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Joint Optimization of CHP Plant, Electric and Thermal Storage Units using MPC

Master Thesis

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Abstract

The growing amount of photovoltaic and wind power plants and its further expected rise cause serious challenges for the electrical power grid. The compensation of the fluctuating energy production of these facilities as well as achieving the EU2020 climate targets and the climate targets, which were set in the Kyoto protocol, are the most challenging tasks for energy supply companies and grid operating companies in nowadays. Storing the energy in big battery storages is still, due to the high investment costs of batteries, their limited lifetime and low energy density, an expensive and energetically not satisfying solution of this problem. The possibility if a combined heat and power (CHP) plant, in combination with a thermal storage, is able to replace the use of battery storages is investigated in this work as well as which conditions would be necessary to make it possible. Three models of the system with different complexities were developed and after deciding which one is used for further simulations, three different CHP technologies were taken into consideration for the further calculations and simulations. These technologies are:

- Combustion Engine CHP
- Gas Turbine CHP
- Fuel Cell CHP

To find answers for the research objectives simulated load profiles for different types of buildings and data from simulated photovoltaic facilities are used to run different test case simulations and simulate a realistic fluctuation of PV power. The results which are elaborated in this work show that it is possible to replace battery storages with a CHP and a thermal storage. The most economic and the energetically most useful variant are presented at the end.

- Chapter 1: Introduction
- Chapter 2: Methods and Materials
- Chapter 3: MPC Formulation and Case Studies
- Chapter 4: Results
- Chapter 5: Conclusion and Outlook

Kurzfassung

Die wachsende Anzahl von Photovoltaik- und Windkraftwerken in den letzten Jahren und dem zu erwartenden weiteren Anstieg dieser, stellt für das elektrische Energienetz eine wachsende Herausforderung dar. Die Kompensation der fluktuierenden Energieerzeugung dieser Anlagen sowie die Erreichung der EU2020 Klimaziele und die Einhaltung der im Kyoto-Protokoll festgesetzten Klimaziele stellen eine der grössten Herausforderungen der heutigen Zeit an die Energieerzeuger und Netzbetreiber dar. Die Speicherung der erzeugten Energie in Akkuspeichern stellt nach wie vor, aufgrund der hohen Kosten und niedrigen Leistungsdichte und begrenzten Lebensdauer der Akkus, eine sehr teure und energetisch nicht zufriedenstellende Lösung dieses Problems dar. Die Untersuchung ob ein Kraft-Wärme-gekoppeltes Kraftwerk, kombiniert mit einem thermischen Speicher, den Einsatz von Akkuspeichern ersetzen kann und in der Lage ist die fluktuierende Erzeugung von PV und Windkraftanlagen kompensieren, beziehungsweise welche Bedingungen dafür nötig sind, ist Hauptziel dieser Arbeit. Nach der Erstellung dreier, verschieden komplexer, mathematischer Modelle und der Auswahl eines der dreien werden drei verschiedene Typen von KWK zur näheren Betrachtung herangezogen:

- Verbrennungsmotorgetriebene Kraftwerke
- Gasturbinengetriebene Kraftwerke
- Elektrochemische Kraftwerke mit Brennstoffzellen

Um die gestellten Forschungsfragen zu beantworten werden verschiedene, auf realen Daten basierende Lastprofile simuliert, sowie Daten von Photovoltaikanlagen verwendet und verschiedene Testszenarien simuliert.
Die Ergebnisse der Simulationen zeigen, dass es unter gewissen Voraussetzungen möglich ist Akkuspeicher durch KWK und thermische Speicher zu ersetzen. Die wirtschaftlich und die energetisch sinnvollste Variante werden im weiteren Verlauf erarbeitet und präsentiert

- Kapitel 1: Einleitung
- Kapitel 2: Methoden und Materialien
- Kapitel 3: MPC Formulierung und Testszenarien
- Kapitel 4: Ergebnisse
- Kapitel 5: Zusammenfassung und Ausblick

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Abbreviations

PV	Photovoltaic
MPC	Model Predictive Control
CHP	Combined Heat and Power Plant
CE	Combustion Engine
GT	Gas Turbine
FC	Fuel Cell
CI	Confidence Intervall
PIMPC	Perfect Information MPC
DEMPC	Deterministic MPC
STMPC	Stochastic MPC
SoC	State of Charge

List of Symbols

$C_{\mathrm{el}}^{\mathrm{lin,deg}}$	costs for linear degration of the battery storage
$C_{\mathrm{el}}^{\mathrm{quad,deg}}$	costs for quadratic degration of the battery storage
$C_{\mathrm{el}}^{\mathrm{grid,\ in}}$	costs for purchasing power from the grid
$C_{\mathrm{el}}^{\mathrm{grid,\ out}}$	earnings for exported power to the grid
$C_{\mathrm{el}}^{\mathrm{chp}}$	costs for gaining power from the CHP
$C_{\mathrm{el}}^{\mathrm{PV,curt}}$	curtailment costs
C^{pen}	penalty costs for not provided heat
CS	PV clear sky output value
$C_{\mathrm{th}}^{\mathrm{chp}}$	costs of providing heat by the CHP
$C_{\mathrm{th}}^{\mathrm{gas}}$	costs of providing heat by the gas burner
$C_{\mathrm{th}}^{\mathrm{stor}}$	costs of charging/discharging the thermal storage
$E_{\mathrm{el}}^{\mathrm{cap}}$	energy capacity of the battery storage
$E_{\mathrm{el}}^{\mathrm{s}}$	SoC of the battery storage
$E_{\mathrm{th}}^{\mathrm{cap}}$	energy capacity of the thermal storage
$E_{\mathrm{th}}^{\mathrm{h}}$	SoC of the thermal storage
FC	PV forecast profile
fc	predicted PV forecast profile
G	heat load
h^{chp}	heat to power ratio of the CHP
k	Index over the optimization horizon, $\in [1, N]$
L	electrical load
MD	error compensation PV profile
N	MPC horizon length
$P_{\mathrm{el}}^{\mathrm{cap}}$	power capacity of the battery storage
$P_{\mathrm{el}}^{\mathrm{s}}$	charge/discharge power of battery storage
$P_{\mathrm{th}}^{\mathrm{cap}}$	power available from the thermal storage
$P_{\mathrm{th}}^{\mathrm{cap}}$	power extracted/send from/to thermal storage
PV	photovoltaic production
P_{n}	nominal total power of the CHP
$P_{\mathrm{el}}^{\mathrm{max}}$	nominal electrical power of the CHP
$P_{\mathrm{el}}^{\mathrm{min}}$	minimum electrical power of the CHP
$P_{\mathrm{gas}}^{\mathrm{max}}$	maximum thermal power of the gas burner
$P_{\mathrm{gas}}^{\mathrm{min}}$	minimum thermal power of the gas burner
$P_{\mathrm{grid}}^{\mathrm{out,max}}$	maximum grid export
$P_{\mathrm{grid}}^{\mathrm{in,max}}$	maximum grid consumption
$p_{\mathrm{el}}^{\mathrm{chp}}$	electrical power provided by the CHP
$p_{\mathrm{el}}^{\mathrm{s,in}}$	power sent to battery storage
$p_{\mathrm{el}}^{\mathrm{s,out}}$	power extracted from battery storage
$p_{\mathrm{grid}}^{\mathrm{out}}$	power exported to grid
$p_{\mathrm{grid}}^{\mathrm{in}}$	power consumed from grid
$p_{\mathrm{th}}^{\mathrm{s,in}}$	thermal power send to thermal storage
$p_{\mathrm{th}}^{\mathrm{s,out}}$	thermal power extracted from thermal storage
$p_{\mathrm{th}}^{\mathrm{chp}}$	thermal power available from CHP
$p_{\mathrm{th}}^{\mathrm{ico}}$	thermal power utilized for internal applications

List of Symbols

$p_{\mathrm{th}}^{\mathrm{gas}}$	thermal power available from gas burner
$p_{\mathrm{th}}^{\mathrm{mis}}$	missing heat
$p_{\mathrm{th}}^{\mathrm{was}}$	waste heat
$p_{\mathrm{el}}^{\mathrm{PV,heat}}$	excess PV power to generate heat
$p_{\mathrm{th}}^{\mathrm{PV,heat}}$	thermal power provided by PV
r^{chp}	ramping ability of CHP unit
$T^{\mathrm{min,on}}$	minimum on-time of CHP
$T^{\mathrm{min,off}}$	minimum off-time of CHP
$t_{\mathrm{on}}^{\mathrm{chp}}$	time period in which the CHP is operated
$t_{\mathrm{off}}^{\mathrm{chp}}$	time period in which the CHP is not operated
X	Curtailment of PV

Δt	timestep duration
$\eta_{\mathrm{th}}^{\mathrm{c}}$	Charge efficiency of the thermal storage unit
$\eta_{\mathrm{th}}^{\mathrm{d}}$	discharge efficiency of the thermal storage unit
$\eta_{\mathrm{el}}^{\mathrm{c}}$	charge efficiency of the storage unit
$\eta_{\mathrm{el}}^{\mathrm{d}}$	discharge efficiency of the storage unit
$\eta_{\mathrm{e/th}}$	PV to heat efficiency
$1 - \eta^{\mathrm{sd,th}}$	self discharge per timestep of thermal storage

Chapter 1

Introduction

This chapter will provide a short overview of the motivation for this work, explains the research objectives, gives a short introduction in the system which is modeled and introduces the available combined heat and power plant technologies. The assumptions which were made are cited and an overview of the structure of the chapters is given at the end.

1.1 Motivation

Renewable energy resources like wind power or photovoltaic are expected to get more and more important within the next years. Especially because of the EU2020 targets, they are a fast growing field in electrical engineering and most of the financial resources for developing new technologies are budgeted for renewable energy sources. But because they are a supply-driven technology they will cause problems for the reliability and the viability of the energy supply grid. Finding solutions, especially for cheap storages and quick replacement of wind power or photovoltaic (PV) in case of fluctuating wind and sun energy, will be one of the big tasks to improve the status quo of the power grid. Battery storages are on a good way to get cheaper and more efficient within the next five to ten years but in nowadays they are still too expensive and have a too low power density for a wide use. Especially in rural areas with a decentralized, weakly crosslinked grid and long lines the high penetration of the grid with photovoltaic and wind power plants can cause serious problems. To ensure safe operations of the grid the flexibility of the whole power system has to be increased. Most of the PV, especially when located on roofs is connected to the grid on the low voltage level and in case of low load the PV feeds electrical power into the grid. In case of high PV or wind penetration and low loads the low voltage level in-feed can lead to local over-voltage and destroy electrical devices. In general, the connection of combined heat and power plant (CHP) units to the power system improves the voltage profile and reduces losses. The loss reduction depends on the injection capacity and the network characteristics [13]. One example for this problems is Bavaria where nearly every building in the rural areas and small villages is equipped with photovoltaic. The weakness and the missing flexibility of the grid in this areas can cause serious problems for certain grid conditions [11]. This effects on the grid could be reduced by storing the produced energy in big battery storages and extract it in the evening and in the morning when the demand is higher but the PV is not working. Another way to deal with this problem could be the use of a CHP combined with a thermal storage instead of the battery storage. Combined heat and power plants which offer the possibility of flexible operation, combined with a thermal storage can help to increase the efficiency for generating heat and electrical power and act as a substitute for battery storages. By operating the CHP in electric load following mode and using the waste heat for several applications, f.e. for district heating, the overall efficiency of a system like that can be increased up to 85%. This increase in energy efficiency can result in lower costs and reduction in greenhouse gas emissions compared to the conventional methods of generating heat and electricity separately.

1.2 Research Objectives

The goal of this project is to analyze how a CHP could compensate the fluctuation of the electric power produced from renewable energy sources while using a thermal storage to compensate the fluctuation of the induced CHP heat generation. In other words, to analyze how the combination of a CHP and a thermal storage unit can play the role of an electric storage unit. It is also investigated how it can help to increase the efficiency of the whole system. To get more realistic results the model should be extended to be able to deal with uncertainties in the PV forecast.

1.3 System Overview

The whole system consists of a CHP plant with a prime mover and a generator, a thermal storage and an additional gas burner which can charge the thermal storage or serve load in times when the CHP is not operating. There are also a photovoltaic production and a battery storage integrated in this project to implement the fluctuating supply of a photovoltaic system and to find the optimum for controlling the CHP. A scheme of whole system is given in figure 1.1. When the CHP plant is operating, the waste heat of the plant is used to meet the heat demand at that time and the surplus heat is used to charge the thermal storage to use it later when needed. It would also be possible to use an electric boiler instead of the additional gas burner to charge the thermal storage by using energy provided by the power grid. This would offer the possibility to make a contribution to increase the reliability and viability of the power grid but there are more effective ways to store surplus energy which is provided by the power grid, f.e. with pumped hydro power plants. And, on the other hand it is not the task of this work to help improving the power grid's viability in case of too much produced energy, but it is to improve the viability in case of missing power from wind and photovoltaic power plants.

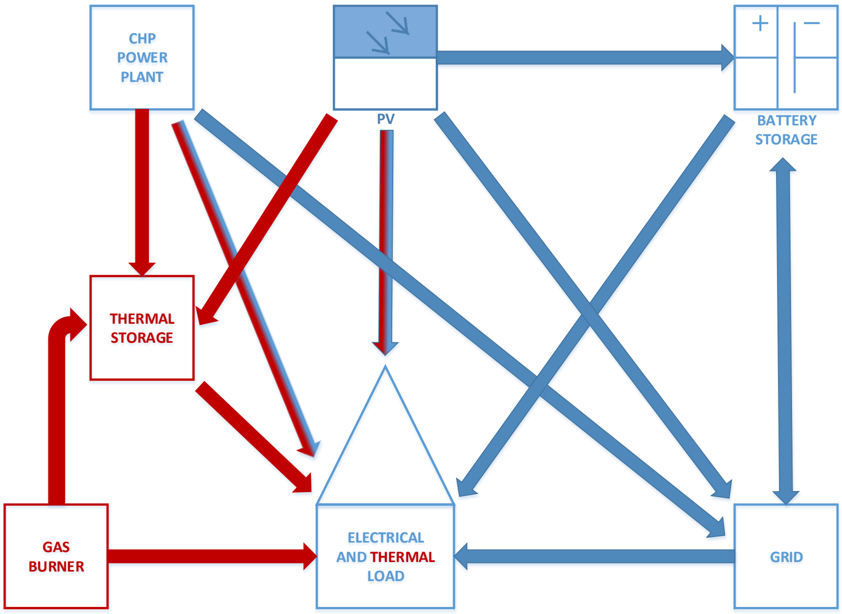

Figure 1.1: System scheme

Internal combustion engines and combustion turbines are two technologies which are currently used in various CHP applications. A quite new technology which also has the potential to be used in CHP applications are fuel cells. Fuel cells produce power electrochemically, just like batteries, except that they consume fuel to maintain the chemical reaction. Fuel cells have no moving parts and provide a quiet and clean, very effective output of both, electricity and heat. Fuel cells are manufactured in various different types in which Proton exchange membrane fuel cells (PEMFC) and Solid oxide fuel cells (SOFC) attract the most attention and development budgets [5]. Requirements for CHP's operating in electric load following mode are flexible prime movers which have short start up and stop-times such as internal combustion engines, micro-turbines (down scaled gas turbines) and low temperature fuel cells have. This is important for using the CHP plant as replacement of conventional battery storage to provide services like peak shaving or primary frequency control. Other technologies were also reviewed for this work and neglected because of performance or economical reasons.

1.4 Assumptions

To get a comparable situation between the different possible types of CHP's and to change the type for the model within a short period of time it is assumed that, neglecting the different maintenance intervals of the different types, maintenance will always happen in summer. Due to the lower load profile in summer the possibility that the CHP will not be operated for a few days is at its highest. Assuming a perfect weather forecast, it is possible to know when these situations appear and schedule the maintenance for these days. This assumption is on the one hand to simplify the model because it is not necessary to consider maintenance any more, and on the other hand closer to reality.

The different start-up and shut-down times are also neglected because they all are lower than one hour, which represents one timestep in the model. This can be assumed because it does not make a difference when the CHP is switched on, it just makes a difference when the power is delivered. So if it is known when the CHP is needed to be operated, it is also known when it is necessary to start it. In the same way the moment when the full thermal power is available is handled because this period is also less than one hour. The heat-to-power ratios are assumed as fixed values for the model which is used to compute the final results. Although the heat to power ratio usually depends on the percentage of full load on which the CHP is operated at a certain time, this behavior can be neglected because the CHP is operated above a certain part load. Below this level the changes of the heat to power ratio characteristics would not be negligible any more but above this level they are. In the simple model which is used to get a decision basis for the necessary degree of complexity the CHP can be operated also below the minimum operating power. For this model it is assumed that the heat to power ratio is constant also below the minimum operating power because the model was developed to get a comparative situation to set the degree of complexity.

Investment costs for the CHP and the thermal storage are neglected in this work, so depreciation and amortization costs are also not taken into consideration for all different facilities which are used in the model.

1.5 Structure

- Chapter 2 will give an overview of different **CHP technologies**, what a CHP consists of and the most important parameters to characterize a CHP. A survey of the different technologies which are used for CHP applications or seem to be promising for CHP applications within the next ten years is given in chapter 2, followed by a section containing **information about thermal storages and gas heating**. A detailed **description of the framework model** which is used in this work is explained. It describes all the different parts of the framework and their behavior. The **parameter setting** for every part of the framework and the **data acquisition and the definition of the**

CHP size are further located at the end of the chapter.

- Chapter 3 contains a short explanation of the **MPC strategy**, the **three different model complexities** and their differences. The three different models are compared and the decision to use the most complex model for further simulations is justified. The different **case studies** to answer the research questions are also explained in chapter 3 and the regarding results are shown in chapter 4.

- Chapter 5 at the end includes the **conclusions of this work and the outlook** on further research possibilities.

Chapter 2

Methods and Materials

The literature research to prepare for the thesis is summarized in this chapter. After a general introduction in CHP technologies the different technologies and their status of development are explained, the most important parameters for CHP applications are introduced and the three chosen technologies are explained in detail. An explanation of the requirements of a CHP is given before the key parameters of the different technologies are compared. In the model description in this chapter the framework model and its containing parts are explained. The chapter concludes with the parameter setting for the different parts of the framework and explains the acquisition of the necessary data.

2.1 Technologies in CHP

Combined Heat and Power (CHP), also known as cogeneration, is a system that efficiently generates electrical power and uses the waste heat of the prime mover for domestic heating, producing steam, district heating or as necessary process heat for various processes. With absorption chillers the heat can also be used for meeting cooling demands such as air condition or space cooling. Cogeneration has been used for centuries, even Thomas Edison used the waste heat from his first power plant to produce steam which he sold to help paying the generation expenses. Unfortunately cogeneration has not attracted reasonable development budgets over the last decades. This changed when governments all over the world started searching for alternatives to replace conventional coal and oil fired power plants to reach the Kyoto targets and, referring to this targets, increase the efficiency for generating electrical power.

Today especially conventional combustion engines, both spark ignition and diesel engines, and combustion turbines, also called gas turbines, are used in CHP applications but there are much more technologies which can be used for generating electricity and heat. Latest researches focus on fuel cells, steam turbines and also stirling engines in which it seems that fuel cells are the most promising technology and will be well developed within the next ten years [4]. Although fuel cells still have problems with a comparatively short lifetime and a decreasing power output over their lifetime, they offer a higher electrical efficiency than stirling engines and steam turbines and it looks like fuel cells will be the best alternative compared with gas turbines and combustion engines. Stirling engines are based upon a thermodynamic cycle, the so called Carnot process, but their primary product ist heat and their electrical efficiency within a range of 10-30% is very low. Therefore they are not useful in a electric load following CHP application where the primary target is to produce electrical power because the produced electricity can be seen as a by-product of the stirling engine [4]. Steam turbines are also not considered because they do not look like they could appear as a useful technology for CHP applications within the next decade. Therefore their electric efficiency is too low right now (10-20% [3]) and their heat-to-power ratio is not competitive to the other technologies (in a range of 9/1 to 3/1 [3]).

CHP power plants are build in scales up to a few hundreds of megawatts but small scale CHP facilities are also available in a range of a few kilowatts. Table 2.1 shows a classification of CHP's which is used to describe the different CHP sizes in the following chapters.

CHP size	Power Range
small	up to 1MW
medium	1MW - 100MW
large	above 100MW

Table 2.1: CHP size classification

2.1.1 CHP Key Parameters

The decision which types of CHP's can be used to fulfill the given tasks best depends on some special parameters of the different types of possible CHP's. These parameters are shown in table 2.2.

Parameter	Sign	Unit
Nominal Power	P_n	[kW]
Minimum On-Time	$T_{min,on}$	[h]
Minimum Off-Time	$T_{min,off}$	[h]
Heat to Power Ratio	h	[p.u.]
Minimum Power	P_{min}	[kW]
Electric Efficiency	η_e	[%]
Thermal Efficiency	η_{th}	[%]
Overall Efficiency	η	[%]
Ramp up	r_{up}	$\frac{W}{h}$
Ramp down	r_{down}	$\frac{W}{h}$

Table 2.2: Key parameters for CHP

Nominal power P_n in table 2.2 means the rated total power of the CHP plant. The overall efficiency η of the system is defined as the sum of the electrical efficiency η_e and the thermal efficiency η_{th} . The residual to 100% indicates the losses of the system (f.e. friction losses etc.) and the waste heat which cannot be utilized due to other reasons. Especially because of the alternating loads of the system the 'ramp up' parameter r_{up} and 'ramp down' parameter r_{down} are important because they indicate the ability of the system to follow fast changing load characteristics. This is necessary to provide a satisfying supply of energy. The heat to power ratio h for the given system should fit the ratio of heat demand and electricity demand as good as possible to minimize the waste heat and the production costs and, in this case, provide best overall and economical efficiency. The minimum power parameter P_{min} describes the minimum power level the CHP can be operated at and which is important for the ability to meet a certain part load demand. The minimum on- and off-times ,$T_{min,on}$ and $T_{min,on}$, describe the minimum time periods the CHP has to be operated or shut down.

2.1.2 Combustion Engines

Combustion engines have been invented in the nineteenth century by Nikolaus Otto (spark ignition engine) and Rudolf Diesel (diesel engine). The system of combustion engines bases on burning a mixture of fuel and air in a burning chamber either by igniting a spark in SI-engines or caused by compression of the mixture in diesel engines. The burning mixture expands and drives a piston which is mechanically connected to a crankshaft. This crankshaft is connected to a generator to generate electrical power. Combustion engines can be fitted with a turbo-charger and intercooler to increase the power output. Recovering the waste heat of a combustion engine to use them as a cogeneration device can be provided by using the heat from exhaust gases, the cooling systems including jacket water, lubricating oil and charge air. Recovering heat from the about 450 to 650°C hot exhaust gases and the about 120°C hot jacket water promise the biggest gain of heat.

A big advantage of Combustion engines is that they can run on different types of fuel. While diesel engines can be operated with diesel or oil, spark ignition engines offer a even more widespread field of possible fuels containing gasoline, natural gas, propane and also landfill gas [7].

Combustion engines are a fast growing segment of the small and part of the medium size CHP market (up to 10 MW) and have the advantage that they have been developed for more than hundred years and so they are well developed today and offer competitive costs in purchase and operation. A large majority of smaller combustion engines are used as backup power for facilities during emergency situations and are operated with gasoline or diesel. Traditionally, these generators were noisy, dirty suppliers of electricity without using the waste heat of the engine and exhausting the heat directly to the atmosphere instead of capturing it for useful purposes. Today, manufacturers are producing various highly efficient cogeneration devices which can be used in small and medium sized building applications. Especially natural gas fired spark ignition engines offer low first costs, fast start up and significant heat recovery potential. Table 2.3 shows the key parameters of available combustion engines.

Parameter	Combustion Engine
Available Power Range [W]	10k-65M
Minimum On-Time [h]	≤ 2
Minimum Off-Time [h]	≤ 2
Heat to Power Ratio [p.u]	1
Minimum Power [p.u.]	0.4
Electrical Efficiency [%]	25-45
Thermal Efficiency [%]	40
Overall Efficiency [%]	65-85
Ramp [%nominal power/h]	100

Table 2.3: Parameter values for available combustion engines [4], [7], [8]

The heat-to-power ratio, which means the ratio of thermal energy output to the mechanical energy output is quite constant for the whole load characteristic and about 1. This means the thermal output is quite equal to the electrical output, even at part load. This makes the part load heat-to-power characteristics for combustion engines more acceptable for applications with similar heat and electrical loads than the ones of gas turbines. Both types, diesel and spark ignition engines operate reasonably well up to half the rated power, i.e. their electrical and thermal efficiencies are quite constant on a high level over the whole load characteristics. The efficiency for electricity production does not decrease below 80% of value at full load at SI-engines and not below 90% at diesel engine [3]. This means that SI-engines are more reasonable for heat-driven CHP applications, where meeting the heat demand is the main target because of their higher temperature level. Caused by the fact that the CHP needs to be very flexible to achieve the goal of this work combustion engines seem like a proper way for fulfilling all the requirements of this application because of their rapid start capability and their high efficiency even when their operating on part load.

The electrical efficiency of combustion engines varies from 25-45% depending on the size and the type of the engine. Large scale diesel engines usually have a higher electrical efficiency than small scale and spark ignition ones have. The overall efficiency also depends on the type of the engine and is usually around 65-85% while the thermal efficiency is usually a few percents higher for spark ignition engines than for diesel engines, once more depending on the scale [1]. The lower thermal efficiency for diesel engines is caused by the fact that not the whole waste heat from the exhaust can be recovered because condensation in the exhaust has to be prevented to avoid oxidations of the exhaust pipe.
Combustion engines offer a very short start up and stop time period which is in a range of a few seconds for small engines up to 15 minutes for large engines [2] and makes them really flexible in operation. In peaking or emer-

gency power situations, combustion engines can quickly supply electricity on demand and also in the event of an electrical utility outage, they have minimal auxiliary power requirements. Generally only batteries are required [8]. The maintenance costs for combustion engines are quite high because of a lot of moving parts but they depend on the revolutions per minute the engine is operating. While the maintenance interval is bigger than 30 000 operating hours for engines with 720 rpm this value decreases to 8 000 operating hours for engines with 1800 rpm which is quite equal to a annually overhaul [8]. Combustion engines are available in a range from small industrial engines with a few kilowatts up to large engines for power plants with 65 megawatts [8].

2.1.3 Gas Turbines and Micro Turbines

Gas turbines (also referred to as combustion turbines) and micro turbines (down scaled gas turbines) are also possible solutions for CHP applications. The working principle of gas turbines include the compression of the intake air by a compressor, mixing the compressed air with a suitable fuel and igniting the mixture in a combustion chamber. The hot combustion gas expands in the turbine and drives the shaft and provides mechanical power for the compressor and the generator for electricity production. With an additional recuperator which could be used, the exhaust gas can help to preheat the intake air and increase the electrical as well as the overall efficiency. After that the thermal energy of the exhaust gas is used for the heat recovery of the system and the residual heat which can not be recovered leaves the exhaust as warm exhaust gas.

Gas turbines are used all over the world to produce useful power and heat from a single fuel source. They produce electricity through their generators while providing useful heat captured from the turbines exhaust flow. Gas turbines are available in different cycle configurations in which single shaft configurations are the simplest concepts and are used especially in small and medium generation capacities less than 25 megawatts [6]. Gas turbine systems with a two shaft configuration are also available in micro turbine scales, are more complex and cause higher maintenance costs but offer the possibility to reduce the outlay on power electronics. The second shaft, where the generator is located, is connected via a gearbox to the first shaft where the compressor and the turbine are mounted. Thus the generator can rotate with less rotations per minute and can be connected directly to the 50Hz grid [8]. The turbine-compressor shaft usually turns in high rotational speeds of about 80,000 to 120,000 rpm, but nevertheless micro turbines provide a startup time of less than 1 hour [6]. Micro turbines offer a number of advantages compared to combustion engines including compact size, low weight, small number of moving parts and lower noise [7].

Micro turbines are able to be operated with different types of fuel, for example natural gas, propane, or even high quality fuels like kerosene. They offer low emission levels, while bigger gas turbines are mostly build just for one type of fuel, for example propane [7].
Gas turbines in every size, from microturbines with a few kilowatts up to large gas turbines with hundreds of megawatts are a good possibility to realize CHP power plants with a certain base load. For emergency and peaking power applications gas turbines are not the best solution because of their bigger time constants in load following and their longer start up and stop time periods. Table 2.4 shows the key parameters of available gas turbines which were taken into consideration in this work.

Parameter	Gas Turbine
Available Power Range [W]	10k-100M
Minimum On-Time [h]	≤ 5
Minimum Off-Time [h]	≤ 3
Heat to Power ratio [p.u]	3 - 1
Minimum Power [p.u.]	0.75
Electrical Efficiency [%]	30
Thermal Efficiency [%]	45
Overall Efficiency [%]	75
Ramp [%nominal power/h]	90

Table 2.4: Parameter values for available gas turbines [4], [6], [7]

The heat to power ratio of micro turbines depends on the specific design of the turbine and the recuperator, typical heat to power ratios are in the range of 3/1 to 1/1. Using a recuperator in addition to a gas turbine or a micro turbine can decrease the fuel consumption in a range of 30 to 40% [7], which causes an increase in efficiency. This is possible because the intake air gets preheated in the recuperator by the exhaust gases. Thereby less fuel is needed to heat the air in the burning chamber by burning fuel to reach the same expansion volume in the turbine. Micro turbines and also gas turbines, both with a recuperator, usually reach overall efficiencies up to 75% which is a bit worse than the efficiency of internal combustion engines. Their electrical efficiency is also just about 20 to 30% and drops significantly at part load. Therefore gas turbines of every size and configuration should not be operated below 3/4 of full load and are usually supposed to operate at full load. Micro turbines provide reasonable electrical efficiency of about 30%, offer low emission levels and need minimal maintenance [7]. However in the lower power ranges combustion engines have better efficiency than micro turbines.

Micro turbines can start up within one hour in case they are build for fast starting and also stop within one hour. Larger turbines (medium and large scaled turbines) need much more time to start up and to stop. For gas turbine driven large CHP's with more than 100 megawatts 4-5 hours of start up time are quite usual and also 2 hours of stopping time are common [1]. The maintenance intervals and the maintenance costs differ on the type and the configuration of gas turbines. Especially between single shaft and two shaft configurations there are big differences because of the more moving parts of the two shaft configuration.The biggest advantage of the single shaft gas turbines are their few moving parts and caused by that, their longer maintenance intervals. This leads to lower maintenance costs compared to combustion engines and gas turbines with two shafts. Gas turbines used in larger cogeneration power plants and with more complex configurations, f.e. two shaft configuration, are usually down for maintenance in summer when there is no or just a low heat demand. Another reason for this is that they could not be operated at reasonable costs in summer. Gas turbines are available in nearly every size from small micro turbines with about 30 kilowatts up to large ones with hundreds of megawatts and also any desired configuration is available. There are 30 kilowatts microturbines with a two shaft configuration and recuperator as well as 200 megawatts gas turbines on a single shaft configuration and a recuperator. This flexibility offers the possibility to get the best turbine for every application.

2.1.4 Fuel Cells

Fuel cells are the newest technology devices available for CHP applications. They are electrochemical energy conversion devices that convert the chemical energy of the fuel directly into electricity and heat without involving any combustion process or moving parts. Sometimes fuel cells are called electrochemical engines because they are, in a simple way, a cross between a battery and a heat engine [5]. The working principle of fuel cells is the electrochemical conversion from hydrogen reacting with oxygen into electrical energy with water and heat as by-products. Therefore an electrolyte is needed to ensure the electrochemical reaction. The types of fuel cells differ in materials used for electrolyte, the fuels they can handle and, referring to the electrolyte, the working temperature range is different for the different types [5].

The main types of fuel cells available in different stages of development are alkaline fuel cells (AFC), polymer electrolyte membranes (PEMFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC) and direct methanol fuel cells (DMFC). SOFC are working on a high temperature level (850 to 100°C) which causes a better thermal efficiency but also causes a need of high quality materials to resist the high temperatures. There is a trend to decrease the working temperature of SOFC's to 500 to 750°C which would be better for the used mate-

rials and allows faster starting, but these SOFC's are not available yet [5]. PEMFC's on the other hand operate on a comparatively low temperature level of about 100 to 120°C. The low operating temperature of PEMFC's makes them attractive for mobile applications such as in vehicles and also for CHP applications.
Fuel Cells can operate with different types of fuel. While high temperature fuel cells like SOFC and MCFC are able to deal with methane and coal gas, low temperature fuel cells like PEMFC can handle only pure H_2. To operate the low temperature fuel cells with methane or coal gas an external processor is needed to deal with this hydrocarbon fuels.

As mentioned above PEMFC and SOFC attract the biggest development budgets and are the most attractive types for CHP applications in nowadays. Compared to SOFC technology low temperature fuel cells like PEMFC's use circulating demineralized water for cooling while SOFC's use air. SOFC is further more capable of internally reforming hydrocarbon fuels and doesn't need a external processor if hydrocarbon fuels like Methane are used. The main characteristics of fuel cell technologies is that they have no moving parts, a high efficiency, quiet operations and compared to combustion engines or gas turbines, depending on the fuel, low or zero emissions [5]. Fuel cells can be used in different applications and the size of potential markets is enormous, from very small mobile applications in mobile phones to auxiliary applications or prime movers in vehicles and up to large scale megawatt electrical power generation fuel cells can be a proper technology to replace batteries, combustion engines or coal- and oil-fired power plants. In Japan the use of fuel cell micro-CHP systems in residential applications, especially because of their high overall efficiency and their low and, if necessary, variable heat to power ratio [4] has become quite popular. For this work only PEMFC's were taken into consideration because SOFC's need too much time for starting up and stopping. Fuel cells of every type but especially low temperature fuel cells such as PEMFC will be more efficient in respect of electrical power generation within the next ten years. Table 2.5 shows the key parameters of available and competitive fuel cells which could be used in a CHP application.

Parameter	Fuel Cell
Available Power Range [W]	0.5k-500k
Minimum On-Time [h]	≤ 2
Minimum Off-Time [h]	≤ 7
Heat to Power ratio [p.u]	≤ 1
Minimum Power [p.u.]	0.3
Electrical Efficiency [%]	50
Thermal Efficiency [%]	45
Overall Efficiency [%]	95
Ramp [%nominal power/h]	30

Table 2.5: Parameter values for available fuel cells [5], [6], [7]

Usually the heat to power ratio of fuel cells is 0.95/1 for PEMFC and about 1/1.5 for SOFC but it can be varied by adding a additional afterburner/auxiliary burner [5]. An auxiliary burner is just a simple gas burner who uses the same fuel the fuel cells does to provide additional heat if needed. To use an additional afterburner too much fuel has to be supplied to the fuel cell so that not the whole amount of fuel can be processed in the fuel cell. This means that the exhaust gases of the fuel cell also contain a certain amount of fuel and then the exhaust gases can be burned to produce additional heat.
The electrical efficiency of fuel cells is in a range of 45 to 50% for both, SOFC and PEMFC, whereas the thermal efficiency is around 45%. Fuel cells of every type have excellent load following characteristics, in both power generation and cogeneration applications. The efficiency increases at lower loads down to one-quarter of rated power [7] which makes them a proper solution for electric load following CHP applications which most of the time operate at part load.
Low temperature fuel cells provide a quite short start up and stop time which is below 1 hour regarding to their low temperature. High temperature fuel cells and especially SOFC, which operate on the highest temperature level of all fuel cells, need more time to warm up and to start. The high temperatures of SOFC's for example extend the start up time period (up to 24h for cooling/warming cycles) to a non acceptable time period for CHP applications compared to other fuel cell technologies [5].

The maintenance costs of fuel cells are not a big factor because of the lack of moving parts. However ancillary systems such as pumps and fans which are needed for operating the fuel cells cause maintenance costs [7]. Well developed SOFC are available from manufacturers up to 100 megawatts while PEMFC are only available up to 500 kilowatts [1] but they will be available in larger scales within the next ten years.

2.1.5 Key Parameter Comparison

The nominal power of all possible types of CHP power plants should be the same size to ensure a qualitatively comparable situation for deciding which type is most suitable. Therefore it is necessary that all the different types are available in that size even to compare them in the model. Due to the start-up time of the different types and the requirement that the system has to have rapid start capabilities there are only three types of possible CHP plants that come into consideration for the given problem. These three types are combustion engines which look promising especially because of their rapid start and black start capability, a heat-to-power ratio of about 1 and a minimum power of 40% of rated power. Gas- and micro turbines with less good parameter values than combustion engines but also acceptable and fuel cells which provide the best electrical efficiency and the lowest heat-to-power ratio where also taken into consideration. Especially in the range of small and medium CHP applications combustion engines have a higher electrical efficiency than gas turbines and for residential cogeneration systems combustion engines seem to be the only systems available at reasonable costs [6]. Solid oxide fuel cells are not a attractive technology for CHP power plants because of their long heating and cooling cycles and their vulnerability due to fast variations of temperature [5]. PEMFC is chosen instead of all other fuel cell technologies because besides SOFC it is the only fuel cell technology that is well developed and available today in a wide range of size at reasonable costs or will be in a few years [5]. A comparison of the key parameters of the three possible types is shown in table 2.6 below.

Parameter	Comb. Engine	Gas Turbine	PEMFC
Available Power Range [W]	10k-65M	10k-100M	0.5k-500k
Minimum On-Time [h]	≤ 2	≤ 5	≤ 2
Minimum Off-Time [h]	≤ 2	≤ 3	≤ 7
Heat to Power Ratio [p.u]	~1	3 - 1	≥ 1
Minimum Power [p.u.]	0.4	0.75	0.3
Electrical Efficiency [%]	25-45	30	50
Thermal Efficiency [%]	40	45	45
Overall Efficiency [%]	65-85	75	95
Ramp [%nominal power/h]	100	90	30

Table 2.6: Parameter values for possible CHP technologies

2.2 Model Description

The test cases to investigate the different model complexities which have been developed are operated with a load profile from the DrCEUS System for the California Energy Commission's California Commercial End-Use Survey

(CEUS) [10]. The same load profiles have been used for all the test cases to get comparable results for all different CHP types and complexities. To get a proper solution for the optimization problem three versions of different complexities are elaborated in chapter 3. The first one represents the most simple version or the base version which consists of a CHP only defined by some basic parameters and basic constraints. In the second version there is a minimal operating power added which includes the fact that the CHP in reality cannot be efficiently operated below a certain part load ratio. This means the CHP can either be switched off or operated within a range between the minimum operating power and the rated power. In the third version which is the most complex one, operating the CHP depends further more on a minimum on- and off-time period. The electrical output of the CHP is furthermore subjected to ramp constraints. These three models will be elaborated and compared together to get a decision basis for deciding which model provides the most economically way to calculate the results, concerning computational expenses and accuracy of the results.
Nevertheless all three models contain the same components, which are:

1. A **combined heat and power plant** implemented as a electrical and thermal power generation unit with a variable power output.
2. A **thermal storage** implemented as storage unit with a time dependent capacity.
3. A not defined type of **battery storage** implemented as storage unit with a certain capacity.
4. An aggregation of **PV** panels, implemented as a non-buffered generation unit with curtailable supply.
5. A **connection to the grid**, implemented working either as a non-buffered generation unit or as a conventional load.
6. A **gas burner** implemented as an additional heat generation unit.

2.2.1 Combined Heat and Power plant

The CHP plant is modeled as a non-buffered generation unit which can provide electrical power and, as a by-product, heat power. The aim of the CHP is to provide enough heat and electricity to meet both, the heat and the electricity demand in case of too less PV power. CHP's are available in sizes from a few kilowatts up to hundreds of megawatts like explained earlier in section 2.1 and in table 2.1. Especially in urban distribution networks new CHP's cause observable impacts on the network power flow, protection and voltage regulation. Therefore new CHP plants must be evaluated carefully to prevent the risks of unwanted effects on the security and the quality of local electricity supplies [9]. The modelling of the CHP is explained more in detail in chapter 3.

2.2.2 Thermal Storage

The additional thermal storage for the application investigated in this project is modelled as a not defined type of storage. This is because the different thermodynamical behaviors of different types of thermal storages are not investigated in this work. Thermal storages for CHP applications usually are big water containers which are heated by the CHP and used as a buffer for peak demand or times when the CHP is not operating [2]. Using houses respectively their walls or ground soil is also possible to realize thermal storages. Especially storing thermal energy in walls in houses looks like the most innovative solution. Therefore the heat can be stored in the walls in the houses which are connected to a district heating network and extracted when needed for other applications. This offers the possibility that no additional storage is needed. Using this type of storage would cause a higher time dependency of the state of charge and of the maximum power that can be send to the storage or can be extracted. The state of charge (SoC), the maximum and the minimum of the state of charge are time dependent because it is not possible to store as much thermal energy in house walls in summer as in winter. When there are high temperatures outside in summer and people do not want to heat their flats and houses or when the water container is on a higher temperature level because of the high ambient temperature the maximum charging power decreases. Due to the same reason the maximum discharging power is also time dependent. This means, that in a worst case scenario when the thermal storage, no matter what type it is, is f.e. half charged and the ambient temperature rises there is no more possibility to store the waste heat of the CHP into the storage. In this case the heat produced by the CHP has to be emitted to the atmosphere which represents the worst situation for the overall efficiency for the CHP. The thermal storage in this work is realized as a water container with a fixed storage capacity and a time dependent state of charge, but implementing a time dependent capacity profile for using walls is also prepared within the model. The operating costs of the thermal storage are mostly represented by the operating costs of the necessary pumps and valve drives. The key parameters of the thermal storage are shown in table 2.7.

Parameter	Sign	Unit
State of Charge	$\mathrm{SoC}^{\mathrm{th}}(t)$	[kWh]
Max State of Charge	$\mathrm{SoC}^{\mathrm{th}}_{\mathrm{max}}(t)$	[kWh]
Min State of Charge	$\mathrm{SoC}^{\mathrm{th}}_{\mathrm{min}}(t)$	[kWh]
Self Discharge	$1 - \eta^{\mathrm{sd,th}}$	[%]

Table 2.7: Key parameters of the thermal storage

2.2.3 Battery Storage

The battery storage in this work in based on the battery model from a former project. It is modelled with a certain capacity and a state of charge which is time dependent due to the self discharge of the batteries. The operating costs for the battery storage contain the costs of linear and quadratic degradation of the storage. The degradation of the storage means that the capacity of the batteries is decreasing when the batteries are used, thus the batteries have to be replaced after a certain time when their capacity gets too low. To simulate these costs charging and discharging the batteries leads to linear and quadratic degradation costs.

2.2.4 Photovoltaic

The photovoltaic panels are implemented as a non buffered generation unit in the model. The produced energy is used to meet the electrical demand or to produce heat to meet the heat demand or charge the thermal storage instead of curtailing it. The PV profile is provided by real PV data from different places. For the calculations in this chapter from section 3.1.2 to section 3.1.4 a profile from Reno,CA is used and for further calculations PV data containing also forecast data is used. This forecast data includes a predicted PV profile for a whole year and a PV profile for the clear sky PV production of the given system. The clear sky profile represents the maximum of possible PV production for the given system for clear sky, i.e. it represents the PV production profile for a year without clouds and best irradiation.

2.2.5 Grid Connection

The whole system modelled in this work is connected to the power grid. The connection to the grid is modelled as a non buffered unit which can generate power in case of grid purchase and act like a conventional load in case of grid export. The grid connection and the power flow is limited by line constraints for purchasing and exporting power from and to the grid. The costs for the purchase and the earnings are calculated with a time dependent grid tariff profile with different values for purchasing and selling power.

2.2.6 Gas Burner

The additional gas burner in the model provides thermal power to meet the heat demand if the thermal power provided by the CHP and the power extracted from the thermal storage are not enough to meet the demand. Therefore the gas burner is modelled as a non buffered generation unit for heat power. As shown in section 3.1.2 the gas burner can be operated between a minimum power level and the maximum power which represents the nominal power of the gas burner. Usually this gas burners are part of a heat power plant and are sized to meet the whole heat demand on themselves to ensure the heat supply even when the CHP is down because of troubles or technical faults. Table 2.8 shows the key parameters of the gas burner.

Parameter	Sign	Value	Unit
Minimum Power	$\mathrm{P}^{\mathrm{gas}}_{\mathrm{min}}$	150	[kW]
Maximum Power	$\mathrm{P}^{\mathrm{gas}}_{\mathrm{max}}(t)$	1500	[kW]

Table 2.8: Key parameters of the thermal storage

2.3 Parameter setting and data acquisition

2.3.1 MPC Horizon

The MPC Horizon N was set to 120 hours for all the different test cases which have been simulated. These 120 hours represent a forecast window of five days.

2.3.2 Photovoltaic Profile

Photovoltaic (PV) is used to produce electrical energy from sunlight. Due to that the PV is not able to produce energy during the night and the production is lower on cloudy days, this fluctuation has to be compensated. The PV production profiles used in this work are real PV profiles and are scaled down to a realistic scenario related to the load profiles.

For the simulations in section 3.1.5 and for the case studies defined in sections 3.2.1 to 3.2.3 a real PV profile from Reno CA is used. For further considerations another PV profile which also contains forecast data to calculate a predicted use of the CHP. The real PV profile with the forecast and also the profile for the predicted clear sky PV power profile are computed online for a PV facility in Stabio, a city in Ticino, Switzerland [23]. Assuming a perfect forecast data for the whole horizon is a simplification which is used to provide results for the test cases defined in the sections 3.2.1 to 3.2.4. In reality, of course, the forecast data never provides perfect information of the real irradiation and weather conditions in the future. Therefore the PV data in the model is replaced by a real PV profile for the current timestep and a forecast PV profile for the upcoming timesteps in the MPC horizon computed by [23] for the further simulations from section 3.2.5 on.

Due to the data from [22] and the computed relation between usable area of buildings and the roof areas the possible area for PV can be calculated. Due to the values for the electrical power consumption of different buildings shown in table 2.9 the PV data is scaled down to a realistic scenario to match the values of the annual energy consumption of the different building types. Table 2.9 shows the different consumptions of electrical energy of different types of buildings per squaremeter and year.

Type of building	Electricity$[kWh/m^2a]$
Hotels and lodging buildings	150
Offices	110
Colleges/School buildings	80
Health care buildings	200
Grocery stores	220
Warehouses	60

Table 2.9: Consumption of electrical energy [20] [21]

2.3.3 Load Profiles

To run simulations which are quite realistic it is necessary to use real load profiles. These profiles can be generated online from real load profiles for different types of buildings for both, electricity and heating, from the California Commercial End Use Survey (CEUS) [10]. The different possible types of load profiles are shown below.

Load profiles available for:

- All office buildings
- Retail buildings
- Colleges
- Warehouses
- Miscellaneous buildings
- Health care buildings
- Restaurants
- Lodging buildings and hotels

- Grocery stores

Table 2.6 in section 2.1.5 shows that the technologies used in this work operate at a heat to power ratio range from ≤ 1 up to 3. To answer the main question of the project, under which conditions a CHP could compensate the fluctuation of renewable energy sources, the load profiles which match the heat to power ratio of the CHP best have to be found.

To decide which of the given load profiles are the best to investigate it is necessary to compare them with the heat to power ratios of the different CHP technologies. Because the CHP should compensate the fluctuation of the PV, the real PV profile elaborated in section 2.3.2 has to be subtracted from the load profiles as shown in equation 2.1 below and under consideration that there is no battery storage and no electricity is purchased from the grid.

$$p_{\mathrm{el}}^{\mathrm{chp}}(k) = L(k) - PV(k) \tag{2.1}$$

Equation 3.3 in section 2.2.1 shows how the heat to power ratio is calculated. This heat to power ratio has to be compared with the heat-to-power ratios of the different load profiles. The heat to power ratios of the load profiles is calculated with the thermal load related to the electrical load for every timestep, following equation 2.2.

$$\frac{p_{\mathrm{heat}}(k)}{p_{\mathrm{elec}}(k)} = h_{\mathrm{load}}(k) \tag{2.2}$$

Regarding to those calculations and their results the load profiles of college buildings, health care buildings and lodging buildings are chosen for further considerations. The load profiles are now named from 1 to 3 as shown in table 2.10.

Type of buildings	Load Profile Number
College Buildings	1
Health Care Buildings	2
Lodging Buildings	3

Table 2.10: Definition of Load Profile Numbers

The results of these calculations for the three chosen load profiles and, to have a comparison, for the profile of warehouses are shown in figures B.1 to B.8 in appendix B.

2.3.4 Size definition of the CHP and the Thermal Storage

To find the best size of the CHP and the thermal storage it is necessary to investigate on the operating costs for different sizes of CHP's combined with different sizes of thermal storages. The operating costs for CHP's depend on the size of the CHP and the produced power. The costs for the thermal storage consist only of the operating costs for the pumps which are needed for the heat exchange between the CHP and the storage.

As explained earlier in section 2.1 the efficiency of the power plants, despite what type it is, increase for larger scaled CHP's which causes the effect that the production costs per kWh of produced energy decrease because less fuel is needed for the same amount of power output.

The prices for the used fuel also decrease with a bigger amount of used fuel bought by the operator of the CHP. From a literature review the cost functions of the three different CHP types can be figured out and show, as expected, decreasing characteristics for the operating costs [19]. The cost function for the operating costs can be calculated with interpolating the given values for different sizes and types in the literature and from this function the values for the operating costs for the chosen CHP size [14] [15] [16]. The operating costs for the thermal storage contain only the operating costs of the pumps to send power to the storage or extract it.

In reality the size definition of a CHP is an investment cost versus operating cost problem. Because the investment costs are neglected in this work the size definitions for the CHP and the thermal storage are done a bit arbitrarily. The problem here is to dimension the CHP as large as possible to ensure the cheapest operating costs but small enough that it is still provides a good performance. The minimum operating power reduces the maximum possible rated power of the CHP because the CHP should be able to operate in times of low load. Therefore the CHP should be small enough that the minimum operating power is still below the lowest value of the load profile. Figure 2.1 shows the cost functions for the operating costs depending on the size of the CHP. To define the operating costs of the different CHP types operating costs of various sizes of CHP's and different technologies were used [14] [15] [16]. These values were interpolated to get the operating cost function of the different CHP types.

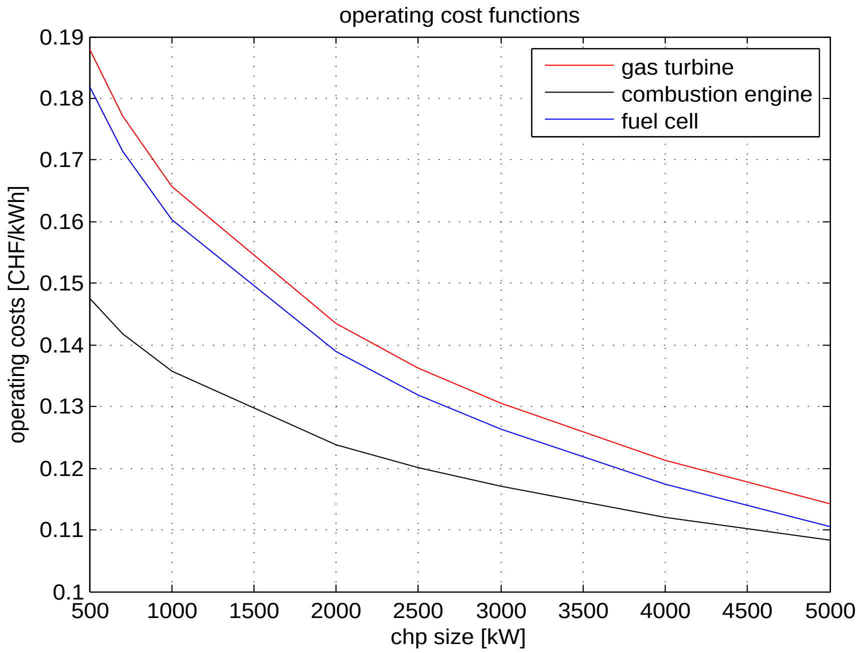

Figure 2.1: Operating costs depending on the CHP size

Due to the operating cost function in figure 2.1 the best results which represent the minimal costs could be reached with the largest CHP taken into consideration (5000 kW). Though the restrictions for operating the CHP, f.e. the minimum operating power, require a smaller size of the CHP. Due to these restrictions the chosen CHP size for the further simulations is at a nominal power of 2000kW. This provides a supply of the whole electrical energy even if there is no PV power and no connection to the grid and the possibility to meet the maximum heat demand only by using the CHP. The storage size is set to 2000kWh. With this size the storage is able to provide enough energy to meet the heat demand at least as long as the CHP needs to start up. This ensures that a full thermal storage can compensate an outlay of the gas burner until the CHP starts to produce heat. The parameter set for the further simulation runs is shown in table 2.11.

Parameter	Description	Value	Unit
P_n	Rated (Nominal) Total Power of the CHP	2'000	[kW]
$E_\mathrm{th}^\mathrm{cap}$	Nominal capacity of the thermal storage	2'000	[kWh]
$P_\mathrm{th}^\mathrm{cap}$	Maximum charge or discharge power of the thermal storage	800	[kW]

Table 2.11: CHP parameter set

The other parameters which represent the boundaries for the CHP parameters depend on these parameters and can be calculated with table 2.6 in section 2.1.5.

Chapter 3

MPC Formulation & Case Studies

In the following chapter a general description of MPC is given. After this description the three different model complexities are explained and the objective functions and constraint sets are explained. After the justification for choosing the most complex model five different test cases are defined. Every one of the first four test cases is simulated for every load profile and for all three types of CHP's. The last test case, which investigates the impact of the forecast data and is developed to improve the performance of the MPC is simulated only with a fuel cell CHP and for a lodging building load profile.

3.1 MPC

The optimization problem and the controlling of the different facilities in the framework is solved with a so called MPC controller. A short introduction in MPC is given here, for a more detailed explanation one can have a look at [27].

3.1.1 General Description of MPC

The idea of a model based predictive control method (MPC) was introduced at the end of the 1970's. The realisation of this method was based on the work on Model Predictive Heuristic Control (MHRC) [28] and Dynamic Matrix Control (DMC) [29] and became popular first in the petro-chemical industry [24]. MPC does not mean a certain control algorithm, it describes a strategy which can be realized with different algorithms. This strategy consists of certain steps which are shown in figure 3.1 and are explained below (figure from [26]).

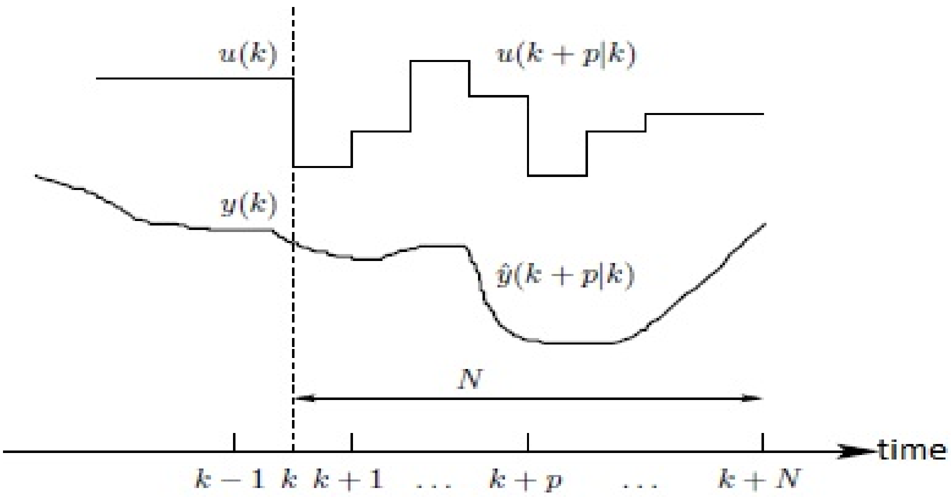

Figure 3.1: MPC strategy

The output of the controller is precalculated for every timestep from k to $k+N$, while N represents the prediction horizon. These calculated values for the output variable y depend on the known in- and output variables up to timestep k and on the future values of the variables $u_{k+p|k}, p = 0...N-1$ which have to be optimized. This means that the value for variable y for timestep $k+p$ gets set at timestep k. Then the actuating signal $u_{k|k}$ is send to the process and at timestep $k+1$ it starts again by deleting all actuating signals and calculates new values from $k+1$ to $k+1+N$. The time horizon is now shifted one timestep ahead which leads to a closed loop control method [26].

The biggest advantage of a MPC controlled framework compared to other control strategies is that the MPC controller is able to take care of constraints. Thereby the MPC is able to solve optimization problems. If the model does not have any constraints the solution can be given as an explicit solution. For models with constraints or non-linear models the solution has to be calculated in a numerical way. The complexity of the optimization problem depends on the number of optimization variables, the structure of the model and the constraints. For real time applications with small timesteps one have to take care that the calculation does not take more time than one timestep. For the model in this work this is not necessary though.

The equations describing the optimization problem and the general model descriptions are cited below, starting with the base version, followed by the additional equations and constraints of the more complex versions. To compare the models all three of them were operated with the same input parameters and had to deal with the same load profiles. The results of this comparison are shown in section 3.1.5.

3.1.2 Simple CHP model

The general electricity and heat balance equations represent the law of conservation of energy, i.e. for the electricity production that every single watt which is produced by the CHP, the PV or purchased from the grid has to be used in any way. The same legality applies to the heat balance equation. This equations are the base equations for all the three models.

The electricity balance equation is defined as the sum of all electrical power terms in the system. The load $L(k)$ is defined as:

$$L(k) = p_{\text{grid}}^{\text{in}}(k) + p_{\text{el}}^{\text{s,out}}(k) + PV(k) - p_{\text{grid}}^{\text{out}}(k) - p_{\text{el}}^{\text{s,in}}(k) - X(k) + p_{\text{el}}^{\text{chp}}(k) \quad (3.1)$$

The grid import and grid export is represented by $p_{\text{grid}}^{\text{in}}(k)$ and $p_{\text{grid}}^{\text{out}}(k)$ while $p_{\text{el}}^{\text{s,out}}(k)$ and $p_{\text{el}}^{\text{s,in}}(k)$ represent the discharging and the charging power of the battery storage. The produced PV power is represented by $PV(k)$ and the curtailed PV power is represented by $X(k)$. The power which is produced by the CHP is considered with $p_{\text{el}}^{\text{chp}}(k)$.

The heat balance equation shows that the heat load $G(k)$ is defined as the sum of all thermal power values in the system:

$$G(k) = p_{\text{th}}^{\text{chp}}(k) + p_{\text{th}}^{\text{gas}}(k) - p_{\text{th}}^{\text{s,in}}(k) + p_{\text{th}}^{\text{s,out}}(k) + p_{\text{th}}^{\text{mis}}(k) - p_{\text{th}}^{\text{was}}(k) \quad (3.2)$$

$p_{\text{th}}^{\text{chp}}(k)$ and $p_{\text{th}}^{\text{gas}}(k)$ represent the produced heat of the CHP and the gas burner, while $p_{\text{th}}^{\text{s,in}}(k)$ and $p_{\text{th}}^{\text{s,out}}(k)$ represent the power which is send or extracted from the thermal storage. The missing heat term $p_{\text{th}}^{\text{mis}}(k)$ represents the amount of missing heat if the model is not able to meet the heat demand. Excess heat which can not be used within the system and has to be emitted to the atmosphere is represented by $p_{\text{th}}^{\text{was}}(k)$.

The constraints for the simple model of the CHP are mostly just boundary constraints which means that this model is simple and the constraints in this model just prevent the power and energy variables from getting negative.

The connection between the electrical power and the produced waste heat is defined with the heat to power ratio h as seen in equation 3.3.

$$h = \frac{p_{\text{th}}^{\text{chp}}(k)}{p_{\text{el}}^{\text{chp}}(k)} \tag{3.3}$$

The SoC of the thermal storage $E_{\text{th}}^{\text{h}}(k)$ has to be less or equal than the maximum storage capacity at time k:

$$0 \leq E_{\text{th}}^{\text{h}}(k) \leq E_{\text{th}}^{\text{cap}}(k) \tag{3.4}$$

The available power from the thermal storage $P_{\text{th}}^{\text{h}}(k)$ has to be less or equal than the maximum power capacity of the storage at time k:

$$0 \leq P_{\text{th}}^{\text{h}}(k) \leq P_{\text{th}}^{\text{cap}}(k) \tag{3.5}$$

The SoC of the battery storage $E_{\text{el}}^{\text{s}}(k)$ has to be less or equal than the maximum storage capacity at time k:

$$0 \leq E_{\text{el}}^{\text{s}}(k) \leq E_{\text{el}}^{\text{cap}}(k) \tag{3.6}$$

The available power from the battery storage $P_{\text{el}}^{\text{s}}(k)$ has to be less or equal than the maximum power capacity of the storage at time k:

$$0 \leq P_{\text{el}}^{\text{s}}(k) \leq P_{\text{el}}^{\text{cap}}(k) \tag{3.7}$$

Surplus heat from CHP at time k,$p_{\text{th}}^{\text{was}}(k)$ which cannot be stored in the thermal storage or used at time k and has to be emitted to the atmosphere:

$$0 \leq p_{\text{th}}^{\text{was}}(k) \tag{3.8}$$

If the heat demand cannot be met at time k penalty costs have to be paid for the amount of missing heat which is represented by:

$$0 \leq p_{\text{th}}^{\text{mis}}(k) \tag{3.9}$$

When the gas burner is operated, its power output $p_{\text{th}}^{\text{gas}}(k)$ has to be between ist minimum and its maximum power output:

$$p_{\text{gas}}^{\text{min}}(k) \leq p_{\text{th}}^{\text{gas}}(k) \leq p_{\text{gas}}^{\text{max}}(k) \tag{3.10}$$

Electrical power generation $p_{\text{el}}^{\text{chp}}(k)$ of the CHP refers to the following equation:

$$0 \leq p_{\text{el}}^{\text{chp}}(k) \tag{3.11}$$

The objective function contains all the costs for the generation of electrical and thermal power, the operating costs for the storages and the earnings of the grid export.
In the simple model the objective function does not contain operating costs of the thermal storage, it just represents the costs of thermal power generation:

$$\begin{aligned} obj^{\text{th}} &= \sum_k p_{\text{th}}^{\text{mis}}(k) \cdot C^{\text{pen}} \cdot \Delta t + p_{\text{th}}^{\text{chp}}(k) \cdot C_{\text{th}}^{\text{chp}} \cdot \Delta t \\ &+ p_{\text{th}}^{\text{gas}}(k) \cdot C_{\text{th}}^{\text{gas}}(k) \cdot \Delta t \end{aligned} \tag{3.12}$$

The objective function for the costs of electrical power generation is represented by the following equation:

$$\begin{aligned} obj^{\text{el}} &= \sum_k [p_{\text{el}}^{\text{chp}}(k) \cdot C_{\text{el}}^{\text{chp}} + [p_{\text{el}}^{\text{s,in}}(k) + p_{\text{el}}^{\text{s,out}}(k)] \cdot C_{\text{el}}^{\text{lin,deg}} \\ &+ [p_{\text{el}}^{\text{s,in}}(k) + p_{\text{el}}^{\text{s,out}}(k)]^2 \cdot C_{\text{el}}^{\text{quad,deg}} \\ &+ p_{\text{grid}}^{\text{out}}(k) \cdot C_{\text{el}}^{\text{grid, out}}(k) + p_{\text{grid}}^{\text{in}}(k) \cdot C_{\text{el}}^{\text{grid,in}}(k) \\ &+ X(k) \cdot C_{\text{el}}^{\text{PV,curt}}] \cdot \Delta t \end{aligned} \tag{3.13}$$

The different terms in the objective functions represent the costs for the different parts in the framework. The variables have been explained above below the power and heat balance equations. The different terms which represent the costs are explained in table 3.1 below and the values for these costs are cited.

	Type of costs	Value	Unit
$C^{\text{pv}}_{\text{curt}}$	Curtailment costs	0.001	[CHF/kWh]
$C^{\text{batt}}_{\text{lin, degr}}$	Linear degradation costs	0.06	[CHF/kWh]
$C^{\text{batt}}_{\text{qua, degr}}$	Quadratic degradation costs	0.20	[CHF/kWh]^2]
$C^{\text{chp,ce}}_{\text{el}}$	El. Power Gen. costs CE	0.1239	[CHF/kWh
$C^{\text{chp,gt}}_{\text{el}}$	El. Power Gen. costs GT	0.1435	[CHF/kWh]
$C^{\text{chp,fc}}_{\text{el}}$	El. Power Gen. costs FC	0.1389	[CHF/kWh]
$C^{\text{stor}}_{\text{th}}$	Heat Storage costs	0.01	[CHF/kWh]
$C^{\text{chp}}_{\text{th}}$	Heat Gen. costs CHP	0.01	[CHF/kWh]
$C^{\text{gas}}_{\text{th}}$	Heat Gen. costs gas burner	0.12	[CHF/kWh]
C^{pen}	Penalty costs	100	[CHF/kWh]

Table 3.1: Values of operating costs

The MPC controller solves the following optimization problem:

$$\min_{\mathbf{u}_k} obj(\mathbf{u}_k, x_k) = obj^{\text{el}} + obj^{\text{th}} \tag{3.14}$$

subject to the power balance equations and the constraint set (3.1 - 3.11).

The control input and system states are:

$$\begin{aligned}
\mathbf{u}_k &= [u_k, u_{k+1}, \ldots, u_{k+N-1}] \geq 0 && (3.15)\\
u_k &= [E^{\text{s}}_{\text{el}}(k), p^{\text{in}}_{\text{grid}}(k), p^{\text{out}}_{\text{grid}}(k), p^{\text{s,out}}_{\text{el}}(k), p^{\text{s,in}}_{\text{el}}(k), && (3.16)\\
&\quad X(k), p^{\text{chp}}_{\text{el}}(k), E^{\text{h}}_{\text{th}}(k), p^{\text{s,in}}_{\text{th}}(k), p^{\text{s,out}}_{\text{th}}(k), p^{\text{chp}}_{\text{th}}(k),\\
&\quad p^{\text{gas}}_{\text{th}}(k), p^{\text{mis}}_{\text{th}}(k), p^{\text{was}}_{\text{th}}(k)]^T \geq 0\\
x_k &= [E^{\text{s}}_{\text{el}}(k-1), E^{\text{h}}_{\text{th}}(k-1)]^T && (3.17)
\end{aligned}$$

3.1.3 Standard CHP model

In this version a minimum operating power constraint for the CHP and costs for charging and discharging the thermal storage are added. These constraints represent the costs for operating necessary auxiliary systems such as pumps. Another effect of these constraints are that sending heat power to the thermal storage and extracting heat from the storage at the same time is prevented because it is cheaper to emit the waste heat to the atmosphere than to charge and discharge the thermal storage at the same time. Nevertheless this does not prevent the controller from working in that way to 100 % but it minimizes the values of charging/discharging at the same time to values that can be neglected because of the following reasons.

1. 90% of the occurring values are just numerical calculation issues and the values are ≤ 1 milliwatt

2. The other 10 percent of the occurring values are ≤1 watt which is ≤0.001 % of the rated power of the CHP

The minimum operating power represents the fact that the CHP can not be operated below a certain percentage of the rated power.

The electrical power output of the CHP $p_{\mathrm{el}}^{\mathrm{chp}}(k)$ is now restricted by the minimum operating power. Therefore equation 3.18 has to be added to the constraint set:

$$p_{\mathrm{el}}^{\mathrm{min}}(k) \leq p_{\mathrm{el}}^{\mathrm{chp}}(k) \leq p_{\mathrm{el}}^{\mathrm{max}}(k) \tag{3.18}$$

The thermal objective changes to take the costs of the thermal storage, $C_{\mathrm{th}}^{\mathrm{stor}}$, into account:

$$\begin{aligned} obj^{\mathrm{th}} &= \sum_{k}[p_{\mathrm{th}}^{\mathrm{mis}}(k) \cdot C^{\mathrm{pen}} + p_{\mathrm{th}}^{\mathrm{chp}}(k) \cdot C_{\mathrm{th}}^{\mathrm{chp}} + \\ &+ p_{\mathrm{th}}^{\mathrm{gas}}(k) \cdot C_{\mathrm{th}}^{\mathrm{gas}} + C_{\mathrm{th}}^{\mathrm{stor}} \cdot (p_{\mathrm{th}}^{\mathrm{s,in}}(k) + p_{\mathrm{th}}^{\mathrm{s,out}}(k))] \cdot \Delta t \end{aligned} \tag{3.19}$$

3.1.4 Complex CHP model

The most complex version of the CHP model includes all the constraints and objective functions of the more simple versions and is extended with more complex constraints to build a model which is more realistic. Therefore the parameters for a minimum on time and a minimum off time are added which represent the fact that there is a need to operate the CHP for a certain time if it is switched on and also not to operate it for a certain time after switching it off. The behavior of the CHP between the minimum and the maximum power is also represented more accurately because of the added ramp constraint. With the ramp constraint a more realistic time dependent behavior of the CHP while operating is ensured.

The ramp-shaped characteristics curve is represented by the following constraint and has to be added to the constraint set:

$$p_{\mathrm{el}}^{\mathrm{chp}}(k-1) - r^{\mathrm{chp}} \leq p_{\mathrm{el}}^{\mathrm{chp}}(k) \leq p_{\mathrm{el}}^{\mathrm{chp}}(k-1) + r^{\mathrm{chp}} \tag{3.20}$$

The minimum operating time and the minimum shut-down time are represented with the equations below and are also added to the constraint set:

$$t_{\mathrm{on}}^{\mathrm{chp}} \geq T^{\mathrm{min,on}} \tag{3.21}$$

$$t_{\mathrm{off}}^{\mathrm{chp}} \geq T^{\mathrm{min,off}} \tag{3.22}$$

3.1.5 Degree of Complexity

The test case operated by the simple model provided a objective value for the overall costs of the CHP system which is in a range of ≤ 2 % of the objective value of the overall costs of the complex model. The big disadvantage of the simple model is the missing constraint for the waste heat for which reason this model does not prevent the controller from charging and discharging the thermal storage. This offers the controller the possibility to get rid of the surplus of thermal power in case of a full charged thermal storage by sending and extracting heat power from the thermal storage at the same time. Although this is just a theoretically problem it affects the objective function because releasing the waste heat to the atmosphere instead of charging and discharging the thermal storage would cause costs or, at least, lead to a loss of earnings. A prevention of this is realized in the two more complex models and shows off in the appearing costs for operating the thermal storage in these two models. In table 3.2 the results of the three different models operating with a combustion engine CHP are shown. All the three different models were simulated for one month (January). The results for the gas turbine and the fuel cell CHP behave in the same way and are shown in the tables A.1 and A.2 in the appendix.

Variable	Costs	Simple model [CHF]	Standard model [CHF]	Complex model [CHF]
$C_{el}^{grid, in} - C_{el}^{grid, out}$	Energy costs	−3′634	−3′282	−3′140
$C_{el}^{PV,curt}$	Curtailment costs	21′604	21′618	21′618
$C_{el}^{lin,deg}$	Lin. Degradation costs	304	304	304
$C_{el}^{quad,deg}$	Qu. Degradation costs	313	315	318
C_{el}^{chp}	El. Power Gen. costs	14′204	13′927	13′839
C_{th}^{stor}	Heat Storage costs	0	183	176
$C_{th}^{chp} + C_{th}^{gas}$	Heat Gen. costs	5′920	6′184	6′266
C^{pen}	Penalty costs	0	0	0
$\sum C$	Overall operating costs	38′711	39′249	39′381

Table 3.2: Operating costs for Combustion Engine Model

The results show that the overall operating costs differ in a range of ≤ 2% from the most accurate value which is the one of the most complex model.The overall costs increase with the degree of complexity of the model because the energy costs and the gas burner costs increase. The increase of these costs results from the additional restrictions for operating the CHP and the referring increased use of the gas burner. The costs for the simple model are lower than the ones for the complex one because of the missing costs for the heat storage which are not realized in the simple model.

Therefore the generation costs for the electric power are 10 to 15% higher than in the more complex models because the CHP is operated more often in the simple model due to the missing constraints regarding the minimum operating power. This also effects the energy costs because of the larger amount of produced power, more power is exported to the grid which increases the earnings of the grid export and decreases the energy costs. The negative value of the energy costs shows, that more energy is exported than purchased from the grid.

The curtailment costs of the PV are nearly the same for all the three models and their difference is negligible because it is in a range of ≤0.1%. The standard model and the complex model do not even show a difference regarding the curtailment costs. The costs of the battery storage which are represented in the linear and quadratic degradation costs also show nearly no difference between the models. The thermal storage in this test case is quite small and has a capacity of only 400 kWh because these runs are made to figure out what model complexity for the CHP model is the best and therefore the impact of the storage size must not be in an affective range.

The generation costs for the electric power decrease the more complex the model gets because the CHP is operated less often in the more complex models due to more constraints concerning the power generation of the CHP. Operating the CHP gets less attractive to the controller in the more complex models because of more boundaries and restrictions for operating the CHP. Hence, the operating hours decrease and regarding to them the operating costs also decrease. The fewer operating hours of the CHP also effect the costs of the thermal power generation for the standard and the complex model. The costs for generating heat from the CHP are low and represent only the costs for operating the cooling pumps. The main part of the CHP's operating costs are attributed to the generation of electricity. Although the costs for heat generation from the waste heat of the CHP decrease the overall costs for the heat power generation increase. As shown in table 3.2, these costs contain the costs for utilizing the waste heat of the CHP and also the costs of the gas burner. If the operating hours of the CHP decrease, the operating hours of the gas burner increase to produce enough heat power to meet the demand of thermal power. This causes the increasing costs for the heat power generation because operating the gas burner to produce heat is more expensive than using the waste heat of the CHP if the CHP is already operating. The penalty costs represent a penalty which has to be paid if not enough thermal energy can be produced and the heat demand can not be met.

The minimum power of the CHP in the standard and the complex model is realized by using binary variables. The realization of the minimum power of the gas burner is realized in the same way. These binary variables force the controller either to shut the CHP down or operate it above the minimum operating power. The binary variables ensure this function but they need more resources to compute the simulation. While simulation runs using the simple model provide results after 100 seconds, simulations using the complex model need at least 966 seconds to provide results. The run times of the simulations depend further on the CHP constraints and the load profile. The given value with 966 seconds represents the fastest simulation for the CE CHP. Simulations for the GT CHP take almost 1.5 hours which is 5400 seconds.

3.1.6 Complexity Setting

For further calculations and simulations the most complex model will be used caused by the fact that the ramping behavior is needed. For the use of combustion engines and gas turbines which are able to go up or down in a range of 100 respectively 90 % of full power within one hour this would not be so important. Compared to fuel cells with their lower ramping ability of output power (around 30% of full power per timestep) the difference in the ramping behavior is too big to neglect it to get comparable situations for the simulations. The minimum-on and minimum-off time also represent a parameter that cannot be neglected to get proper and realistic results of the simulations. This is because fuel cells cannot be operated immediately after stopping them. They need a minimum off time for controlled cooling until they can be operated again and also a minimum operating time when started [14]. Gas turbines also need a minimum off time after operating because they need time for controlled slowing down, here especially turbines with really high rotations per minute [15]. Combustion engines on the other hand can stop immediately and have a lower minimum off-time. The minimum on- and off-time of combustion engines depends on the size of the engine but is always lower than the one of gas turbines or fuel cells [16].
Neglecting the ramping behavior and also not using the minimum on and off times of the different CHP types would, caused by the facts explained above, lead to a unfair and unrealistic comparison of these three technologies why for further calculations and simulations the complex model is used to provide proper and realistic results of this work.

3.2 Case Studies

To analyze how the CHP has to be operated to fulfill the tasks, the following test cases are defined. The test cases up to 3.2.4 are computed for all three types of CHP's, the test case to investigate the impact of the deviation of the forecast PV data from the real PV profile in section 3.2.5 is computed only for the fuel cell CHP. All test cases were defined with a MPC horizon of 120 hours which is 5 days.

3.2.1 Base Case

The first test case is defined with a PV and a conventional battery storage connected to the power grid and a gas burner to meet the heat demand. This represents the status quo without the use of a CHP to get a comparable situation for the further simulations with the CHP. The excess power of the PV in this case study is curtailed if it is not needed to meet the load profile and can not be used for charging the battery storage or exported to the grid due to the line limits of the power grid. The power balance equation and the constraints which refer to this case have already been defined in section 2.2 and will not be cited here again. The CHP term in the power balance equation is zero for this test case and the constraints which limit the CHP are not used here. As shown below in figure 3.2 the heat demand of the thermal load is met only with the thermal energy produced by the gas burner of the system.

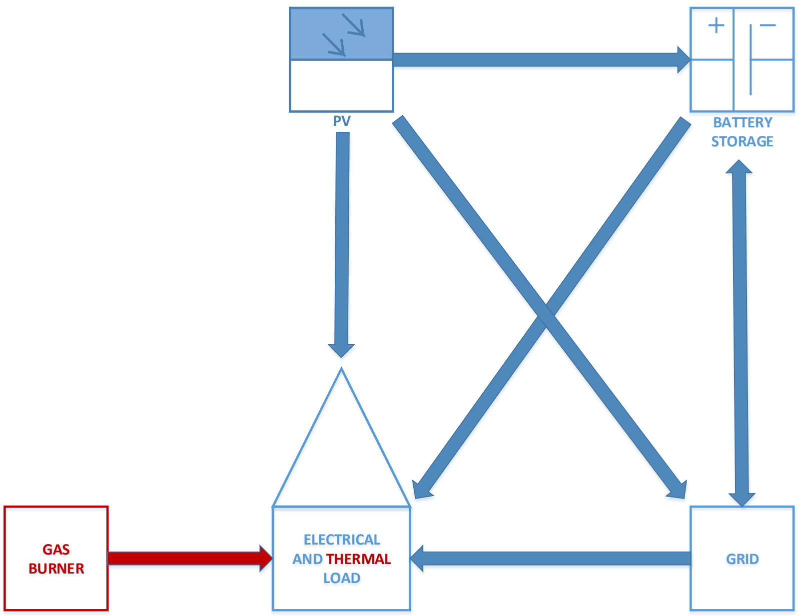

Figure 3.2: Framework scheme for base case

3.2.2 CHP

To figure out how a CHP combined with a thermal storage could play the role of a conventional battery storage this test case is defined as follows:

The CHP is operated to compensate the fluctuating PV power and to produce heat for the district heating network. The battery storage is set to zero for this case and the excess PV power which cannot be used is curtailed.

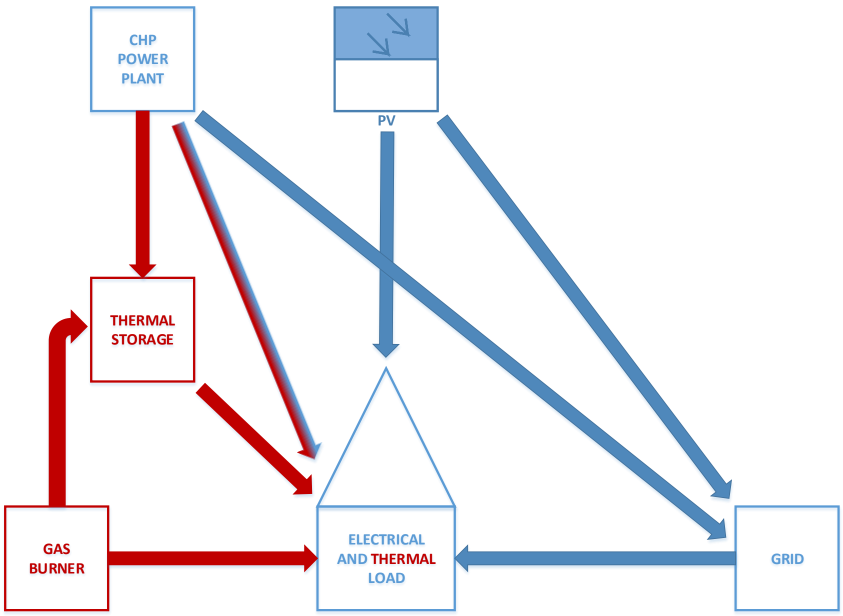

Figure 3.3: Framework scheme for CHP case

Figure 3.3 shows the scheme of this test case. The battery storage is set to zero now, which means that the surplus energy of the PV has to be sold to the grid or curtailed. The CHP now should play the role of the battery storage in cases of no or too few PV power. It also provides electrical and thermal power to meet the thermal and electrical load profile. The gas burner can be seen as a backup for the CHP and the thermal storage to provide thermal power in terms when the CHP is down or provides too less thermal power and the thermal storage is empty. The power balance equations and the constraint set regarding to this test case are defined in section 2.2. The constraints which describe the behavior of the battery storage are neglected and the battery storage terms in the power balance equation are set to zero.

3.2.3 PV to heat

The scheme of this test case as it is shown in figure 3.4 is the same as for the first test case shown in figure 3.2 but the PV can provide thermal power as well as electrical power now. In reality the PV would not be used in this way very often because of the lower efficiency of producing heat with the electrical output of the PV compared to solar thermal collectors. But nevertheless there could be situations where the PV would produce energy which cannot be used at that time and instead of curtailing it, it is, of course, better to use it. The power balance equation in section 2.2 is no longer sufficient to describe this system. The new power balance equations which also contain the PV power which is used to generate heat are shown in the equations below. The terms representing the electrical and the thermal power from the CHP are set to zero.

$$\begin{aligned} L(k) &= p_{\mathrm{grid}}^{\mathrm{in}}(k) + p_{\mathrm{el}}^{\mathrm{s,out}}(k) + PV(k) - p_{\mathrm{grid}}^{\mathrm{out}}(k) \\ &- p_{\mathrm{el}}^{\mathrm{s,in}}(k) - X(k) - p_{\mathrm{el}}^{\mathrm{PV,heat}}(k) + p_{\mathrm{el}}^{\mathrm{chp}}(k) \end{aligned} \tag{3.23}$$

$$\begin{aligned} G(k) &= p_{\mathrm{th}}^{\mathrm{chp}}(k) + p_{\mathrm{th}}^{\mathrm{gas}}(k) - p_{\mathrm{th}}^{\mathrm{s,in}}(k) + p_{\mathrm{th}}^{\mathrm{s,out}}(k) \\ &+ p_{\mathrm{th}}^{\mathrm{mis}}(k) - p_{\mathrm{th}}^{\mathrm{was}}(k) + p_{\mathrm{th}}^{\mathrm{PV,heat}}(k) \end{aligned} \tag{3.24}$$

$$0 \leq X(k) + p_{\mathrm{el}}^{\mathrm{PV,heat}}(k) \leq PV(k) \tag{3.25}$$

$$p_{\mathrm{th}}^{\mathrm{PV,heat}}(k) = \eta_{\mathrm{e/th}} \cdot p_{\mathrm{el}}^{\mathrm{PV,heat}}(k) \tag{3.26}$$

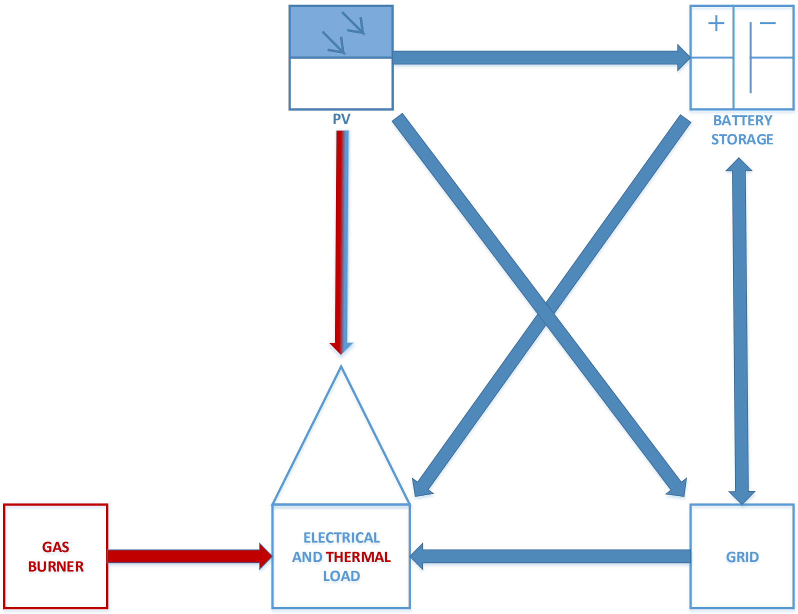

Figure 3.4: Framework scheme for PV to heat

Figure 3.4 shows the scheme of the test case which also uses excess PV power to meet the heat demand of the load. The surplus PV power which is not used by the load and cannot be sold to the grid is used to produce thermal power by a electric boiler for warm water or by a electric radiator for domestic heating.

3.2.4 CHP and PV to heat

The scheme for this test case corresponds to the one in 3.2.2 except that here the PV is also used for heating. This does not mean that the PV is used to generate thermal energy every time, this happens just in case the PV production is higher than the sum of the demand and the power exported to the grid. The CHP provides electrical and thermal power to be used in the framework for all possible applications. The power balance equations and additional constraints for this test case are defined in equations 3.23 to 3.26 in section 3.2.3.

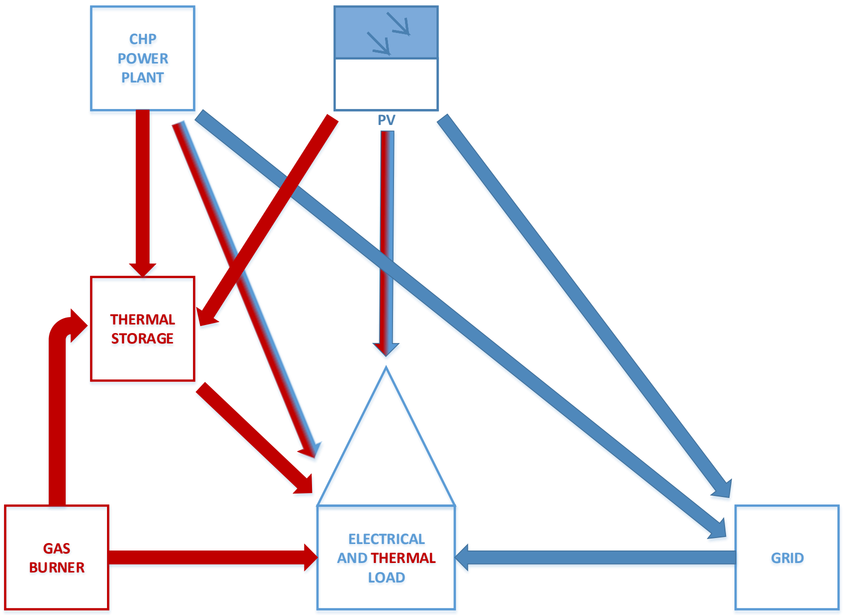

Figure 3.5: Framework scheme for CHP and PV to heat

3.2.5 Forecast uncertainty

Up to this test case all the input profiles for the MPC controller were assumed deterministic. This means the controller knows the real values of its input variables from timestep k to $k+N$ in the future, while N represents its timestep horizon. To make the simulations more realistic a PV forecast profile for the timesteps $k+1...k+N$ can be used. The whole PV data, including the real PV profile and the forecast profile is increased by 20% to increase the impact of the PV on the whole system. The fuel cell CHP is used for this test case and has to be operated by the MPC to meet the demand of load profile 3. To validate the method which is used, an upper and a lower bound for the simulations are created. This bounds are:

- **Perfect Information MPC (PIMPC):**
  The perfect information MPC uses the values of the real PV input profile, i.e., the values of the input profile are assumed as deterministic again. Due to this assumption the power balance equations given in equations 3.23 and 3.24 and the additional constraints in equations 3.25 to 3.26, are valid for the PIMPC for all timesteps $k...k+N | k \in \mathbb{N}$. Because there is no case in which the controller could perform better than with the values of the real PV profile this provides the cheapest results and the practical upper bound.

- **Deterministic MPC (DEMPC):**
  The deterministic MPC uses the values of the real PV profile just for timestep k and the values of the PV forecast profile for all timesteps $k+1...k+N$. No assumptions regarding the correspondence of the forecast profile and the real PV profile are made. The controller acts like the values of the forecast profile would be the values of the real PV profile for the future timesteps. The equations used for the PIMPC (3.23 and 3.25 above) are now valid only for timestep k. For the future timesteps $k+1...k+N$ the controller uses the power balance equation 3.27 and equation 3.28 as additional constraints.

$$
\begin{aligned}
L(k+t) &= [p_{\text{grid}}^{\text{in}}(k+t) + p_{\text{el}}^{\text{s,out}}(k+t) + FC(k+t) \\
&- p_{\text{grid}}^{\text{out}}(k+t) - p_{\text{el}}^{\text{s,in}}(k+t) - X(k+t) \\
&- p_{\text{el}}^{\text{PV,heat}}(k+t) + p_{\text{el}}^{\text{chp}}(k+t)]
\end{aligned}
\tag{3.27}
$$

$$
0 \le X(k+t) + p_{\text{el}}^{\text{PV,heat}}(k+t) \le FC(k+t) \tag{3.28}
$$

$$
\forall t \in [1, N]
$$

Standard Deviation

The standard deviation is a measure of the scattering of a random variable around its expected value. According to the definition of Galton, the standard deviation can be calculated to define a confidence interval around the expected value, within a certain percentage of the real values are located [25]. Table 3.3 shows the percentage of the values within and outside the confidence interval depending on factor z multiplied by the standard deviation following equation 3.29[1].

$$CI(k) = FC(k) \pm z \cdot \sigma(k) | k \in \mathbb{N} \tag{3.29}$$

$z \cdot \sigma$	Percentage within CI	Percentage outside
1σ	68.27 %	31.73 %
2σ	95.45 %	4.55 %
3σ	99.73 %	0.27 %
4σ	99.99 %	0.01 %

Table 3.3: Percentage within and outside the confidence interval

To improve the performance of the deterministic MPC a confidence interval of $\pm 2\sigma$ is used. This provides an area around the forecast profile where, according to table 3.3, the value for the real PV profile is located with a percentage of 95.45%. To build the controller in a way to handle this, new constraints are necessary. The standard deviation profile for every hour of the year is computed using the real PV profile and the forecast PV profile of the last ten days and the next ten days. To get the values for the first ten days of the year, the real PV profile and the forecast profile of the last ten days of the same year are used. To compute the standard deviation profile for the last ten days of the year the first ten days of the same year are used. The equations for timestep k are the same as for the PIMPC configuration, shown in equations 3.23 and 3.25. Equations 3.30 and 3.31 show the new power balance equations for the timesteps from $k+1$ to $k+N$. The new constraint to limit the curtailment and the PV power used for heating is shown in equation 3.32.

[1] CI...confidence interval

$$
\begin{aligned}
L(k+t) \quad \leq \quad & [p_{\text{grid}}^{\text{in}}(k+t) + p_{\text{el}}^{\text{s,out}}(k+t) + [FC(k+t) + 2\sigma(k+t)] \\
- \quad & p_{\text{grid}}^{\text{out}}(k+t) - p_{\text{el}}^{\text{s,in}}(k+t) - X(k+t) \\
- \quad & p_{\text{el}}^{\text{PV,heat}}(k+t) + p_{\text{el}}^{\text{chp}}(k+t)]
\end{aligned} \tag{3.30}
$$

$$
\begin{aligned}
L(k+t) \quad \geq \quad & [p_{\text{grid}}^{\text{in}}(k+t) + p_{\text{el}}^{\text{s,out}}(k+t) + [FC(k+t) - 2\sigma(k+t)] \\
- \quad & p_{\text{grid}}^{\text{out}}(k+t) - p_{\text{el}}^{\text{s,in}}(k+t) - X(k+t) \\
- \quad & p_{\text{el}}^{\text{PV,heat}}(k+t) + p_{\text{el}}^{\text{chp}}(k+t)]
\end{aligned} \tag{3.31}
$$

$$
0 \quad \leq \quad X(k+t) + p_{\text{el}}^{\text{PV,heat}}(k+t) \leq FC(k+t) - 2\sigma(k+t) \tag{3.32}
$$

$$
\forall t \in [1, N]
$$

Clear Sky Profile

For further improvement of the MPC performance the confidence interval around the forecast profile can be limited by the clear sky profile. The clear sky represents the maximum of the possible PV power output under best conditions and can be computed online [23]. This limitation can be used because the value of the forecast profile plus two times the standard deviation (equation 3.29), which is used in section 3.2.5, is sometimes higher than the theoretical maximum PV output. Although the whole PV data is computed from the same source, the clear sky profile seems to be too pessimistic in the first hours of sunlight in the morning. Due to that, limiting the PV forecast by the clear sky profile would not make sense in the early morning hours. To compensate the pessimistic values of the clear sky profile in the morning another profile, calculated as a mean value of the real PV output values of the early morning hours of the last five days, is introduced.

The forecast profile is now handled as an optimization variable which is limited by different constraints. Although this is not the correct way it seems to work in this case. The reasons which make it work in this case will be discussed later in chapter 4. The power balance equation and the constraints for timestep k are again the same as in the earlier sections. The new power balance equation and the constraints for the forecast profile are shown in equations 3.33 to 3.36 below:

$$
\begin{aligned}
L(k+t) &= [p_{\text{grid}}^{\text{in}}(k+t) + p_{\text{el}}^{\text{s,out}}(k+t) + fc(k+t) \\
&- p_{\text{grid}}^{\text{out}}(k+t) - p_{\text{el}}^{\text{s,in}}(k+t) - X(k+t) \\
&- p_{\text{el}}^{\text{PV,heat}}(k+t) + p_{\text{el}}^{\text{chp}}(k+t)]
\end{aligned} \tag{3.33}
$$

$$
0 \leq X(k+t) + p_{\text{el}}^{\text{PV,heat}}(k+t) \leq fc(k+t) \tag{3.34}
$$

$$
fc(k+t) \leq min(FC(k+t) + 2\sigma, CS(k+t) + MD(k+t)) \tag{3.35}
$$

$$
fc(k+t) \geq FC(k+t) - 2\sigma \tag{3.36}
$$

$$
\forall t \in [1, N]
$$

The scheme of this test case is the same that it is used for earlier simulations in 3.2.4 and the setup used here also uses the excess PV power to generate heat.

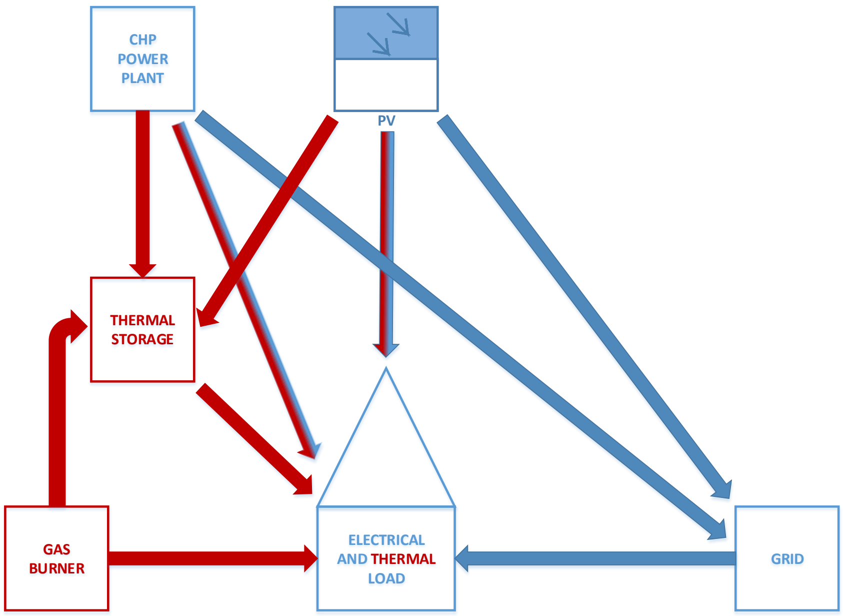

Figure 3.6: Framework scheme for Forecast Uncertainty case

Chapter 4

Results

The results of the simulations of the different case studies are presented and discussed in this chapter. The graphs and tables in this chapter show only the results which are necessary to explain and discuss the results. The tables with the detailed results data are located in appendix C.

4.1 Economic Impact of CHP and PV to heat

Figure 4.1 shows the different objective cost values for the base case and the CHP case study. It also shows the impact of the different CHP types on the objective costs for one year. It shows that the objective costs are lower for the CHP case than for the base case, no matter what type of CHP is used. The higher costs for the health care building load profile are mainly caused by the higher heat load. This is also the reason why the objective costs between the fuel cell CHP and the gas turbine CHP differ the most for this case. Although they are quite the same for the other two load profiles there is a gap of almost 30% for the health care building load profile. This gap results from the different heat to power ratios and shows that it is important to use a CHP which heat to power ratio matches the one of the load profile. The combustion engine CHP provides the cheapest objective costs for all three different load profiles. This results on the one hand from the lower operating costs of the combustion engine CHP and, on the other hand on the higher flexibility of the combustion engine CHP compared to the other types. The lower costs of all three CHP types for all load profiles, compared to the base case without a CHP have several reasons. At first the CHP's provides electricity which lowers the amount of grid imported power. The second reason is the provided heat, which decreases the amount heat produced by the gas burner. Because the main cost component for operating the CHP is caused by the produced power, the gained heat is seen as a by-product and therefore cheaper. Gaining the CHP's waste heat is cheaper than the heat from the gas burner. In other words, operating the CHP is cheaper than importing power from the grid and burning gas. The third reason for the decreasing costs is the bigger amount of exported power which is sold to the grid. The breakdown of the operating costs for all cases is shown in the tables C.1 and C.2 in the appendix.

From an economic view, using a combustion engine provides the best way to provide heat and power for the given load profiles in the CHP case followed by the gas turbine CHP and the fuel cell CHP.

Figure 4.2 shows the objective costs for the CHP and PV to heat case. Compared to the results shown in 4.1 the costs for all test cases decreased after using the excess PV power to generate heat. One can see that the costs for the fuel cell CHP are now lower than the ones for the gas turbine CHP for the college and lodging buildings load profiles. This results from the impact of the gained heat from the PV and the different heat to power ratios. Because heat is now also provided by the PV, the heat load for the CHP is lowered and a lower heat to power ratio is an advantage now.

The costs for the combustion engine CHP for the college building load profile decrease to 85% of the value with no PV heat whereas the costs for the fuel cell CHP decrease to 30% of the value from the CHP case. This shows that using the excess PV power does not improve the conditions for the combustion engine CHP as much as it does for the fuel cell CHP. One can see that the FC CHP gets in a competitive economic range to the CE CHP although its operating costs are higher. The impact of the usage of the heat gained from the PV is shown in detail for the CE CHP in figure 4.3. Figure 4.3 also illustrates that the possible decrease of the costs depends on the heat to power ratios of the load profile and the CHP.

From an economic view the use of the excess PV power to generate heat is a good way to handle the surplus of production. Although the PV heat case provided an improvement of the objective costs for this test cases, this won't work for other systems. Especially if the load profile is always higher than the PV production or less PV is installed, no heat would be gained from the PV at any time and the PV to heat case would not make sense. Anyway, the PV to heat test case is just a theoretical case because the PV facility for this work was sized assuming that every possible squaremeter is used to install PV. In reality the size of the installed PV will be chosen due to more restrictions, f.e. grid limitations.

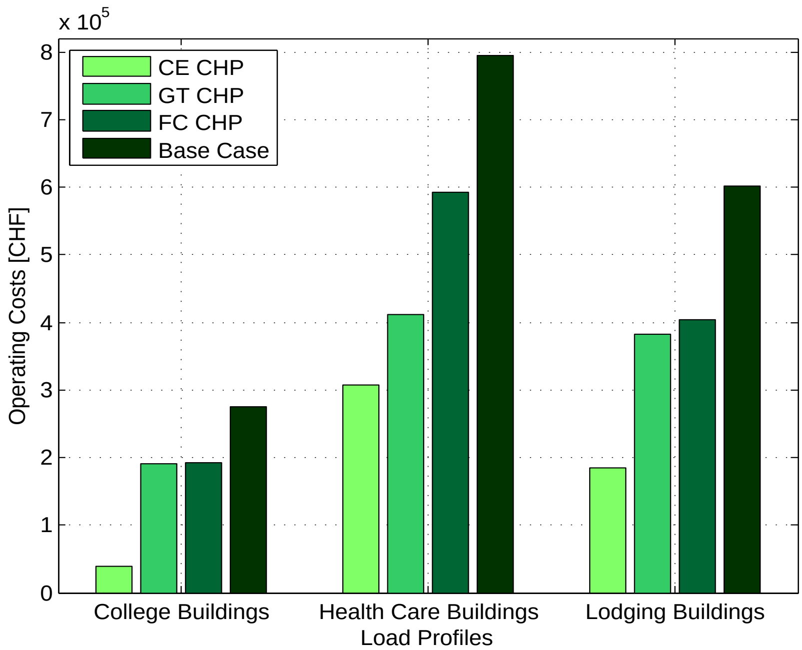

Figure 4.1: Objective costs of Base case and CHP case

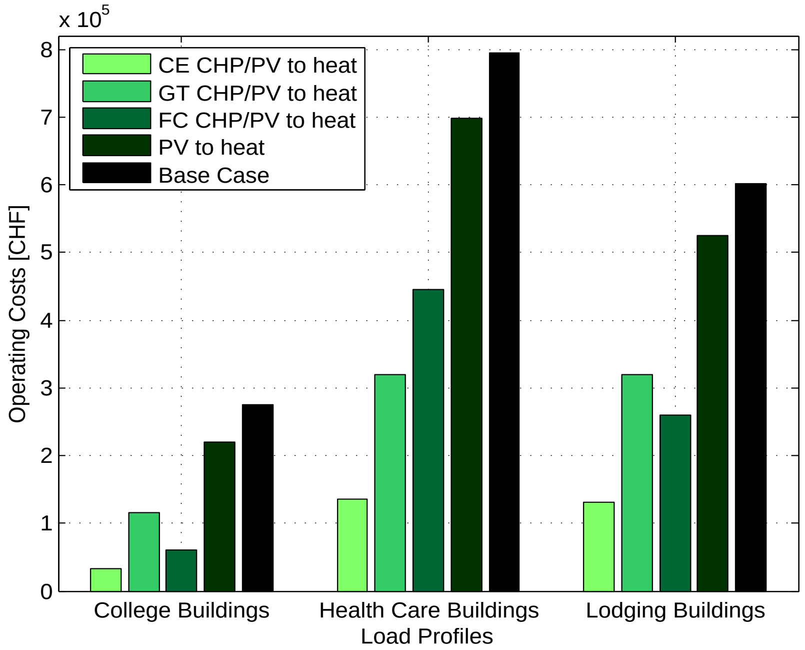

Figure 4.2: Objective costs of PV to heat and CHP/PV to heat case

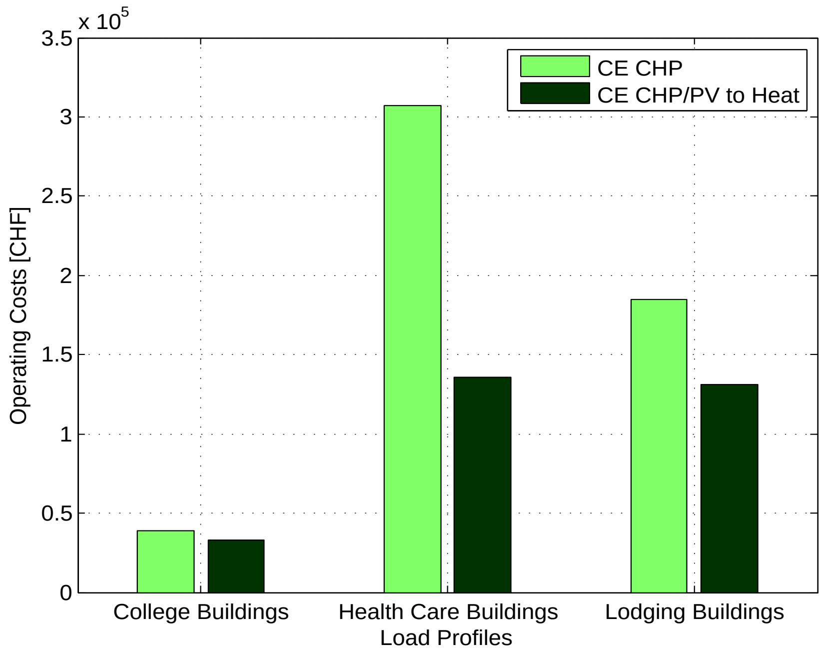

Figure 4.3: Objective costs of CE CHP and CE CHP/PV to heat case

Figure 4.4 and table 4.1 show a comparison of the objective costs of the base case, a modified base case and a CHP case operated for the lodging building load profile. The modified Base Case was simulated to find out under which conditions the battery storage would be competitive compared to a FC CHP with thermal storage. In other words under which conditions it would not make sense to replace a battery storage by CHP and thermal storage. The FC CHP is used for this simulation because it represents the most expensive CHP case operated for the lodging building load profile (see also table 4.1). In figure 4.4 one can see that the major components of the operating costs of the base case are the costs for burning gas. These costs are about 89% of the amount of the whole operating costs for the FC CHP case. Decreasing the objective costs for the base case is possible just by decreasing the energy costs and the costs for the battery storage. The costs for burning gas can not be decreased because the whole heat demand has to be met by the gas burner in the base case. Consequently, decreasing objective costs assume a decreasing amount of energy and battery costs. Just cheaper costs for the battery storage would not provide satisfying results because the battery costs of the base case are lower than the difference between the base case and the CHP case. To decrease the battery costs and the energy costs is possible only by decreasing the operating costs of the battery and increasing the capacity of the battery storage. A bigger battery storage leads to lower energy costs because more energy can be stored in the battery and extracted when needed which leads to decreasing grid import. Table 4.1 shows that with a 4000kWh battery storage and with lower battery costs the costs can be reduced and get in a range of 8% of the FC CHP costs. To reach that situation which is almost competitive to the FC CHP case the operating costs of the battery storage have to decrease by 70% (0.02 CHF for linear degradation and 0.06 CHF for quadratic degradation). Because these costs depend on the investment costs and the lifetime of the battery storage the costs for battery storages have to decrease by 70% to be competitive to CHP applications and thermal storages.

The battery storage is oversized for the PV to heat case because of the following reason. Charging the battery storage gets less attractive for the controller because of the objective function. The controller always tries to fulfill all given tasks at lowest costs. Charging and discharging the battery leads to degradation costs, whereas converting the excess PV power to heat just leads to a loss of energy and exporting power to the grid leads to earnings. The controller tries to sell as much PV power to the grid as possible, because this represents an active decrease of the objective costs. The residual power is then mostly converted into heat to meet the heat demand or, at least, prevent costs and only a small part is used to charge the battery. Due to that the battery storage for the PV to heat test case gets never fully charged.

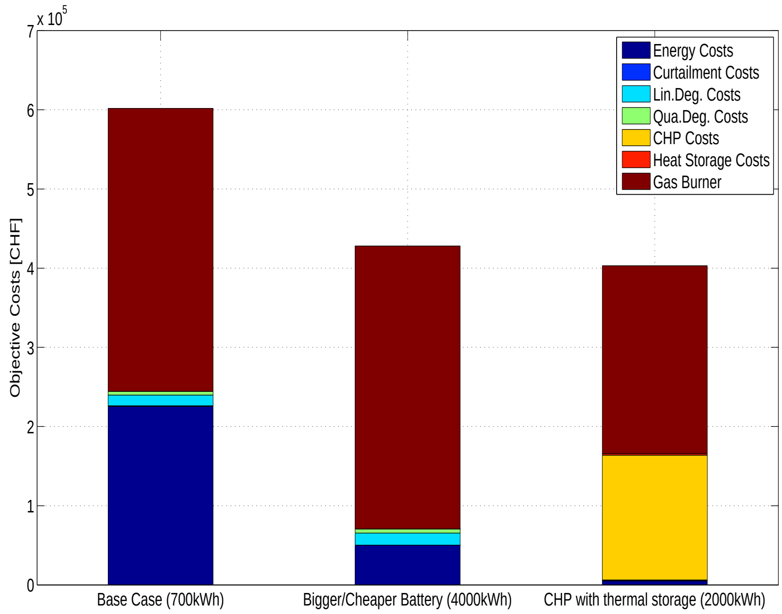

Figure 4.4: Objective costs of Base case and CHP case

Costs	Value [CHF]		
	Base Case	Cheaper&Bigger Battery	CHP&Thermal Storage
Energy Costs	225'300	50'223	5'167
Curtailment Costs	879	66	1'003
Lin. Deg. Costs	13'509	15'169	0
Quad. Deg. Costs	4'662	5'167	0
Heat Stor. Costs	0	0	1'933
Heat Gen. Costs	357'430	357'430	237'395
Overall Costs	601'782	428'055	403'164

Table 4.1: Objective Costs of Base Case and modified PV to heat cases

4.2 Technical Impact of CHP and PV to heat

As shown in figure 4.5 even in winter, when the load profile is higher than in summer, a lot of the produced PV power gets curtailed. Due to grid limitations, load profile and restrictions of the battery storage it is not possible to use the whole PV power at the timestep when it is produced. Compensating the fluctuation the PV power production with a CHP is one of the main goals of this work. Regarding to that the overall energy efficiency has to be investigated also. The results of the investigations on the produced and wasted energy are explained below figure 4.5.

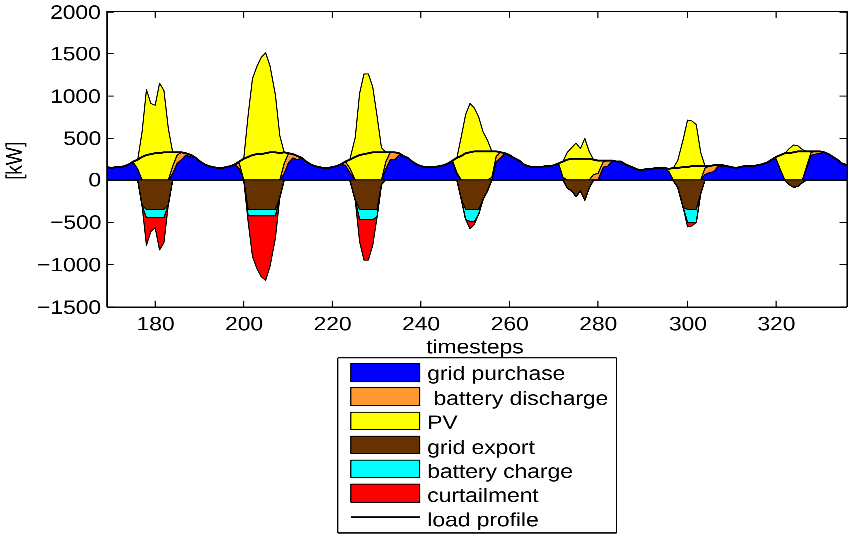

Figure 4.5: Electric Load Profile in January, Base Case

Figure 4.6 shows that the usage of a CHP and a thermal storage provides an improvement on the overall efficiency only in case of a fuel cell CHP and only for the college building load profile. The decrease of "wasted energy"[1] in case of using a fuel cell CHP compared to the base case is below 1%. For all other cases and load profiles the overall efficiency decreases because of an increase of the waste energy. This deterioration was expected because of the missing battery storage for the CHP case and the additional heat production of the CHP. The missing battery storage causes an increase in curtailed PV power because no produced PV power can be send to the battery storage in the CHP case, i.e., no PV power is buffered in the battery storage. The second reason for the increase of the waste energy is the heat production of the CHP and the gas burner. Every time the CHP or the gas burner are

[1]Waste energy is defined as the sum of curtailed PV power and waste heat

operated and the heat load profile is lower than the actual production and the excess heat can not be send to the thermal storage, it is emitted to the atmosphere. This is the same as for the gas burner in the base case, but the heat production of the CHP is a new component in this case. Every time the CHP is operated to meet the electrical demand and the produced heat can not be used to charge the thermal storage or for meeting the heat demand it has to be wasted. The wasted energy has the highest value of all three types of CHP's for the college building an the health care building load profile. The high value for the CE CHP is caused by the lower fuel prices of the CE CHP and, again, by the defining the CHP heat as a by-product of the electrical power output. The CE CHP is operating at a higher level than actually needed especially in winter because the feed-in tariff of the grid is higher than the costs for producing power and heat.

The use of a CHP and a thermal storage to increase the efficiency compared to the base case makes sense from a technical view only for the college building load profile and only if a FC CHP is used. However, even this improvement is negligible. The usage of a CHP would only make sense for a lower PV production or a higher load profile for both heat and power. Figure 4.8 shows a comparison of the wasted energy of the base case, the CE CHP case, the CE CHP case with 60% less PV production and a base case with also 60% less PV. One can see that a decreasing the PV production by 60% leads to a decrease of the wasted energy. For the health care building load profile the wasted energy is zero now and also for the lodging building a the college building load profiles it is below 1% of the consumed energy for the CHP case. For the base case the waste energy can be reduced to almost zero percent (0.0005 %). The wasted energy decreases as long as the curtailed PV power decreases. Regarding to that, the test case with 60% less PV production represents the energetically optimal size of the PV for the given load profiles and no PV to heat.

If the excess PV power is used to generate heat, the waste energy[2] can be reduced for most of the test cases. Figure 4.7 shows the waste energy values for the PV to heat and the CHP/PV to heat test cases. The amount of wasted energy is reduced by almost 40% for the PV to heat case. The amount of wasted energy for the CHP/PV to heat cases is now lower for all types of CHP and the college building load profile. The main reason for that is the additional thermal power provided by the PV which can be used to charge the thermal storage now. Charging the thermal storage in times when the CHP is shut off and using this thermal energy to meet the heat demand helps to extend the shut off periods of the CHP and leads to less

[2]For the PV to heat cases the waste energy consists only of waste heat, not of curtailed PV power

wasted energy. This happens especially on evenings in summer, when extracting heat power from the storage and meeting the electrical demand by purchasing power from the grid is cheaper than operating the CHP to meet both, or operating the gas burner to meet the heat demand. The amount of waste heat is zero for the CE and FC CHP's and at a low level for the lodging building load profile caused by the higher heat to power ratio of these load profiles. The amount of waste heat for the GT CHP test cases is lower than for the PV to heat case only for the college building load profile because in this test case the GT CHP is operated mostly only in winter and shut down in summer. In summer the heat and power demand for this case is met by grid purchase for the electrical load and the gas burner and the heat from the PV for the thermal load. Operating the GT CHP in summer is not an attractive way for the controller because the load profile is below the minimum operating power of the CHP and the feed-in tariff of the grid is below the costs of operating the GT CHP. For the comparatively higher load profiles of health care and lodging buildings the GT CHP is operated also in summer. Due to the higher heat to power ratio of the GT CHP and the high minimum power rate, this leads to an increasing amount of waste energy because the sum of produced heat by PV and CHP is bigger than the needed amount to meet the heat demand.

From a technical view, using a CHP to improve the performance of the given system only makes sense in combination with PV to heat. The energetically best results with the lowest values of wasted energy were provided from the fuel cell CHP in combination with PV to heat for all three load profiles, followed by the CE CHP and the GT CHP.

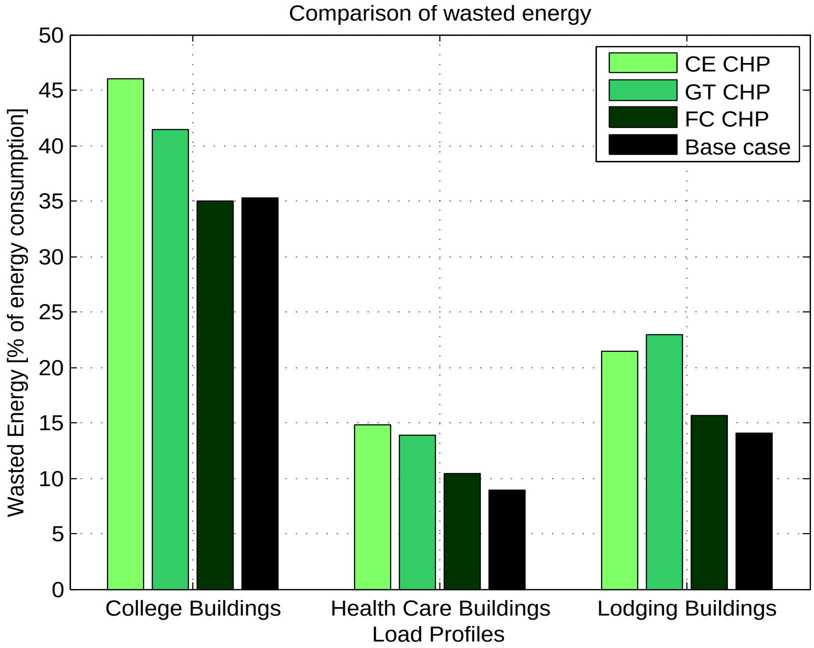

Figure 4.6: Wasted energy of Base case and CHP case

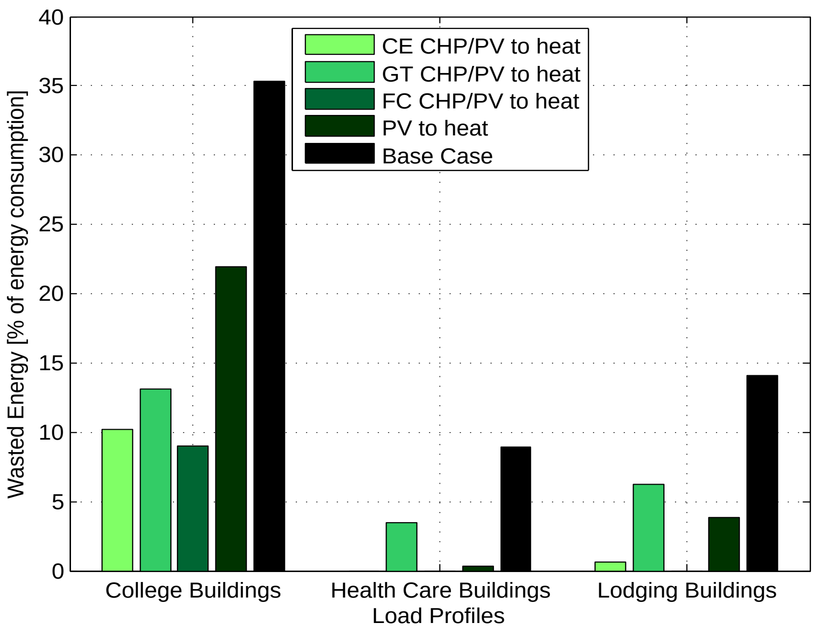

Figure 4.7: Wasted energy of PV to heat and CHP/PV to heat case

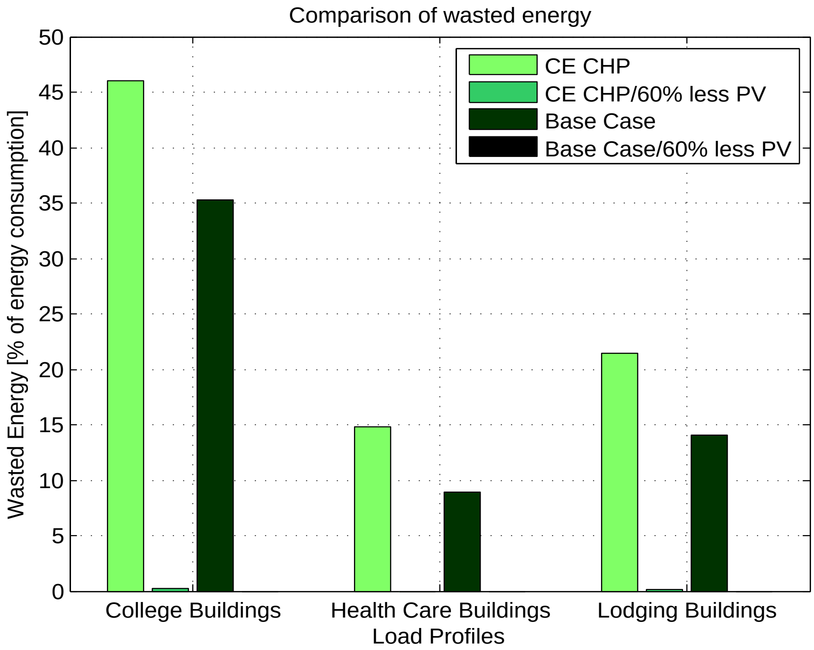

Figure 4.8: Comparison of the wasted energy with the 60% less PV case

4.3 Impact of forecast uncertainty

Table 4.2 shows the objective costs for the different setups which where developed to deal with the forecast uncertainty. Figure 4.9 shows that the objective costs of the PIMPC and the DEMPC, represented by the red lines, differ only about 7%. This small difference results from good forecast data for the PV production. Using a confidence interval of $\pm 2\sigma$ leads to an improvement of the objective costs of 2%. This improvement results from a better use of the gas burner to meet the heat demand. Because the PV production is higher than the load profile most of the time when the PV is operating the forecast data is also higher than the load profile. This leads to a negligible impact on the electrical part of the system by using the forecast data instead of the real PV production profile. The excess PV power is used to generate heat and so using the forecast data effects mostly only the thermal part of the system. The low flexibility and the low heat to power ratio of the FC CHP are also a reasons for the low impact on the electrical part of the system.

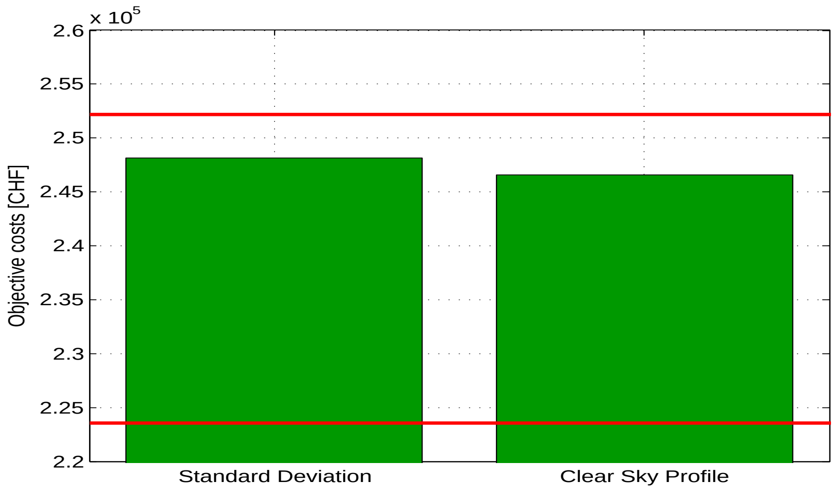

Figure 4.9: Comparison of objective costs

Costs	Value [CHF]			
	DEMPC	Standard Deviation	Clear Sky Profile	PIMPC
Energy Costs	-5’724	-6’314	-6’6069	-6’690
Power Gen.Costs	184’337	184’193	184’233	184’819
Heat Stor. Costs	6’064	6’627	6’926	8’653
Heat Gen. Costs	67’544	63’630	61’477	48’858
Heat Penalty Costs	0	0	6’610	0
Overall Costs	252’221	248’136	246’567	235’640

Table 4.2: Uncertainty impact on objective costs

As shown in figure 4.10 the thermal power produced by the CHP is constant for all four different MPC setups and only the usage of the gas burner and the PV heat change. The lower costs of the standard deviation setup and the clear sky setup result from a better timed use of the gas burner and the thermal storage when better forecast data is provided. The figure shows that the output power of the gas burner decreases with better forecast data and is at its highest value for the DEMPC. This happens because the controller has better values for the available PV heat in case of better forecast data and its not necessary to operate the gas burner on a higher level.

Although the setup which limits the forecast data by the clear sky profile uses the lowest possible value for the predicted output the overall objective costs decrease compared to the standard deviation setup. Figure 4.11 shows that the controller always takes the lowest possible forecast value, which is represented by $FC - 2\sigma$. This setup seems to work for this test case, although the controller is working in a wrong way.

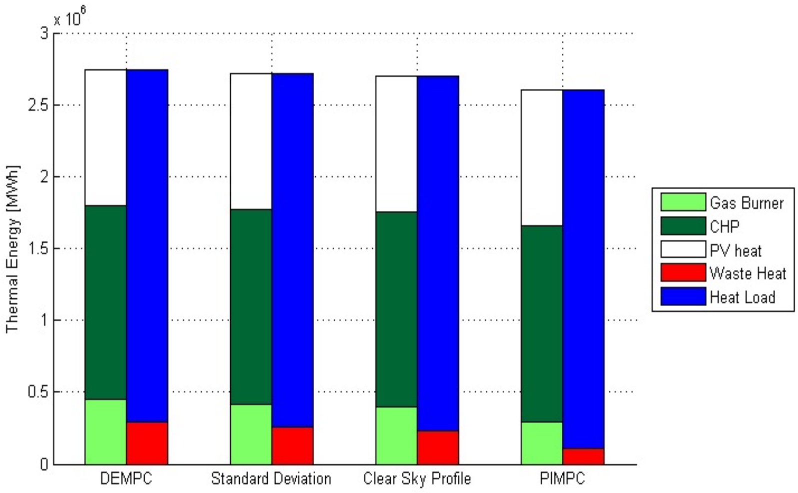

Figure 4.10: Thermal energy production

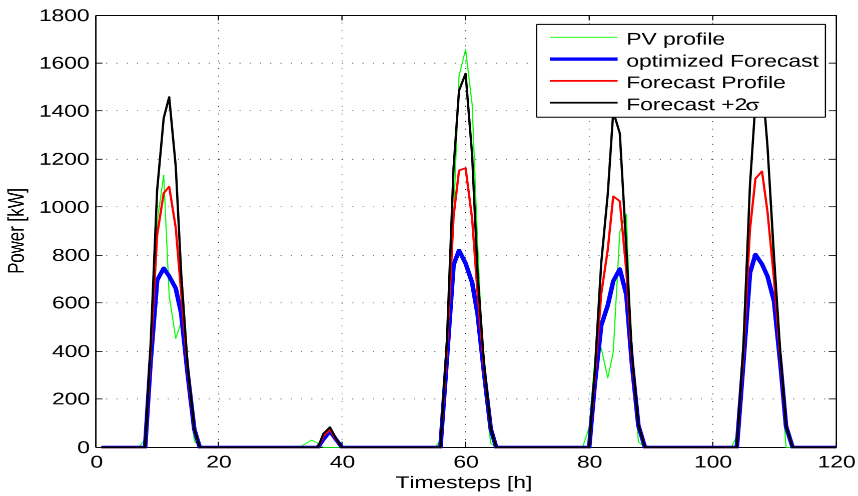

Figure 4.11: Suggested PV forecast

Chapter 5

Conclusion and Outlook

This chapter summarizes the most important findings and achievements of this thesis and concludes with an outlook for further research.

5.1 Conclusions

In this thesis a model has been developed to define the type, size and the use of a CHP combined with a thermal storage. Every facility in the framework has been modeled and their parameters and costs have been gained either from real data or computed from scientific tools online. A CHP, PV infeed, a power grid, a gas burner, a battery storage and a thermal storage have been developed and simulated over a one-year time period. The results have been analyzed with the objective to answer if a CHP combined with a thermal storage can play the role of a battery storage to compensate the fluctuation of PV infeed and to provide thermal energy in order to meet a certain heat demand. The most important findings are briefly listed below:

Replacing a battery storage with a CHP and a thermal storage: The replacement of battery storages with a CHP and a combined thermal storage to compensate the fluctuation of renewable energy sources like photovoltaic or wind power is possible. The result which CHP type and technology is the best depends on two aspects, either the most economic variant or the energetically best variant. While the combustion engine CHP provides the most economic solution for all three different load profiles the fuel cell CHP provides the energetically best variant when it is operated to meet load profile 2 and the excess PV power is used to generate heat. In this case the whole produced energy, not considering the system losses, is used, neither PV power gets curtailed nor has the system to emit waste heat to the atmosphere.
Even in the case of not exporting power to the grid in case of high PV and/or CHP power production and instead of exporting curtailing the excess power and emitting heat to the atmosphere, replacing the battery storage with a CHP-thermal storage combination is still more economic than using a battery storage. Though, the heat to power ratio, as one of the most important parameters of the CHP, has to match the heat to power ratio of the load profile, or at least, be as equal as possible to provide a energetically and economic useful replacement of the battery storage. Whereas for example the fuel cell CHP with a heat to power ratio below 1 provides a more economic solution for college and lodging buildings the gas turbine CHP with a heat to power ratio above 1.5 provide a more economic solution for health care building applications due to the higher heat demand in that type of buildings.
Due to the lower load profiles for both, heat and power, the operating hours and the time of the year when the CHP's, no matter what type, are operated is mostly in winter, especially in case of using the excess power from the PV to generate heat. The use of the excess PV power to generate heat instead of curtailing it is a proper way to improve the whole system in two ways. On the one hand it can help to improve the energy balance when the

produced heat can be used for heating applications or send to the thermal storage and on the other hand it improves the economic performance of the whole system because the generated heat is produced in a cheaper way than it would be by burning gas or starting the CHP just to produce heat.

Impact of uncertainties in the PV forecast:
The impact of using the forecast data instead of the real PV profile for all future timesteps first of all effects the usage of the gas burner and the waste heat which has to be emitted to the atmosphere. Due to the, compared to the load profile, high power which is provided by the PV, the impact on the electrical part of the framework is negligible. The effects on the thermal part of the framework on the other hand are first of all effects on the usage of the gas burner and the waste heat of the system. Due to the high PV power the PV profile is most of the time higher than the load profile when the PV is operating. The forecast data is also higher than the load profile which leads to a similar behavior for every test case, no matter the quality of the forecast data. For the thermal part of the framework the impact is higher because of the usage of the excess PV power to generate heat. A worse quality of the forecast, especially if the forecast is lower than the real profile, leads to a higher production of the gas burner although enough heat could be produced by the PV. Improving the quality of the forecast data by limiting the possible values for the PV production with a confidence interval leads to an improvement of the gas burner usage and a decreasing amount of waste heat. This leads to lower operating costs and a more economic performance of the whole system.

5.2 Outlook

Based on the presented results and findings this thesis offers a lot of interesting research opportunities for further projects. The most interesting are briefly cited below:

Combined PV/solar facilities: Investigating on the performance of the a system like the one elaborated in this thesis combined with a solar thermal facility to produce heat directly from the sun providing a higher efficiency.

New storage technologies could provide a cheaper solution than battery storages are. Investigating the impact of replacing the battery storage with a H_2 - storage and producing H_2 with the excess power from the PV and using it as fuel for the fuel cell.

Grid stability and viability: Elaborating how the given framework could be used for grid stabilization.

Improving the MPC controller: Finding and implementing new MPC strategies to handle forecast errors not only in the PV forecast but in the load profile data as well. Developing a robust MPC to deal with unexpected incidents like line errors load shedding.

Appendix A

Comparison of different complexities

A.1 Gas Turbine

Variable	Costs	Simple model [CHF]	Standard model [CHF]	Complex model [CHF]
$C_{el}^{grid, in} - C_{el}^{grid, out}$	Energy costs	4′091	3′651	3′467
$C_{el}^{PV,curt}$	Curtailment costs	21′597	21′640	21′640
$C_{el}^{lin,deg}$	Lin. Degradation costs	318	380	372
$C_{el}^{quad,deg}$	Qu. Degradation costs	341	415	400
C_{el}^{chp}	El. Power Gen. costs	8′668	8′759	8′909
C_{th}^{stor}	Heat Storage costs	0	351	259
$C_{th}^{chp} + C_{th}^{gas}$	Heat Gen. costs	2′813	7′378	7′659
C^{pen}	Penalty costs	0	0	0
$\sum C$	Overall operating costs	37′828	42′583	42′706

Table A.1: Operating costs for Gas Turbine Model

A.2 Fuel Cell

Variable	Costs	Simple model [CHF]	Standard model [CHF]	Complex model [CHF]
$C_{el}^{grid, in} - C_{el}^{grid, out}$	Energy costs	−1′555	−1′362	−1′377
C_{curt}^{pv}	Curtailment costs	21′605	21′607	21′607
$C_{lin, degr}^{batt}$	Linear degration costs	302	302	302
$C_{qua, degr}^{batt}$	Quadratic degration costs	312	314	314
C_{el}^{chp}	El. Power Gen. costs	12′092	11′959	11′972
C_{th}^{stor}	Heat Storage costs	0	176	176
$C_{th}^{chp} + C_{th}^{gas}$	Heat Gen. costs	8′198	8′270	8′258
C^{pen}	Penalty costs	0	0	0
$\sum C$	Overall operating costs	40′954	41′266	41′252

Table A.2: Operating costs for Fuel Cell Model

Appendix B

Heat to Power ratios of various load profiles

Figures B.1 to B.4 show all heat to power ratios for the investigated load profiles for every timestep.

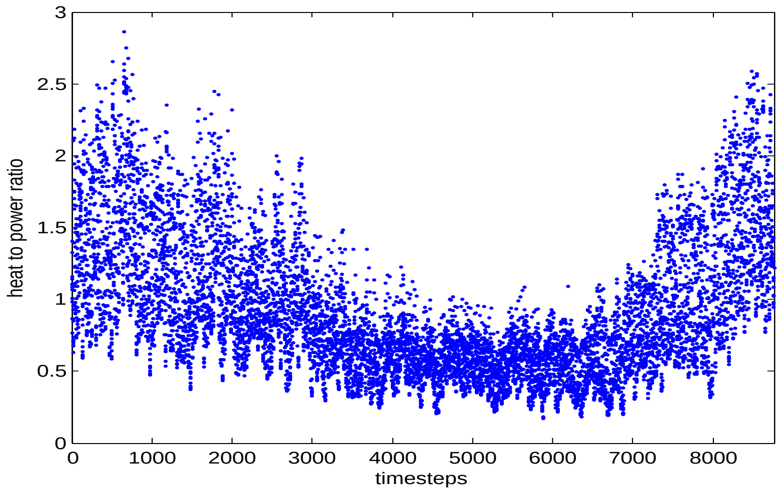

Figure B.1: Heat to power ratios for every timestep for College buildings

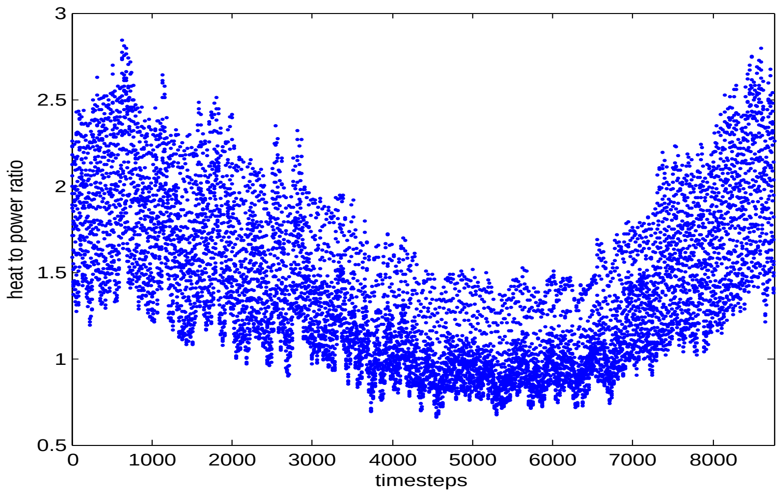

Figure B.2: Heat to power ratios for every timestep for Health care buildings

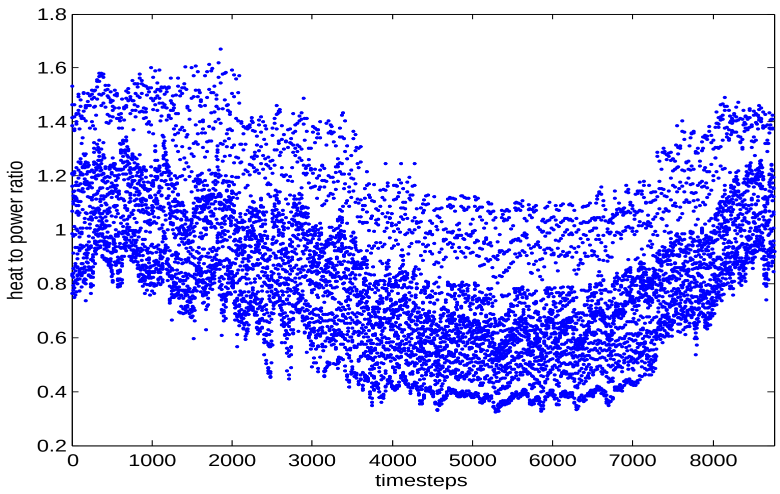

Figure B.3: Heat to power ratios for every timestep for Lodging buildings and hotels

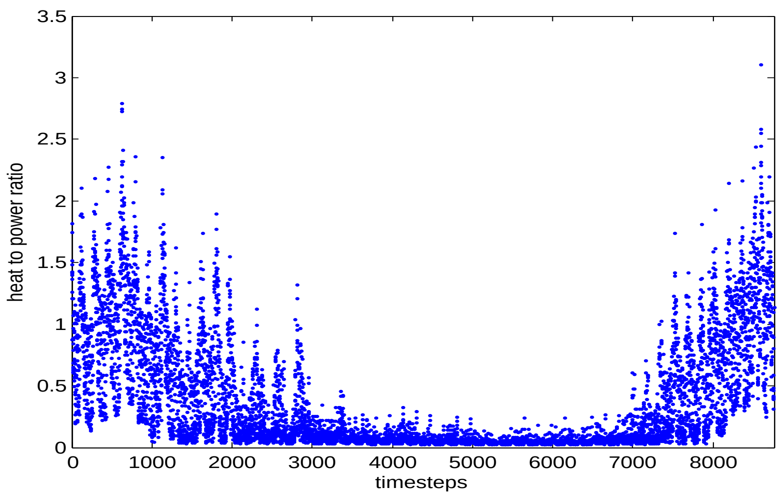

Figure B.4: Heat to power ratios for every timestep for warehouses

Figures B.5 to B.8 show the frequencies of the different heat to power ratios for the different load profiles. The choosen load profiles for Colleges, Health care buildings and Lodging buildings show a high density of heat to power ratios for the single timesteps around 1, whereas all the other profiles show heat to power ratios with the highest densities below 1 and are not useful for further considerations in this work.

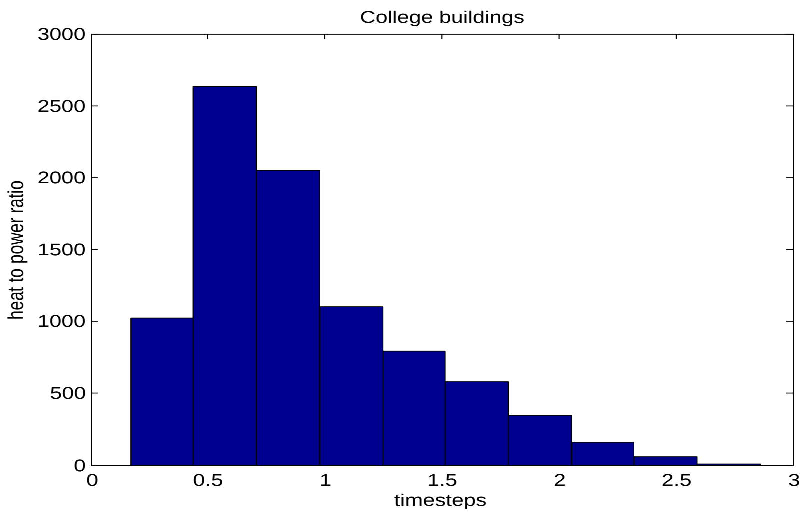

Figure B.5: Frequency of heat to power ratios for Colleges

Figure B.6: Frequency of heat to power ratios for Health care buildings

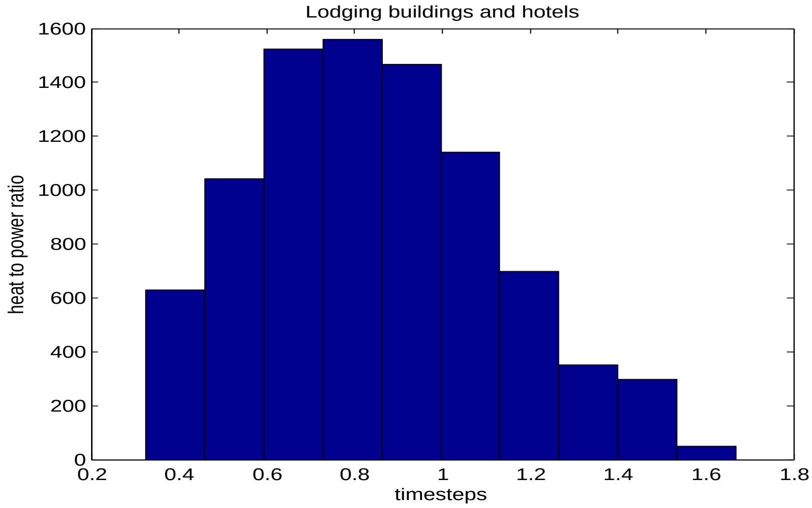

Figure B.7: Frequency of heat to power ratios for Lodging buildings and hotels

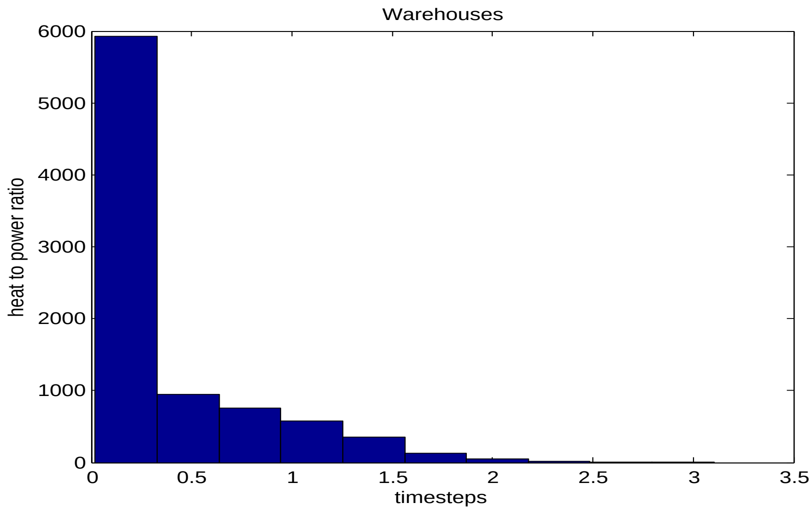

Figure B.8: Frequency of heat to power ratios for Warehouses

Appendix C

Detailed Results

	Base Case			**PV to heat**		
	College	Health Care	Lodging	College	Health Care	Lodging
Energy costs	30'695	200'816	225'300	40'446	228'737	240'418
Curtailment costs	1'206	730	879	0	0	0
Lin. Deg. costs	13'163	13'046	13'509	11'324	4'653	9'701
Quad.Deg. costs	4'443	4'525	4'662	3'855	1'607	3'461
Pwr. gen. costs	0	0	0	0	0	0
Heat storage costs	0	0	0	0	0	0
Heat gen. costs	225'554	559'594	357'432	163'795	456'565	271'054
Penalty costs	0	15'562	0	0	6'610	0
∑costs	**275'062**	**794'276**	**601'784**	**219'422**	**698'174**	**524'636**

	CE CHP			**CE CHP/PV to heat**		
	College	Health Care	Lodging	College	Health Care	Lodging
Energy costs	-150'568	-186'060	-129'014	-61'995	-176'710	-58'968
Curtailment costs	1'745	1'209	1'376	0	0	0
Lin. Deg. costs	0	0	0	0	0	0
Quad.Deg. costs	0	0	0	0	0	0
Pwr. gen. costs	137'932	239'583	206'600	73'826	260'944	158'205
Heat storage costs	12'039	3'879	12'914	12'049	7'512	12'965
Heat gen. costs	37'514	248'453	93'069	8'845	44'062	18'875
Penalty costs	0	0	0	0	0	0
∑costs	**38'667**	**307'066**	**184,951**	**32'737**	**135'809**	**131'082**

Table C.1: Breakdown of costs for Base Case, PV to heat, CE CHP and CE CHP/PV to heat

	GT CHP			GT CHP/PV to heat		
	College	Health Care	Lodging	College	Health Care	Lodging
Energy costs	-28’481	-84’576	29’325	939	-68’093	78’697
Curtailment costs	1’330	875	1’023	0	0	0
Lin. Deg. costs	0	0	0	0	0	0
Quad.Deg. costs	0	0	0	0	0	0
Pwr. gen. costs	61’658	257’697	160’524	42’994	251’367	125’912
Heat storage costs	7’503	22’969	16’151	14’077	23’592	17’561
Heat gen. costs	149’455	214’452	176’058	57’555	112’411	97’444
Penalty costs	0	0	0	0	0	0
∑costs	**191’491**	**411’431**	**383’101**	**115’586**	**319’281**	**319’627**

	FC CHP			FC CHP/PV to heat		
	College	Health Care	Lodging	College	Health Care	Lodging
Energy costs	-37’558	-6’254	5’167	-70’435	-38’705	-18’063
Curtailment costs	1’327	851	1’003	0	0	0
Lin. Deg. costs	0	0	0	0	0	0
Quad.Deg. costs	0	0	0	0	0	0
Pwr. gen. costs	57’975	149’305	157’646	82’221	173’964	170’342
Heat storage costs	2’305	220	1’933	10’953	1’440	7’799
Heat gen. costs	167’913	447’659	237’395	37’142	307’910	99’472
Penalty costs	0	0	0	0	0	0
∑costs	**191’983**	**591’795**	**403’164**	**59’895**	**444’610**	**259’554**

Table C.2: Breakdown of costs for GT CHP, GT CHP/PV to heat, FC CHP and FC CHP/PV to heat

Base Case						
	College		Health Care		Lodging	
	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]
PV	3'362	164.31	3'362	95.90	3'362	96.97
Grid Import	908	44.42	1'739	49.62	1'886	54.42
Grid Export	-994	-48.62	-841	-24.01	-878	-25.34
Battery Discharge	97	4.79	99	2.77	100	2.90
Battery Charge	-121	-5.93	-120	-3.43	-124	-3.59
Curtailment	-1'206	-58.97	-730	-20.85	-879	-25.36
Load	**2'046**	**100.00**	**3'506**	**100.00**	**3'467**	**100.00**
Gas Burner	1'879	107.61	4'663	100.00	2'978	100.81
Waste Heat	132	-7.61	0	0.00	24	-0.81
Thermal Load	**1'747**	**100.00**	**4'663**	**100.00**	**2'954**	**100.00**

Table C.3: Energy balance of Base Case

CE CHP						
	College		Health Care		Lodging	
	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]
PV	3'362	164.31	3'362	95.90	3'362	96.97
Grid Import	94	4.63	0	0	45	1.32
Grid Export	-1'309	-63.99	-1'502	-42.84	-1'026	-29.60
Battery Discharge	0	0	0	0	0	0
Battery Charge	0	0	0	0	0	0
Curtailment	-1'745	-85.29	-1'209	-34.50	-1'377	-39.70
CHP	1'644	80.34	2'856	81.44	2'463	71.01
Load	**2'046**	**100.00**	**3'506**	**100.00**	**3'467**	**100.00**
Gas Burner	175	10.05	1'833	39.29	570	19.31
CHP	1'644	94.11	2'856	61.23	2'462	83.37
Waste Heat	-1	-0.07	0	0	-3	-0.09
Th.Stor. Charge	-637	-36.52	-206	-4.42	-683	-23.15
Th.Stor. Discharge	566	32.41	181	3.90	607	20.47
Thermal Load	**1'747**	**100.00**	**4'663**	**100.00**	**2'954**	**100.00**

Table C.4: Energy balance of CE CHP case

GT CHP						
	College		Health Care		Lodging	
	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]
PV	3'362	164.31	3'362	95.90	3'362	96.97
Grid Import	780	38.14	678	19.35	1'114	32.13
Grid Export	-1'195	-58.41	-1'451	-41.40	-1'104	-31.83
Battery Discharge	0	0	0	0	0	0
Battery Charge	0	0	0	0	0	0
Curtailment	-1'330	-65.04	-869	-24.79	-1'016	-29.30
CHP	429	21.00	1'786	50.94	1'111	32.05
Load	**2'046**	**100.00**	**3'506**	**100.00**	**3'467**	**100.00**
Gas Burner	1'174	67.21	1'480	31.75	1'277	43.22
CHP	859	49.20	3'753	76.61	2'222	75.24
Waste Heat	-242	-13.87	-265	-5.69	-456	-15.45
Th.Stor. Charge	-397	-22.75	-1'205	-25.84	-846	-28.66
Th.Stor. Discharge	353	20.21	1'080	23.17	757	25.65
Thermal Load	**1'747**	**100.00**	**4'663**	**100.00**	**2'954**	**100.00**

Table C.5: Energy balance of GT CHP case

FC CHP						
	College		Health Care		Lodging	
	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]
PV	3'362	164.31	3'362	95.90	3'362	96.97
Grid Import	656	32.06	807	23.02	896	25.85
Grid Export	-1'062	-51.88	-887	-25.31	-922	-26.61
Battery Discharge	0	0	0	0	0	0
Battery Charge	0	0	0	0	0	0
Curtailment	-1'328	-64.89	-851	-24.27	-1'004	-28.94
CHP	417	20.40	1'075	30.66	1'135	32.73
Load	**2'046**	**100.00**	**3'506**	**100.00**	**3'467**	**100.00**
Gas Burner	1'366	78.22	3'645	78.17	1'888	63.93
CHP	396	22.70	1'021	21.90	1'078	36.50
Waste Heat	0	0	0	0	0	0
Th.Stor. Charge	-123	-7.06	-12	-0.27	-103	-3.49
Th.Stor. Discharge	107	6.14	9	0.20	90	3.06
Thermal Load	**1'747**	**100.00**	**4'663**	**100.00**	**2'954**	**100.00**

Table C.6: Energy balance of FC CHP case

PV to heat						
	College		Health Care		Lodging	
	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]
PV	3'362	164.31	3'362	95.90	3'362	96.97
Grid Import	924	45.18	1'804	51.46	1'917	55.28
Grid Export	-941	-46.01	-719	-20.51	-800	-23.09
Battery Discharge	84	4.12	34	0.98	72	2.08
Battery Charge	-104	-5.11	-43	-1.23	-89	-2.58
Curtailment	0	0	0	0	0	0
PV to heat	-1'215	-62.49	-932	-26.60	-993	-28.66
Load	**2'046**	**100.00**	**3'506**	**100.00**	**3'467**	**100.00**
Gas Burner	1'365	78.15	3'805	81.59	2'259	76.47
Waste Heat	-833	-47.70	-27	-0.59	-249	-8.43
PV heat	1'215	69.55	886	19.00	944	31.96
Thermal Load	**1'747**	**100.00**	**4'663**	**100.00**	**2'954**	**100.00**

Table C.7: Energy balance of PV to heat case

CE CHP/PV to heat						
	College		Health Care		Lodging	
	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]
PV	3'362	164.31	3'362	95.90	3'362	96.97
Grid Import	429	20.97	2	0.07	289	8.34
Grid Export	-1'337	-65.34	-2'105	-60.05	-1'215	-35.03
Battery Discharge	0	0	0	0	0	0
Battery Charge	0	0	0	0	0	0
Curtailment	0	0	0	0	0	0
CHP	933	45.62	3'492	99.60	2'074	59.81
PV to heat	-1'342	-65.56	-1'246	-35.52	-1'043	-30.09
Load	**2'046**	**100.00**	**3'506**	**100.00**	**3'467**	**100.00**
Gas Burner	<1	0.01	26	0.57	1	0.02
CHP	933	53.45	3'492	74.89	2'074	70.21
Waste Heat	-386	-22.15	0	0	-39	-1.32
Th.Stor. Charge	-669	-38.30	-327	-7.02	-651	-22.07
Th.Stor. Discharge	594	34.01	288	6.18	579	19.59
PV heat	1'275	72.98	1'183	25.38	991	33.57
Thermal Load	**1'747**	**100.00**	**4'663**	**100.00**	**2'954**	**100.00**

Table C.8: Energy balance of CE CHP/PV to heat case

GT CHP/PV to heat						
	College		Health Care		Lodging	
	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]
PV	3'362	164.31	3'362	95.90	3'362	96.97
Grid Import	850	41.57	697	19.90	1'284	37.02
Grid Export	-1'102	-53.85	-1'332	-37.98	-972	-28.02
Battery Discharge	0	0	0	0	0	0
Battery Charge	0	0	0	0	0	0
Curtailment	0	0	0	0	0	0
CHP	299	14.64	1'752	49.96	877	25.30
PV to heat	-1'364	-66.67	-974	-27.78	-1'084	-31.27
Load	**2'046**	**100.00**	**3'506**	**100.00**	**3'467**	**100.00**
Gas Burner	429	24.60	644	13.83	666	22.54
CHP	599	34.31	3'503	75.13	1'755	59.41
Waste Heat	-498	-28.51	-281	-6.03	-400	-13.53
Th.Stor. Charge	-744	-42.60	-1'244	-26.68	-927	-31.37
Th.Stor. Discharge	664	38.00	1'115	23.91	830	28.08
PV heat	1'296	74.20	928	19.84	1'030	34.87
Thermal Load	**1'747**	**100.00**	**4'663**	**100.00**	**2'954**	**100.00**

Table C.9: Energy balance of GT CHP/PV to heat case

FC CHP/PV to heat						
	College		Health Care		Lodging	
	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]	Energy [MWh]	Percentage [%]
PV	3'362	164.31	3'362	95.90	3'362	96.97
Grid Import	526	25.72	660	18.82	766	22.10
Grid Export	-1'123	-54.89	-884	-25.21	-902	-26.02
Battery Discharge	0	0	0	0	0	0
Battery Charge	0	0	0	0	0	0
Curtailment	0	0	0	0	0	0
CHP	638	31.17	1'350	38.49	1'322	38.11
PV to heat	-1'357	-66.31	-982	-28.00	-1'080	-31.16
Load	**2'046**	**100.00**	**3'506**	**100.00**	**3'467**	**100.00**
Gas Burner	259	14.83	2'459	52.73	724	24.52
CHP	606	34.69	1'282	27.49	1'255	42.51
Waste Heat	-342	-19.59	0	0.00	-6	-0.21
Th.Stor. Charge	-580	-33.23	-77	-1.65	-413	-13.99
Th.Stor. Discharge	515	29.48	67	1.43	367	12.42
PV heat	1'289	73.82	932	20.00	1'027	34.75
Thermal Load	**1'747**	**100.00**	**4'663**	**100.00**	**2'954**	**100.00**

Table C.10: Energy balance of FC CHP/PV to heat case

Appendix D

Constraint Parameter Set

Constraint Parameter Set			
$E_{\mathrm{el}}^{\mathrm{cap}}$	energy capacity of the battery storage	700	[kWh]
$E_{\mathrm{th}}^{\mathrm{cap}}$	energy capacity of the thermal storage	2000	[kWh]
N	MPC horizon length	120	[-]
$P_{\mathrm{el}}^{\mathrm{cap}}$	power capacity of the battery storage	250	[kW]
$P_{\mathrm{th}}^{\mathrm{cap}}$	power available from the thermal storage	1000	[kWh]
P_{n}	nominal total power of the CHP	2000	[kW]
$P_{\mathrm{gas}}^{\mathrm{max}}$	maximum thermal power of the gas burner	1500	[kW]
$P_{\mathrm{gas}}^{\mathrm{min}}$	minimum thermal power of the gas burner	150	[kW]
$P_{\mathrm{grid}}^{\mathrm{out,max}}$	maximum grid export	350	[kW]
$P_{\mathrm{grid}}^{\mathrm{in,max}}$	maximum grid consumption	700	[kW]
Δt	timestep duration	1	[h]
$\eta_{\mathrm{th}}^{\mathrm{c}}$	Charge efficiency of the thermal storage unit	0.95	[-]
$\eta_{\mathrm{th}}^{\mathrm{d}}$	discharge efficiency of the thermal storage unit	0.95	[-]
$\eta_{\mathrm{el}}^{\mathrm{c}}$	charge efficiency of the storage unit	0.9	[-]
$\eta_{\mathrm{el}}^{\mathrm{d}}$	discharge efficiency of the storage unit	0.9	[-]
$\eta_{\mathrm{e/th}}$	PV to heat efficiency	0.95	[-]
$1 - \eta^{\mathrm{sd,th}}$	self discharge per timestep of thermal storage	0.999	[-]

Combustion Engine CHP			
$P_{\mathrm{el}}^{\mathrm{min}}$	minimum power of the CE CHP	800	[kW]
r^{chp}	ramping ability of CE CHP	2000	[kW/h]
$T^{\mathrm{min,on}}$	minimum on-time of CE CHP	2	[h]
$T^{\mathrm{min,off}}$	minimum off-time of CE CHP	2	[h]
h	heat to power ratio of CE CHP	1	[-]

Gas Turbine CHP			
$P_{\mathrm{el}}^{\mathrm{min}}$	minimum power of the GT CHP	1500	[kW]
r^{chp}	ramping ability of GT CHP	1800	[kW/h]
$T^{\mathrm{min,on}}$	minimum on-time of GT CHP	5	[h]
$T^{\mathrm{min,off}}$	minimum off-time of GT CHP	3	[h]
h	heat to power ratio of GT CHP	2	[-]

Fuel Cell CHP			
$P_{\mathrm{el}}^{\mathrm{min}}$	minimum power of the FC CHP	600	[kW]
r^{chp}	ramping ability of FC CHP	600	[kW/h]
$T^{\mathrm{min,on}}$	minimum on-time of FC CHP	2	[h]
$T^{\mathrm{min,off}}$	minimum off-time of FC CHP	7	[h]
h	heat to power ratio of FC CHP	0.95	[-]

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