the following equation:

$$\begin{aligned} heat_{demand}(o,n) = P_{DH}(o,n) + P_{HP}(o,n) * COP \\ + \left(dis_{TES} * Pdis_{TES}(o,n) - \frac{Pchr_{TES}(o,n)}{chr_{TES}} \right) \\ + P_{CHP}(o,n) * \frac{\eta_{CHP}}{1+\alpha_{CHP}} \\ + \sum_{p} losses * trans_{heat}(o,p,n); \end{aligned} \tag{3.21}$$

where, dis_{TES} and chr_{TES} corresponds to discharging and charging efficiency of TES, which is taken as 0.95 in the present context (refer table 3.3). Similarly, η_{CHP} is the efficiency of the CHP plant and α_{CHP} is the ratio between electricity and heat produced by the CHP plant. The term $\frac{\eta_{CHP}}{1+\alpha_{CHP}}$ represents the heating efficiency of the CHP plant. This large term was used in place of a single term representing heating efficiency because this term is helpful while doing sensitivity analysis around 'α'. The term '$losses$' refers to transmission after losses and the value is 0.95. In the equation (3.21), P_{DH} represents the heating power taken from the grid. $P_{HP}(o,n) * COP$ corresponds to the heating power obtained from HP. $dis_{TES} * Pdis_{TES}(o,n)$ is the power gained by the building from TES at every instance considering discharging efficiency. $\frac{Pchr_{TES}(o,n)}{chr_{TES}}$ is power added from the building to TES considering charging efficiency. The penultimate term of the right hand side represents the power input from CHP plant. The last term of the equation corresponds to sum of transmission from all nodes 'p' to node 'o' considering losses of 5% in the line.

3.1.4.2 Electrical system balance

Electrical system interplays with heating system via HP and CHP plant. Interaction of these two energy alternatives is highly dependent on the difference in pricing of electrical and heating system. A complicating factor for CHP plant is, if a certain amount of heat is produced, depending upon the alpha value, a certain amount of electricity is produced even if its market price is higher or vice-versa as there is already an investment made in the purchase of fuel, so the secondary output is complementary to the system. The electrical balance equation is as follows.

$$\begin{aligned} elec_{demand}(o,n) &= P_{elec}(o,n) - P_{HP}(o,n) \\ &+ \left(dis_{battery} * Pdis_{battery}(o,n) - \frac{Pchr_{battery}(o,n)}{chr_{battery}} \right) \\ &+ P_{CHP}(o,n) * \frac{\alpha_{CHP} * \eta_{CHP}}{1+\alpha_{CHP}} \\ &+ P_{PV}(o,n) + \sum_{p} losses * trans_{elec}(o,p,n); \end{aligned} \tag{3.22}$$

where, $dis_{battery}$ and $chr_{battery}$ are the discharging and charging efficiency of the battery, each of which is taken to be 0.95 (refer table 3.3). The term $\frac{\alpha_{CHP}*\eta_{CHP}}{1+\alpha_{CHP}}$ as a whole represents electrical efficiency of the CHP plant. In the above equation (3.22), P_{elec} corresponds to electrical power taken from the grid. P_{HP} is the electrical power of HP. A minus sign corresponds to work is done on the system in the form of use of electricity by HP. Third term in the RHS has the same logic as TES (from equation (3.21)). Also, CHP term is same as the equation (3.21), only difference being extra α_{CHP} term is multiplied to correspond electrical output. Contribution of power from solar PV is represented by P_{PV} and transmission lines contribution to individual buildings on the electrical system is same as the heating system.

3.2 Input data for the model

In this section different input parameters to the GAMS model are described in a broad manner.

To begin with, heat and electricity prices are input to the model. Heat price is taken from Göteborg energi and electricity price is taken from Nordpool spot price for SE3 region. These prices for every hour is represented in the graphs below.

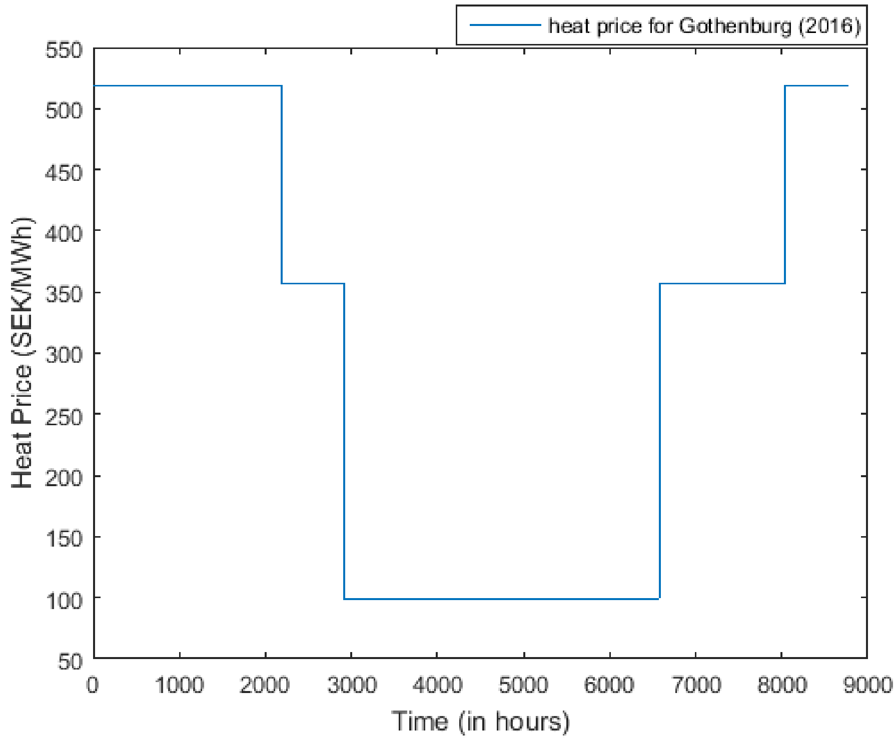

Figure 3.3: Göteborg energi heat price setting for 2016 in Gothenburg region

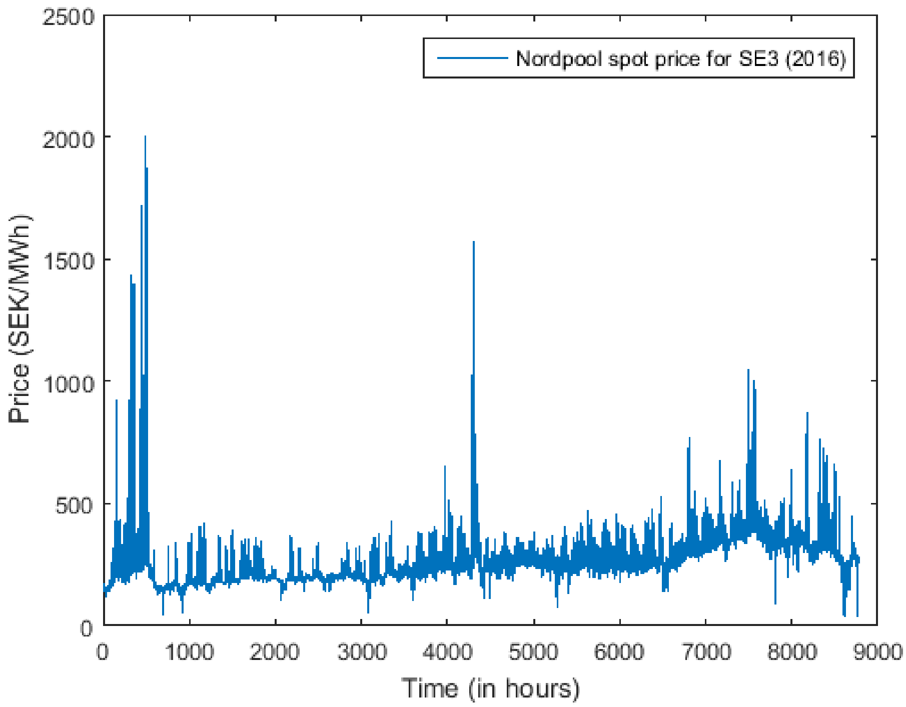

Figure 3.4: Nordpool spot price for 2016 in SE3 region

Other standard necessary parameters used in the model are represented in the following table.

Table 3.3: Few properties of energy alternatives represented as scalar in the model

Property	Values
COP of HP (as per Akademiska Hus)	2.5
Charging efficiency of TES	0.95[26]
Discharging efficiency of TES	0.95[26]
Maximum charge rate of TES*	0.20
Maximum discharge rate of TES*	0.20
Ratio between electricity and heat produced by CHP	0.6 [27]
Overall efficiency of CHP	0.94 [27]
Fuel price of CHP (in SEK per MW)	325 [28]
Charging efficiency of Battery	0.95[29][30]
Discharging efficiency of Battery	0.95[29][30]
Maximum charge rate of Battery	0.20 [31]
Maximum discharge rate of Battery	0.20 [31]

*Maximum charge and discharge rate of TES is taken same as batteries, since both of them perform similar function of energy storage.

The following table represents the cost of different energy alternatives used in the model alongwith their lifetime in years.

Table 3.4: Technologies with investment cost and lifetime

Technology	Price (SEK/KW or SEK/KWh)	Lifetime (Years)
HP	18000 SEK/KW[32]	15[32]
CHP	3170 SEK/KW[28]	20[28]
TES	10[26]	25 SEK/KWh[26]
Battery	12060[31]	15 SEK/KWh[31]
Solar PV	18000[33]	30 SEK/KW[34]

The conversion of prices not in SEK was done to SEK using following conversion rate:

1 € =9.6 SEK

1 USD = 9 SEK.

3.3 Scenario Description

In this section, various simulation cases and the reason behind conducting these studies are described in a broad manner.

3.3.1 Base case

In this case, none of the energy alternatives are considered. At present, Chalmers has CHP plant (currently CHP plant is not producing any electricity), heat only boiler, HP (both located at Kraftcentralen) and solar PVs (installed on rooftops and walls of some of the buildings). Electricity generated from solar PV is mainly in summer and the quantity is meagre. Due to lack of data availability for heat generated (from heat only boiler and HP) and electricity generated (from solar PV) within Chalmers campus, they are not part of present analysis. Base case is mainly present to find out the annual energy cost of 12 buildings analyzed within Chalmers. This case is also used for comparison with other cases.

The figures 3.5 and 3.6 represents heat and electricity demand of the 12 buildings in 2016 with hourly resolution.

The explanation for the shape of DH curve is intuitive. DH power is highest in winter months i.e. January, February, March and December. It decreases gradually towards middle of the year and lowest in June to August, when the heating requirement is minimum. Water heating measurements was not done separately. During summer, it is generally conducted through electric water heaters, so they are part of electric load and in winter, make negligible percent contribution as compared to space heating.

For the electrical side, power consumption is almost same throughout at the year. It decreases in the middle of the year when DH consumption is minimum and energy requirements is mainly due to electrical components and ventilation requirement of Chalmers. Also, lecture halls, conference rooms etc. has almost no energy consumption as summer holidays are going on during that period. A clear dark blue line can be observed running below peaks. This represents lower energy consumption during weekends.

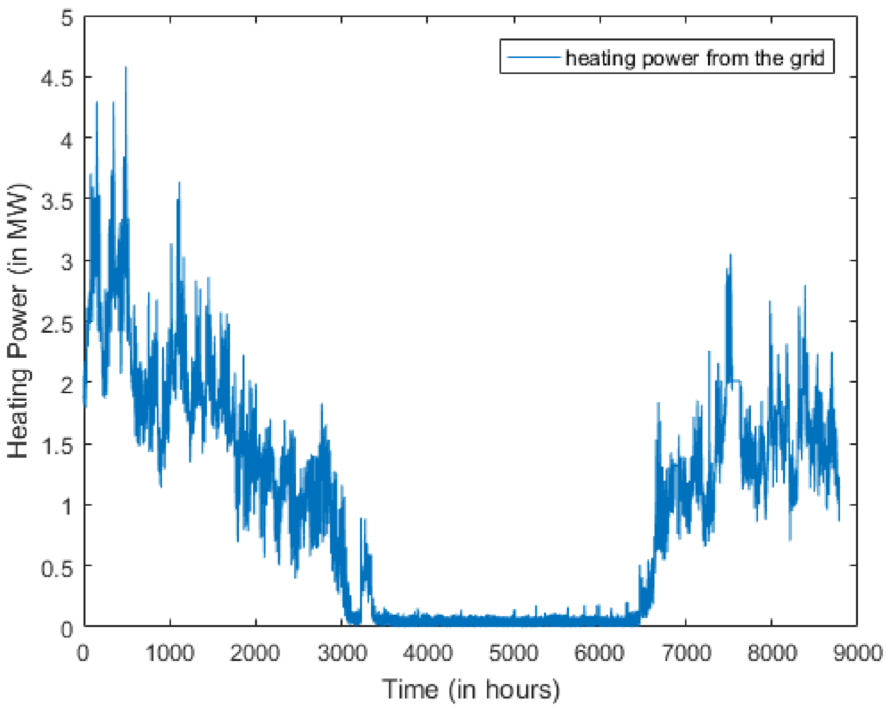

Figure 3.5: Base case: DH power consumption curve of all buildings (in MW)

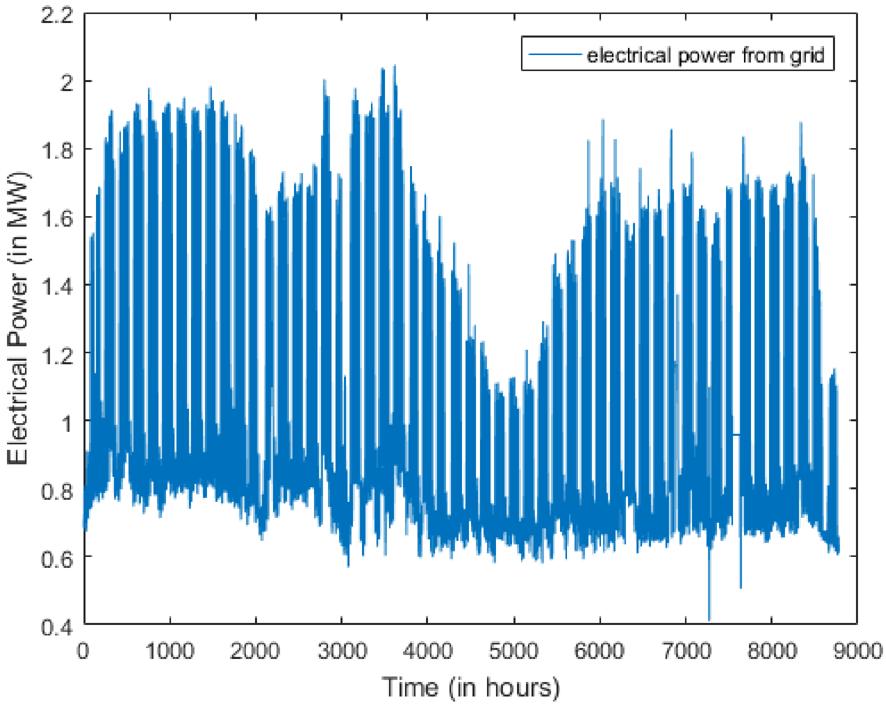

Figure 3.6: Base case: Electrical power consumption curve of all buildings (in MW)

3.3.2 Consideration of all possible energy alternatives

In this case, all the energy alternatives i.e. HP, CHP, TES, solar PV and batteries are taken into consideration without any further constraints. Since investment in new energy alternatives is involved, annualized cost has to be calculated. Equations (3.23) and (3.24) are used to find the annualized investment cost. Since, rate of interest or 'i' has to be decided by the user and annualized investment cost is highly dependent on this value, a sensitivity analysis was done with i= 5, 7.5 and 10%. Following table represents various values of annualized investment cost for different 'i'.

Table 3.5: Annualized investment cost for different values of rate of interest

Technology	Annualized Investment cost		
	i=5%	7.5%	10%
HP	1728000	2034000	2358000
CHP	253600	310660	370890
TES	710	900	1100
Battery	1157760	1362780	1579860
Solar PV	1170000	1530000	1908000

Price and lifetime data from table 3.4 was used to calculate the annualized investment cost i.e. equivalent annual cost of owning, operating and maintaining a technology over its entire life. As annualized investment cost considers yearly investment cost in a certain technology and present analysis is for one year, so sensitivity analysis of this parameter assumes importance. The following set of equations are used to calculate the annualized investment cost.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}; \tag{3.23}$$

where, 'i' is the rate of interest and 'n' is the number of years the technology lasts or the lifetime of the technology. CRF or capital recovery factor converts presents value of technology into a set of equal annual payments over a specified time i.e. lifetime and at a specified discount rate.

$$A = Price * CRF; \tag{3.24}$$

where, 'A' is the annualized investment cost, which is 'price'(obtained from table 3.4) times 'CRF'.

Apart from this case, the 'i' value is fixed at 5% for the remaining scenarios, because low value of 'i' (amongst all the 'i' values considered in the project) assures maximum capacity presence of different energy alternatives due to its low price.

3.3.3 Varying COP of HP

COP of HP is an important parameter as it decides the amount of waste heat that can be utilized. Higher value of COP indicates higher utility of HP with same amount of work done on it. Since HP is related to other energy alternatives, their contribution can change significantly depending upon contribution from HP. Chalmer's HP has a COP of around 2.5 (refer table 3.3), was used as a starting point. Analysis was done till a COP value of 4.5 with an increment of 0.5. In reality also COP is varying depending upon temperature difference between incoming and outgoing water temperature, outdoor temperature, temperature difference between evaporator and outdoor air, temperature difference between condenser and indoor temperature etc.

3.3.4 Peak limit restriction

In this case, limit was placed on the maximum amount of heat and electricity that can be imported from grid at any instance. This was done by imposing the following constraints in addition to the existing constraints in the model:

$$P_{elec,DH} \leqslant limit_{peak} \tag{3.25}$$

3.3.5 Varying CHP parameters

In this case, various CHP parameters are varied stepwise and its effect on total cost and other outputs were observed.

3.3.5.1 CHP fuel price variation

CHP fuel prices varies depending on moisture content (changes every season) in the wood pellets. So, sensitivity analysis was done with different fuel price starting from 250 SEK/MWh to 375 SEK/MWh with an increment of 25 SEK/MWh. For all the other cases, CHP fuel price was taken to be 325 SEK/MWh (refer table 3.3)

3.3.5.2 Ratio between electricity and heat variation

'α' varies according to the amount of heat and electricity produced at every instance (both heat and electricity are variable themselves). Since, the model is linear and linear solver cannot solve a variable in the denominator of a fraction, So fixed value of α=0.6 was taken for other cases, as it lies in the denominator of both heating and electrical balance equation (refer equations 3.21 and 3.22) (refer table 3.3). But, in this case, different fixed values of 'α' were taken starting from α=0.4 to 0.9 with an increment of 0.1.

3.4 Varying initial investment in energy alternatives

Different values of annualized investment rates are calculated based on different expected rate of return. Once the capacity is decided by the investment model, then real purchase of energy alternatives are made based on present pricing. The total investment then made becomes 'sunk cost' i.e. total investment is made at once and return services is regular return service is expected.

FED project is limited by the total amount of money it can spend on aggregate purchase of energy alternatives. Analysis was done to investigate the capacity contribution of different alternatives under different set of initial investment limitation. Following eq.(3.26) was incorporated to the existing investment model to impose the initial investment cost limitation constraint condition.

$$\sum_{o} \sum_{tech} cap(o, tech) * cost(tech) \leqslant Investment_{initial} \tag{3.26}$$

where, every term is similar to corresponding term in equation (3.1). The term '$Investment_{initial}$' corresponds to sum total initial investment required to be made in all energy alternatives. The initial investment for present analysis was taken to be 5 million, 7.5 million and 10 million SEK.

3.5 Varying specific energy alternative price

The price of certain energy alternative were reduced and other alternatives price were kept same to understand the price at which these make contribution. Following table was created to show to difference in pricing for different alternatives.

Table 3.6: Sensitivity analysis of different energy alternatives at different annualized investment cost

Scenario	HP	CHP	TES	Battery	Solar PV
1	1	1	1	1	1
2	1	1	1	1	0.6
3	1	1	1	1	0.4
4	1	1	1	1	0.3
5	1	1	1	1	0.2
6	1	1	1	1	0.1
7	1	1	1	0.6	1
8	1	1	1	0.4	1
9	1	1	1	0.3	1
10	1	1	1	0.2	1
11	1	1	1	0.1	1
12	1	1	1	0.1	0.1

In the above table 3.6, 1 corresponds to consideration of full annualized cost and other numbers corresponds to the fraction of annualized investment cost charged. For example: 0.6 represents 60% of annualized investment cost. Here price reduction of HP, CHP and TES is not considered because they do not require price reduction for making energy contribution in the Chalmer's case. Case 1 is standard case where all energy alternative price are taken at their standard values.

4

Simulation, Results and Interpretation

This chapter deals with results presentation from simulation of scenarios described in the last section of previous chapter and interpretation based on graphs and comparison table.

4.1 Base Case

This case describes the present condition of Chalmers. Thus, electricity and heat consumed from grid reflect directly the energy demand for considered buildings. In reality though, there is heat only boiler and HP supplying heat throughout the year, but they are not part of present consideration due to lack of data. The results from base case is summarized in the table below:

Table 4.1: Base case

Properties	Values
Total annual cost (SEK/yr)	$8.38 * 10^6$
$\sum DH_{grid}$ (MWh)	8612.7
$\sum elec_{grid}$ (MWh)	8848.3
$\sum DH_{grid}+\sum elec_{grid}$ (MWh)	17461
$PeakDH_{grid}$ (MW)	4.58
$Peakelec_{grid}$ (MW)	2.04

Electrical and heat energy consumed from grid is same as demand from buildings, represented by figures 3.5 and 3.6 in the previous chapter. From the graphs, it is clear that average heat consumed over most parts of the year is less than that of electricity. But, heat peak from grid is high because demand is high for few hours at the beginning of the year when it is extremely cold. Also, the heat and electricity consumed on an annual basis is almost same. As the peak of heat is much higher than electricity peak from grid, there is lot of peak reduction potential when investment is done in energy alternatives. Total annual cost is also high mainly due to large heat consumption in early winter months when price is quite high.

4.2 Consideration of all possible energy alternatives at different annualized investment cost

As described before, in this case all energy alternatives are considered without any further constraints. Once there is decision of investing in energy alternatives, then there is discussion on deciding the rate of interest of determining the annualized investment cost. The results of sensitivity analysis over different values of rate of interest are summarized in the table below.

Table 4.2: Energy alternatives consideration at different annualized cost

Properties	i=5%	7.5%	10%
Initial investment (SEK)(*10^7)	1.52	1.40	1.25
Annualized investment (SEK)(*10^6)	1.43	1.56	1.63
Total annual cost (SEK/yr)(*10^6)	6.40	6.65	6.89
$\sum DH_{grid}$ (MWh)	400.79	542.96	938.49
$\sum elec_{grid}$ (MWh)(*10^4)	1.18	1.16	1.17
$\sum DH_{grid}$+$\sum elec_{grid}$ (MWh)(*10^4)	1.22	1.22	1.26
$PeakDH_{grid}$ (MW)	0.78	0.94	1.20
$Peakelec_{grid}$ (MW)	2.52	2.46	2.48
HP_{capa} (MW_{elec})	0.75	0.68	0.64
CHP_{capa} (MW_{fuel})	0.36	0.38	0.20
TES_{capa} (MWh_{heat})	55.52	51.04	40.69
$Battery_{capa}$ (MWh_{elec})	0	0	0
$SolarPV_{capa}$ (MW_{elec})	0	0	0

Referring to the above table 4.2 it is clear that total annual cost is increases with increase in rate of interest and at the same time there is overall reduction in capacity of HP, CHP and TES. Initial investment is also decreasing as there is less capacity addition from different alternatives. Heat contribution from grid is increasing, but electricity contribution is first decreases and then increases, because the capacity of CHP increases in the second case reducing the import of electricity from grid on an annual basis. This is the same reason for less increase in heat import in second case as compared to first case than third case as compared to second case. There is increase in electrical peak in all of the cases as compared to base case, but decrease in heat peak as compared to base case. There is increase in electrical power consumption from grid mainly due to presence of HP and large decrease heat power from grid also due to HP. This results in net decrease in total energy consumption from grid.

Comparison is made between base case and scenario with 10% rate of interest. It is found that, there is 21% increase in peak for electrical side and 74% decrease in heat peak. Similarly, there is 32% increase in electricity consumption, but 89% decrease in heat consumption from grid, resulting in 28% net decrease in energy consumption. This results in overall decrease in total annual cost by 18% as compared to base case.

The contribution from energy alternatives and grid to both heat and electricity are almost similar in all of the rate of interest scenario. So, graphs were plotted only for the last case i.e. i=10%. From the graph 4.1 below it is clear that heat contribution from grid is almost zero from February. But, average electricity consumption has increased throughout the year. The heat curve is more flat as compared to base case mainly due to TES. Average electricity consumption is increased as compared to base case especially in winter months but heat consumption from grid is reduced by large margin and it is 0 in summer months. In the figure 4.2, CHP and HP are utilized to their full capacity in winter month since there is high need of both heat and electricity during these periods. Then their contribution is almost sparse especially for CHP in summer months because of high fuel price and low need of energy particularly heat.

In the figure 4.3, it is clear that energy contribution from HP towards electricity is negative because of work being done by the system. Similar to heat side, CHP makes full contribution to electricity in winter months, but the capacity is less since α is less than 1 i.e. 0.6. In the figure 4.4, energy content of the TES is varying frequently in winter months. In the summer months there is sparse charging of TES probably from HP when the electricity price is lower, to be used in winter months again when the heat price is high. Around 3500 hour onwards there is continual increase in energy available at TES till 7200 hour, suggesting these storage have the tendency to be used as seasonal storage. But, then energy stored is not a decay function depending on time (in reality there will be energy loss with increase in time) in the present thesis. So, energy available in TES as per model is overestimated.

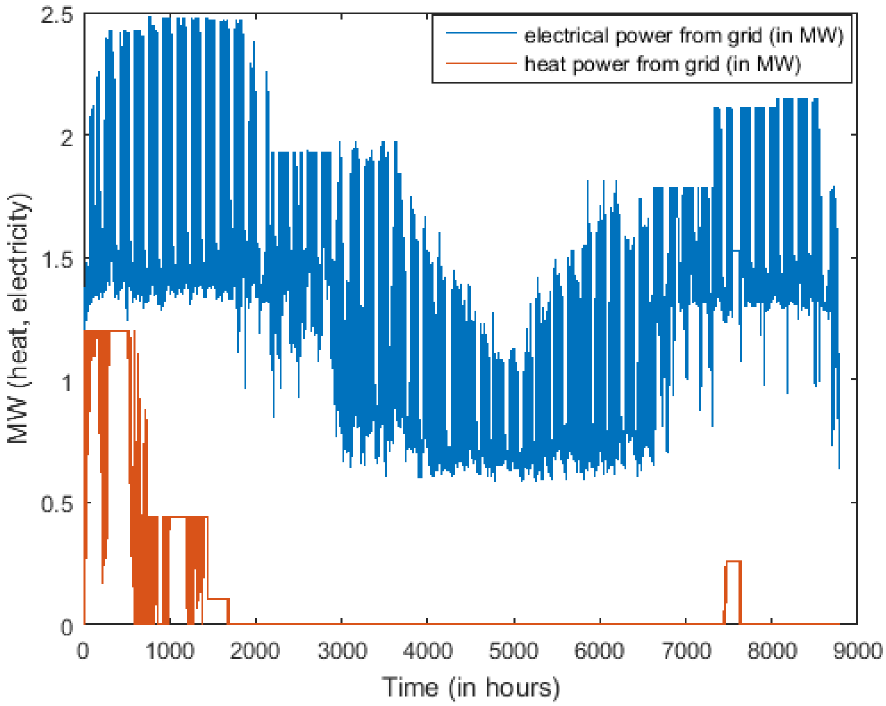

Figure 4.1: Cumulative electricity and heat contribution from grid for i=10%

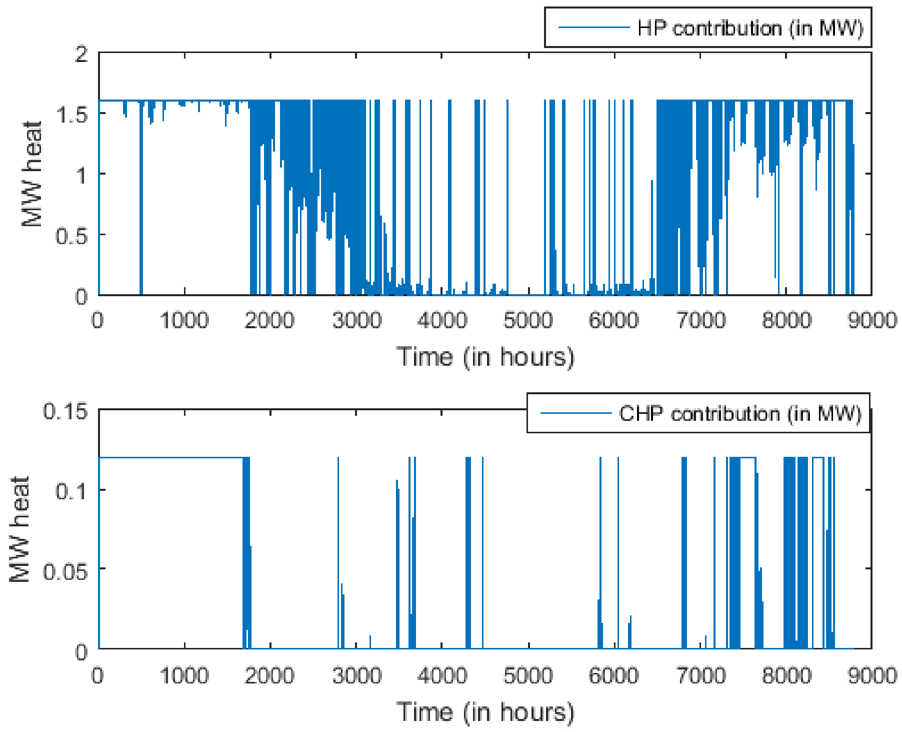

Figure 4.2: Cumulative heat contribution by energy alternatives for i=10%

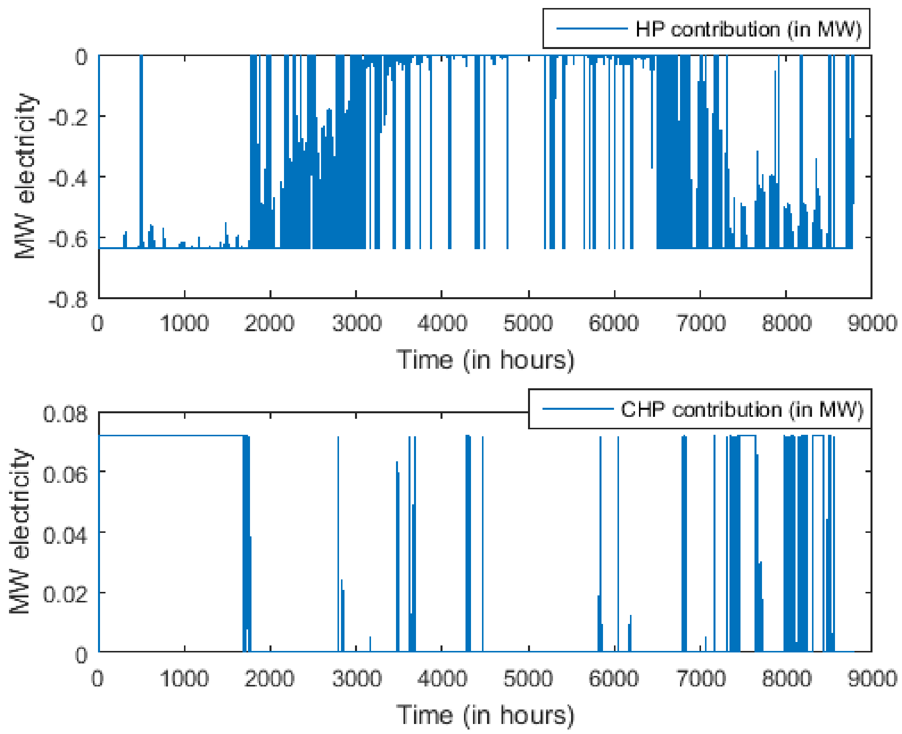

Figure 4.3: Cumulative electricity contribution by energy alternatives for i=10%

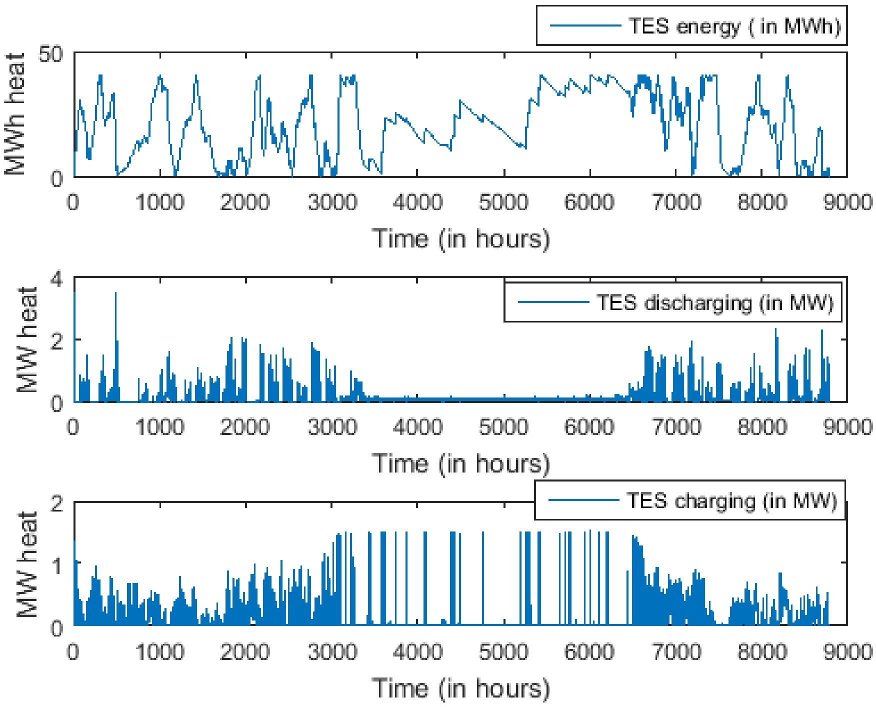

Figure 4.4: TES energy, charging and discharging curve for i=10%

4.3 Varying COP of HP

In all the simulations COP of HP is taken to be scalar quantity i.e. COP is considered to be a fixed quantity. But, in reality COP varies all the time as explained in the previous chapter. Also, it is an important parameter determining the capacity of HP, so a sensitivity analysis was done around is parameter to analyze how much it affect the presence of other alternatives in the system and results are presented in the table 4.3 below.

Referring to the table 4.3 and comparing HP with COP = 3 with base case it is found that there is a 82.5% decrease and 25% increase in heat and electricity peak respectively in the present scenario as compared to base case. There is a total annual cost decrease of 28% as compared to base case. There is 31% increase in electrical power production but a large decrease of 95% in heat power consumption from grid.

The contribution from energy alternatives and grid to both heat and electricity are similar in almost all cases, except the fact that CHP ceases to make contribution after HP's COP exceeds value of 3. Capacity of CHP decreases because with increase in COP, same capacity of HP can produce more heat output for corresponding electrical input resulting in less heat contribution from CHP. Furthermore it is observed that TES capacity first increases and then decreases as the heat variation decreases because from COP=3.5 only HP makes contribution towards heat.

Table 4.3: Energy alternatives consideration at different values of COP of HP

Properties	COP=2.5	3	3.5	4	4.5
Initial investment (SEK)(*10^7)	1.52	1.28	1.11	0.99	0.9023
Annualized investment (SEK)(*10^6)	1.42	1.21	1.04	0.94	0.85
Total annual cost (SEK/yr)(*10^6)	6.39	5.99	5.70	5.48	5.30
$\sum DH_{grid}$ (MWh)	400.09	435.32	429.26	388.09	362.74
$\sum elec_{grid}$ (MWh)(*10^4)	1.18	1.16	1.12	1.09	1.07
$\sum DH_{grid}+\sum elec_{grid}$ (MWh)(*10^4)	1.22	1.20	1.16	1.13	1.11
$PeakDH_{grid}$ (MW)	0.77	0.80	0.79	0.72	0.69
$Peakelec_{grid}$ (MW)	2.52	2.55	2.46	2.40	2.34
HP_{capa} (MW_{elec})	0.75	0.66	0.57	0.52	0.47
CHP_{capa} (MW_{fuel})	0.36	0.06	0	0	0
TES_{capa} (MWh_{heat})	55.28	67.88	71.09	57.31	51.82
$Battery_{capa}$ (MWh_{elec})	0	0	0	0	0
$SolarPV_{capa}$ (MW_{elec})	0	0	0	0	0

Since scenario with COP=3 is the last case where where CHP makes positive contribution to Chalmers energy network, it was decided to use this scenario for representing energy contribution from grid and energy alternatives.

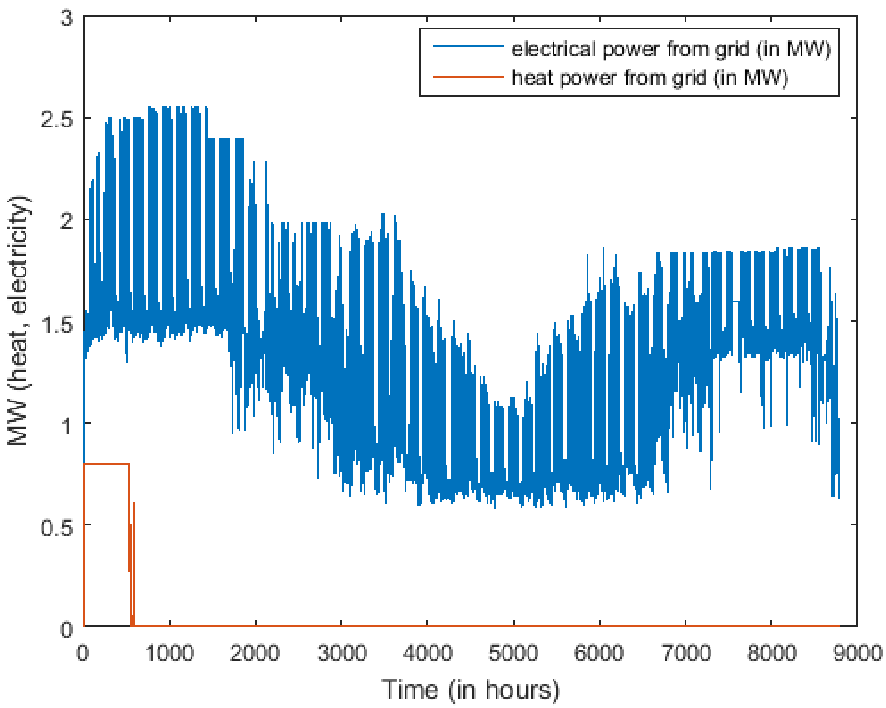

Figure 4.5: Cumulative electricity and heat contribution from grid HP's COP=3

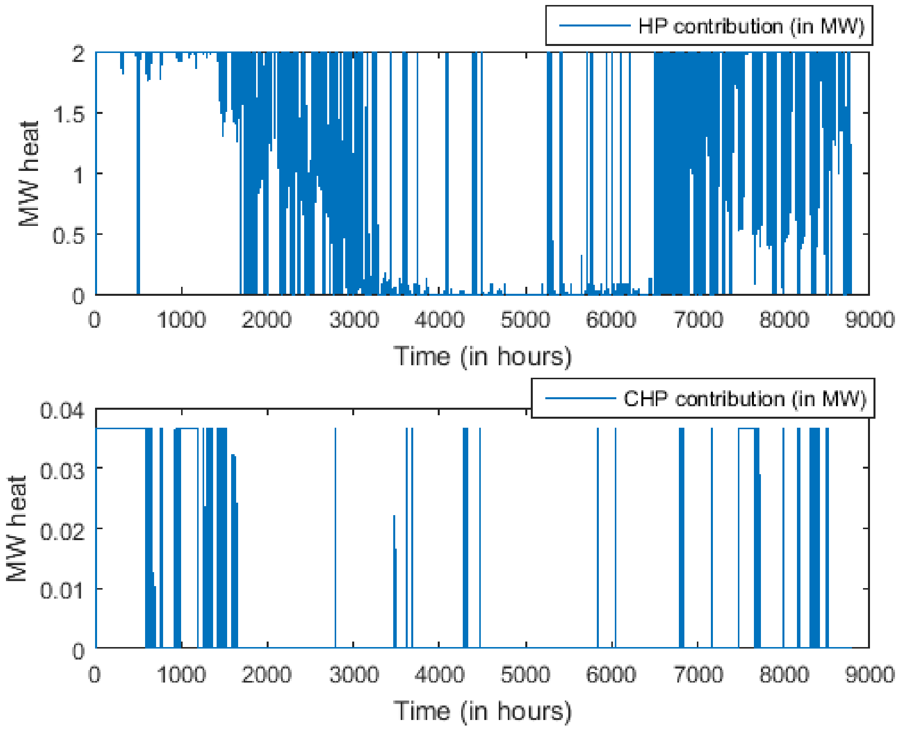

Figure 4.6: Cumulative heat contribution by energy alternatives for HP's COP=3

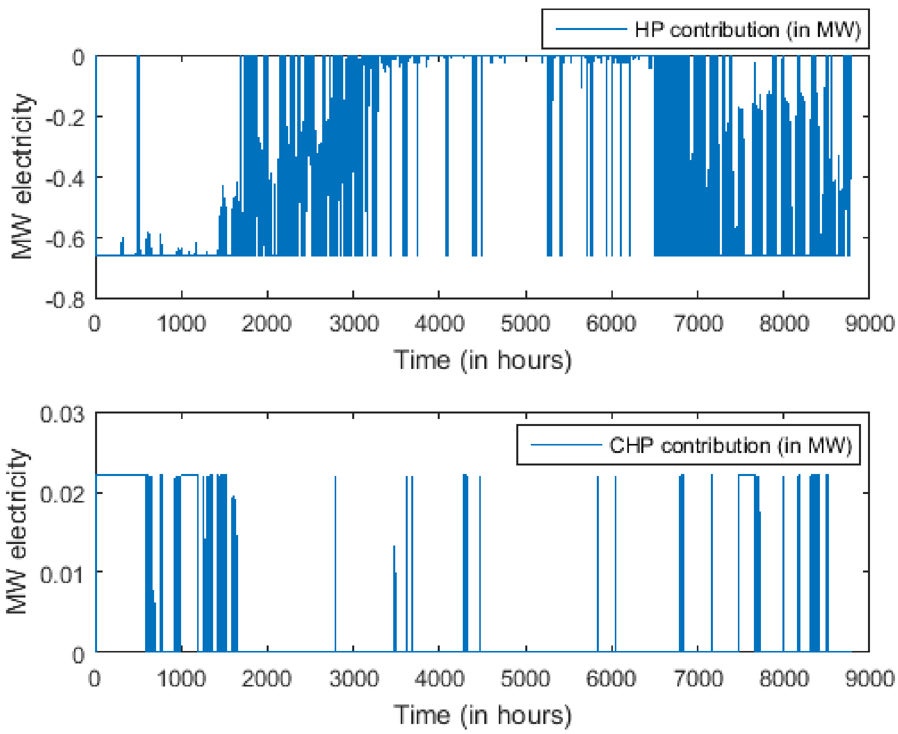

Figure 4.7: Cumulative electricity contribution by energy alternatives for HP's COP=3

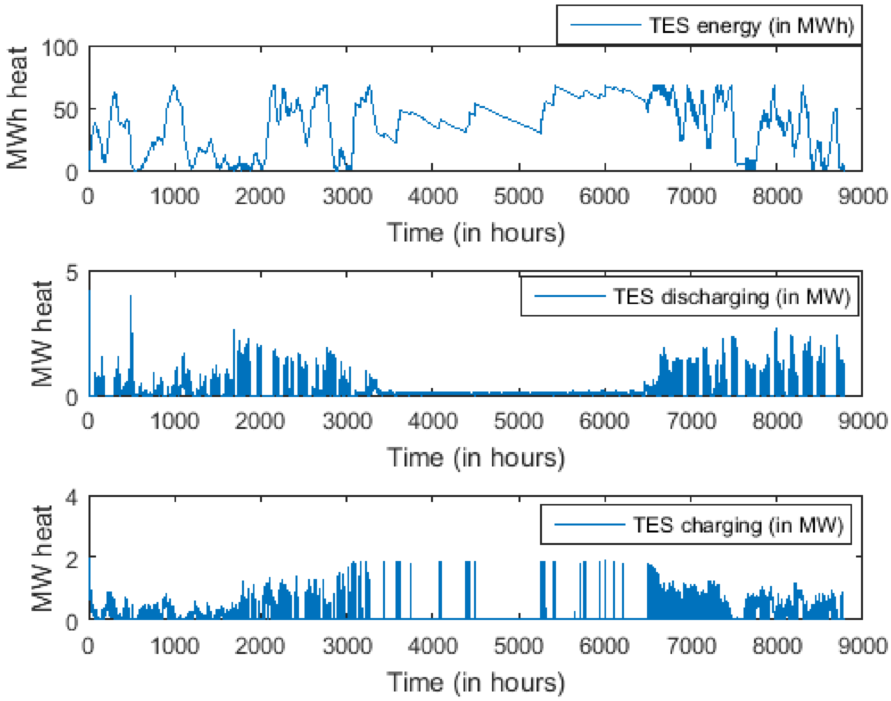

Figure 4.8: TES energy, charging and discharging curve for HP's COP=3

From the figure 4.5 above, it is clear that average electrical power consumption increased as compared to base case. From 0 till 1700 hours there is a shift in electrical power consumption from 0.8-1.8 MW range in base case to 1.5-2.5 MW range with COP=3 case. But, the positive aspect is now heat consumption from grid is limited to initial 600 hours and there are no peaks suggesting possibility of a micro-grid for heating side.

HP, CHP and TES are the energy alternatives contributing to heating side. As previous case, HP contribution is almost to full capacity till 1500 hours (refer figure 4.6). But, CHP contribution is sparse even in the early winter months and its cumulative capacity is also quite low as compared to variation in annualized investment cost case.

Referring to figure 4.7 representing electrical contribution by energy alternatives, it is observed that that there is negative electrical contribution by HP. Since CHP produces both heat and electricity at the same time, there is sparse contribution by CHP to electrical side as well. Overall effect is net negative contribution to electrical side from energy alternatives for most part of the year.

The energy and power contribution from TES figure 4.8 above is similar to the previous case with different annualized investment case, except the fact that energy storage in TES is longer than previous case, especially over summer starting from 3000 hour to 7600 hour. Also, the maximum power flow both during charging and discharging is comparatively higher as compared to previous case.

4.4 Analysis of effect of peak limit restriction

In this case, peak power from grid is limited by putting extra constraint on the model as described in the previous chapter. While working on the results, it was realized that peak limit on electricity from grid is sufficient to restrict heat peak and no extra constraint need to be enforced on heating side as expected earlier. The reason is, restriction on maximum input of electricity from grid at any instance increases CHP contribution, resulting in decrease of heat intake from grid. Thus limit on electricity imposed implicit limit on heat. Table 4.4 below represents comparison between important variables at different peak limit on electricity.

Table 4.4: Comparative study of energy interaction at different electricity peak limits

Important Variables	Limit= 2.4 (MW)	2.2	2	1.8	1.6	1.4
Initial investment (SEK)(*10^7)	1.52	1.51	1.52	1.54	1.60	1.62
Annualized investment (SEK)(*10^6)	1.42	1.40	1.40	1.40	1.45	1.45
Total Annual Cost (SEK)(*10^6)	6.40	6.41	6.45	6.50	6.56	6.66
$\sum DH_{grid}$(MWh)	379.34	353.71	326.80	304.92	243.79	200.84
$\sum elec_{grid}$(MWh)(*10^4)	1.16	1.12	1.08	1.05	1.02	0.95
$\sum DH_{grid}+\sum elec_{grid}$ (MWh)(*10^4)	1.20	1.16	1.12	1.08	1.04	0.97
$PeakDH_{grid}$ (MW)	0.76	0.74	0.73	0.72	0.65	0.59
$Peakelec_{grid}$(MW)	2.4	2.2	2	1.8	1.6	1.4
HP_{capa} (MW_{elec})	0.72	0.67	0.63	0.59	0.58	0.54
CHP_{capa} (MW_{fuel})	0.54	0.82	1.09	1.35	1.63	1.99
TES_{capa} (MWh_{heat})	49.79	44.90	39.55	37.09	31.84	26.96
$Battery_{capa}$ (MWh_{elec})	0	0	0	0	0	0
$SolarPV_{capa}$ (MW_{elec})	0	0	0	0	0	0

On careful observation of initial and annualized investment, it is found that, cost decreases or remains same till 2 MW peak limit and then increases, suggesting that cost-wise it is most effective to limit peak around around 2 MW, which is also the peak of base case. But, the total annual cost increases because of increasing fuel consumption associated with increase in utilization of CHP. For other important variables, there is a continuous decreasing trend except capacity of CHP suggesting CHP mostly compensates the peak electricity demand when there is limit on peak electrical power from grid. In reality though, CHP mostly covers base load, but in the present model since there is no ramping limits, so it is able to cover peak load even if it is at the cost of increasing total annual cost. From the above table using peak limit = 1.4 as a basis of comparison with base case, it was observed that there is an overall grid electricity increase of 8% and heat decrease of 97%. Heat peak from

DH decreased by 87% resulting in total annual cost decrease by 20%. Peak limit 1.4 scenario is also used to plot graphs for heat and electricity contribution from energy alternatives and grid, because this represents extreme of all scenarios presented in above table and depicts significant impact of electricity import limitation.

From the figure 4.9, it is clear that peak limit constraint acts as a limiting/binding constraint for 0-4500 hours, 6000-7200 hours and 8000-last hour. This increases total cost as compared to previous cases, as the remaining electricity comes from CHP plant. Heat from grid is limited to few initial hours similar to previous cases.

For the heat side, there is positive energy gain both for HP and CHP (refer figure 4.10). CHP is the sole contributor of heat from 3000 to 6500 hours. Referring to contribution of energy alternatives on the electricity side (refer figure 4.11), it is noted that there is a net positive contribution from energy alternatives for most hours in the first 4000 hours, resulting in less grid contribution as compared to base case. In the middle of the year i.e. from 4500-5500 hours, there is no electricity input from energy alternatives since the peak limit constraint is not binding. Similarly at the end of the year the constraint is again binding resulting in net positive contribution from energy alternatives.

TES acts as a short term storage both at beginning and end of the year (refer figure 4.12). From 3000-4500 hours, CHP produces more heat than demand (as it is already running for electricity production). This extra heat is compensated by TES efficiency losses (even though charging and discharging takes place at different time in different buildings), since there is equality constraint in heat balance equation.

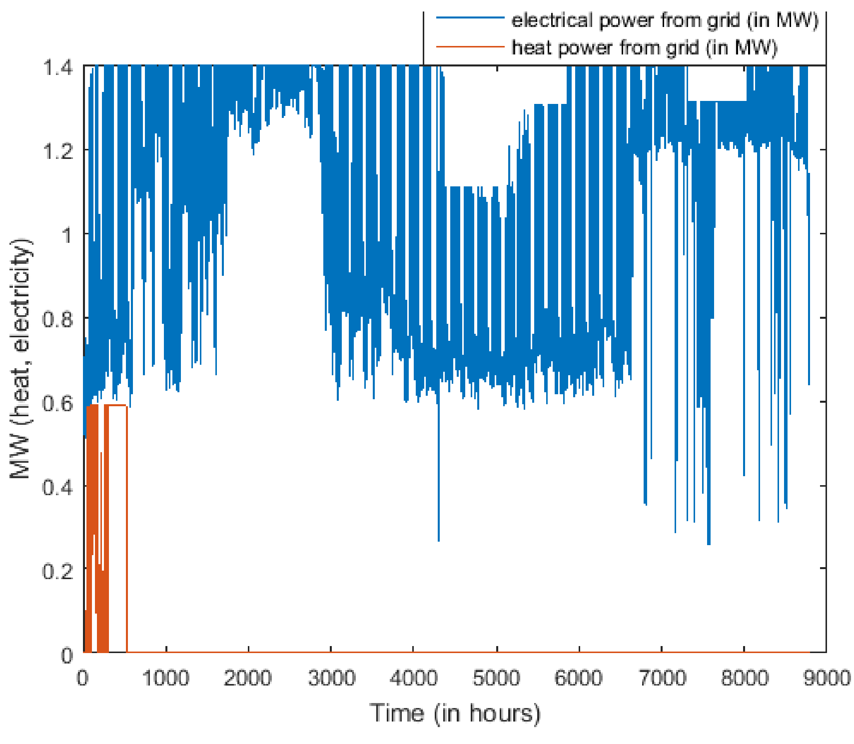

Figure 4.9: Cumulative electricity and heat contribution from grid for electricity peak limitation = 1.4 MW

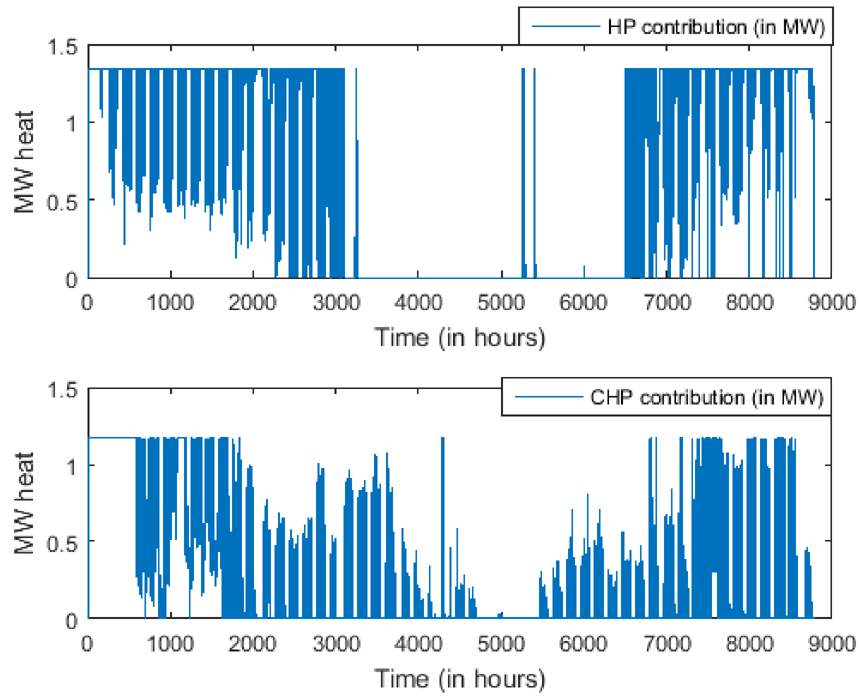

Figure 4.10: Cumulative heat contribution by energy alternatives for electricity peak limitation = 1.4 MW

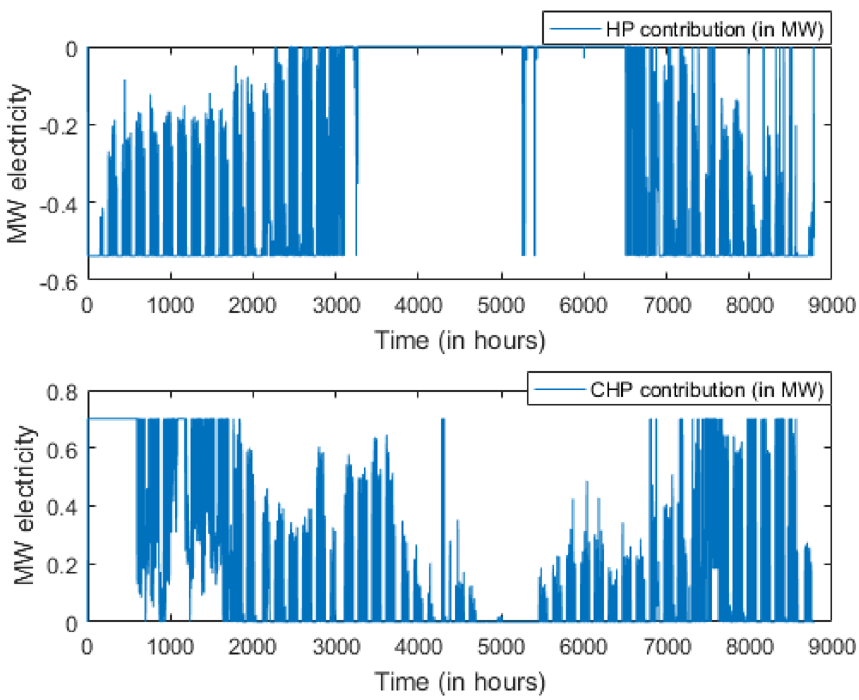

Figure 4.11: Cumulative electricity contribution by energy alternatives for electricity peak limitation = 1.4 MW

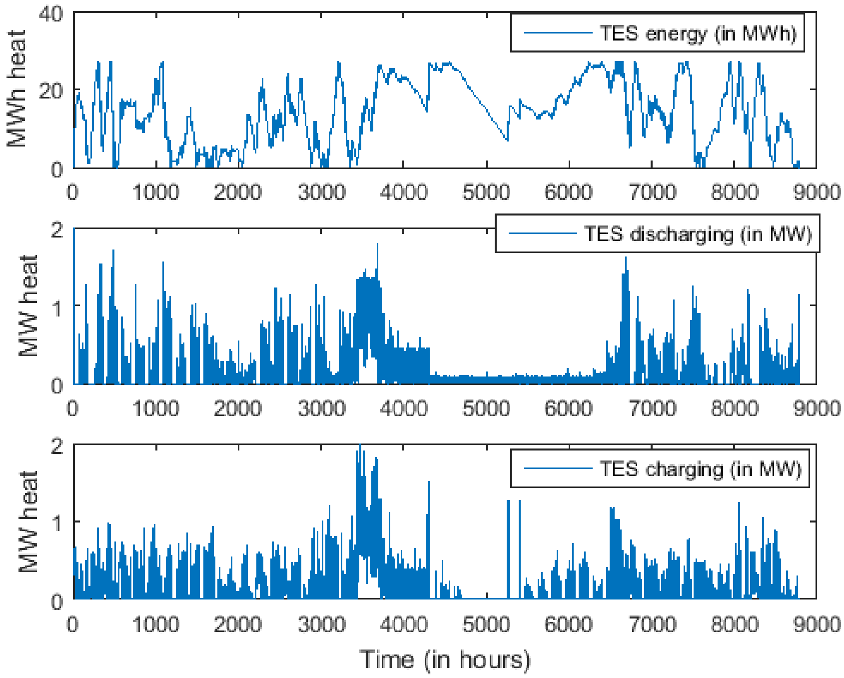

Figure 4.12: TES energy, charging and discharging curve for electricity peak limitation = 1.4 MW

4.5 Varying CHP parameters

In this section sensitivity analysis is done on various CHP parameters such as fuel price and ratio between electricity and heat produced from CHP or 'α'. Comparison of important variables such as such as initial investment cost, total annual cost, etc. are presented in tables and graphs are plotted for energy intake from grid and energy alternatives contribution.

4.5.1 Varying CHP fuel price

CHP fuel price is an important parameter affecting the capacity contribution from CHP. Since, CHP contributes to both electricity and heat, capacity of other energy alternatives are affected simultaneously. Important variables at different CHP fuel price is presented in the comparison table 4.5 below. Total annual cost is increasing with increasing with fuel price and at the same time capacity of CHP is decreasing. Price reduction due to decrease in CHP capacity is compensated by increase in TES and HP capacity. Peak DH and peak electricity from grid is increasing with increasing in CHP fuel price because CHP contributes both to heat and electricity and reduction in its capacity results in increase in electricity and heat import from grid. But rise in peak electricity is prominent as compared to heat because:

1. Increase in capacity of HP with increasing fuel price ensures less and less heat import from grid. But on an overall basis heat import is slowly increasing because of rapid decrease of CHP capacity.

2. Increase in capacity of HP, increases electricity import from grid as the capacity of CHP is also decreasing. Overall effect is, increase in electricity peak and consumption on an annual basis.

With increasing fuel price, capacity of CHP reduces rapidly, so after the first scenario, every other results in more electricity consumption than base case and have higher peaks.

Table 4.5: Comparative study of energy interaction at different CHP fuel price

Important Variables	Price=250 (SEK/MW)	275	300	325	350	375
Initial investment (SEK)(*10^7)	1.42	1.46	1.49	1.52	1.51	1.51
Annualized investment (SEK)(*10^6)	1.25	1.33	1.38	1.42	1.43	1.43
Total Annual Cost (SEK)(*10^6)	6.21	6.31	6.36	6.39	6.40	6.40
$\sum DH_{grid}$(MWh)	308.66	368.81	377.31	400.09	448.25	451.64
$\sum elec_{grid}$ (MWh)(*10^4)	0.86	1.04	1.12	1.18	1.21	1.22
$\sum DH_{grid}+\sum elec_{grid}$ (MWh)(*10^4)	0.89	1.08	1.16	1.22	1.26	1.26
$PeakDH_{grid}$ (MW)	0.73	0.75	0.77	0.78	0.82	0.83
$Peakelec_{grid}$(MW)	1.74	2.07	2.29	2.52	2.69	2.71
HP_{capa} (MW_{elec})	0.42	0.58	0.66	0.75	0.79	0.80
CHP_{capa} (MW_{fuel})	2.02	1.14	0.78	0.36	0.04	0
TES_{capa} (MWh_{heat})	29.54	46.27	48.10	55.28	68.30	72.29
$Battery_{capa}$ (MWh_{elec})	0	0	0	0	0	0
$SolarPV_{capa}$ (MW_{elec})	0	0	0	0	0	0

First fuel price i.e 250 SEK/MW is used for comparison with base case. It is observed that electrical peak decreased by 15% and heat peak is decreased by 84% compared to base case. Similarly, electrical energy consumed from grid on an annual basis is decreased by 3% and at the same time heat energy from grid is reduced by 96%. The total cost is reduced by 26% compared to base case. There is a large capacity addition of CHP as the fuel price is quite low in the first scenario, this results in decrease of both reduction of heat and electricity consumption from grid.

Graphs are plotted for the case where CHP fuel price was considered to be 250 SEK/MW. Referring to figures 4.13 and 4.14 it is clear that from 3300 hour to 6500 hour heat load is completely taken by CHP plant, which results in decrease of electrical power consumption from grid rather than increase, since CHP at the same time produces electricity. The heat contribution from energy alternatives is almost always positive, except few hours around summer when demand is 0.

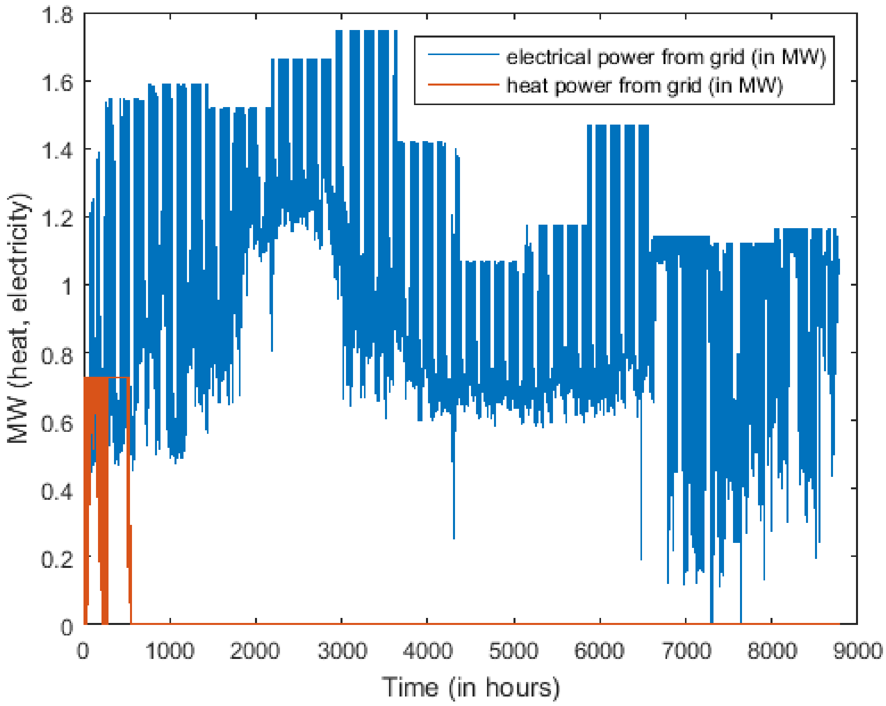

Figure 4.13: Cumulative electricity and heat contribution from grid for CHP fuel price=250 SEK/MW

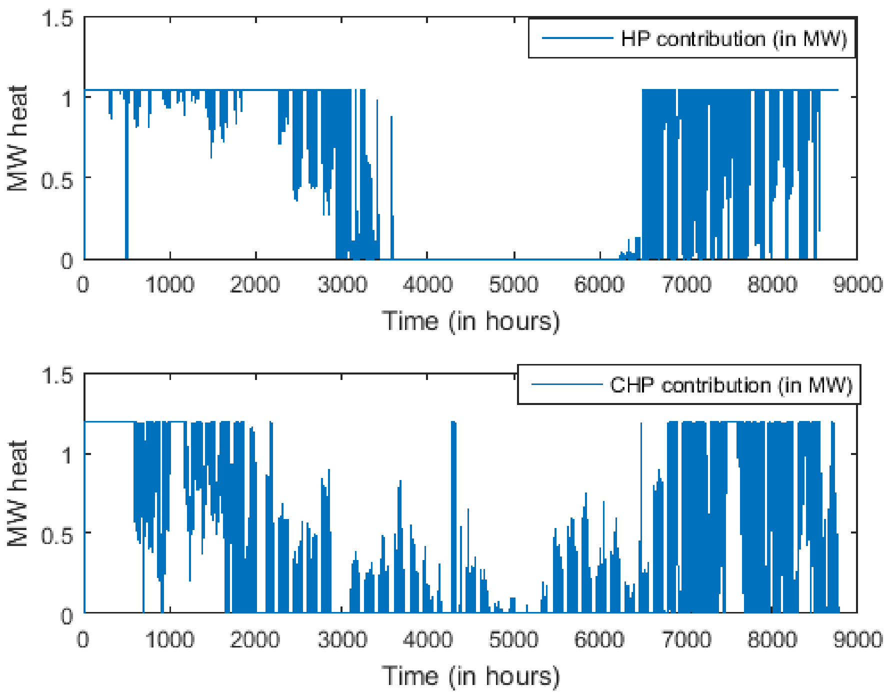

Figure 4.14: Cumulative heat contribution by energy alternatives for CHP fuel price=250 SEK/MW

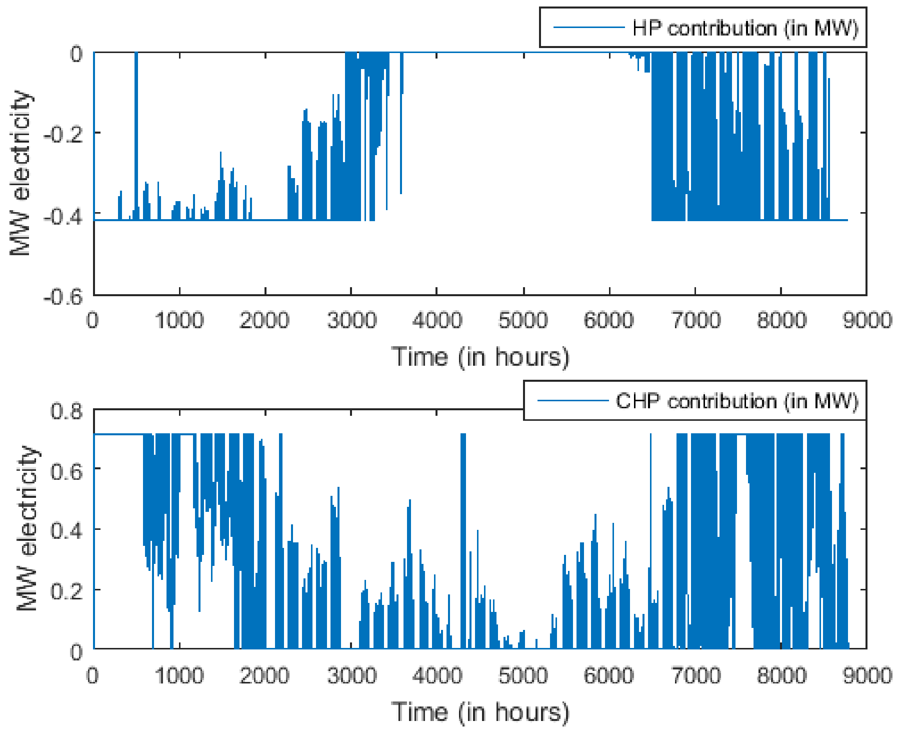

Figure 4.15: Cumulative electricity contribution by energy alternatives for CHP fuel price=250 SEK/MW

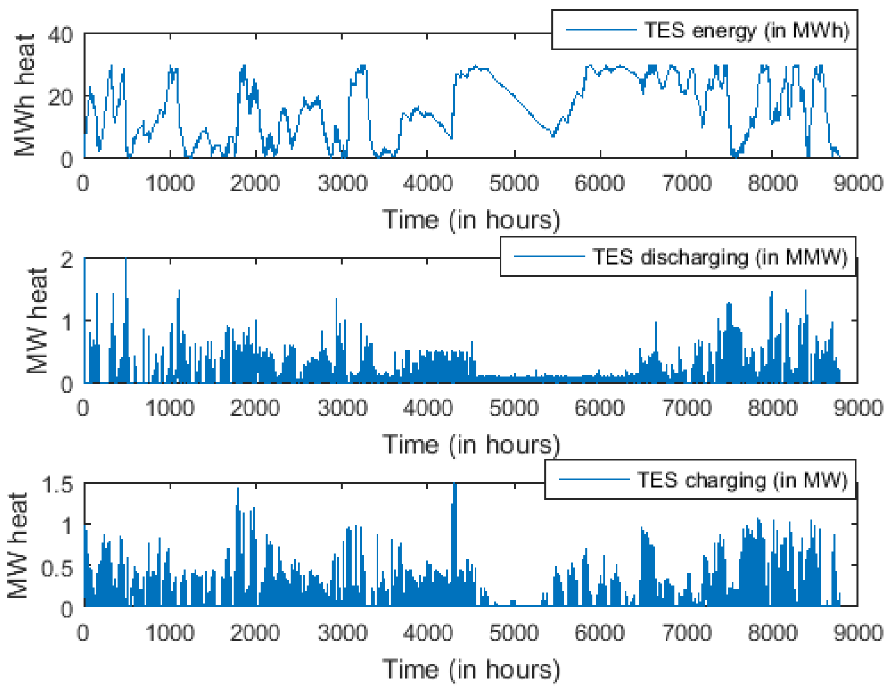

Figure 4.16: TES energy, charging and discharging curve for CHP fuel price=250 SEK/MW

Referring to figure 4.15 it is clear that there is net production of electricity from energy alternatives for most of the times, so electricity peaks from grid is lower than base case. Till 700 hours when heat price is high and demand is high, then HP operates at full capacity but this results in high electricity consumption. So, CHP also operates at full capacity, resulting around 0.3 MW net positive electricity production from energy alternatives. Thus, the curve for electricity consumption from grid reduces from 0.8-1.8 MW range (base case) to 0.5-1.6 MW range. Similar explanation can be given for other hours as well. This results in lower average electricity consumption from grid as compared to base case.

TES acts as seasonal storage mainly starting from around 3600 hour to 7500 hour i.e. from June to start of November. Before and after the above mentioned time range, TES acts as a short term heat storage device (refer figure 4.16). There is a dip in the middle of energy curve for TES around 4700-6000 hours. It is the time when heat production from HP is 0 and dip in heat production from CHP, but there is still little heat demand. Thus around one-and-half month heat demand is almost completely managed by TES.

4.5.2 Varying alpha

α is another important parameter determining directly the capacity of CHP plant and indirectly capacity of other alternatives. Since, useful energy available is same in all cases i.e. η does not change, increase in α means slight increase in electricity production and more decrease in heat production since electricity is higher grade of energy as compared to heat. Table below represents comparison between important parameters for different values of α.

Table 4.6: Comparative study of energy interaction with different CHP α values

	α=0.4	0.5	0.6	0.7	0.8	0.9
Initial investment (SEK)(*10^7)	1.50	1.51	1.52	1.52	1.54	1.55
Annualized investment (SEK)(*10^6)	1.42	1.42	1.42	1.43	1.44	1.45
Total Annual Cost (SEK)(*10^6)	6.40	6.40	6.39	6.39	6.39	6.38
$\sum DH_{grid}$(MWh)	421.91	410.08	400.09	395.88	390.46	385.11
$\sum elec_{grid}$ (MWh)(*10^4)	1.20	1.19	1.18	1.17	1.17	1.16
$\sum DH_{grid}$+$\sum elec_{grid}$ (MWh)(*10^4)	1.24	1.23	1.22	1.21	1.20	1.20
$PeakDH_{grid}$ (MW)	0.78	0.78	0.78	0.77	0.77	0.77
$Peakelec_{grid}$(MW)	2.61	2.58	2.52	2.48	2.45	2.41
HP_{capa} (MW_{elec})	0.76	0.76	0.75	0.74	0.74	0.74
CHP_{capa} (MW_{fuel})	0.20	0.28	0.37	0.42	0.47	0.52
TES_{capa} (MWh_{heat})	62.63	58.64	55.28	53.88	52.06	51.24
$Battery_{capa}$ (MWh_{elec})	0	0	0	0	0	0
$SolarPV_{capa}$ (MW_{elec})	0	0	0	0	0	0

From the table 4.6 above using α=0.4 scenario as a basis of comparison with base case, it is found that electricity peak is increased by 28% where as corresponding heat peak is decreased by 83%. Similarly electricity and heat consumption from grid on an annual basis is increased by 36% and decreased by 95% respectively as compared to base case. Large decrease in heat energy consumption from grid results in low total annual cost i.e. 23% less than base case. The contribution from energy alternatives and grid to both heat and electricity are almost similar for different values of α. Graph were plotted only for the first case i.e. $\alpha = 0.4$. Graphs for other α values are almost similar.

Referring to the figure 4.17 below, it is observed that average electricity consumption curve has shifted from 0.8-1.8 MW in base case to 1.5-2.5 MW from 0-1800 hours. Between 3500-6500 hours, base case electricity consumption is almost similar to base case as there is hardly any contribution from any energy alternative towards electricity. Heat contribution from grid is 0 after 600 hours from beginning of the year because of simultaneous contribution from CHP and HP. In the middle of year from 3500 hour to 6500 hour when there is rarely any contribution from HP and CHP but there is marginal heat demand, it is covered by energy stored in TES (refer figures 4.18 and 4.20).

For the electricity side, there is net negative contribution from energy alternative especially between 0-3000 hours and 6500-8784 hours resulting in upward shift of electricity demand from grid curve. The remaining hours electricity demand is almost same to base case (refer figures 4.17 and 4.19).

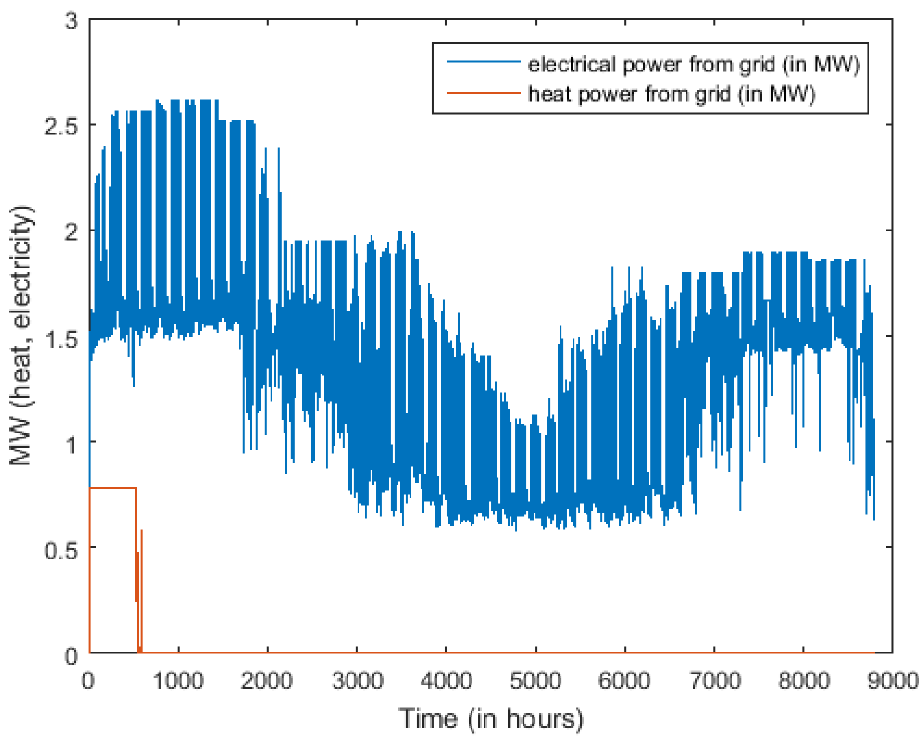

Figure 4.17: Cumulative electricity and heat contribution from grid for alpha = 0.4

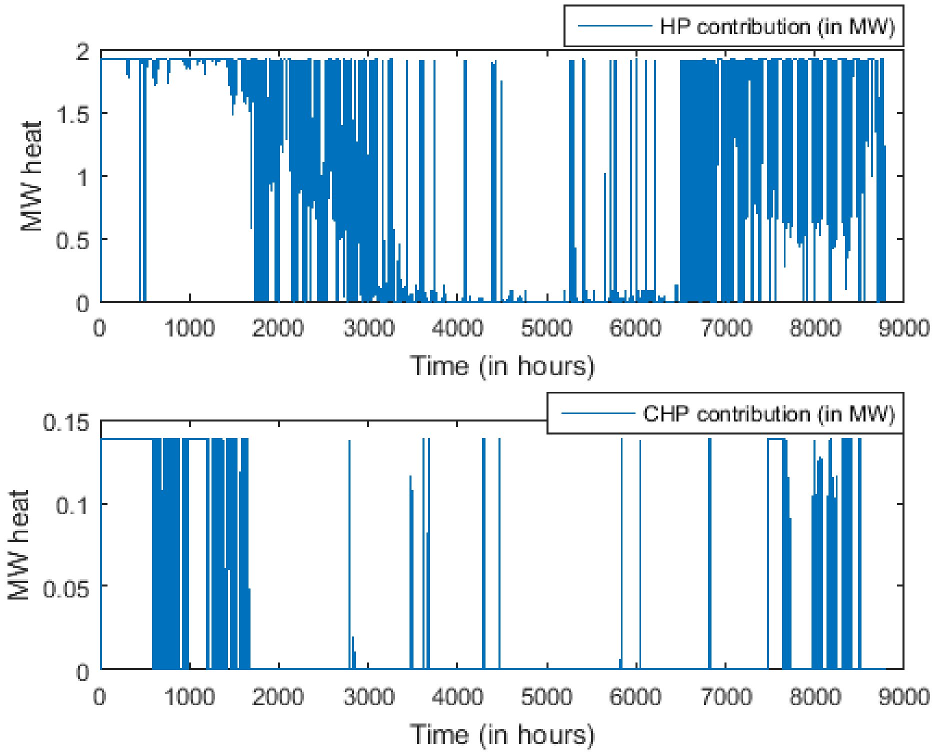

Figure 4.18: Cumulative heat contribution by energy alternatives for alpha = 0.4

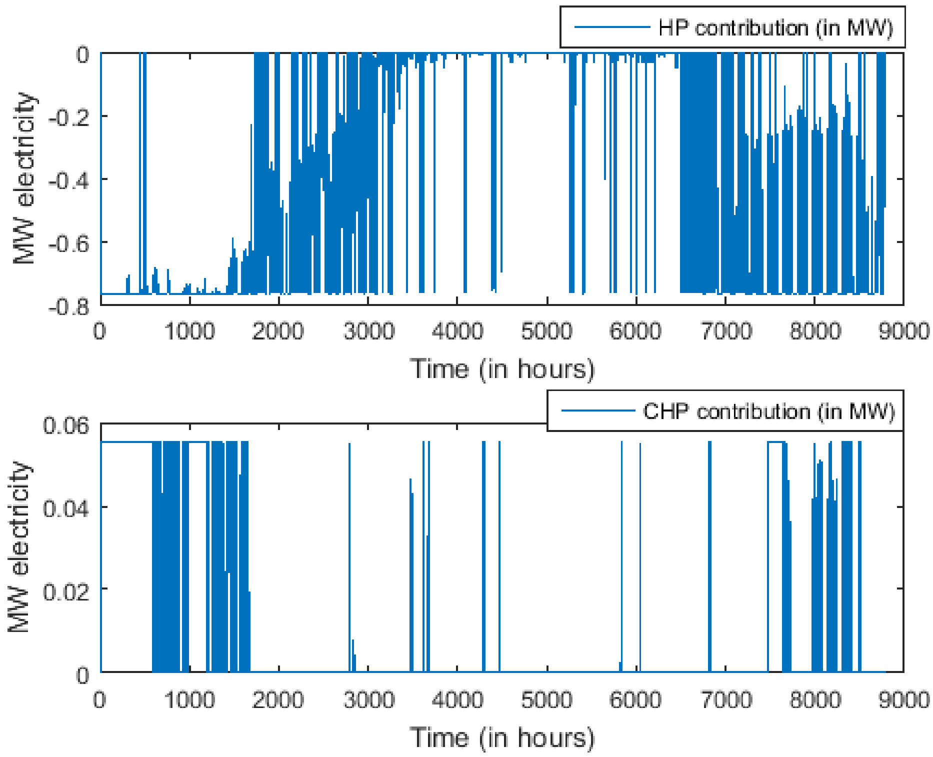

Figure 4.19: Cumulative electricity contribution by energy alternatives for alpha = 0.4

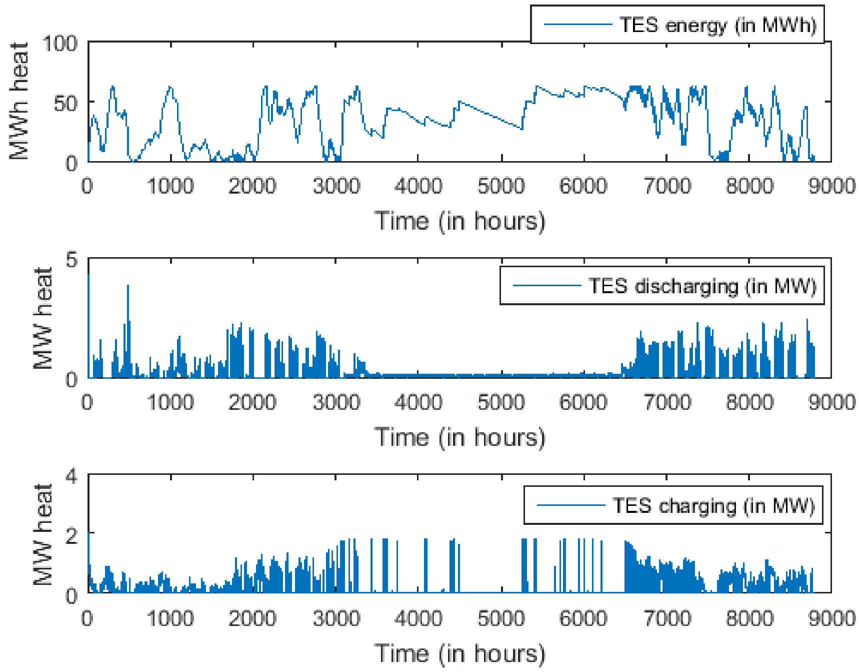

Figure 4.20: TES energy, charging and discharging curve for alpha =0.4

4.6 Initial investment cost limitation

Initial investment reflects the present price of an energy alternative, not taking into consideration the lifetime of it. This variable directly decides the capacity of an energy alternative. Analysis of different variables was done under different set of initial investment condition and represented in the comparison table below.

Table 4.7: Energy alternatives consideration at different annualized cost

Properties	Initial Investment cost		
	10 million	7.5 million	5 million
Initial investment (SEK)(*10^7)	1	0.75	0.5
Annualized investment (SEK)(*10^5)	9.5254	7.1432	4.7479
Total annual cost (SEK/yr)(*10^6)	6.6054	6.9075	7.2882
$\sum DH_{grid}$ (MWh)(*10^3)	1.9006	3.2395	4.9695
$\sum elec_{grid}$ (MWh)(*10^4)	1.1562	1.1019	1.0325
$\sum DH_{grid}$+$\sum elec_{grid}$ (MWh)(*10^4)	1.3463	1.4258	1.5294
$PeakDH_{grid}$ (MW)	1.6187	1.9576	2.3068
$Peakelec_{grid}$ (MW)	2.4507	2.3173	2.1790
HP_{capa} (MW_{elec})	0.5390	0.4040	0.2662
CHP_{capa} (MW_{fuel})	0	0	0
TES_{capa} (MWh_{heat})	29.8412	22.7219	20.8479
$Battery_{capa}$ (MWh_{elec})	0	0	0
$SolarPV_{capa}$ (MW_{elec})	0	0	0

From the above table it is observed that, CHP contribution is zero for all the cases of limitation on initial investment. This suggests that, if budget is limited then high initial investment cost alongwith the fuel cost of CHP plant do not justify its presence in the Chalmers campus. This rather promotes solutions with short lifetime, i.e. HP. With decreasing initial investment the capacity contribution from HP and TES is decreasing. Since the capacity of HP is decreasing, the electricity consumption from grid is decreasing with subsequent scenario, as there is no electricity contribution from CHP. This is the same reason why DH contribution from grid is increasing. Same explanation goes for increasing heat peaks and decreasing electricity peaks with subsequent scenarios. There is slow decrease in electricity contribution from grid but large increase in heat contribution with each subsequent scenario mainly because of the COP factor of HP.

5 million SEK investment scenario is used for comparison with base case. The electricity input from grid increased by 17%, where as heat input from grid is decreased by 42% compared to base case. Similarly electricity peak increased by 6%, where as heat peak decreased by 49% in comparison with base case. As a result of large decrease in heat consumption from grid and less increase in electricity consumption, the total annual cost reduced by 13% as compared to base case.

The contribution from energy alternatives and grid both for heat and electricity are almost similar for different investment cost, except the fact that energy contribution from grid increases rapidly with decrease in initial investment cost, especially for heat during later part of the year. The case of 5 million initial investment limitation is presented below.

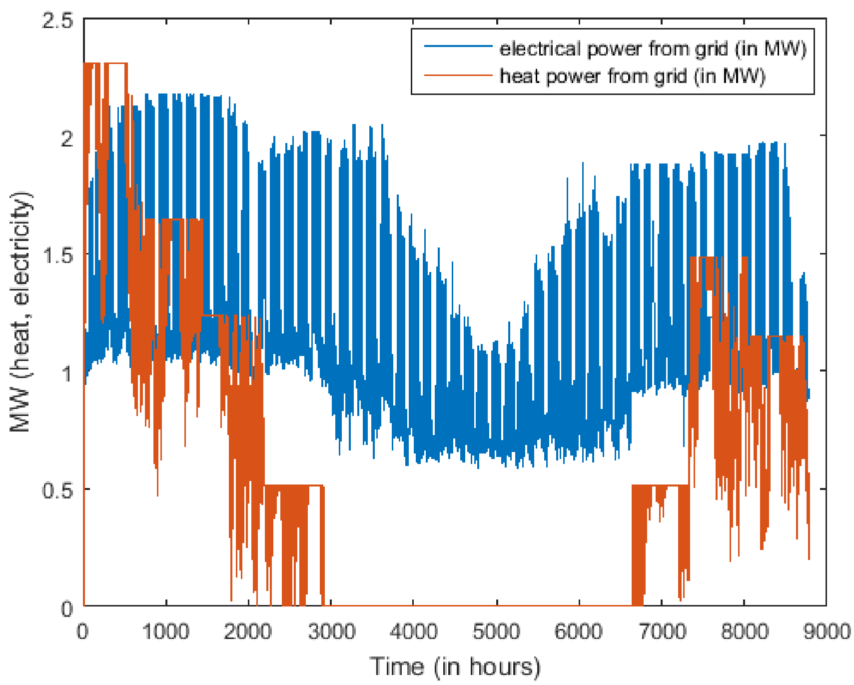

Figure 4.21: Cumulative electricity and heat contribution from grid for 5 million SEK initial investment

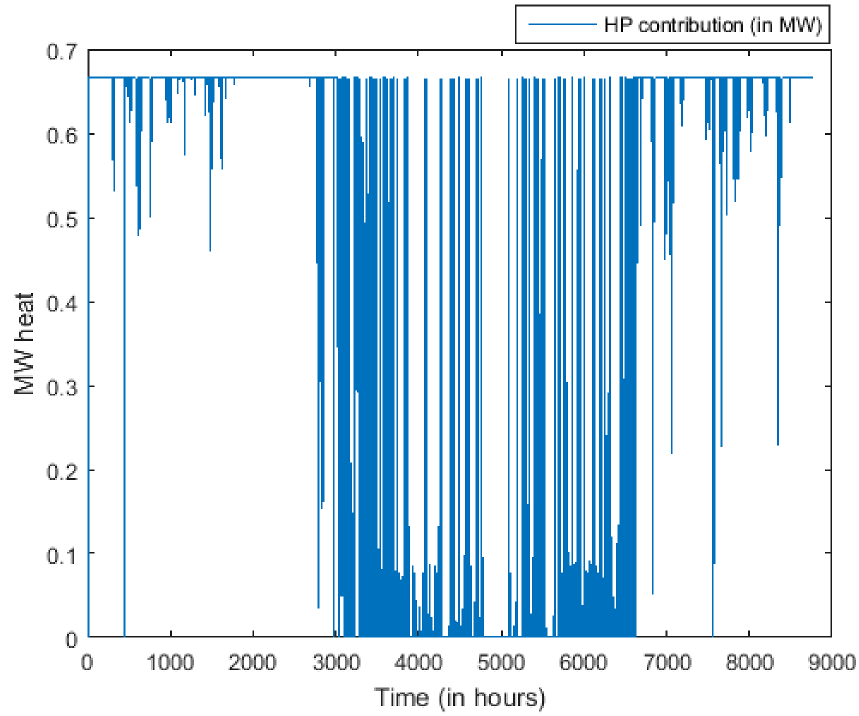

Figure 4.22: Cumulative heat contribution by energy alternatives for 5 million SEK initial investment

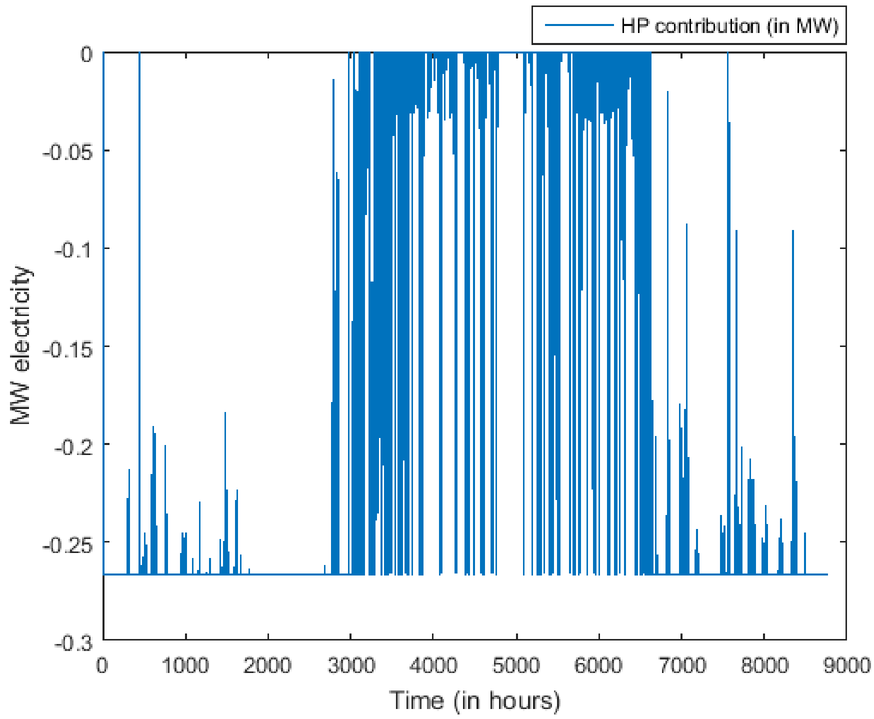

Figure 4.23: Cumulative electricity contribution by energy alternatives for 5 million SEK initial investment

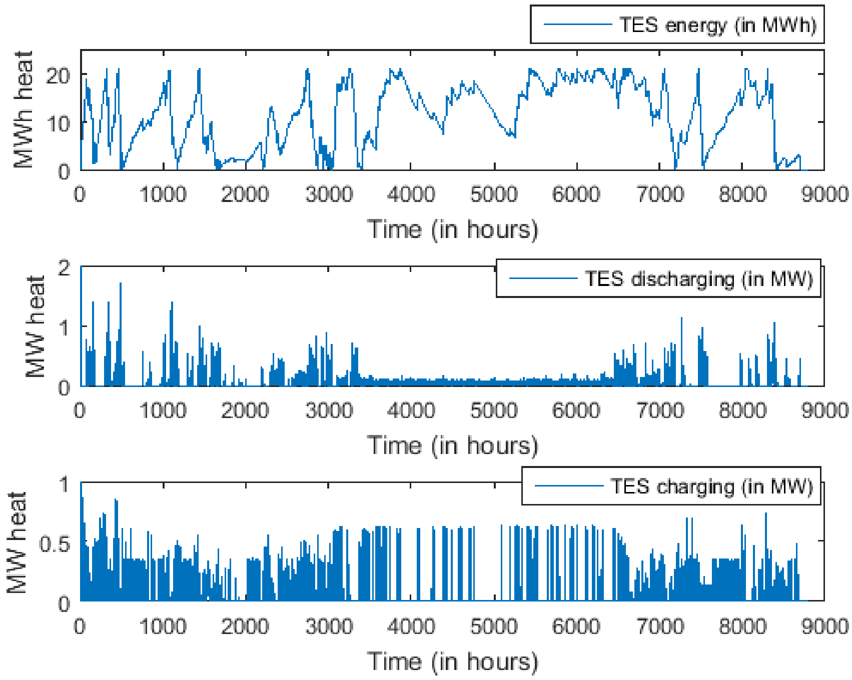

Figure 4.24: TES energy, charging and discharging curve for 5 million SEK initial investment

Referring to the figure 4.21, it is observed that electricity consumption from grid top profile looks almost similar to base case, but values are little higher, except the middle of the year. On the heating side, there is no contribution from grid between 3000-6700 hours. For other hours, heat contribution from grid is low and flat as compared to base case because of positive intermittent contribution from HP and storage by TES. TES together with HP do not allow peaks, as peaks means comparatively higher price for less hours. From figure 4.22, it is clear that HP makes full capacity contribution for almost entire winter at the beginning (0-2900 hours) and end (7500-8784 hours) of the year and makes sparse contribution during rest of the year. But in the middle of the year, a lot of heat is stored in TES to be used in later part of the year (refer figure 4.24). In the summer, sparse contribution from HP is compensated by continuous discharging from TES. But, the capacity is less than most of the other cases because of low initial investment allowed and subsequently low capacity contribution from HP. This results in large import of heat from grid and subsequent high total annual cost than most of previous cases. TES acts as a short term storage from 0-3500 hour as its energy is completely drained intermittently during this period. But from 3500th hour onwards, it act as long term storage where energy is stored till 7200th hour without getting completely drained because of low heat demand during this period. TES again acts as short term storage in later part of the year feeding heat to the system when heat price is high.

On the electricity side, there is net negative contribution from energy alternatives i.e. negative contribution from HP and no contribution from any other alternatives (refer figure 4.23). In the winter, both at the beginning and end of the year, when HP operates at full capacity, thus electricity import from grid moves up by 0.25

MW. But, during the rest of the year, it is almost same as the base case.

4.7 Energy alternatives price reduced

It was noted that solar PV and battery didn't play any role in any of the cases mentioned above, so it was decided to do a sensitivity analysis of annualized investment cost of them to decide the price at which they make an positive impact on the system. Table below represents the values of important variables when prices of battery and solar PV is reduced with prices reduced in reference with the table 3.6 mentioned in the previous chapter.

Table 4.8: Sensitivity analysis with energy alternatives price of battery and solar PV reduced

Important variables	1	5	6	12
Initial investment (SEK)(*10^7)	1.52	1.56	7.17	7.76
Annualized investment (SEK)(*10^6)	1.42	1.45	5.10	5.61
Total annual cost (SEK/yr)(*10^6)	6.39	6.39	6.20	6.20
$\sum DH_{grid}$ (MWh)	400.09	400.56	398.43	403.58
$\sum elec_{grid}$ (MWh)(*10^4)	1.18	1.18	1.02	1.02
$\sum DH_{grid}$+$\sum elec_{grid}$ (MWh)(*10^4)	1.22	1.22	1.06	1.06
$PeakDH_{grid}$ (MW)	0.77	0.77	0.77	0.78
$Peakelec_{grid}$ (MW)	2.52	2.52	2.47	2.43
HP_{capa} (MW_{elec})	0.75	0.75	0.75	0.75
CHP_{capa} (MW_{fuel})	0.36	0.36	0.37	0.35
TES_{capa} (MWh_{heat})	55.28	55.44	55.03	56.61
$Battery_{capa}$ (MWh_{elec})	0	0	0	0.35
$SolarPV_{capa}$ (MW_{elec})	0	0.02	3.14	3.23

Scenario 1 represents case where all energy alternatives have actual price. Scenario 5, 6 represents case where solar PV price is reduced to 20% and 10 % of actual price respectively (other energy alternatives price remain same). Scenario 12 represents case where price of both battery and solar PV are reduced to 10% of actual price (prices of remaining alternatives remains the same). Above mentioned scenarios are picked up from table 3.6 and represented in the table 4.8, since values of important variables in other scenarios are same as the scenario 1.

It is clear from the above table that battery does not have an impact on the system even if its price is reduced to 10% compared to present pricing suggesting electricity price fluctuation at present is not sufficient to justify high pricing of batteries and round cycle efficiency losses. But, if the same reduction is done with solar PVs price also reduced to 10% of its present price, then it make capacity contribution to the Chalmers campus because, large fluctuation and overproduction associated with solar PV electricity production makes it profitable to have battery both for stabilization of electricity consumption from grid and storage of overproduced solar PV electricity. From scenarios 5 and 6, it is observed that, once the solar PV starts making contribution, then its capacity rises fast with subsequent cases because of zero running cost.

From the above table, since in scenario 12 all energy alternative are making contribution, it is used as a basis of comparison with base case. The electrical power consumption from grid increased by 16%, where as heat consumption reduced by 95% as compared to base case. Similarly electrical peak increased by 19% and heat peak from grid is reduced by 83%. This results in total annual cost reduction of 26% in comparison with base case. Figures below represent electrical and heat power consumed from grid and energy alternatives on an yearly basis for scenario 12.

From figure 4.25, it is found that unlike other cases, there are lot of instances especially in summer when electrical power consumption from grid is 0. This is mainly because of the presence of large capacity solar PV (refer figure 4.27). On the electrical side, from 3000-5800 hours, there is negative contribution from HP, negligible contribution from CHP and positive contribution from solar PV. But, the positive contribution from PVs is high enough to result in overall decrease in average power consumption from grid during these hours.

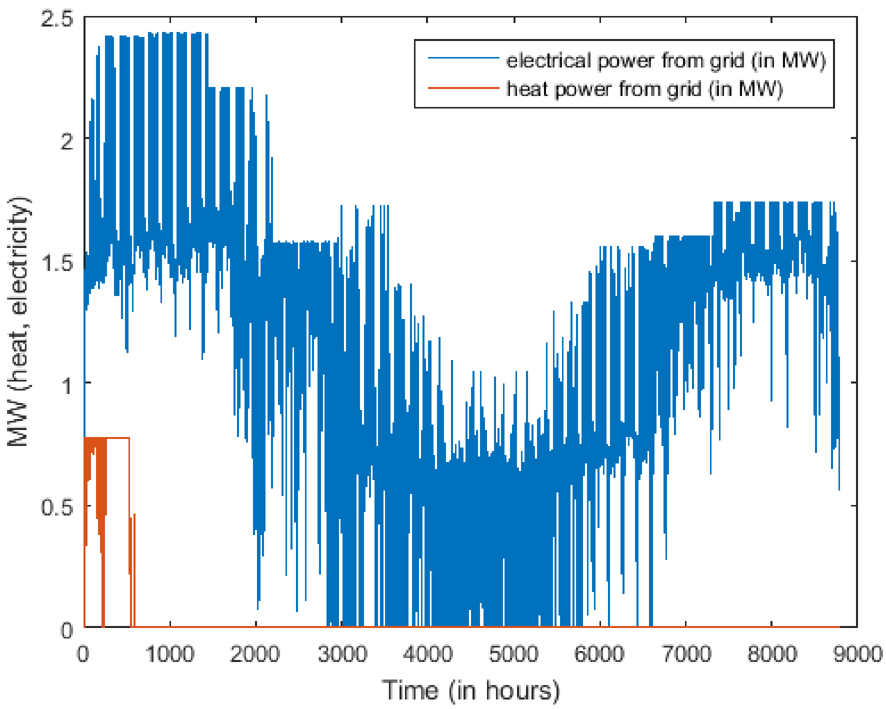

Figure 4.25: Cumulative electricity and heat contribution for battery and solar PV price reduced

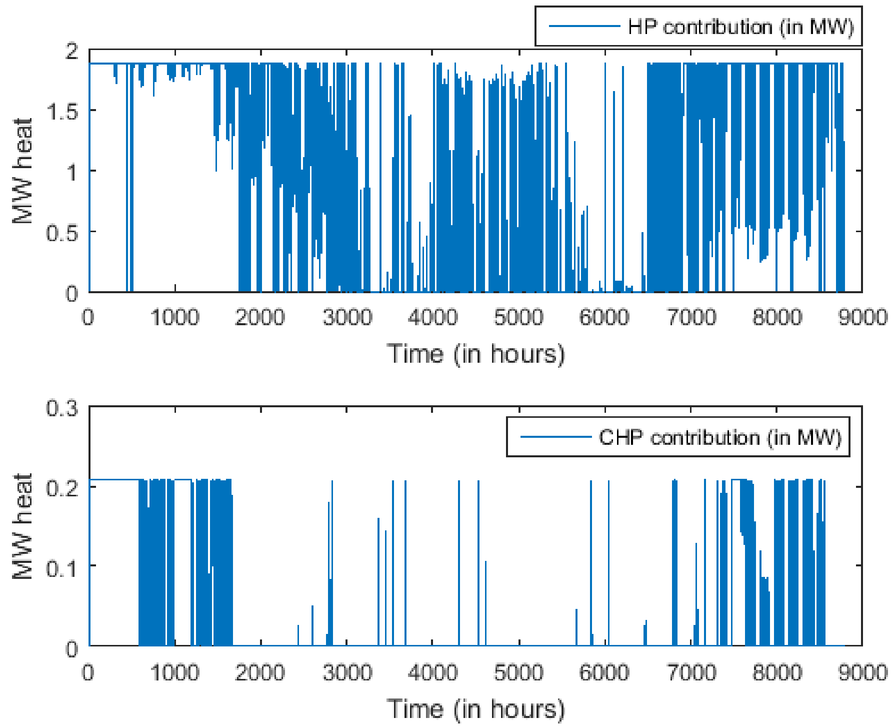

Figure 4.26: Cumulative heat contribution by energy alternatives for battery and solar PV price reduced

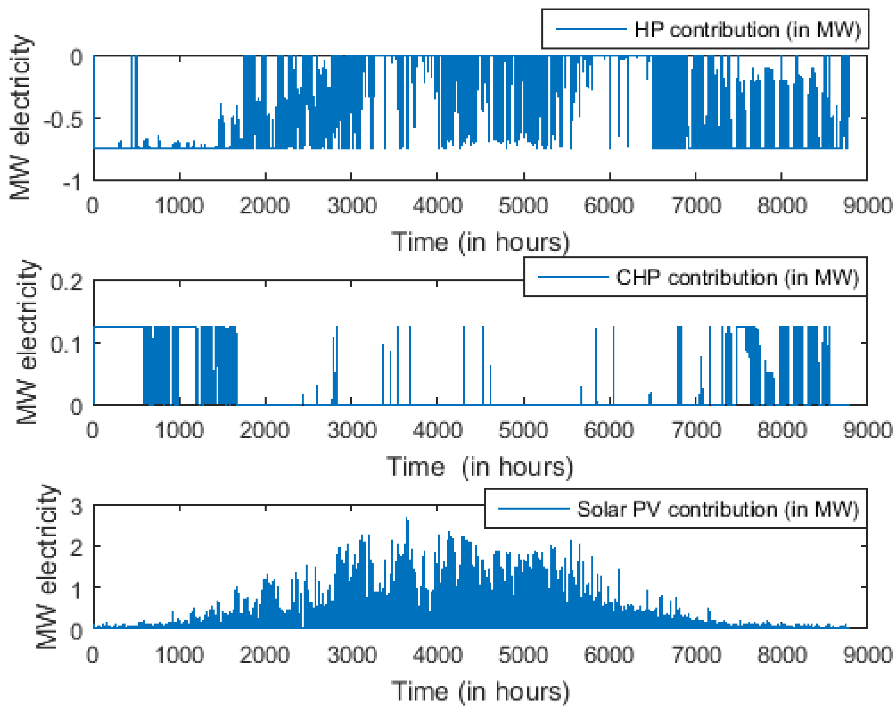

Figure 4.27: Cumulative electricity contribution by energy alternatives for battery and solar PV price reduced

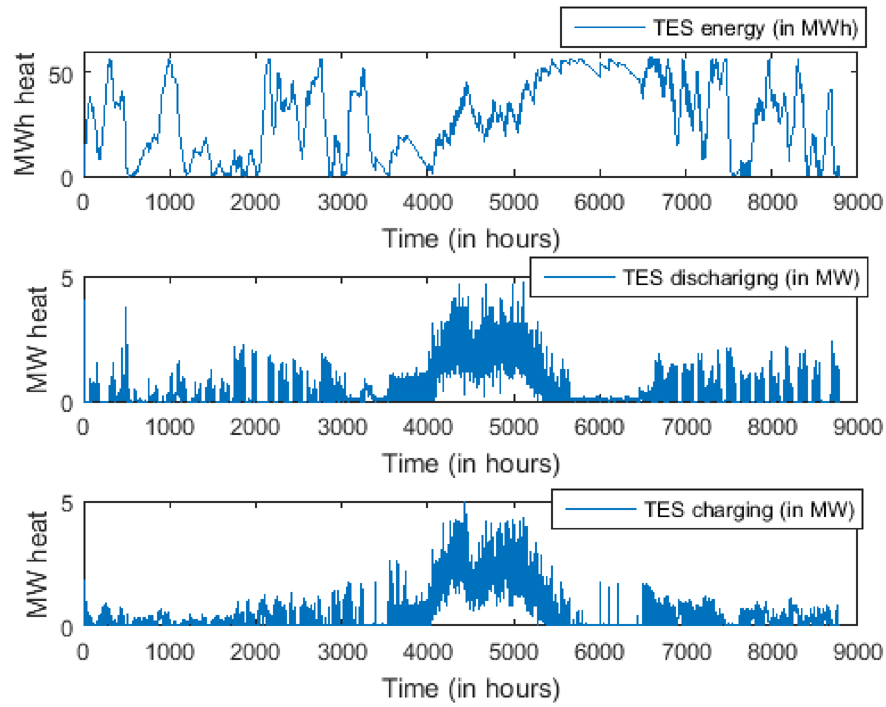

Figure 4.28: TES energy, charging and discharging curve for battery and solar PV price reduced

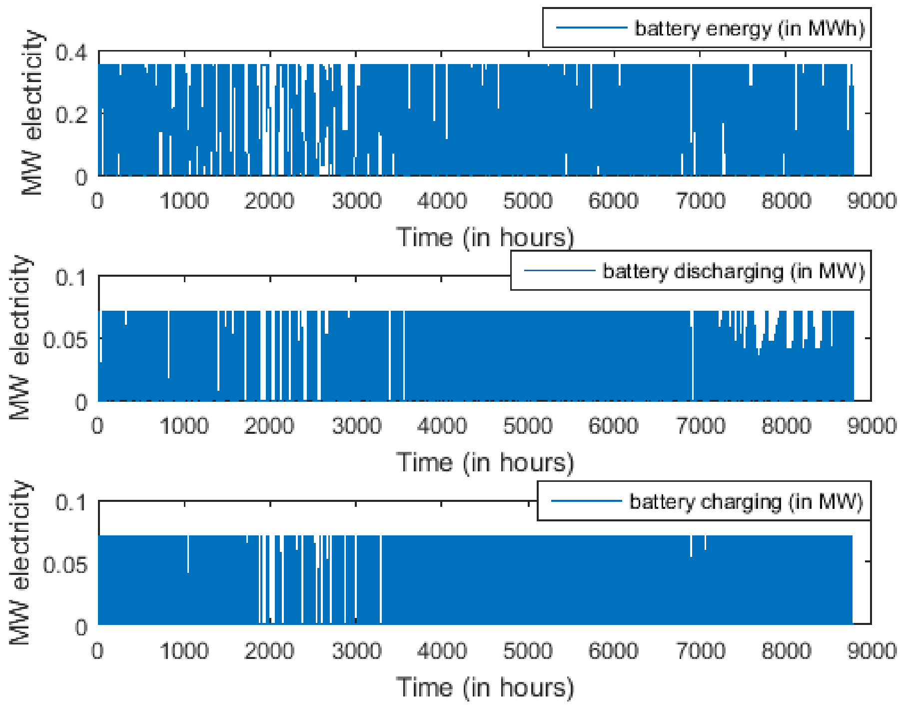

Figure 4.29: Battery energy, charging and discharging curve for battery and solar PV price reduced

From figure 4.26, it is observed that there is heat production of around 1.5 MW from 4000-5500 hours. But the heat demand from buildings during this time period is not so high. The reason for extra production of electricity is solar PV (and no provision of selling the extra electricity, since lower limit of transmission from distribution grid is 0 and not negative). This results in consumption of extra electricity by HP and extra production of heat. Since, heat demand balance equation is constrained by equal sign, this results in intake and release of heat by TES at almost same time, resulting in efficiency losses. This counteracts extra heat present in the system (refer figure 4.28) and some of the heat is stored in the TES for use in later part of the year when heat price is high. A solution to this, is to make production side of heat demand balance equation greater than equal to demand side. But, there is a risk of over-investment in TES, since model do not allow over-production of heat.

From figure 4.29, it is observed that both charging and discharging takes place year round resulting in large fluctuation of energy present in the battery. This is different from TES heat storage in other cases, where charging takes place mostly in summer and discharging in the remaining parts of the year. It is due to the fact that electricity demand is does not vary as much as heat demand over the year. Also, battery is not present in previous cases because electrical demand variation on an annual basis is not high enough to justify its presence in the system.

On the heating side, there is power intake from grid only for first 600 hours. For the remaining hours, heating demand is met by heat production from HP and CHP and storage and re-use by TES (refer figures 4.25, 4.26 and 4.28). For the first two months, HP and CHP runs at full capacity for most of the hours, which allows to meet most of the heat demand and use some surplus for short term storage in TES. It act as a long term storage between 4000-7500 hours. The peculiar thing about charging and discharging in this scenario is, it is high around 3500-5600 hour (even though it takes place at different hours for different buildings within those hours) when the actual heat demand is low. The main reason is fluctuating operation of HP during this time (other cases HP generally do not operate around summer). Its electricity counterpart, the battery shows a lot of fluctuation over the year for charging, discharging and the amount of energy stored in battery, even if its capacity is quite low as compared to TES. Large fluctuations is mainly due to combination of following reasons:

1. Large fluctuation in electricity provided by solar PVs especially in summer.
2. Large variation in electricity demand from grid over over the year due to large fluctuation in energy intake by HP and energy release by CHP (especially in winter).
3. Large variation in electricity price over the year.

4.8 Comparison between different cases

Table below represents comparison between scenarios (the ones which are discussed in details) of different cases with base case.

Table 4.9: Comparison of important variables in different cases w.r.t. base case

Scenarios of different cases	$Peakelec_{grid}$ (MW)	$PeakDH_{grid}$ (MW)	$\sum elec_{grid}$ (MWh) (*10^4)	$\sum DH_{grid}$ (MWh)	Total Annual cost (SEK/yr) (*10^6)
Base	2.0	4.6	0.9	8612.7	8.4
i=5%	2.5(21%↑)	0.8(83%↓)	1.2(32%↑)	400.8(95%↓)	6.4(24%↓)
i=10%	2.5(21%↑)	1.2(74%↓)	1.2(32%↑)	938.5(89%↓)	6.9(18%↓)
COP=3	2.5(25%↑)	0.8(82%↓)	1.2(31%↑)	435.3(95%↓)	6.0(28%↓)
Peak limit =1.4	1.4(31%↓)	0.6(87%↓)	0.9(8%↑)	200.8(97%↓)	6.6(20%↓)
CHP fuel price =250	1.7(15%↓)	0.7(84%↓)	0.8(3%↓)	308.6(96%↓)	6.2(26%↓)
α=0.4	2.6(28%↑)	0.8(83%↓)	1.2(36%↑)	421.9(95%↓)	6.4(23%↓)
Initial Investment =5 million	2.2(6%↑)	2.3(49%↓)	1.0(17%↑)	4969(42%↓)	7.3(13%↓)
Scenario 12	2.4(19%↑)	0.8(83%↓)	1.0(16%↑)	403.6(95%↓)	6.2(26%↓)

5 Discussion

Discussion chapter presents discourse about few assumptions and the impact it might have on results or simplification over model formulation of energy alternatives. But, sincere effort is made in master's thesis to present sensitive analysis of parameters which have significant impact on the results.

5.1 Network constraints

The heating and electrical distribution network has their own distinct structure. But in the present context, interconnection between buildings both for electrical and heating side are taken to be same (based on the district heating network within Chalmers). Losses vary with demand, but in the present thesis, it was taken to be 5% of power transmitted for all cases both for heating and electrical network. Still, 5% is fairly justified in case of electrical distribution network in Europe. But, district heating transmission losses is a function of outdoor temperature and flow. The more the temperature difference between incoming fluid and outdoor temperature, more is the losses. Reduction in supply temperature can reduce losses but could result in unacceptable low temperature levels for customers. Reduction in supply temperature will increase fluid flow, resulting in higher pumping costs. Thus the transmission losses in heat network is highly varying. In [35], it was found that exergy losses formed during heat distribution were about 16% of total exergy in the system. They concluded that temperature of hot water supplied and returning are the most important factors affecting these exergy losses. Thus, attempts are generally made for low incoming temperature and large insulation to reduce transmission losses. Since, district heating network was not designed in details in the present work, incoming and outgoing fluid temperature was not considered in elaborate manner. Considering the above factors would have definitely increased the simulation time.

5.2 Balance equations

The heat demand balance equation was subjected to equality constraint. This resulted in efficiency losses associated with TES to compensate for overproduction of heat by energy alternatives. For example: in the peak limit of 1.4 MW case and reduced energy alternatives price case (scenario 12). Making production side of the balance equation greater than equal to would have solved this problem but this would have resulted in overestimation of TES, since the model does tolerate overproduction of heat. Other way is to allow export of heat to the local distribution grid at presumably lower price. Then, overproduction might reduce, because of lower price associated with selling heat to grid.

5.3 Energy alternatives case

In this section different energy alternatives are explicitly analyzed to determine impact of distinct assumptions.

5.3.1 HP case

The formulation of HP equation was both for electrical and heat balance equations are pretty much straightforward. COP is considered fixed for the analysis. Since HP is playing a major role in all cases analyzed, a sensitivity analysis was done around COP. The problem is, whatever COP is taken, it is fixed for whole year, but in reality, it is a function of outdoor temperature (atleast for air-source HP which is taken into consideration in the present research work) which varies all the time.

The detailed analysis of HP would involve modelling of individual component and then combining all components to complete the loop. For example: evaporator temperature has to be lower than outdoor temperature or waste heat temperature so as to absorb heat from surrounding. Similarly temperature of the fluid transferring heat to indoors has to be at higher temperature than room temperature for effective heat transfer. But the current model don't take the above observations into consideration.

The source of waste heat is also not explicitly defined in the model i.e. it is assumed that waste heat comes from somewhere and is a free source. The problem with implementing this in reality will be uncontrollable source temperature. If a model has a COP of 2.5, then 1.5 unit of free waste heat has to come from somewhere undefined in the present model and the optimization tool utilizes this free heat source to use HP as much as possible, especially when there is large difference in heat and electricity price. That is why in all cases analyzed, HP was making positive contribution to the heating side.

Chalmers is already self sufficient in heat on an annual basis due to presence of HP near kraftcentralen, but in the base case this was not considered. So, installed capacity value obtained in the present research work is actually overestimated, which means that more focus of the FED project will be to make Chalmers self sufficient on the electrical side. Then it becomes obvious that there shall be more spending on other energy alternatives as compared to present model.

5.3.2 CHP case

In CHP, electricity and heat contribution changes with time depending upon where we extract process heat (for condensing steam turbine) or district heat (for condensing and back pressure turbine). Thus, heat extraction is dependent upon demand.

This affects the ratio between electricity and heat i.e. α. Similarly, if the CHP condenser pressure is too low, it signifies maximum electricity extraction, leaving less opportunity for heat withdrawal. More electricity extraction signifies less total efficiency, the reason being electricity is superior form of energy and more heat has to be input to the system for same amount of electricity extraction as compared to heat. Since analysis in the present thesis is done without taking these things into consideration, simulation does not exactly correspond to real case scenario. But, a good guess of α and η was made based on referring to some articles and taking Rya plant of Göteborg Energi as template. Thus, result from the current model are not far from real case and can be used directly for making further calculation on behaviour of CHP in presence of other energy alternatives. Due to high sensitivity of α, a simulation was done around this critical parameter.

The CHP model in the present analysis uses wood pellets as raw material. Since a detailed analysis was not made on the boiler exhaust temperature and pressure, it is difficult to know exact work delivered at any given point of time. In general, wood pellets have low superheated temperature and pressure as compared to corresponding coal boiler. Low temperature at turbine inlet means lot of saturated steam at low pressure turbine exhaust especially if more electricity is extracted from CHP (depending upon the requirement of the overall system). This means more corrosion of turbine blades and less overall efficiency, which is not taken into consideration in present formulation.

CHP plant operation cannot be varied randomly at any rate due to limitation on ramp rate. But this constraint was not imposed on the model because this would have led to unit commitment model to be solved by Mixed Integer Programming (MIP) solver in GAMS. Then, it is difficult to run the model over a year, due to large simulation time.

5.3.3 TES case

In the present analysis a clear cut model formulation was done to for TES. Apart from that, there is prominent distinction between power exchange and energy available at TES, where as for other technologies there is not much difference between power and energy (except batteries) since every variable was calculated based on hourly resolution.

TES can be stratified, where flow rate is a function of capacity of TES i.e. it does not matter how much energy is available in storage tank, the only thing that matters is temperature difference between receiving and sending level. But, if a TES is mixing type, then flow rate is a function of energy available in tank and more withdrawal of power would mean less availability of next instant. In the present thesis, simulations were done considering TES as stratified type in all the cases.

5.3.4 Batteries case

The methodology behind the battery model formulation is similar to TES, the only difference being it act as an energy alternative from electrical side. If the price is reduced by 90% of present price, then they are making an impact on the model, and that too in the presence of of solar PVs. This indicates one should wait for some more years for battery price to reduce to incorporate it as an electrical energy storage device or wait for more renewables to be inducted in grid, so that there is increase in variation of electrical energy pricing.

5.3.5 Solar PV case

Similar to batteries, solar PVs' prices are too high to make capacity contribution to present energy system of Chalmers campus. Also, location of Gothenburg is such that not much electricity can be extracted out of installed solar PVs.

Solar PV has the advantage of very low running cost and high lifetime. This suggests that once decision has been made to make investment in certain capacity of solar panels then it is always available to give maximum possible electricity output (based on capacity and solar incidence) without much interruption. On the other side, if the production from solar panels is more than required (by Chalmers in this case) then difference in tariff structure for selling and buying (one get low price for selling electricity to the grid and charged more when purchasing from the grid) would lead to losses considering the high investment already made. Hence proper capacity determination is necessary before installation. Also the problem is, solar incidence varies between years similar to other renewables like wind. Thus, it is very difficult to determine the exact capacity to make optimum electricity contribution over its long lifetime. t present, grid electricity price is below 1 EUR/W making it difficult for solar PVs to become cost competitive. Also, in the model since nordpool prices are used directly, local energy generation from solar panels is difficult.

Some solar PVs are already installed on the rooftops and facades of some of the buildings under consideration in the present research work. So, they should have been part of base case. But, since data was not available for them and their contribution is less as compared to amount of electrical energy required by the buildings, they were neglected in the current research work.

6
Conclusion and future work

This chapter present conclusion and future work in the same order. The conclusion section provides overview of entire master's thesis work and overall analysis of results from different simulation. Future work presents further works that can be associated and carried out with the help of present research.

6.1 Conclusion

Energy consumption analysis of 12 buildings within Chalmers campus was done in the current research work with focus on analyzing the interaction between heating and electrical network. First of all, a database was developed where electricity and heat consumed by different buildings for 2016 was collected with hourly resolution. A model was developed with help of optimization tool called general algebraic modelling system (GAMS). All energy alternatives constraints were explicitly formulated, viability was checked and then universal model was built. Switches were placed on each and every energy alternatives to allow user to decide on their presence in creation of different scenarios. Dimensioning of all energy alternatives was done under different set of simulating conditions with the objective of total cost minimization. CHP and HP acted as the interface between electrical and heating network. different energy alternatives complemented each other, for example: in winter when the requirement of both heat and electricity are high, HP operated to fulfill high heat demand but it increased electricity demand which was overcome by CHP operating at full capacity at the same time. CHP in turn also compensated some heat demand. Energy alternatives are also competing at some instances, for example: on a winter day when electricity demand is high and it is profitable to run CHP plant to avoid high cost electricity from grid then the heat produced as a by-product from CHP plant compete with heat produced from HP plant, especially if demand is low. Few noteworthy points obtained during model simulation are presented below:

1. There is almost no contribution from batteries in any simulation except the case where where energy alternatives price is reduced both for batteries and solar PVs. The reason is variation in electricity price over the year at present situation is not sufficient enough to justify its high annualized price and losses due to round cycle efficiency.
2. Solar PV contribution corresponds to solar incidence as expected. Since its price is too high even with low rate of interest, they also do not make contribution in any of the cases, except case where its price was reduced to 20% of

the present price. This justifies the fact that high pricing of solar PV do not allow them to compete with other cheaper energy alternatives option in the present energy demand and pricing condition.

3. There is HP contribution to the Chalmers DH network in all cases mentioned in the previous chapter because of high COP and low electricity price as compared to heat price for most part of the year.
4. CHP is not present in case where COP of HP exceeds 3.5, indicating significant contribution from HP for heat side. Thus, high fuel price does not allow CHP to be present in the system to solely provide electricity. It is also not present in the scenario when CHP fuel price becomes equal to or exceeds 375 SEK/MW. When there is an initial investment limitation of 10 million SEK or less, then also CHP is not present in the system signifying high purchasing price of it not being able to compete with other cheaper energy alternative option or direct energy purchase from grid.
5. HP heat supply variation due to rapidly fluctuating electricity price leads to large scale variation in heat import from grid. The above mentioned reason along with low annualized cost and largely fluctuating heat demand justify the presence of TES in the system in almost all cases.
6. Base case represents the most expensive case of all the cases analyzed suggesting the need to make immediate investment in energy alternatives to reduce the total annual cost (refer table 4.9).
7. There are different criteria under which different cases look favourable. For example: if sole consideration is reduction of total annual cost then, it is better to have an initial investment limitation of 5 million SEK. Similarly if sole consideration is reducing heat consumption from grid on an annual basis, then it is better to have a peak limit of 1.4 MW on the electricity side (refer table 4.9). If a limit is placed on electricity import, then energy alternatives contribution especially CHP would so vary that, heat contribution from grid is also restricted. Thus, an additional redundant peak limit on heat import from grid is not required.
8. Of the parameters included in sensitivity analysis, it seems that the results are most sensitive to varying CHP fuel price. At very low value of CHP fuel price, all the variables of importance are lower than base case. This is not so, in any other sensitivity analysis done (refer table 4.9).

6.2 Future Work

There are a lot of work beyond the scope of present thesis, but related to it and are interesting from energy systems modelling perspective. This section briefly discusses some of the works, which can follow the present work. Some of prospective research works are listed below:

1. Demand response of buildings: Buildings have internal heat storage capacity depending upon its thermal mass. There is a possibility of utilizing building itself as a heat storage media. This will help to reduce peak load and shift demand in time without any extra investment. But, care has to be taken so that thermal comfort of people is not affected. Single node lumped capacitance

model was developed at the beginning of the present thesis work to determine the capacitance and resistance of each and every building. But when these inherent properties was used to see the demand response, the model did not work properly (reference to single node model analysis can be found in Appendix A). Then it was realized that multiple node model is required for analysis of commercial Chalmers building, which made the model too complex to be solved for a full year. Using Chalmers buildings heat storage potential for analysis of its energy systems, is an exciting future research work.

2. Interaction between heating and cooling: There is a lot of energy savings potential if heat from one portion of the building can be transferred to another. For example: exhaust air from absorption chiller installed at some buildings can be utilized as source of waste heat for heat pump in the same or adjacent building.
3. Analysis of cooling system: Cooling network of Chalmers was left out of analysis in the present thesis work. But, it is interesting to analyze interaction between cooling, heating and electricity. For example: careful analysis has to be done to make sure that heating and cooling do not take place at the same time in same parts of the buildings.
4. Possibility of micro-grid of energy system: Chalmers university campus at present is self sufficient on heating for most part of the year except extremely cold winter months but not so in case of electricity. There is a possibility of proper co-ordination between different energy alternatives so as to make a micro-grid of energy system on an annual basis.
5. Determining the variable pricing for district heating: Göteborg Energi has a step-wise pricing for district heating network even though different instances have different cost if the primary energy use for DH is considered. Marginal pricing considering the energy use from different energy source and different plant can give an accurate estimation of DH pricing. Introducing variable pricing will also increase the usage of TES.

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A

Appendix 1

In this chapter detailed explanation is done of the way in which single node lumped capacitance model of Chalmers campus buildings was done.

A.1 Demand response

For creating the model of the building a single node lumped capacity model from Ning (2012) paper was selected. The reason being to keep the model simple. It consists of resistance and a capacitance, where resistance was determined from hourly energy consumption data obtained from metrys.se site administered by Akademiska Hus. The equation is as follows:

$$T_{in}(n+1) = T_{out}(n+1)+P_{in}(n)*R-(T_{out}(n+1)+P_{in}(n)*R-T_{in}(n))*e^{-1/(R*C)} \quad \text{(A.1)}$$

where, $T_{in}(n+1)$, $T_{out}(n+1)$ represents estimated indoor temperature of building and outdoor temperature respectively at $(n+1)_{th}$ hour. Similarly, $P_{in}(n)$, $T_{in}(n)$ represents power input to the building and indoor temperature at $(n)_{th}$ hour. R, C are inherent thermal properties associated with buildings, first being thermal resistance and the second being thermal capacitance of the building.

In the thesis the following temperature range is assumed, to calculate the value of 'C'. The indoor temperature range is as follows:

$$20 < T_{in} < 25 \quad \text{(A.2)}$$

where, 20 is lower temperature range of thermal comfort, 25 is upper temperature range of thermal comfort. Power input to a building is directly proportional to difference between indoor and outdoor temperature. The proportionality constant is represented by K_{loss} and denoted as 'loss coefficient'. This is represented by the following equation.

$$P_{in}(n) = K_{loss}(n)(T_{in}(n) - T_{out}(n)) \quad \text{(A.3)}$$

where, $P_{in}(n)$, $K_{loss}(n)$, $T_{in}(n)$ and $T_{out}(n)$ are power input to building, loss coefficient of building, building indoor temperature and outdoor temperature respectively at any hour 'n'.

The important thing to be kept in mind is that K_{loss} is inherent property associated with building and thus independent of time. But, in the above equation, K_{loss}

obtained is a function of time. To remove discrepancy, this is averaged out over the year, by using the following equation.

$$K_{avg} = \sum_{n=1}^{lasthour} K_{loss}(n) \tag{A.4}$$

where, K_{avg} is the average value of heat loss co-efficient over the year. Then 'R' was calculated using the following formula:

$$R = 1/K_{avg} \tag{A.5}$$

where, R is the thermal resistance of the building. Thermal capacitance of the building was iteratively determined by the equation (A.1). The indoor temperature limits are set for deciding capacitance so that thermal comfort of people indoors are not compromised, by the use of following equation.

$$T_{low} \leqslant T_{in} \leqslant T_{high} \tag{A.6}$$

The outdoor temperature taken into consideration for this research was average of temperature reading of four places nearer to Chalmers obtained from temperatur.nu site. The four places are: Linnestaden, Backa, Krokslatt and Lunden.

Power consumption is a function of outdoor temperature. As the outdoor temperature increases there is lesser need for heating demand. Beyond a certain outdoor temperature there is no need for utilization of heat carriers, radiators for example. These temperatures and corresponding hours are mainly clouded around the middle of the year. But they are also sparsely located throughout the year. For finding the temperature above which the heating appliances stop consuming power, outdoor temperature versus heat consumption was plotted.

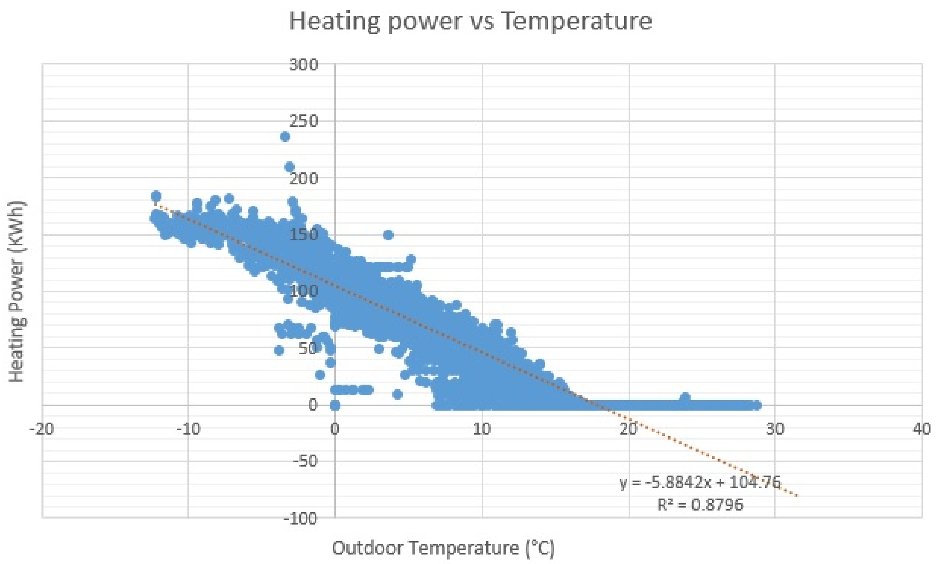

Figure A.1: Heating power consumption vs Outdoor Temperature for a sample building within Chalmers

In the figure A.1 above, a trendline was plotted to determine the outdoor temperature at which the power consumption becomes zero. For the sample building, tvärgata 3 mathematiska the outdoor temperature at which power consumption became zero was found to be 17.8 °C. The accuracy of this trendline (represented by R^2) was around 0.89 (the more closer this number is to 1, means that the trendline is more accurate representation of all plotted points in the graph). This same procedure was repeated for the remaining buildings (buildings for which heating data could be obtained from metrys.io site i.e. 12 buildings in total) and point of intersection with x-axis was obtained. The average value of outdoor temperature for different buildings was obtained by weighting against R^2. The value obtained was 18°C. The final value of 'R' and 'C' obtained for every building is represented by following table A.1.

Table A.1: Inherent physical property of the buildings

Buildings	Resistance, 'R' (°C/KW)	Capacitance, 'C' (KWh/°C)
Maskingränd Edit	0.114	260000
Kemigården 1 fysik origa 3	0.197	90000
Chalmersplatsen 4 administration	0.341	6500
Hörsalar HB	1.602	25000
Hörsalsvägen 7 maskinteknik	0.168	550000
Hörsalsvägen 11 elteknik	1.388	68000
Kemigården 1 fysik origa 1	0.162	100000
Sven hultins gata 6	0.266	100000
Sven hultins gata 8 väg och vatten	0.143	150000
Tvärgata 1 biblioteket	1.956	48000
Tvärgata 3 mathematiska	0.245	140000
Tvärgata 6 lokalkontor	6.248	25000