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E.ON Energy Research Center
EBC | Institute for Energy Efficient Buildings and Indoor Climate

Bachelor thesis

Energy system optimization of urban districts

An analysis of energy computer tools with a focus on modeling combined heat and power plants, heat pumps and thermal storages

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Alexander Sichwart

Matriculation number: 293684

supervised by:
Dipl.-Ing. Jan Schiefelbein
Dipl.-Ing. Christoph Molitor
Prof. Dr.-Ing. Dirk Müller

RWTH Aachen University
E.ON Energy Research Center
Institute for Energy Efficient Buildings and Indoor Climate
Mathieustraße 10, Germany-52074 Aachen

Abstract

This thesis elaborates on the explanation, comparison and application of two energy computer tools, namely EnergyPLAN and COMPOSE. The tools are applied to one energy system that represents an urban district heating network with electricity and heat demands. Corresponding to the topic of distributed generation, the supplying devices of the system are chosen to be a combined heat and power plant, a heat pump and a heat storage. One objective is to investigate the potential of the system to balance incoming intermittent electricity and demands. Another objective is to improve the planning of the system regarding the capacities of the devices.

An important part of this thesis is the analysis of the calculation of the models. The technical optimizations of the defined energy system are explained and evaluated in detail. Finally, the gained information is used to discuss the possible applications for each tool.

Contents

Nomenclature

Symbols and units

Symbol	Meaning	Unit
C	total costs	€
COP	HP thermal efficiency	-
c	specific costs	€/kWh
D	annual demand	kWh
d	hourly demand	kWh
e	electricity production	kWh
e_{HP}	heat pump electricity consumption	kWh
f	fuel consumption	kWh
$f_{CHP,heatbalance}$	CHP fuel consumption for meeting the heat demand	kWh
P	electricity capacity	kW
$Prod$	annual production	kWh
p	hourly production	kWh
$\dot{Q}$	heat capacity	kW
q	hourly heat production	kWh

Greek symbols

Symbol	Meaning	Unit
∂	hourly value of a distribution profile	-
Δ_e	change of electricity production	kWh
$\Delta_{e,HP}$	change of HP electricity consumption	kWh
Δ_q	change of heat production	kWh
μ_{el}	CHP electric efficiency	-
μ_{th}	CHP thermal efficiency	-

Indexes and Abbreviations

Symbol	Meaning
A	route A
B	route B
B,1	first part of route B
B,2	second part of route B
bal	balance
CHP	combined heat and power plant
el	electricity
el.grid	import from electricity grid
exp	export
HP	heat pump
imp	import
int	internal
max	maximal
q	heat
RES	renewable Energy Source
s	storage
I	regulation strategy I
II	regulation strategy II

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1 Introduction

Germany has defined very ambitious goals concerning its energy system. After the incident of Fukushima, the perspective on nuclear energy has changed. As a result the government decided to expand renewable energies. Wind energy has become the most powerful of the renewables with a total power input of 50,67TWh for Germany in 2012[1]. Additionally, the share of power from photovoltaic has increased. For 2012 the total power input amounts 26,13TWh[1]. Besides other technologies, especially electricity from wind and photovoltaic cause electricity disbalance. Therefore, the challenge of growing renewables is to stabilize the electricity grid by reducing surpluses and shortages of electricity.

One aspect that needs to be considered is the development of the decentralized energy systems. Regarding distributed generation for domestic buildings the thermal connection of multiple buildings is of advantage. District heating networks ensure higher thermal and electrical loads. This allows for more efficient devices. Furthermore, each building can save space because it does only require a connection to the supplying central devices rather than own devices for the heat production. On the one hand, these devices need to reduce electricity shortages. For instance, Combined Heat and Power plants are very common facilities for the local energy production. On the other hand, the electricity excess has to be decreased. Heat Pumps can serve as flexible and very efficient power consumers.

Therefore, the combination of the characteristics of CHPs and HPs can have a stabilizing effect on the electricity grid. Due to the fact that the demand of electricity does not coincide with surpluses or shortages of the grid, there is a need of energy storage systems. Heat storages are appropriate for an energy system consisting of CHP and HP because both produce heat. The cheapest heat storage type is the hot water tank and is ,therefore, considered in this thesis.

Provided that the energy system comprises only the three technologies, a hot water tank enables the system to reach a higher level of flexibility in order to balance the electricity grid. Theoretically, a thermal storage system allows the CHP to produce electricity when there is an elecricity scarcity even if there is no need for heat in the building. The heat can than be stored in order to be used afterwards for serving the heat demand. In the best case scenario the storage can deliver heat whenever the operation of neither CHP nor HP is optimal.

The last section reveals the complexity that has to be dealt with by using CHPs, HPs and hot water tanks in an energy system based on heat and electricity. Regarding planning and improvement of energy systems, energy computer tools can be very helpful. These tools are able to calculate an energy system and therefore reveal the impact of certain facilities and decisions on the system and costs. From the many different tools available I am focusing on two of those that are able to model the three mentioned facilities and to calculate their operation on an hourly basis. In fact, these tools are COMPOSE[2] and EnergyPLAN[3].

The objective of my thesis is to investigate how the computer tools work and which weaknesses and strengths they have regarding their ability of modeling in a technically optimized operation mode. I seek to indicate the readers, who are working with CHPs and HPs, if they can benefit from using the tools for their purposes. One possible purpose can be realtime simulations that require specifications of the capacities of the facilities. A short analysis of the energy system on an hourly basis enables the user to infer information from the calculated operation of CHPs and HPs. Accordingly, the information is gained by using a bottom-up approach. With the help of the results of the analysis the user can draw conclusions in order to improve the set up of the realtime simulation.

2 Models and Tools

Models are simplified representations of processes and systems that exist in reality. They are mostly used in order to facilitate the understanding of processes including numerous interdependencies. While the input data for models are reduced, compared to the influences that have to be dealt with in reality, the results can still be of high value. Especially regarding real experiments, simulations with models offer many advantages. Experiments are often very expensive. Therefore, experiments in reality are often substituted by analyses of models or if they are necessary they are made in addition to the modeling. In special cases e.g. for the purpose of forecasting modeling is inevitable. Compared to mental models and experiments, R.B. Hiremath et al.[4] states advantages besides the aspect of complexity that the human brain is limited to deal with. The computational models are explicit i.e. their assumptions are transparent and accessible. Also the logical results of an assumption can be identified. Thus, irrational conclusions on underlying assumptions can be avoided.

The complexity of energy systems evoke the need of modeling. As a result, energy computer models have become very numerous. Furthermore, the first models have been developed very early. Jebaraj and Iniyan[5] show that the energy models exist longer than 3 decades. Their paper defines 6 main types of energy models: energy planning models, energy supply-demand models, forecasting models, optimization models, energy models based on neural networks and emission reduction models. This differentiation is also supported by Mashayekhi et al.[6].

Especially, energy systems seeking to integrate renewable energies need to be modeled because of their high complexity. The urgency of integrating renewables today has made numerous tools available. Connolly et al.[7] show that at least 68 of these computer tools exist today. But there are many more which were not considered. Their review of tools provides an overview and helps to find the appropriate tool for each application. Often models are programed and developed manually in order to fit the individual requirements. Therefore, the number ob models is increasing. The belief of the review is that the numerous tools offer enough variety that they can be used for many purposes. Finding a suitable model saves a lot of time and effort. The search for a suitable tool is made easy by the review categorization. This is necessary because of the wide range of different capabilities and objectives of the models. The categorization made by Connolly et al.[7] comprises many aspects. The following just mention a few of them: type of tool(e.g. simulation/top-down/bottom-up/operation or investment optimization), energy sectors considered(electricity/heat/transport), type of analysis(e.g. Geographical area/Scenario time frame/time step).

From the numerous available tools that concern the integration of renewable energy and distributed generation, a few are mentioned in the following. HOMER[8], for instance, offers very powerful optimization and sensitivity analyses for different technologies. It can calculate a large range of different inputs like the capacity of a facility and finds the optimal solution itself. The model is also able to reduce the time step of calculation up to minutes. Unfortunately, it can not be used for whole energy systems, especially not if the heat sector needs to be considered. Homer focuses on the electricity sector. The same does the tool H2RES[9], which focuses on the electricity sector of energy systems that are not connected to the grid. Thus, it is used for energy island systems.

In addition, there are also excel-based tools like RETSCREEN[10]. It is an energy project analysis tool that helps to evaluate the technical and financial viability of potential renewable energy, energy efficiency and cogeneration projects. The tool is one of the most often used tools with more than 200.000 downloads. Previously RETScreen has been used to assess the feasibility of wind farm development in Algeria [11] and the viability of solar photovoltaic in Egypt[12].

Furthermore, the energy model BALMOREL[13] exists, which puts the focus on the electricity and the combined heat and power sectors on the international level. However, the model and its open source code as well as project generated information, including all details, can be freely accessed. Thus, the model can be modified in order to make it useful for specific purposes. The model is formulated in the modelling language of GAMS[14]. The model has been used for the assessment of the influence of heat pumps on the integration of wind power[15].

Finally, there is the modeling software package energyPRO[16], which consists of multiple parts that can be used seperately but all of them have to be purchased. The model energyPRO is able to optimize an energy system in the electricity and heat sectors. It puts the focus on cogeneration plants and is thus often used for district heating cogenerators with gas engines combined with boilers and thermal storage. The model is characterized by its detailed analysis of devices. It performs the calculation using a 1 minute time step and takes very detailed settings into account as ambient temperatures, solar gain or wind chill. Furthermore different plant operating strategies and financial data can be chosen.

3 Operational modeling in general

This thesis focuses on the operational optimization of an energy system. In terms of operational modeling, the processes are simplified by ignoring the system dynamics of the regulation of processes. Modeling the operation means to neglect the temporal delay of reactions of processes. The picture and the following example help to illustrate this simplification. If the demand rises from one hour to another, the supplying device produces the required energy right away without any delay. Usually the regulation of the device would look like the curve on figure 3.1.

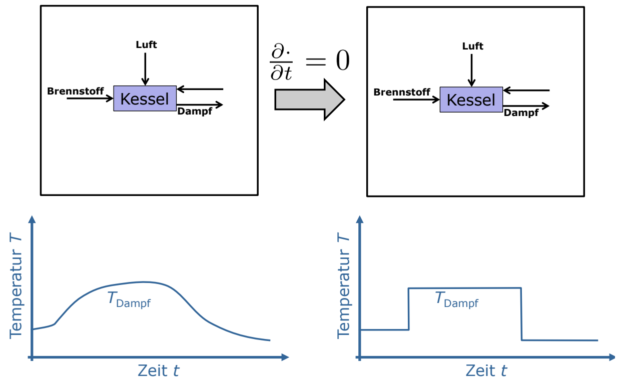

Figure 3.1: Disregard of system dynamics [Reference:[17] Institute of Technical Thermodynamics of RWTH Aachen University. Lecture of Energy Systems Engineering, 2 (2013), p. 32]

Furthermore, it is necessary to understand what the user can expect from modeling the operation of devices. In order to explain the capabilities of these tools regarding the planning of CHPs and HPs, 3 general aspects need to be considered, which are listed below and illustrated by figure 3.2.

- ▷ distribution level

  numer and placement of facilities in a system

- ▷ dimensioning level

  sizing each facility according to capacity

- ▷ operating level

  choosing an operating mode

The tools perform on the operating level. This is the lowest level because it requires information from all the levels above. Accordingly, the operation is dependent on the capacities, their respective efficiencies and the number of the devices chosen for the energy system. The demands are the

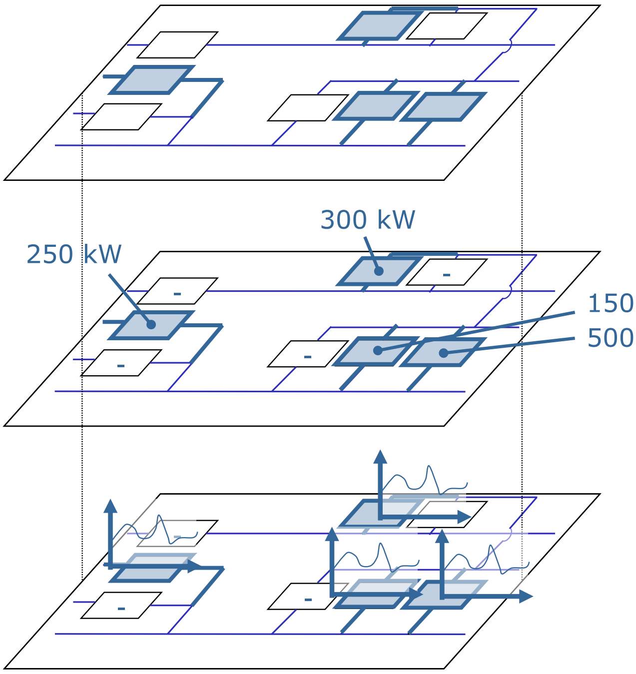

Figure 3.2: Levels for planning the devices of an energy system [Reference:[17] Institute of Technical Thermodynamics of RWTH Aachen University. Lecture of Energy Systems Engineering, 2 (2013), p. 28]

main characteristics of an energy system, but in this case the focus is put on the processes. As a result, the tools aim to optimize the operation of the devices with a certain input(e.g. fix capacity) that the user is providing. The following list shows in which ways energy supplying devices can be optimized:

1. optimize distribution, capacities and operation mode
2. optimize capacities and operation mode
3. optimize operating mode

The list illustrates the dependency of the operation on the information that it requires. It is, therefore, unfeasible to optimize the operation without the information of the upper levels. Thus, the models are not able to tell the user which capacity and number of devices is optimal. Instead, the models show the results of each input. Hence, the user needs several inputs to be analyzed in order to start a comparison of different results. Based on the results, the user is able to identify the best of his or her inputs manually. This way of finding the optimal size of the devices is called bottom up approach.

4 Tools considered for this thesis

This thesis considers two Danish tools, namely EnergyPLAN and COMPOSE. The tools have different strengths and focuses. There are two main reasons for choosing these tools. Firstly, it is their ability to optimize on the operational level as described above. Both are optimization tools that are able to calculate the operation of processes by calculating hourly values in accordance to a specific operational strategy.

Secondly, it is the ability of the two tools to design the energy system that is selected for this thesis. The energy system is mainly characterized by its demands for heat and electricity, which are supplied by a cogenerator, an HP and a heat storage. The two demands and the interdependency of heat and electricity within the CHP and HP necessitate the models to consider both heat and electricity simultaneously. Furthermore, the system's main electricity supply is renewable energy. Due to the intermittent character of RES and also of the demands, a short time step of 1 hour for the calculation is required.

Referring to the categorization mentioned in the introduction, the two tools belong to the same category, namely deterministic input output models. Hence, each input determines a specific output. There are no changes in the results if an analysis with the same input is repeated.

The input of the tools is the user defined energy system including demands, facilities and costs. In detail, the user can define single values (e.g. capacities, annual demand) but also hourly values covering 1 year (e.g. temporal distribution of demand, wind speed data).

The output are mainly hourly values. According to the hour by hour operation each producing device as well as fuel consumptions, import and export of heat or electricity embody specific values for each hour. Furthermore, the tools offer single values like annual values or values regarding costs, emissions or fuel consumptions.

One main difference between the two models is that EnergyPLAN is supposed to assist energy system planning on the national and regional level. The model offers many settings for the energy system regarding the stabilization of the grid. As a result of the large scale objective, it consists of many technologies. These are predefined and thus provide the user only little scope of design. Contrary, COMPOSE offers more flexibility regarding the design of technologies and whole energy systems. Moreover, it is also useful for very small energy systems e.g. districts or even smart houses.

As opposed to EnergyPLAN, COMPOSE does not offer a strict technical optimization. A technical optimization in this case means a calculation of the operational values that disregards costs.

COMPOSE rather describes itself as a techno-economic optimization model[18]. It does not require costs for the calculation but certain operational strategies can only be designed by implementing appropriate costs. A detailed analysis of COMPOSE from the technical perspective is thus worthwhile. The question is if the tool achieves technically optimal results when it is used and told to calculate in a technically smart way. However, a technically optimal operation always depends on the design of the energy system as it . Decisive for an optimal operational strategy is if a system has access to the electricity grid and if any external heat supply is available. Particularly in the case of the reference energy system a technically smart operation means not to overproduce heat or cause heat deficits due to the thermal encapsulation of the system. If the models enable to modify the operational strategies according to specific energy systems is aimed to be answered by an investigation of the model's calculations. Concerning COMPOSE, one part of the answer will be how precisely the costs have to be defined in order to achieve the desired technical optimization. Moreover, the comparison of the tools is very interesting because of the different methodologies. The question formulated for COMPOSE does also count for EnergyPLAN, namely how it performs the technical optimization and if the resulting operation mode can really be described as optimal from the technical perspective.

5 Energy system

This chapter is dealing with the energy system that the two tools are supposed to model for this thesis. Aside from the models' optimizations, the detailed illustrations of the tools focus on this energy system. These explanations will show how to design the energy system. Therefore, a detailed description of the system is conducted at this point.

The chosen energy system is based on the concept of distributed generation. It is a district heating network that comprises 10 residential buildings(figure 5.1). These are integrated into both electricity grid and heat grid. The system is connected to the electricity grid but there is no external heat supply. The buildings vary in size and number of households including also single family houses.

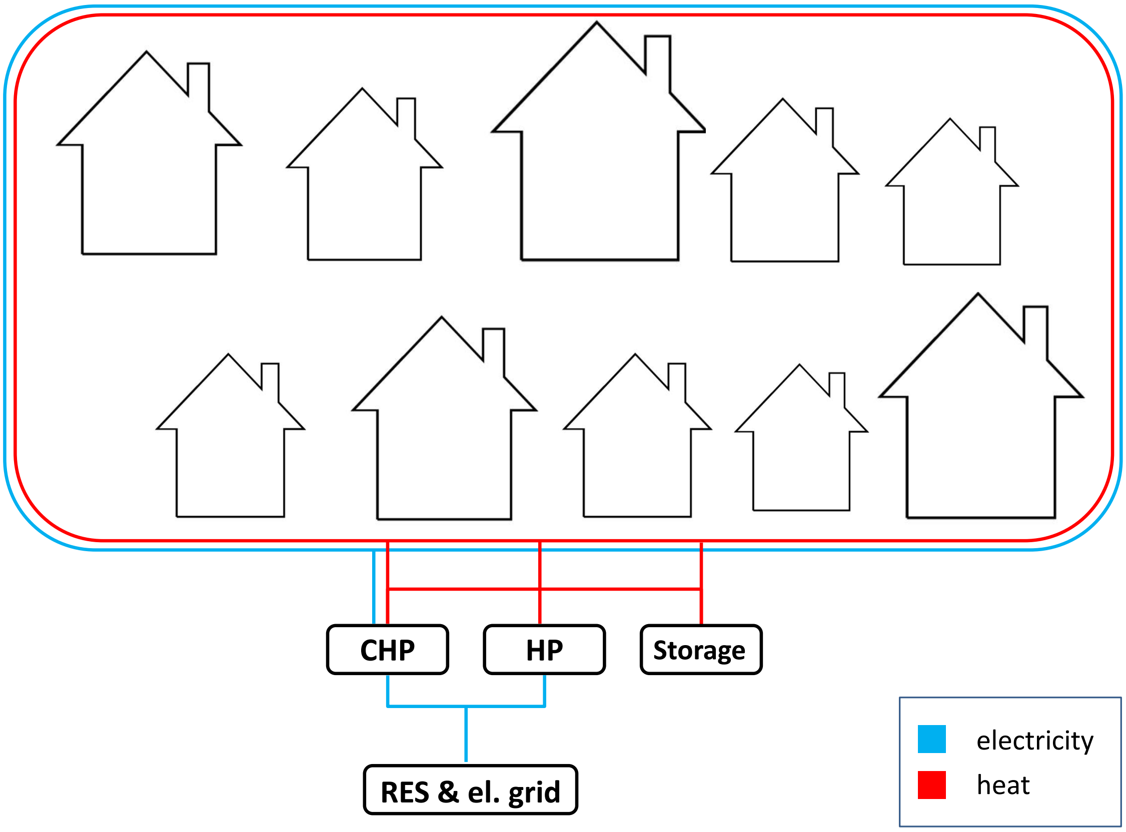

Figure 5.1: Energy system design

The data for the heat demand of these houses are based on simulations made with Dymola[19] performed by the 2DSM-team. The data represents the domestic demand for space heating. Thus, the demand can be very low in the summer because the demand for hot water is not included. Each demand is different from the other. However, these demands can be aggregated because of the thermal grid of the system. In accordance, the figures 5.3 and 5.4 show the heat demand of the whole system. Figure 5.4 reveals the big difference between the demands in winter and summer.

The electricity demand is based on a synthetic standard load profile of German regions for the year 2012[20]. With the help of an appropriate scaling factor the electricity demand can be scaled in order to be a realistic demand according to the dimension of the heat demand. The figure 5.5 illustrates the electricity demand over the year whereas figure 5.6 compares the weekly demands of winter and summer.

For the purpose of investigating the potential of electricity balancing of the energy system, the main external power supply is intermittent renewable energy. The high fluctuation is assured by using wind and photovoltaic data as the renewable energy supply. The photovoltaic data is extracted from the GreenBuilding Library of SimulationX[21]. The wind data is gained from the BDEW[22]. The RES production is scaled down in order to meet a share of 50% of the total electricity demand. For the later analyses, in fact, the annual renewable energy production serves as a decisive parameter of the energy system. The idea is to vary the production rate in relation to the electricity demand in order to observe the impacts of an increasing fluctuation on the comportment of the system. Namely, three variations will be considered that are determined by the ratio of annual renewable energy production in relation to the annual electricity demand: 50%,75% and 100%.

The electricity demand is served primarily by the renewable energy. If required, the chosen energy system imports electricity from the electricity grid. Minimizing these imports is the main challenge of the energy system and its components. Apart from the demand side, the supply side of the system consists of the three devices: a CHP unit and an HP unit combined with a hot water tank. Enabled by the electricity and heat grid, these facilities provide the buildings with heat and electricity. The demands of all the residential buildings necessitate the sizes of the plants. Therefore, each plant has a high capacity. Regarding their production, this is advantageous due to the positive but nonlinear correlation of efficiencies and capacities. Indeed, this positive effect is one reason for establishing district heating networks. Instantly, the capacities of the CHP and HP are defined to be equal and to be able to meet the maximal heat demand. In accordance to the bottom up approach, the results from multiple operational optimizations of different capacities will serve as an indicator for how well the the plants are sized. As a first input, the capacities of the CHP and the HP are equal and amount together the maximum peak of the heat demand. Furthermore, the hot water tank is chosen to contain 5.000 liters. At full content the storage is able to produce heat for about 1 hour at the maximum heat demand. Finally, the energy system has sufficient data to be designed. The different settings of each component that are the input for the tools are displayed in figure 5.2 in the right part of each component. Moreover, the figure shows the boundary of the system and its connection to the electricity grid.

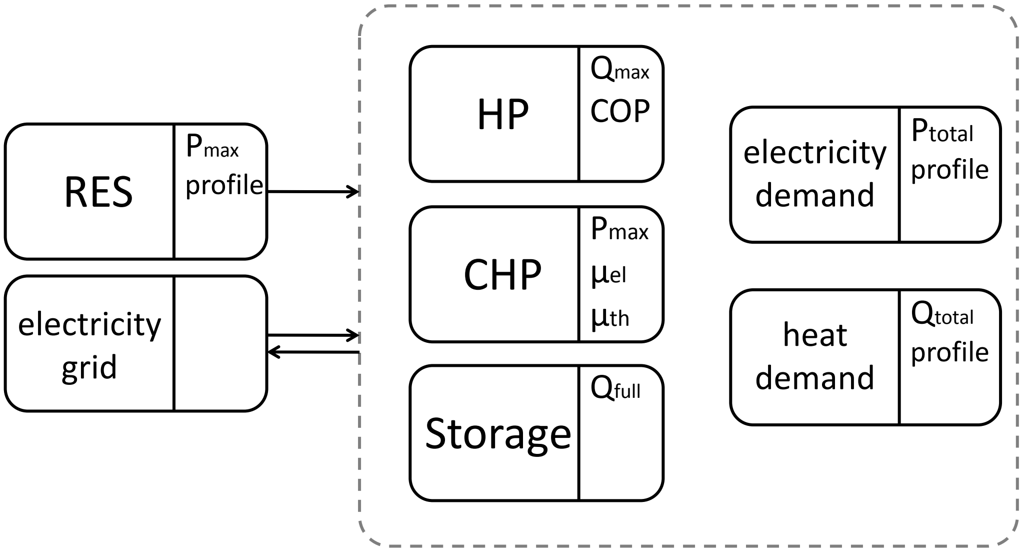

Figure 5.2: Energy system design and input parameters for tools

The defined energy system is supposed to be analyzed for a time period of 1 year because of the operational focus of the analysis. However, the analysis of multiple years is superfluous because each year would lead to the same results as any other year. Moreover, investment operation or planning for further time periods is not of interest.

One other interesting energy system would be a city district with decentralized thermal energy supply units as well as a microgrid. In such a system each domestic building has to provide its heat demand autonomously. Rather than modeling each building solely, the idea is to connect multiple houses electrically. This assures that they are able to communicate and interact on the electricity level whereas the heat cannot be transfered and needs to be produced separately. Unfortunately, the modeling of this kind of system is unfeasible with the selected tools. In fact, a model that is capable to design such a system has not been found during the research for this thesis.

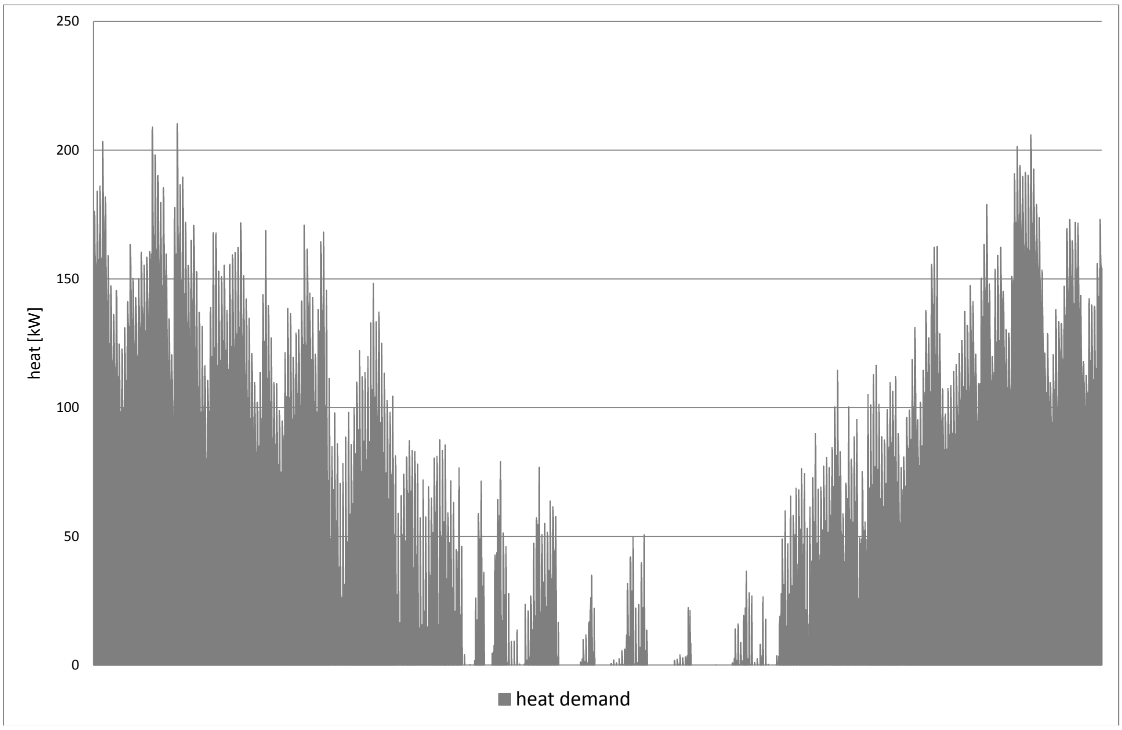

Figure 5.3: Yearly heat demand

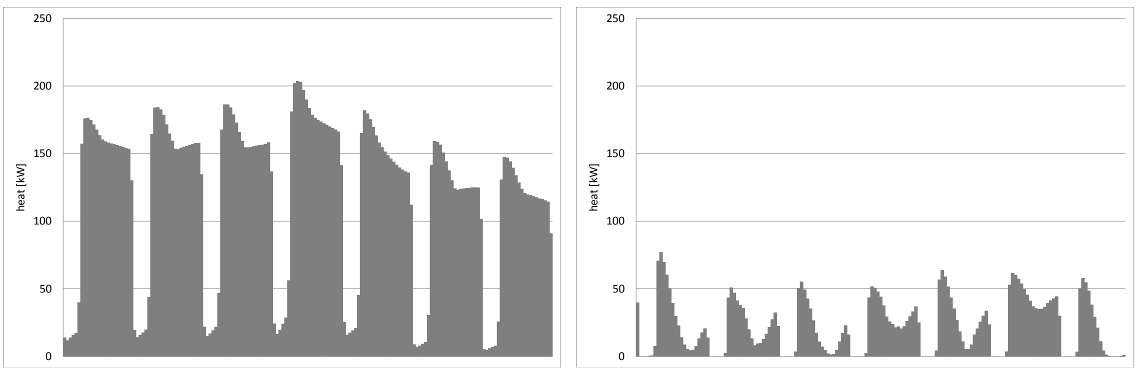

Figure 5.4: Weekly heat demand for winter and summer

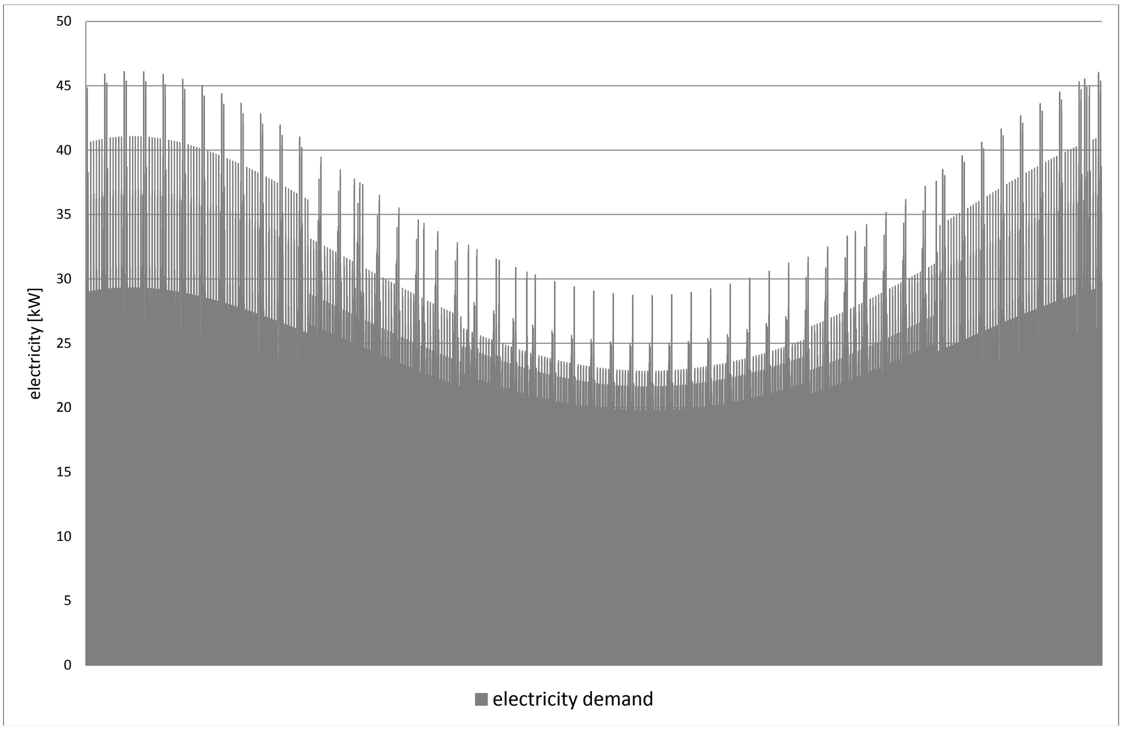

Figure 5.5: Yearly electricity demand

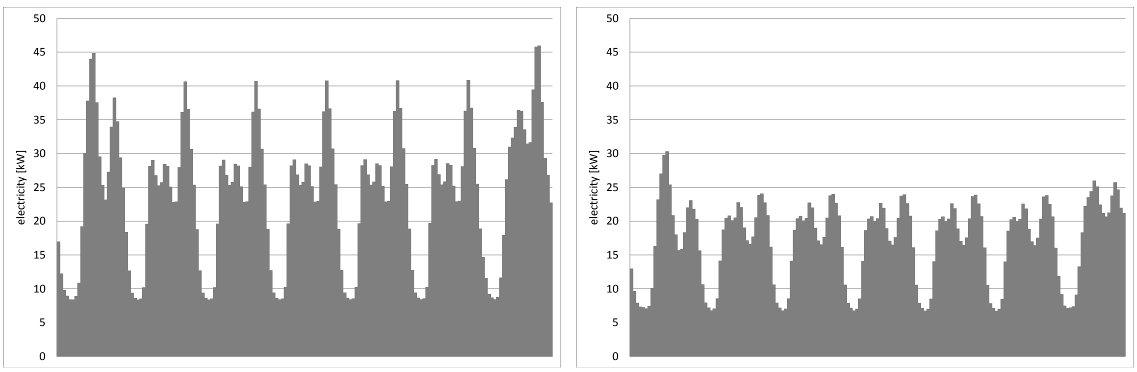

Figure 5.6: Weekly electricity demand for winter and summer

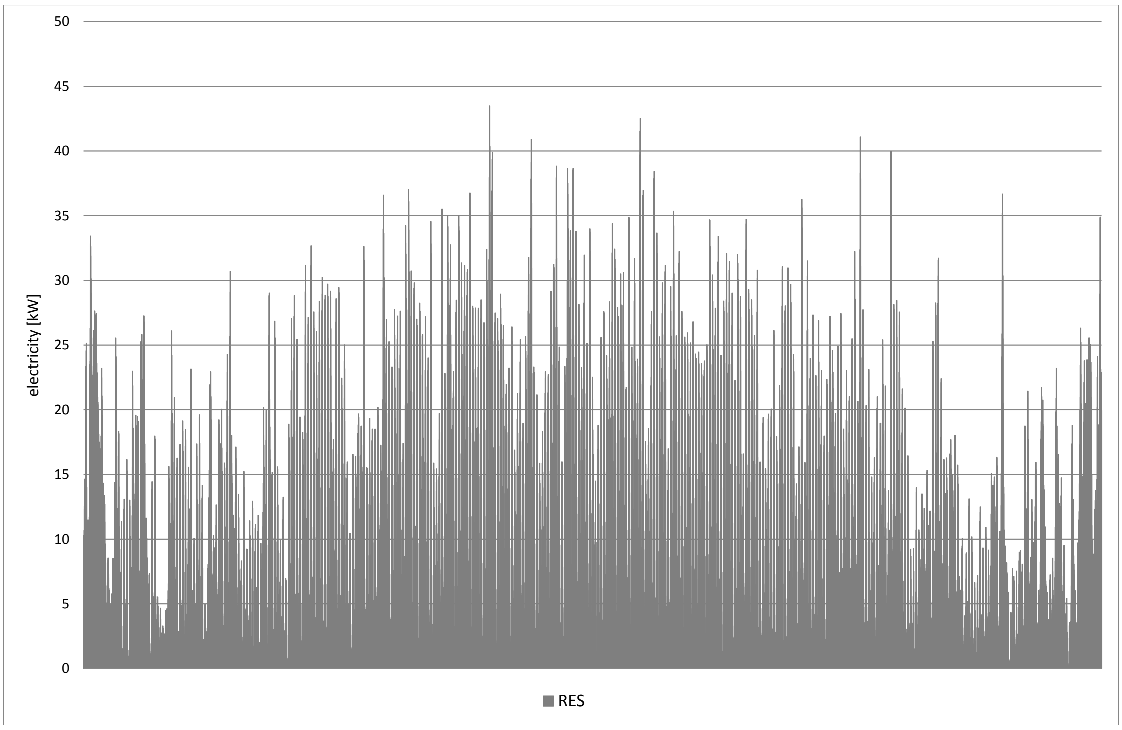

Figure 5.7: Yearly RES production

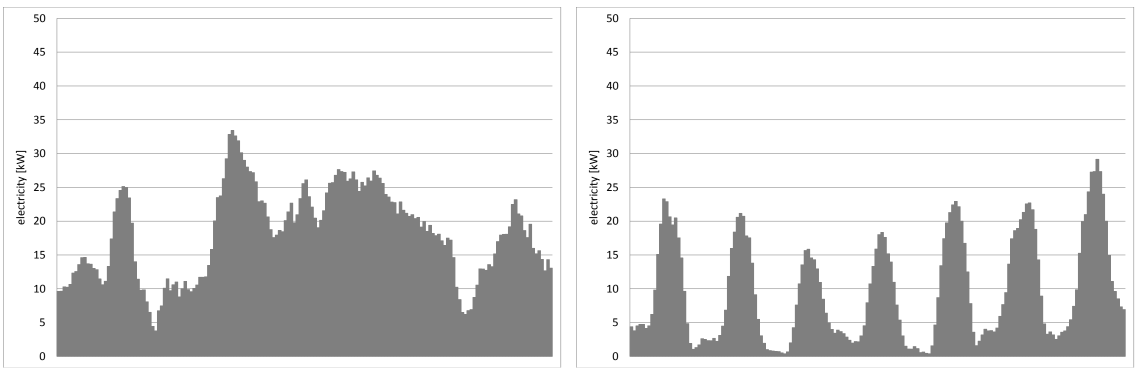

Figure 5.8: Weekly RES production for winter and summer

6 EnergyPLAN

6.1 Brief description of EnergyPLAN

The computer model EnergyPLAN is basically used for national energy systems analyses. It has been developed and expanded on a continous basis since 1999 by the Sustainable Energy Planning Research group at Aalborg University in cooperation with PlanEnergi and EMD A/S[3]. The tool has been utilized for many case studies especially for the Danish energy system, which is characterized by a high share of wind power and CHP of the electricity demand. Accordingly, EnergyPLAN is able to analyse the consequences of an increasing amount of renewable energy. For that reason the model is highly appropriate for analysing the combination of CHP, HP and thermal storage and its potential of electricity balancing.

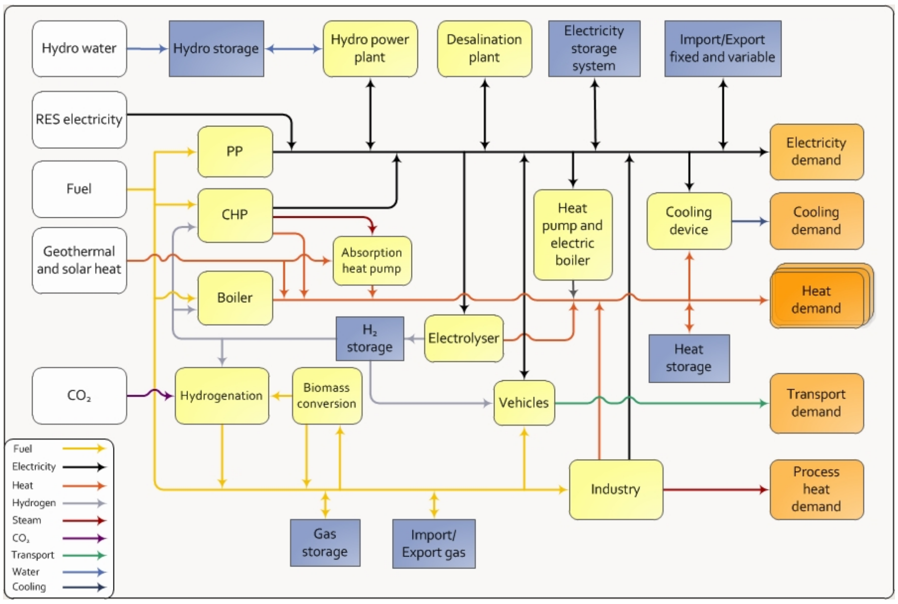

Figure 6.1: Frontpage [Reference:[23] LUND, H. EnergyPLAN: Advanced Energy Systems Analysis Computer Model: Documentation Version 11.0. <http://www.energyplan.eu/> (2013), p.1]

Although the main purpose of EnergyPLAN is to assist national energy planning strategies, it is also advantageous for local energy systems, if the input data are scaled by an appropriate factor. In contradiction to other models that perform analyses on national level, EnergyPLAN analyses energy systems for a time period of 1 year. The calculations are computed based on an hourly basis.

The computation of 1 year takes only a few seconds without the requirement of high computing power: "EnergyPLAN is based on analytical programming as opposed to iterations, dynamic programming, or advanced mathematical tools. This makes the calculations direct and the model very fast when performing calculations."[3]

Moreover, the model covers not only the heat and electricity sectors but also the gas sector and calculations regarding cooling, biomass conversion, transport and many more. For all of these calculations the model defines components with a fixed range of settings that can be used by the user for the design of these components. However, my thesis leaves out all aspects but electricity and heat because the model is not used for national system analyses in the case of this thesis. The two relevant sectors of electricity and heat and the included technologies are illustrated in figures 6.2 and 6.3.

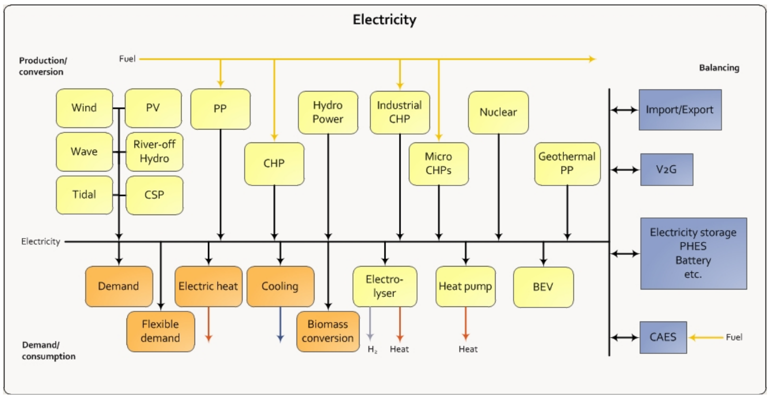

Figure 6.2: Electricity [Reference:[23] LUND, H. EnergyPLAN: Advanced Energy Systems Analysis Computer Model: Documentation Version 11.0. <http://www.energyplan.eu/> (2013), p.13]

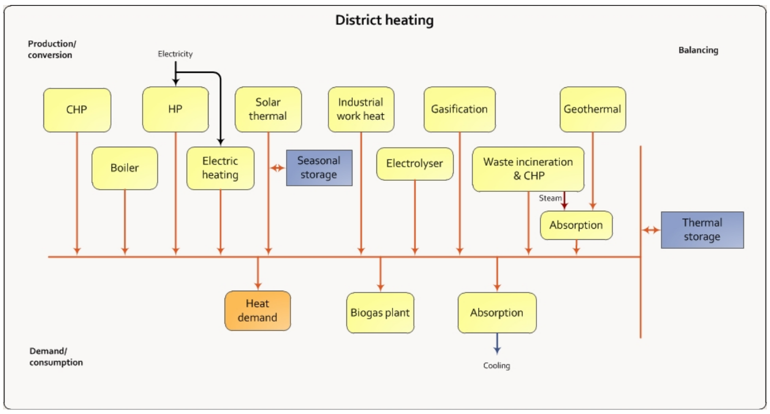

Figure 6.3: Heating [Reference:[23] LUND, H. EnergyPLAN: Advanced Energy Systems Analysis Computer Model: Documentation Version 11.0. <http://www.energyplan.eu/> (2013), p.14]

6.2 Structure and design of EnergyPLAN

The tool and its user interface is structured by tab-sheets. The user is allowed to switch between different sheets easily without any strict order. The principal sheets and their subsheets are shown in table 6.1 in the same order as they appear in the user interface.

Input		Cost	Regulation	Output
Electricity Demand	Industry	Fuel		Overview
District Heating	Transport	Operation		Screen
Renewable Energy	Waste	Investment		Graphics
Electricity Storage	Biomass Conversion	Additional		
Cooling	Synthetic Fuel			
Individual	Desalination			

Table 6.1: EnergyPLAN - structure of graphical user interface

Ahead of the series of principal sheets is the sheet "Frontpage", which is only welcoming the user after the model has been opened. The sheet "Settings" ends this series of sheets. It offers the opportunity to decide about the unity of currency and energy respectively power. The tool indicates all relevant text fields, that the user is able to fill with values, with the respective unity. The choice offered by the tool concerns the scale of the unity, but not the unity itself. Therefore, the user can decide whether the capacity is declared in kW, MW or GW.

The numerous subsheets for the input confirm that EnergyPLAN has chosen a holistic approach for energy systems. In opposition to the little scope for design of components, the model serves a wide range of different technologies that can be implemented into each energy system. The first three input subsheets are the only ones necessary in order to design the reference energy system described above.

The following sheet concerns costs and consists of 4 subsheets. The user is able to define prices, taxes and CO2 costs for a specific number of fuels. Additionally, the model provides the opportunity to define for each type of technology the variable and fixed operation and maintenance costs and also the investment costs. The latter costs are calculated in respect to the lifetime of each technology.

The next main sheet is the regulation sheet. It offers the choice of two different ways to optimize the defined energy system: technical and market economic optimization.

The market economic optimization includes three substrategies, which only concern the vehicle to grid technology, other regulations regarding costs concern the transfer of electricity with external markets.

The technical optimization is based on minimizing the import and export of a system. It is not the goal to minimize emissions or the fuel consumption. There are no such optimizations available in this tool. If the technical optimization is selected, the user can choose from 4 different technical regulation strategies, which are the cornerstones of EnergyPLAN. Within these strategies the model calculates on the basis of technical data and disregards total costs.

Technical regulation strategies:

1. Balancing heat demands
2. Balancing both heat and electricity demands
3. Balancing both heat and electricity demands (Reducing CHP also when partly needed for grid stabilisation)
4. Balancing heat demands using triple tariff[1]

The difference between the second and the third regulation strategies appears whenever the CHP is defined to have a stabilization share. As opposed to regulation strategy II, in situations of electricity overproduction, the third strategy reduces the CHP and increases the HP even when this means to ignore the stabilization share of the CHP. However, a stabilization share for the CHP is not considered for the analysis. Thus, the two strategies lead to the same operation mode of the devices.

Independent from the selection of optimization, the user is able to decide about several possibilities of grid stabilization (e.g. stabilization shares). Besides these options, the user is enabled to define individual strategies to decrease critical electricity export.

Regarding the output, the user has three basic opportunities to view the results of the analysis. First, the user can view them in form of a list on the screen containing hourly, monthly or yearly values. These lists can be customized in the output sheet. Secondly, the user can generate a printed version of the results. Finally, the model is able to display certain hourly distributions of the heat, electricity and gas sector inside the model. The basic structure of the model is illustrated in figure 6.4.

6.3 Modeling the defined energy system in detail

6.3.1 Input

Electricity Demand

The Electricity demand has to be specified in two ways. At first, the distribution has to be defined by importing 8784 values in a text file(.txt) which represent a year of 366 days. Secondly, the user

[1] "The electricity production from CHP units in group 2 is located according to an order of priority, i.e., peak load, high load and low load. The periods of the triple tariff are simply defined as:
Peak load during weekdays between 8.00 and 12.00 (plus 17.00-19.00 in the winter)
High load during weekdays between 6.00 and 21.00, and
Low load during the remaining time."[23]

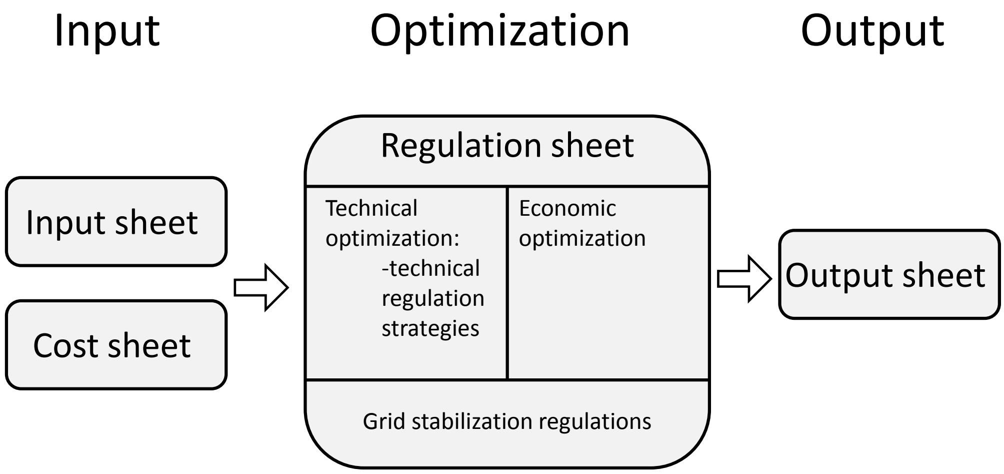

Figure 6.4: EnergyPLAN - structure

has to enter the annual demand taking the declared unit into account. EnergyPLAN is then able to scale the selected distribution that it results in the specified annual demand. Additionally, the model has the capability to calculate flexible electricity demands but this will not be considered in this thesis.

District Heating

The term "district heating" is based on the idea of distributing heat on the local level produced in a centralized location. EnergyPLAN defines three principal groups of district heating systems. The groups are distinguished primarily by the existence and size of CHPs. Thus, the sizes of the district heating networks are different but the influence of the size i.e. the length of the heat pipes has no influence on the calculation of the model. In the first group CHPs are not included. The second group contains small CHPs and finally group 3 consists of large CHP extraction plants in combination with conventional condensing power plants. Solar thermal collectors are very present in this sheet. The technology is covered by all three groups but it is disregarded in this thesis.

Each group has its own demand. If the demand of a group is higher than zero, then this group will be considered for the calculation. The district heating group 2 is appropriate for the energy system of an urban district consisting of CHPs and HPs that are not integrated into a power plant.

EnergyPLAN makes many simplifications that limit the scope for design of the cogeneration unit and the HP unit significantly. The model offers only three characteristics to be decided by the user: capacity, efficiency and fuel type. Moreover, the number of facilities of each technology is determined to 1. Furthermore, the efficiency is constant and independent from the production. The difference in efficiency between e.g. many small CHPs and one large CHP is omitted. Actually, this existent dependency of efficiency and capacity plays an important role for dimensioning a

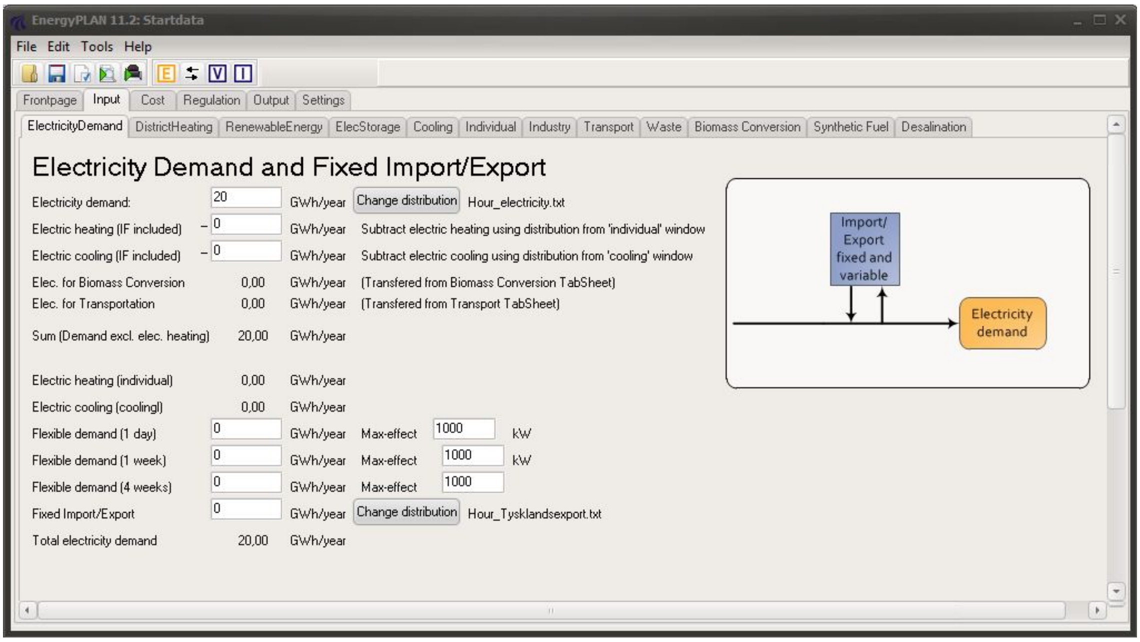

Figure 6.5: EnergyPLAN - Input subsheet "Electricity Demand"

facility and for the operation mode. This results from increasing efficiencies that correlate with an increase of capacity respectively production rate. In terms of operation, one large facility is rather used than multiple facilities with lower efficiency when the demand is sufficiently high. Contrary, multiple facilities mean a higher flexibility, especially when the demand is very low. Summarized, the limitation on one facility of each technology reduces the complexity enormously.

Besides the constant efficiency, the model defines that the production rate ranges between 0% and 100%. This simplification needs to be considered, if the user wants to use EnergyPLAN for the purpose of a local energy system analysis. The reason is that the most of the smaller CHPs and HPs that are used for local energy systems are not operating at very low production rates below 50%. Actually, these facilities are often only operated at full load, i.e. they have only discrete production rates: 0%,100%. Unfortunately, the model does not cover any mixed integer programming. Hence, the production rate must range on a linear basis, which leads to the idea of defining a minimal production rate as a lower bound (e.g. 50%). This is also not considered by the model.

Concerning the heat storage, the user specifies the amount of heat that can be stored. Further characteristics e.g. storage loss and storage content at the beginning of the time period are defined by the model itself. The model puts constraints on the operation of the storage by defining its content at the beginning and at the end as completely loaded.

An idea that emerges when considering the district heating sheet could be to establish an energy system consisting of two district heating networks. Each district consists of several residential buildings that are integrated into an electricity and a heat grid. The only connection to the other

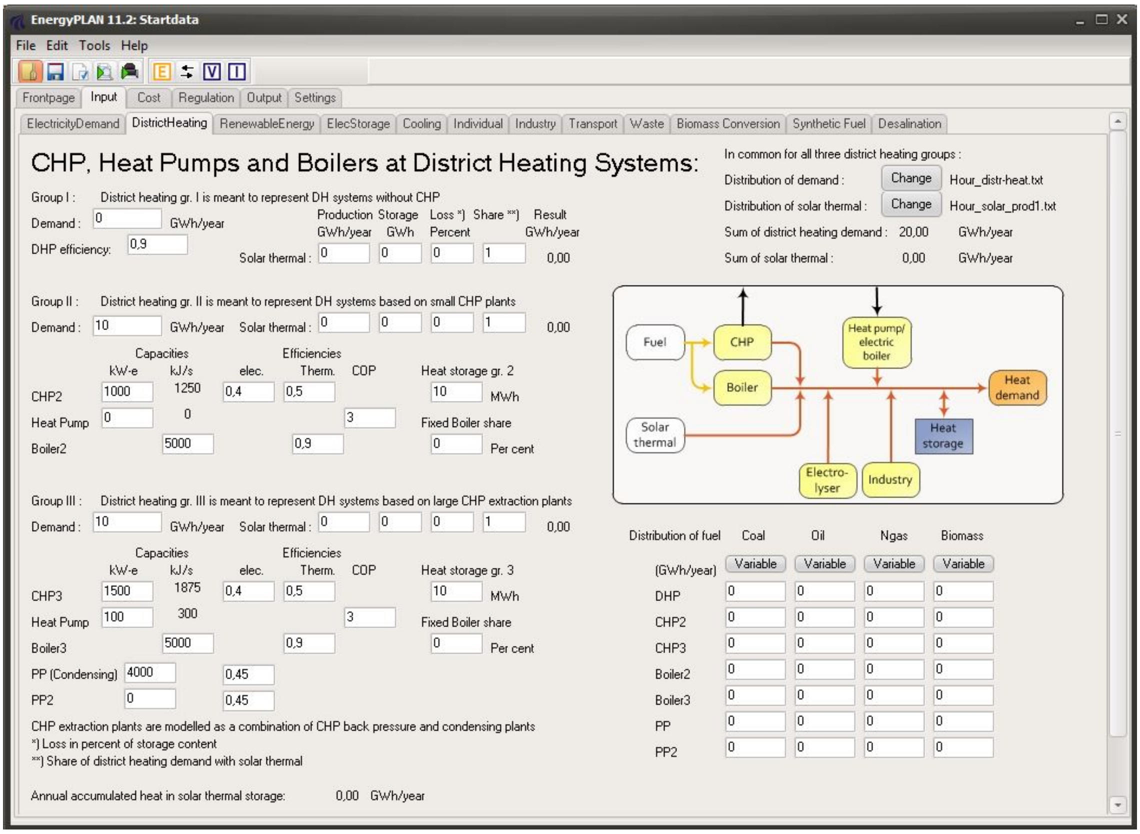

Figure 6.6: EnergyPLAN - Input subsheet "District Heating"

district is electricity. Thus, the districts have to produce heat autonomously but the electricity can be exchanged between them. This idea is not feasible because of two main reasons. First, the CHP unit in district heating group 3 is dependent on the power plant. The model defines the capacity of the cogeneration plant to be always lower than the capacity of the power plant. Hence, the CHP exists only in combination with the power plant because it is supposed to represent a cogeneration extraction plant. As a result, the user is not able to design two similar systems. Second, the communication on the electricity level can not be arranged by the model because the calculations are made separately for each district heating group. These single calculations do not take each other into account. Consequently, the model minimizes the electricity import and export of each group. Afterwards, the total electricity balance is calculated by aggregating the import and export of both groups.

Renewable Energy

EnergyPLAN defines several technologies in the renewable energy sheet. In order to design the intermittent renewable energy that draws through the system, it is sufficing to import the distribution of the hourly values and to define the capacity. Similar to the calculation for demands, the

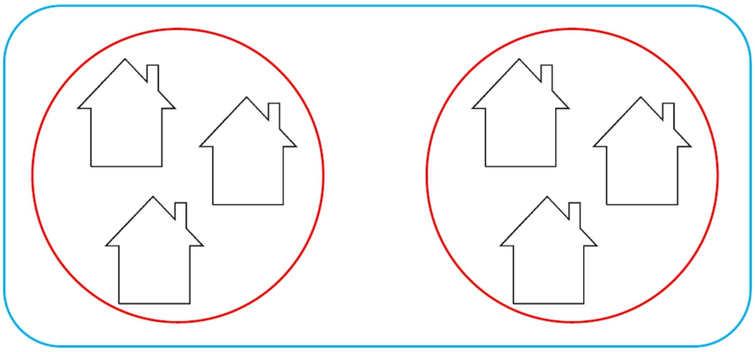

Figure 6.7: Multiple district heating networks

model scales the hourly values appropriately. The textfield corresponding to the correction factor can be ignored if the production ought to be determined precisely by the two inputs capacity and distribution.

Individual

A further oppportunity to model CHP, HP and thermal storage is given in the sheet “Individual”. This sheet takes the decentralized energy production of residential buildings or individual houses into account. The model defines several systems for these houses. Each system is characterized by and strictly bond to one heat demand that the user defines. As a result, each demand necessitates the capacity of the respective device, regardless of the electricity demand. Thus, the technologies included in this sheet cannot be analyzed in terms of electricity balancing. Consequently, this sheet will not be considered for the analysis of this thesis.

However, a further explanation of this sheet is worthwhile because the operation modes of CHPs and HPs for residential buildings usually focus on meeting the heat demand. Moreover, these devices are very often combined with peak load boilers. With respect to the mentioned circumstances, the model defines the following systems that are extendable with solar thermal power and a heat storage.

- ▹ boiler
- ▹ CHP
- ▹ CHP and peak load boiler
- ▹ electric boiler
- ▹ HP
- ▹ HP and electric peak load boiler

Regarding CHP and HP, the user is able to reduce the capacity required in order to meet the heat demand. The capacity can be specified as a share of the maximum heat demand ranging from 0% to 100%. As a consequence, the model adds a peak load boiler to the system. The added boiler consumes the same fuel as the CHP or HP that is reduced in capacity.

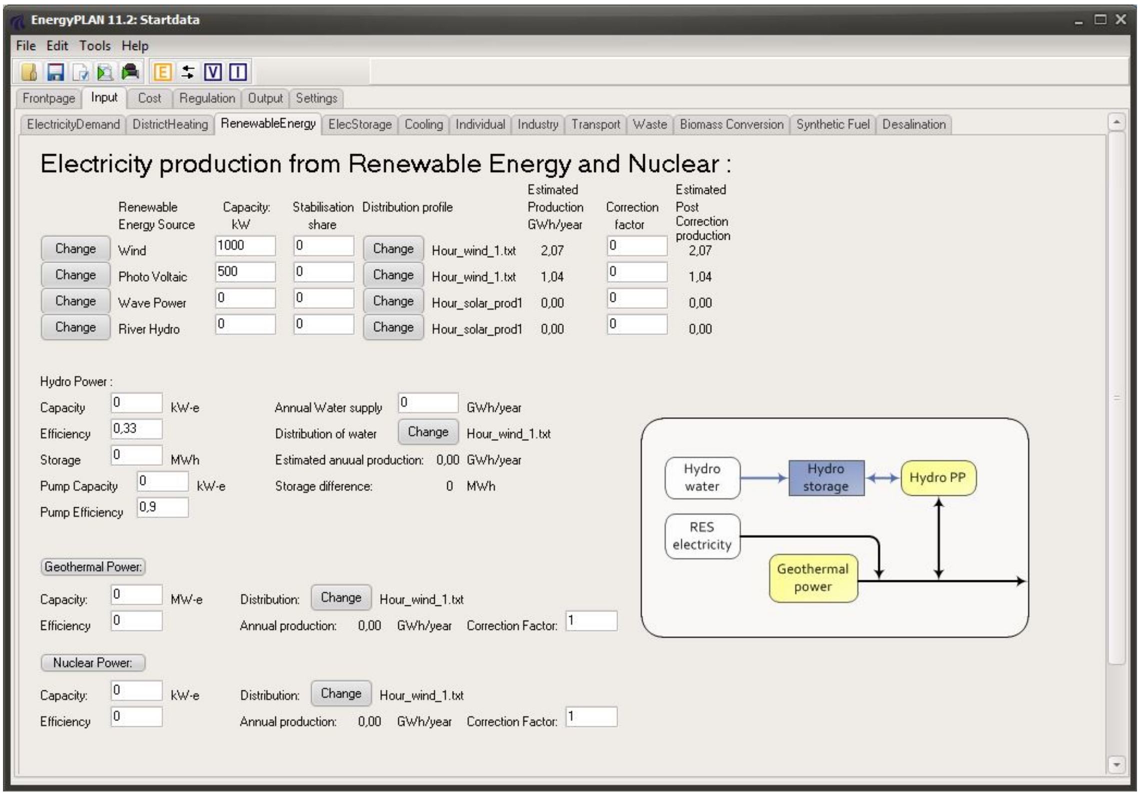

Figure 6.8: EnergyPLAN - Input subsheet “Renewable Energy”

Due to the disregard of electricity, the storage is primarily used for solar thermal collectors as opposed to its purpose in the district heating groups. Therefore, the modeled heat storages of the individual houses cannot provide the flexibility in order to minimize import and export of electricity. Additionally, several analyses revealed that the modeled storage sometimes even induces heat imbalances, which have to be compensated by import and export of heat.

6.3.2 Regulation

The regulation sheet focuses on aspects of grid stabilization. Fr instance, it provides the opportunity to define stabilization shares for the total electricity production or only for the CHP. In addition, the sheet includes strategies for systems with boilers for the reduction of electricity excess. This is very useful for analyses on the national level. In the case of the chosen local energy system comprising only 10 buildings, these possibilities will be disrespected. The idea is rather that the triple of CHP, HP and heat storage is supposed to function as stabilizers themselves. Whereas the HP should embody the negative operating reserve, the CHP is supposed to work as the positive operating reserve.

The optimization strategy is selected to be a technical optimization. If selected, the sheet then offers the 4 different technical regulation strategies. These strategies follow a specific order of

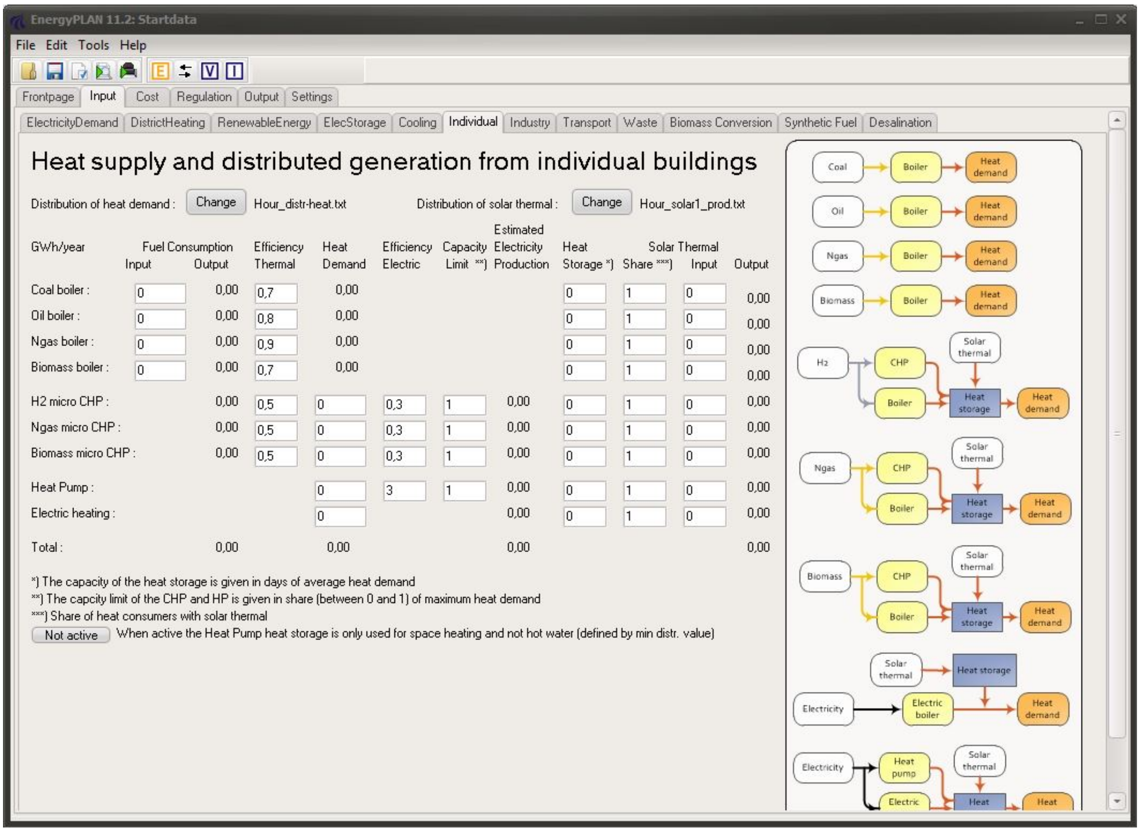

Figure 6.9: EnergyPLAN - Input subsheet "Individual"

calculations. The procedure will be discussed in the detailed investigation of the calculations of EnergyPLAN. Due to the objective of electricity balancing, the second strategy needs to be chosen: "Balancing both heat and electricity demands". A further button occurs when the technical optimization is selected. It concerns regulations of the individual heat pumps that are placed in domestic buildings. Here the user is able to choose if the heat pumps should use all the electricity excess or only the share that cannot be handled by the transmission line. As it was already discussed, the individual devices will not be considered and consequently, the regulations do not play any role for the design and analysis of the energy system.

The model provides the chance to define stabilization shares as well as minimum and maximum loads for the devices for the purpose of electricity balancing. In this case, all stabilization shares and minimum loads are defined as zero and the heat pump maximum load as 1. The regulation of critical excess electricity production is also not considered for the analysis. It is defined as the share of electricity excess that cannot be handled by the transmission line. The user is able to define an order of priority of 8 actions. For instance, the input "62" tells the model to consider action 6 first and then action 2. If the input is "0" all actions will be disregarded. These actions mainly concern a decrease of CHP production with the help of boilers and an increase of electric heating in case of an electricity excess. However, the required devices for the regulation are missing in the chosen

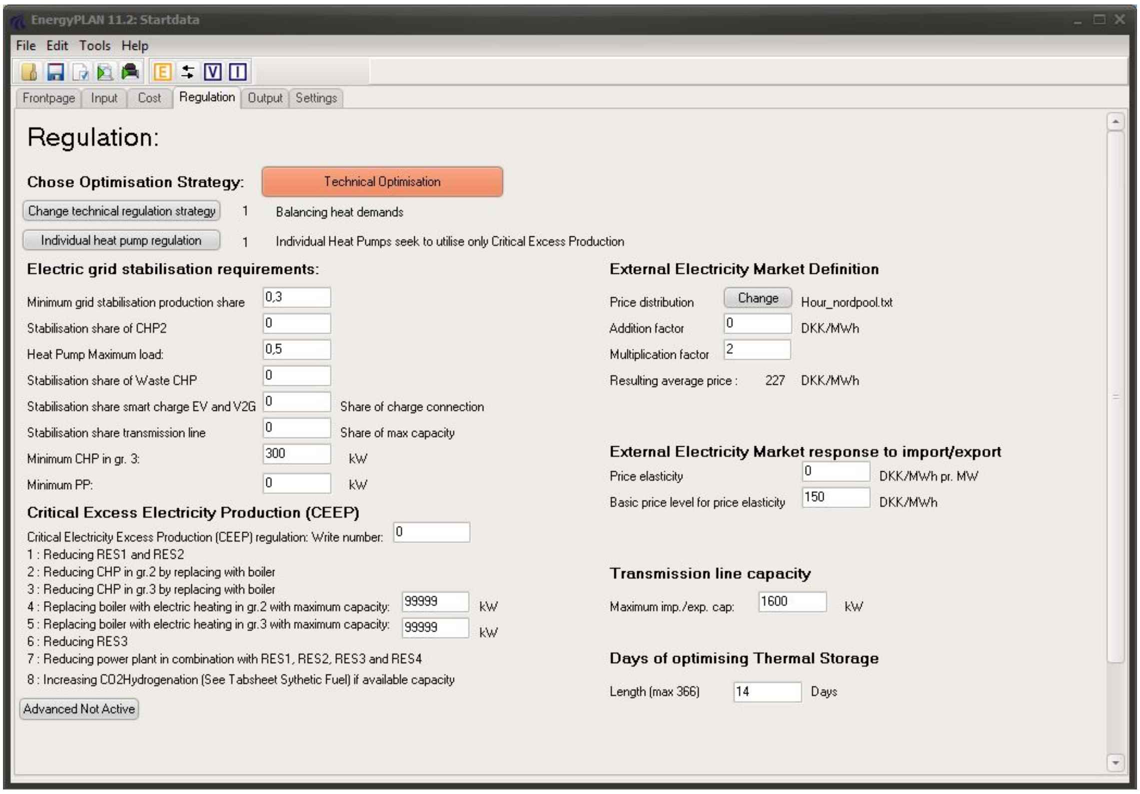

Figure 6.10: Sheet "Regulation"

energy system. The actions from 2,3,4 and 5 function only in combination with boilers. In addition, action number 8 requires hydro technology. Moreover actions 1,6 and 7, which basically reduce the renewable energy production, can be ignored because the renewable electricity production is chosen to be a fixed input that draws through the system.

With the help of the transmission line, the user has the opportunity to define a certain capacity that he decides to be critical. This can also be useful for the excesses of the desired energy system of this thesis. But it can also be defined very high because the critical excess regulation does not play a role in this case. Moreover, the user has the possibility to respect external electricity markets. This is useful for market economic analyses of national systems because the import and export of electricity plays an important role for the costs of the system. However, external markets can be ignored due to the technical focus.

A further aspect concerns the operation of the thermal storage. The sheet provides a textfield for the time period of optimization of the thermal storage. The analysis of the calculations will reveal how the defined period influences the operation of the system.

6.3.3 Output

The ouptut sheet consists of 3 subsheets.

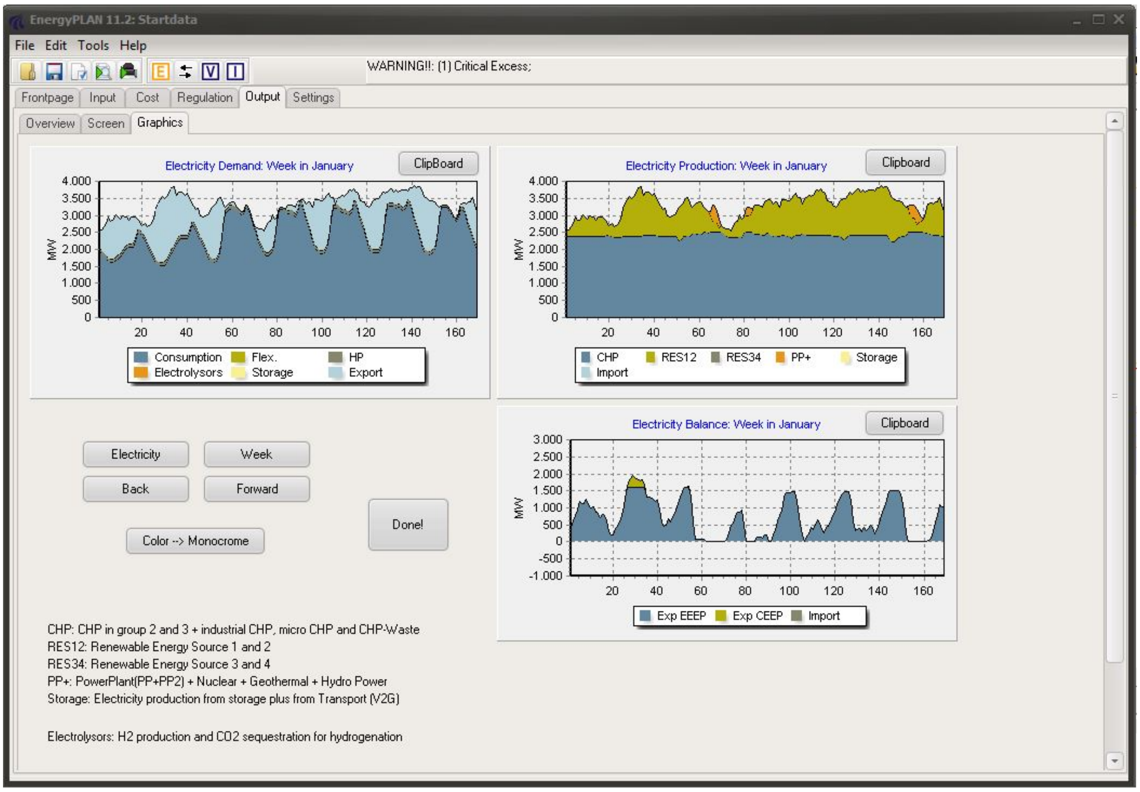

Figure 6.11: Sheet “Output”

On the first sheet the user is informed about the already mentioned three possible outputs of an analysis in EnergyPLAN: the listed values on the screen, the printed version of results and the charts generated by the model.

On the bottom of the first subsheet the model enables the user to run serial calculations. This idea is based on the bottom up approach. The model accepts up to 11 different capacities for one of the 4 possible renewable energy technologies called RES 1,2,3 and 4 (wind, photovoltaic,wave power and river hydro). This helps to compare the different results at once and thus avoids multiple analyses with different inputs. Therefore, the user can identify the best input data or more exactly the best size of a renewable facility regarding electricity balancing.

The second subsheet concerns the customization of the results that can be viewed as a list generated by the model or copied to an excel file. This sheet lists all the available technologies in EnergyPLAN including their consumption and production. Additionally, the model enables to choose from demands, storage contents and energy balances. Usually not all of these values are used within an analysis like in the case of the described energy system. Also the resulting list is likely to be overloaded. Therefore, condensing the list to the relevant data is necessary. Regarding the selected results, the user can choose to generate yearls, monthly or hourly values. The latter can be viewed in a specific period of the year that the user is able to decide. The relevant results of the chosen energy system amount only a little share of the available outputs. The selection can be seen on the next screenshot.

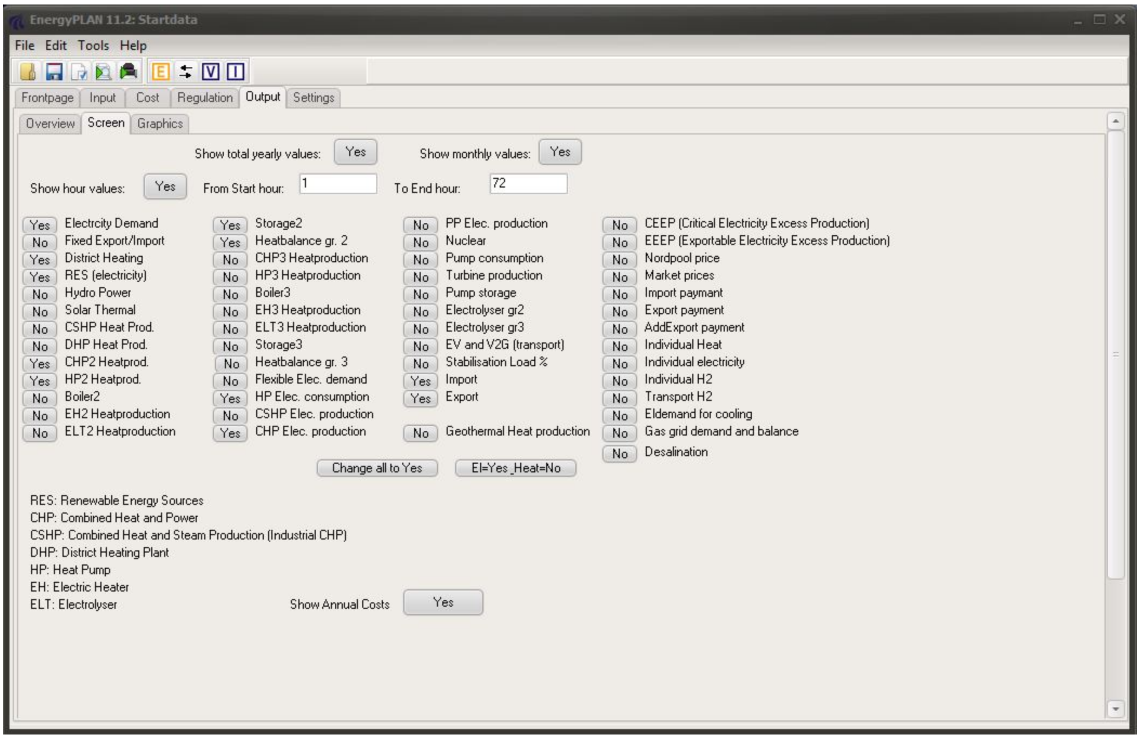

Figure 6.12: EnergyPLAN - Output subsheet "screen"

On the third sheet the user can view the hourly values displayed in 3 charts. Two charts always represent the production and the demand of an energy sector. The user is able to switch between the sectors electricity, heat and gas easily. For electricity and gas the third chart illustrates the balance of the respective grid. If the models is told to show the charts for heat, then the third chart illustrates the content of the thermal storage. The time axis of the graphics can be scaled from 1 day up to a whole year. In addition, the point of time within the year can be chosen by clicking on the"forward" or "backward" button. The temporal scale and position is the same for all three charts. Each chart is based on specific values which are marked in different colours. The values and the respective colours are always displayed as a legend under the chart.

For the purpose of designing the defined energy system, the electricity demand chart includes data like the demand of the buildings, the HP consumption and the electricity excess. It is noteworthy that the model defines the excess of electricity as a demand. The underlying understanding is that the system requires this amount of excess in order to meet the heat and electricity demands of the residential buildings. Accordingly, the production chart comprises the import as a required production in order to meet the demands. Besides, the chart includes the renewable energy production and the electricity production of the CHP. Regarding heat, the demand chart shows the total heat demand of the residences. The heat transfer with the storage can not be seen in this chart. The same applies to the production chart, which displays the heat production of the CHP and HP. The flow of heat into and out of the storage can only be seen in changes of the storage content shown in the third chart. The gas grid is not of interest for the analysis of the system and is thus left out.

6.4 Calculations in EnergyPLAN

The calculations in EnergyPLAN are explained in its documentation[23]. The following demonstrations reflect a detailed examination of the documentation. The documentation of EnergyPLAN mentions the important equations but it does not illustrate the reasons for these equations in detail. The following own explanations seek to improve the way of explaining in order to achieve a good comprehension of the optimization. The chosen indexes are specified for this thesis and are not comparable to the ones used in the documentation. Furthermore, own calculations made in excel confirmed the results of the model except for the calculation of the heat storage. In a first step of this section, the procedure will be explained and afterwards this procedure will be applied to the data of the energy system.

The model follows a fixed procedure of calculations for each analysis. All steps are performed in a determined sequence. The following calculations correspond to the technical optimization of the energy system described in the previous chapter. It is important to keep in mind that these calculations are characterized by the settings explained above for modeling the reference energy system. Therefore, many technologies and aspects of grid stabilization that are included in the fixed procedure of calculations do not play any role for the chosen energy system.

The first calculations by EnergyPLAN are made while editing the sheets of the model. Whenever values in the input sheets are changed, the model calculates the hourly values of the specified demands and renewable energy productions, which are determined by the imported profile and the annual demand respectively the capacity. It is noteworthy that all hourly values amount 8784 values because the model defines that a year consists of 366 days. Regarding the demands (d), each defined distribution and the respective annual demand determine the hourly values based on the following simple equation. The value of the distribution (∂) in hour j over the sum of all values is multiplied by the annual demand (D):

$$
\begin{aligned}
d_j = &\quad D\frac{\partial_j}{\sum_{i=1}^{n}\partial_i} \\
\\
\partial: &\quad \text{hourly value of imported profile} \\
d: &\quad \text{hourly demand} \\
D: &\quad \text{annual demand}
\end{aligned}
\tag{6.1}
$$

The production of renewables is characterized by the capacity. The capacitiy is the maximum of the resulting hourly values. The production value of hour j (p_j) is calculated by multiplying the capacity by the fraction of the value of the distribution in hour j over the maximum of the distribution values:

$$
\begin{aligned}
p_j = &\quad Prod\frac{\partial_j}{\partial_{max}} \\
\\
p: &\quad \text{hourly production} \\
Prod: &\quad \text{annual production}
\end{aligned}
\tag{6.2}
$$

The main calculations start with the command to calculate issued by the user. The calculations associated with the technical regulation strategy “Balancing both heat and electricity demands” can be structured in the following way:

1. Meeting heat demands
2. Reducing electricity excess by decrease of CHP
3. Reducing electricity excess by usage of storage

Firstly, the model calculates the production rates of the CHP and the HP, whereat the heat demands are primarily met by the CHP. Afterwards, the resulting values are used for reducing the electricity excess resulting from the calculations in the first step. This is mainly done by a decrease of CHP production and an increase of HP production. Finally, the storage is operated in order to further minimize the remaining electricity excess.

Beginning with the first step, the electricity is disrespected. Any negative impact on the electricity balance is not taken into account. Focusing on heat demands, the model prioritizes the operation of the CHP. The production is maximized until either the capacity of the CHP ($\dot{Q}$) is arrived or the heat demand (d_q)is met.

$$
\begin{aligned}
q_{CHP} = &\quad min\{\dot{Q}_{CHP}, d_q\} \\
\\
\dot{Q}_{CHP}: &\quad \text{CHP heat capacity} \\
q_{CHP}: &\quad \text{hourly CHP heat production} \\
d_q: &\quad \text{hourly heat demand}
\end{aligned}
\tag{6.3}
$$

Whenever the heat demand exceeds the heat capacity of the CHP, the HP is used to deliver the required heat.

$$q_{HP} = d_q - q_{CHP} \qquad , q_{HP} \geq 0$$
$$q_{HP}: \quad \text{hourly HP heat production} \tag{6.4}$$

If the demand exceeds also the HP capacity, the model considers a boiler to meet the demand. The latter is not part of the system. In the case of a missing boiler,therefore, the capacities have to be sufficiently high. Noteworthy, the calculations for balancing heat demands do not include the heat storage. The storage will only be used for strategies that concern electricity balancing.

Thereafter, the electricity export and import resulting from the technical regulation strategy I are calculated.

$$\begin{aligned} e_{exp,I} &= e_{RES} + e_{CHP} - e_{HP} - d_{el} \qquad , e_{exp} \geq 0 \\ e_{imp,I} &= -(e_{RES} + e_{CHP} - e_{HP} - d_{el}) \qquad , e_{imp} \geq 0 \end{aligned}$$

$$\begin{aligned} e_{exp,I}: &\quad \text{hourly el. export from regulation strategy I} \\ e_{imp,I}: &\quad \text{hourly el. import from regulation strategy I} \\ e_{RES}: &\quad \text{hourly RES el. production} \\ e_{CHP}: &\quad \text{hourly CHP el. production} \\ e_{HP}: &\quad \text{hourly HP el. consumption} \\ d_{el}: &\quad \text{hourly el. demand} \end{aligned} \tag{6.5}$$

In the next main step, the model seeks to minimize the electricity excess resulting from meeting the heat demand. Noteworthy, at this step a decrease of electricity import in order to balance the electricity grid is disregarded. The reduction of electricity excess is made by reducing the production of the CHP. For this purpose the coexisting HP needs to be taken into account. For the subsequent equations the changes(Δ)are defined to be positive for increases and negative for decreases of the respective variable.

The equation that serves as the basis for the calculations is shown adjacently. It reveals the interdependency between the changes in CHP production, HP consumption and electricity export. The HP electricity consumption is defined as positive, therefore, the change in consumption is positive and has to be subtracted.

$$\Delta e_{exp} = \Delta e_{CHP} - \Delta e_{HP}$$
$$\Delta e: \quad \text{changes of el. production} \tag{6.6}$$

Regarding the reduction of electricity excess, EnergyPLAN differentiates between two main routes:

▷ A: eliminating export

- B: maximal increase of HP consumption

These routes are both based on the restriction of the heat balance, which defines the relation between the CHP and HP heat production.

$$\begin{aligned} \Delta q_{CHP} = &\quad -\Delta q_{HP} \\ \Delta q : &\quad \text{changes of heat production} \end{aligned} \tag{6.7}$$

Noteworthy, this equation also applies to energy systems that include boilers. The two routes are based on the interdependency of CHP and HP and their effect on electricity export. The detailed calculations of route A and B will be explained successively to the illustrations below.

The reason for the differentiation of the two routes is to check if the elimination of export can be achieved without a maximal increase of the HP electricity consumption. If this is the case, the decrease of CHP electricity production in route A is lower than in route B. Therefore, the test is run by identifying the minimal reduction of the CHP for each route.

If the minimum is found in route A, the model defines the change in electricity export to be equal to the amount of export resulting from the technical regulation strategy I (meeting heat demands):

$$\Delta e_{exp} = e_{exp,I} \tag{6.8}$$

Rather, if the minimal reduction is identified in route B, the elimination of export is either barely accomplished or is unfeasible by an increase of the HP electricity consumption and a simultaneous decrease of CHP production. Regarding the HP consumption for route B, the change is assumed to be maximal.

$$\begin{aligned} \Delta e_{HP} = &\quad \Delta e_{HP,max} \\ \Delta e_{HP,max} : &\quad \text{maximal change of HP el. consumption} \end{aligned} \tag{6.9}$$

In order to further reduce the export, a next step decreases the CHP production while disrespecting the heat balance. Consequently, the model prefers the import of heat rather than accepting electricity export.

For the detailed calculation of route A, the basic equation 6.6 can be specified more precisely because the change in export is as high as the export that is to be reduced (equation 6.8):

$$e_{\ exp,I} = \Delta e_{CHP_A} - \Delta e_{HP_A} \tag{6.10}$$

Taking the restriction of heat balance(equation 6.7) into account, the following interdependency between the electric HP consumption and the electric CHP production is resulting.

$$\Delta e_{CHP}\frac{\dot{Q}_{CHP}}{P_{CHP}} = -\Delta e_{HP}\frac{\dot{Q}_{HP}}{P_{HP}} \tag{6.11}$$

$$\begin{aligned} P_{CHP}: &\quad \text{CHP el. capacity} \\ P_{HP}: &\quad \text{HP el. capacity} \end{aligned}$$

With the help of this equation the equation 6.10, consisting of 2 variables, can be solved. This is done by replacing the change in electric consumption of the HP (Δe_{HP}) with the expression for it found in the heat balance:

$$e_{\ exp,I} = \Delta e_{CHP_A} - \left(-\Delta e_{CHP_A}\frac{\dot{Q}_{CHP}}{P_{CHP}}\frac{P_{HP}}{\dot{Q}_{HP}}\right) \tag{6.12}$$

$$= \Delta e_{CHP_A}\left(1 + \frac{\dot{Q}_{CHP}}{P_{CHP}}\frac{P_{HP}}{\dot{Q}_{HP}}\right) \tag{6.13}$$

Finally, the decrease of CHP electricity production can be found as:

$$\Delta e_{CHP_A} = \frac{e_{exp,I}}{\left(1 + \frac{\dot{Q}_{CHP}}{P_{CHP}}\frac{P_{HP}}{\dot{Q}_{HP}}\right)} \tag{6.14}$$

Referring to route B, the HP consumes as much electricity as possible. Therefore, the change in HP consumption is maximal (equation 6.9). Due to this fixed increase, the change in CHP electricity production is calculated according to the heat balance:

$$\Delta e_{CHP_B} = -\Delta e_{HP,max}\frac{P_{CHP}}{\dot{Q}_{CHP}}\frac{\dot{Q}_{HP}}{P_{HP}} \tag{6.15}$$

If this decrease of CHP production is smaller than the one resulting in route A this means that the increase of HP consumption barely eliminates the export or is thereupon insufficient. Thus, this first reduction is lower or equal to the existing export.

$$\Delta e_{exp,B_1} \leq |e_{exp,I}| \tag{6.16}$$

Because of the eventually remaining export, the model starts a second reduction of the export in order to eliminate the electricity export. Consequently, the resulting export of route B consists of the sum of the two canges in export(B,1 and B,2) based on the decrease of CHP production.

$$e_{exp,B} = e_{exp,I} + \Delta e_{exp,B_1} + \Delta e_{exp,B_2} \tag{6.17}$$

The model seeks to minimize this term. This corresponds to a maximization of the amount of the second reduction of export ($\Delta e_{exp,B_2}$) because the reduction is defined as a negative change. The only reduction feasible is a further decrease of CHP production. Due to the missing potential of increasing the HP consumption, this reduction causes heat imbalance. The reduction is limited by the remaining production rate of the CHP. Therefore, the reduction of export is limited. Accordingly, there are two cases of reduction. In the first case the reduction is limited by the CHP , thus, the export cannot be distinguished. The remaining decrease of CHP consists of the sum of the production from meeting the heat demand (technical regulation strategy I) and the change in production realized by the increase of HP consumption:

$$\Delta e_{CHP,B_2} = e_{CHP,I} + \Delta e_{CHP,B_1} \tag{6.18}$$

The second case accomplishes the elimination of export without reducing the CHP production to zero. As a result, the equation 6.17 equals zero and the second change in export can be found as:

$$\Delta e_{exp,B_2} = -(e_{exp,I} + \Delta e_{exp,B_1}) \tag{6.19}$$

Afterwards, the model chooses the minimum of these two terms which result in different exports:

$$\begin{aligned} \Delta e_{exp,B_2} = \quad & min\{\, \Delta e_{CHP,B_2} \quad , \quad \Delta e_{exp,B_2} \,\} \\ & \Rightarrow \Delta e_{exp,B} \geq 0 \qquad \Rightarrow \Delta e_{exp,B} = 0 \end{aligned} \tag{6.20}$$

Finally, the heat storage is calculated. EnergyPLAN defines the objective of the heat storage to be the minimization of the electricity export. According to the documentation of the model, the storage is only operated in specific situations. The storage can be loaded in two ways:

- ▷ By increasing the use of HP in situations with electricity export
- ▷ By moving the electricity production from condensing plants to CHP plants

Furthermore, there are two situations for heat storage to be unloaded:

- ▷ By reducing the CHP production in situations with electricity export
- ▷ By reducing th boiler production

In the case of the reference energy system, only the first situations of loading and unloading are considered. These situations are characterized by an electricity excess. As a result, the calculation procedure of the storage system is very simple. Regarding the loading of the storage, the HP increase is either limited by its capacity or by the elimination of electricity excess. The unloading of the storage is limited either by the remaining CHP production rate or again by the elimination of electricity excess.

As a conclusion of the explained calculation procedure, the model forces the devices to reduce the electricity excess. This is even done when the interaction of CHP and HP cannot eliminate the excess. In fact, the model aims to further reduce the electricity excess by decreasing the CHP production (Route B,2),although this causes heat deficits. Concerning the heat storage, the model allows only for the operation during electricity excess. The reason is that the model puts the focus of the storage on the minimization of the electricity excess. In fact, this is only one advantage of using a heat storage but others like a possible reduction of electricity imports by an increase of CHP production during electricity deficits are not considered.

6.5 Evaluation of the calculations in EnergyPLAN

For the evaluation of the calculation procedure, it is of importance to take into account that EnergyPLAN assists for national energy planning and has thus the objective to optimize a system as a whole. Whereas the goal of the analysis of the thesis is to identify the optimal operation mode of the devices in the chosen energy system. The characteristics of the calculations are explained in two steps in accordance to the order of the calculation procedure. Firstly, the computation of the CHP unit and the HP unit is evaluated regardlessly of the storage and secondly, only the thermal storage is discussed.

In terms of the chosen energy system, the model seeks to meet heat and electricity demands while minimizing electricity and heat import and export. This objective belongs to the technical reglation strategy II. The following cases that are used to evaluate the calculations that are characterized by imbalances resulting from the completed calculations of the technical regulation strategy II.

The first case shows a deficit of heat. Moreover, the case is used for the illustration of the calculations made by EnergyPLAN with the help of the tables 6.2 and 6.3. The thermal capacity of HP and CHP are both 105kW. The aggregated thermal capacity then arrives at the maximum load of the heat demand. According to a COP of 3, the maximal HP electricity consumption is 35kW ($e_{HP,max}$). An electric efficiency of 35 % leads to a CHP electricity production of 77kW ($e_{CHP,max}$). The values are rounded hourly values in kW. The balances(abbreviation in the tables: “bal”) included in the following table are defined as positive for excess and as negative for deficit.

This case represents a situation in winter with a high heat demand and a relatively low electricity demand. Therefore, the CHP production exceeds the electricity demand and thus produces excess. Relating to technical strategy I and equation 6.3, the CHP production is maximized until the heat demand is met. Hereafter, the HP production is used to meet the remaining heat demand according to equation 6.4.

The technical regulation strategy II is completed by an adjacent decrease of the CHP production in order to reduce electricity export. Corresponding to equation 6.7, the HP production increases simultaneously as far as the HP capacity allows it to.

hours	heat demand	$CHP_{heat,I}$	$HP_{heat,I}$	$bal_{heat,I}$
1	17	17	0	0
2	40	40	0	0
3	156	105	51	0
4	175	105	70	0
5	175	105	70	0
6	174	105	69	0
7	170	105	65	0

Table 6.2: EnergyPLAN - Meeting heat demands

hours	d_{el}	RES	$CHP_{el,I}$	$HP_{el,I}$	$bal_{el,I}$	$CHP_{el,II}$	$HP_{el,II}$	$bal_{el,II}$	$bal_{heat,II}$
1	8	11	12	0	15	2	5	0	0
2	8	12	29	0	33	6	10	0	0
3	9	12	77	17	63	31	35	0	-8
4	11	14	77	23	56	32	35	0	-26
5	19	15	77	23	49	40	35	0	-16
6	30	15	77	23	38	50	35	0	0
7	38	14	77	22	31	55	31	0	0

Table 6.3: EnergyPLAN - Meeting both heat and electricity demands

In the hours 3 to 6 the HP arrives at its maximum production (electricity consumption of 35kW). However, the cogenerater and the HP unit achieve to balance the electricity demands as it can be seen in the column before last of the table 6.3. This results from 2 reductions of the electricity export according to the route B (equation 6.17). The first reduction includes a decrease of CHP production and a coinciding increase of HP production until the HP capacity is reached. The second reduction is limited by the remaining production rate of the CHP (equation 6.20). In this case, the reduction is not limited because there is enough potential to decrease the CHP production. Thus, the electricity export can be eliminated and the electricity is balanced.

The second reduction is done at the expense of a heat imbalance in hour 3,4 and 5. The reason is that there is no device that can compensate the second decrease of the CHP production. As a conclusion, EnergyPLAN prefers to have heat deficits rather than electricity excesses. Whereas the system could export an electricity excess there is no way to produce the required if no other heat devices are available. Apart from increasing the capacities of the devices, a solution would be to install a boiler in the energy system, which is also the usual case for analyses in EnergyPLAN. Without changing the energy system the better compromise would be to forbid any further reduction of the CHP production. This would avoid heat deficits at the expense of electricity excess that can be exported.

Another imbalance results from the following characteristic of the technical optimization. Noteworthy, the model never produces any heat excess. The first step of the calculation procedure for balancing electricity and heat demands is always to meet the heat demand. In the next step the production is at least reduced but never increased. In situations like illustrated in the table 6.4 this strategy leads to electricity deficits.

hours	CHP_{el}	HP_{el}	el. balance	heat balance
1	37	18	0	0
2	5	0	-8	0
3	5	0	-3	0
4	5	0	0	0

Table 6.4: EnergyPLAN - No CHP heat excess

This situation is characterized by a very low heat demand. This case appears especially during nights. In the first hour the CHP and HP are able to achieve balance for heat and electricity by a simultaneous increase of CHP and decrease of HP production. The CHP is decreased because the resultant production from meeting the heat demand in the first step exceeds the electricity demand. In the next hours of a very low heat demand the CHP production of the CHP, resulting from the first step, does not suffice for meeting the electricity demand. However, the model does not force the CHP to operate in order to avoid the electricity deficit. It prefers to accept the electricity deficit because it always seeks to avoid overproductions of heat. This strategy can be very critical in the case of island energy systems that are not able to import any electricity, whereas heat could be dumped. However, this preference is advantageous for the reference energy system due to its connection to the electricity grid.

A positive effect of this strategy of avoiding heat excess is that the HP unit does not operate in order to reduce excess electricity while the produced heat is not needed. Thus, if there is no heat sink the HP does not operate. This situation is illustrated below.

hours	CHP_{el}	HP_{el}	el. balance	heat balance
1	1	0	0	0
2	0	1	2	0
3	0	1	2	0
4	0	1	1	0
5	0	2	0	0

Table 6.5: EnergyPLAN - No HP heat excess

In this case the renewable energy is high. Therefore, any electricity production is not needed and thus the CHP is turned off. Instead, the electricity excess should be consumed for balancing electricity. The HP is operated in these hours because little heat demand exists. The operation of the

HP is limited by this heat demand in order to avoid heat overproduction. Consequently, this strategy accepts the remaining electricity export.

The conclusion of these three situations is that EnergyPLAN has a contradictory preference: whereas the minimization of electricity excess accepts heat deficits, it does not allow for heat excesses. Furthermore, the minimization of electricity deficits is not allowed if it arouses heat excesses. Summarized, the elimination of electricity excess is top priority but limited by the restriction to avoid heat excesses. The allowance for heat deficits is the main characteristic of the calculations of the model. Finally, the figure 6.13 shows a draft of the calculation procedure of EnergyPLAN, which includes the three critical situations and the respective operational strategies. It also illustrates where exactly the model starts to generate heat deficits.

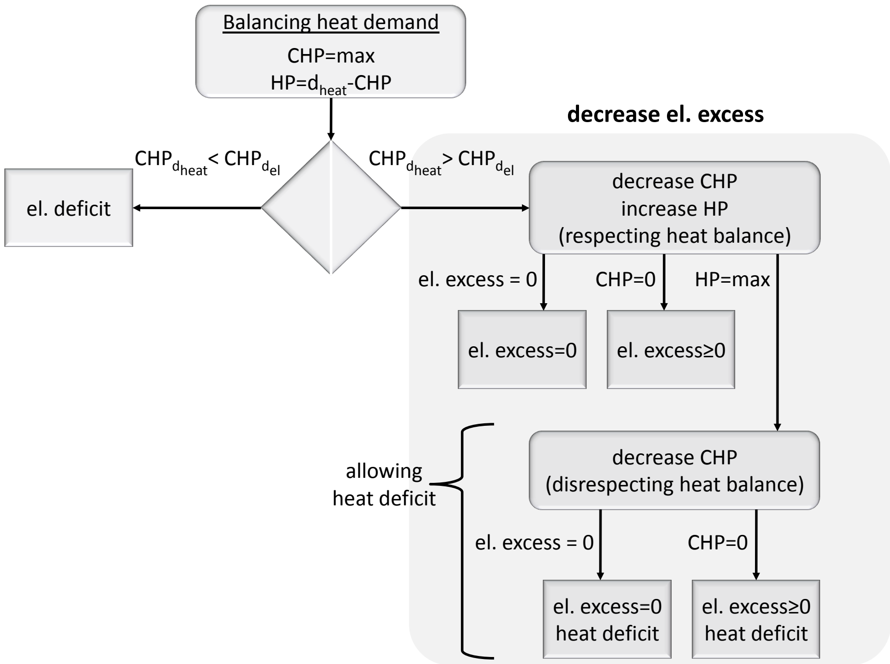

Figure 6.13: EnergyPLAN - calculation procedure

Finally, the calculation of the heat storage is evaluated. Notably, the storage always starts at full load. Furthermore, it disregards any thermal losses. Regarding the reference energy system, the heat storage is not computed by the model. Thus, the storage content and the operational values are zero. This failure occurs for the technical regulations strategies that take the electricity demand into account. A further investigation shows that also for balancing only heat demands the storage causes problems. Here, the storage induces an increase of electricity import. The explanation of the support team of EnergyPLAN is that the heat storage requires a boiler in order to be computed correctly. However, the documentation does not states this restriction of the heat storage. As a result, the storage of the model cannot be applied to the reference energy system. Apart from the need of a boiler, the documentation of the model reveals that the storage is only used for the minimization of electricity excess. Thus, the model disregards the ability of a storage to also reduce electricity deficits by increasing the CHP production during electricity shortages.

7 COMPOSE

7.1 brief description

COMPOSE stands for “Comparing Options for Sustainable Energy” and is a techno-economic energy project assessment tool developed by M.B. Blarke at Aalborg University in Denmark in 2008[24]. Since then, the tool has been improved continuously. The tool is also a social platform that enables the users to share and compare their projects. COMPOSE aims to be an interactive tool that is used for discussing problems regarding energy issues and especially sustainable energy options.

COMPOSE is a parametric linear programming model that combines the system wide perspective with the detailed operational design perspective[24]. Noteworthy, the term system means the embracing energy-economy system that sets the frame conditions for an energy subsystem or energy project. Whereas this thesis uses the term as a synonym for energy project or energy option. For further reading this has to be kept in mind. The model intends to integrate the strengths of EnergyPLAN on the national system level and of EnergyPRO[16] on the operation level[18]. COMPOSE offers high flexibility in designing this energy-economy system and the associated energy option. Furthermore the user is enabled to define the methodology regarding the kind of optimization, the optimization time period and solvers. This high scope for design leads to many different user-defined and thus unique energy systems and characterizes the tool as a modeling framework.

COMPOSE was used to identify options for dealing with intermittent renewables[25]. Moreover, COMPOSE is able to calculate a characteristic value that reveals the intermittency friendliness of a an energy system. This value has been named “relocation coefficient”[1] and played an import role in the article of Blarke and Lund[26] who investigated the benefits of energy storage and relocation options. Additionally, the model was applied to evaluate three different straw-fueled concepts of quad-generation that supply all 4 energy services: electricity, heat, cooling and liquid or gaseous fuels[27]. Furthermore, COMPOSE evaluates a project regarding economic, financial and fiscal costs, CO2 emissions and consumption of primary energy resources. Moreover, the model offers uncertainty analyses. The user is enabled to specify uncertainty ranges for several variables, which are then applied in extensive Monte Carlo risk assessments. Finally, the model is also able to formulate Mixed Integer Linear Programming Models that allow for discrete variables of producing devices.

[1] “The relocation coefficient is defined as the statistical correlation between net electricity exchange between plant and grid, and the electricity demand minus intermittent renewable electricity production.”[24]

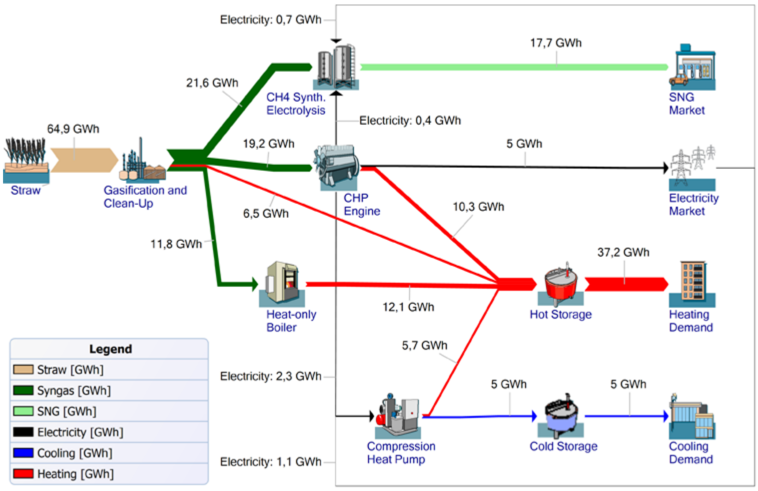

Figure 7.1: Quad-concept 2013 energy balance [Reference:[27] BLARKE, M.B., ENERGIANALYSE.DK. QUAD-generation: Intermittency-friendly distributed generation concepts for flexible production of electricity, heating, cooling, and fuels. (2014), p.11]

The support of COMPOSE is very helpful. Questions are answered very quickly and courageously by the developer of the tool, namely Morten Boje Blarke. Answers and advices are given via email or even via videos as little tutorials. However, the objective of COMPOSE is that the users help each other and work collaboratively with COMPOSE.

7.2 Structure and design of COMPOSE in general

STRUCTURE OF THE MODEL COMPOSE is structured into 3 main areas. These areas are:

- Analysis
- Database
- Interact

7.2.1 Interact

Firstly, the part "interact" is explained. This area includes the integrated wiki of the tool, which can also be accessed via "energyinteractive.net". By clicking on the wiki, the user can read a desription of COMPOSE including explanations of its abilities and its interactive design. Moreover, the user can gain information about recommended software for optimal use of the tool. Recommended are Microsoft Excel, MPL Modeling System and the solvers CPLEX and Gurobi. Excel is used in order to view the hourly results of the specified devices, demands and electricty and heat deficits or excesses. MPL can use the Linear Problem generated by COMPOSE to run it manually in MPL. Both MPL and COMPOSE require solvers. CPLEX and Gurobi are the most common solvers available and can be integrated seemly with the two programs. The licenses for the software except for Excel is freely obtainable for academic purpose. Whereas the license of CPLEX is already integrated into COMPOSE, the others have to be obtained manually. Summarized, COMPOSE embodies two programs in one, namely the modeling software and the solver. However, it is also possible to generate the modeling code for MPL and thus use COMPOSE only to write the code with the help of its graphical user interface.

The wiki can not only be accessed via the interact area. In fact, it is accessible from every point of the tool because it can be displayed in the right lower corner of the window. The wiki offers the possibility to enter information about the user-defined components (e.g. analyses, demands, devices,costs) designed in COMPOSE. For each of the components exists a list of already availabe records. The first in each list is always the “Default” Record, which has an article in the wiki that explains the characteristics of each component. In addition, the wiki offers a search function and displays the status in skype (online or offline) of the user whose component is currently viewed. By clicking on the skype button, the tool opens skype and calls the respective user immediately.

The right corner can also be used for viewing the COMPOSE-TV, which is the second part of the interact area. It consists of a few tutorials and just recently a webinar with students has been added to it. This idea should enhance the interactivity between the users. Thus, every user can create a video for COMPOSE-TV just as any other component in COMPOSE.

7.2.2 Database

The database stores all the components created by the users of COMPOSE for designing energy systems (e.g. devices, demands, costs) and also all relevant components for designing the energy economy system that is the surrounding framework of the energy system respectively energy project. Furthermore, the components for the user-defined methodology can be found here (e.g. solver, operational period, risk). The components of the database can include other components as a part of them. The components are the instruments that are used to design devices, whole projects, the energy economy system and the methodology. This is done in the area named “Analysis”. For better understanding of the model and the components of the database, the analysis area is explained below.

7.2.3 Analysis

The part “Analysis” is also divided into 3 parts.

- ▹ Design Options
- ▹ Define Analysis
- ▹ Analyze Results

Design options

In “Design Option” the user can design his or her energy system which are called options in COMPOSE. An option is mainly characterized by demands and processes. A third aspect can be a storage.

Demands are characterized by the energy type(heat, electricity, cooling, fuel), an hourly and annual distribution and finally the single value of the annual demand, which scales the distribution. The annual profile describes how the the annual demand changes along the planning period of the project. If it is supposed to be constant the values of the annual profile need to be defined to 1.

In addition to the following brief description of processes, the modular structure, which is a key feature of COMPOSE, will be illustrated. According to this modular character, components of the database can serve as superordinate and subordinate components i.e. they can be part of components and simultaneously consist of other components.

The category “process” and the included settings offered by the model lay the foundation for all facilities that produce and consume fuel or energy. Processes can be designed to represent facilities like CHP, HP, renewable electricity production or even PowerToGas. Moreover, the model offers the opportunity to forbid concurrent operation of up to 3 processes. The model offers several possibilities to design a process. These are specific features like, for instance, the energy type that is produced, the capacity of the process and the operation type. The latter can be selected as either “must run”,“continuous” or “discrete”. The first term means that the production of the process is fixed. This us useful for renewable energy like wind power. The second term allows for a linear range of the production rate. The third is used for “on-off” productions. This is possible because the model is able to solve MILPs.

Furthermore, processes include 3 more aspects: efficiency, fuel and cost respectively benefit. These 3 aspects are components of the database. Therefore, they function as subcomponents of the processes. Notably, subcomponents are very common for COMPOSE. These are listed in the respective field and can be viewed in detail by clicking on them. The model then leads to the desired component in the database. The efficiency can represent, for instance, the COP of an HP unit. The user is also enabled to establish multiple efficiencies. Thus, it is possible to create cogeneration plants. Additionally, each efficiency can be modified by allowing it to overproduce, to store the production and to produce apart from the demand also for internal devices. Finally, each process consumes a fuel. The term “fuel” is used as the general input of a process. Hence, the records of the fuel component can be designed to be e.g. electricity, heat, natural gas, oil or biomass. The component “cost benefit” can be used for operational and maintenance costs. The costs for fuel can be established in the process’ subcomponent fuel.

Define Analysis

The next part is called "Define Analysis". Here, the user defines the energy economy system and the methodology that should be used for the analysis of the project. Besides, the user can select an option in order to compare it with a so called reference option. The often applied procedure is a comparison of a sustainable energy option compared to a conventional reference option for solving the underlying energy problem. In addition, the user can select multiple options that result in multiple analyses made by the tool.

The framing energy economy system is just called "System" in the model. It is split into the energy system and the economy system, which are once again components of the database. Apart from these two components, the user defines the country, the year in which the project starts and the constant number of hours for each year.

Concerning the energy system, the user can define prices for the exchange of fuels or electricity between the option and the energy economy system. Regarding electricity, these prices are supposed to be the hourly prices on the spot market. The data has to be found externally whereas Danish data already exists in the tool.

Moreover, the energy system allows for choosing candidate marginal dispatch options. These options are the electricity producing plants that meet the electricity demand of the framing system respectively the national system. According to the merit order, based on the concept of the marginal power plant, these plants are used in the order of increasing marginal costs of electricity production. The objective of listing these plants is to find out if the designed energy option is able to avoid a certain amount of electricity by exporting electricity the superordinate system. This amount is otherwise produced by a plant that has higher marginal costs of electricity production than the designed option. According to the merit order, the designed option would be placed before the next best plant with a capacity that equals the electricity export respectively excess of the option. Any excess electricity production of the option is then the amount of electricity that can be avoided for the next best plant. In case of fossil fuel consuming power plants and an overproducing option, the designed option can save primary energy consumption and CO2-emissions. In the opposite case, a deficit of electricity necessitates the import of electricity, which is then met by the next best power plant. COMPOSE provides characteristic single values that show the impact of these effects (e.g. avoided CO2, avoided fossil fuel consumption, marginal dispatch tier 1, 2, 3, etc. ratio).

Finally, the model offers possible input in terms of intermittency. With the help of the superordinate system's electricity demand and multiple intermittent energy productions, the model is able to calculate the "relocation coefficient" of the designed energy option, which indicates its intermittency-friendliness. In case of intermittent wind power, this means how well the option allows for the integration of wind power into the system.

The component "Economy system" enables to define the planning period of the project, which can range from 1 to multiple years without limitation. Additionally, both the real economical and real financial discount rate can be specified, which are used for discounting future costs to present values and for annualized investments. Furthermore, the value added tax rate can be defined. Finally, the user can choose to add carbon costs caused by the projects local CO2-emissions to the total economic costs of the project.

For the calculations of COMPOSE the user is allowed to choose a solver. The solver CPLEX is already integrated but also other solvers can be used (e.g. Gurobi, COINMP, LPSOLVE and GLPK). The objective of the solvers can be a minimization of economic, financial or fiscal costs. Additionally, the user can decide about the optimization time period. Noteworthy, this is different to the planning period or the calculation time step of 1 hour. The optimization period is the period that will be optimized by the solver regardlessly of previous or following periods. For instance, if the period is selected to be 1 week the solver optimizes one week after the other. Possible optimization periods are 1 day, 2 days, weekly, monthly, semi-year or 1 year.

Furthermore, the user can run an analysis including uncertainty for specific variables (e.g. process capacity, storage capacity or annual demand) by including a risk component. The risk component offers the usage of mathematical distribution functions in order to generate a range of values for the uncertain variable. The number of different values is defined by the number of trials. The model computes all trials and lists the results of the option for each trial in accordance to a Monte Carlo Analysis.

Moreover, the model enables to establish a penalty for overproduction of processes. This “dump penalty” assures that the optimized operation seeks to avoid overproduction. Even very little penalties measured in the used currency (e.g. 0,00001€) can lead to this kind of operation.

Analyze results

The tool offers 3 different kinds of output. One output are the single values that are listed on this page (e.g. demands, production, fossil fuel consumption, CO2-emissions). These values can either be shown in a little graphic or in table. Secondly, the user can open the resulting hourly values of the components that are part of the energy option(e.g. hourly productions of processes, demands). The third output is the written MPL code for the project in form of a textfile (.txt) including all required textfiles (e.g. hourly distributions, demands) that are required for solving the same linear problem in MPL.

7.3 Modeling the defined energy system with COMPOSE

For creating an analysis in COMPOSE it is necessary to learn how to work with the model. Apart from the organizational structure of the tool, it is important to understand the graphical user interface, which is similar for for the most pages of the tool. The graphical user interface is structured in

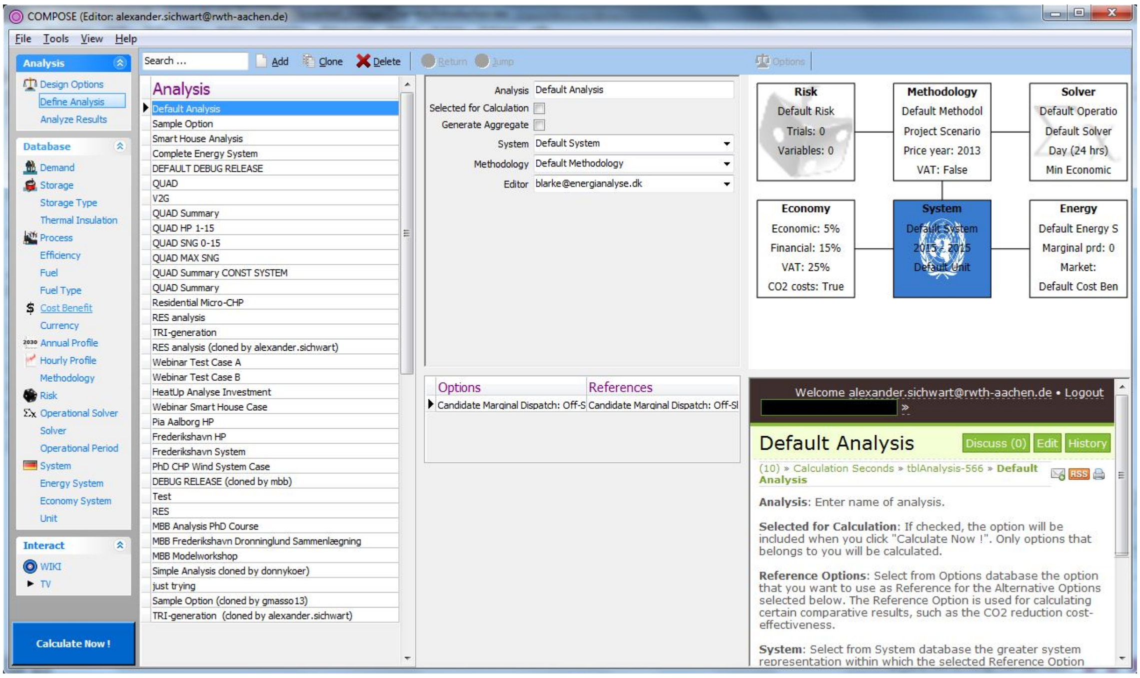

Figure 7.2: COMPOSE - graphical user interface

4 columns. The first column shows the organizational structure of COMPOSE: analysis, database, interact. This column is fixed except for the possibility to show or hide the records included in each of the three areas. The column also serves as an orientation because the user can see where exactly in the organizational structure he or she is working at the moment. On the bottom of this left column is the calculation button, which tells the model to calculate an analysis. It is accessible at any step of working with the tool. The second column lists the available records of the selected component. The next column includes the single value and boolean value settings and the subcomponents of each component. Thus, the user can see the design of each record in this column. Finally, the last column is divided in two. The upper half shows the graphics (e.g. flowchart of energy systems, hourly and annual profiles) and the lower half is used for the interactivity area (wiki or videos).

The creation of an analysis in COMPOSE requires an energy system consisting of demands and processes, a superordinate energy economy system in which the energy system is placed and finally a specification of the methodology i.e. the kind of analysis and optimization. Due to the operational focus in this thesis, most of the financial aspects can be excluded. The costs oriented optimization of the model necessitates to define at least a minimum of costs. These costs are operational costs. Any taxes and fixed costs like investment costs are disregarded. As a result, the framing system can be designed very simple because most of its settings do not influence the operational optimization. Consequently, the economy system consists only one relevant setting for the desired analysis, namely the number of years of the planning period. In this case it is supposed to be an analysis of 1 year due to the operational focus. Whereas both the economic and financial discount rates, the VAT rate and the carbon costs do not play any role for the operational optimization. The values are thus not important. However, an economy system is required. For such a case the user can choose the default record of the respective component. Regarding the energy system, the default record is also sufficient. The reason is that the analysis concentrates on the local energy system and the operational costs. It does not require any market prices for electricity or fuels, which can be defined here. In addition, the specification of marginal power plants and intermittent demand and supply can be disregarded because these are only used for the calculation of single value results (e.g. avoided CO2, avoided fossil fuel consumption, intermittency-friendliness).

Furthermore the component "methodology" needs to be defined. For the analysis of the thesis the settings concerning the candidate marginal power plants and the kind of calculation of investment costs can be disregarded. Moreover, the risk component is not considered for the analysis. Of importance is the component "Operational Solver". It allows for choosing the solver, the operational period and the kind of the optimization (economic, financial or fiscal costs minimization). For the purpose of this thesis the optimization should achieve a technically reasonable operation mode i.e. minimize fuel consumption and balance heat and electricity. Therefore, only variable costs are considered. COMPOSE can be instructed to operate in a certain way by deciding appropriate costs. For this kind of optimization it is recommended to choose the economic optimization because it ignores any financial cost components and is oriented towards variable and fixed costs without taking taxes into account. Contrary, a financial optimization is used by investors, as it is based on actual market costs including taxes. The division allows for powerful analyses of how to design fiscal instruments (e.g. find the tax on electricity to make a particular technology feasible from a financial perspective**). However, as only operational costs are implemented all three optimizations lead to the same results. The operational period is defined to be 1 year because the operation should achieve the best results for a whole year. Gurobi is selected as the solver but also other solvers like CPLEX can be used. Another important setting for the methodology component is the dump penalty. Even a very low value ensures that dumping of produced energy is minimized, which makes sense for a technical optimization.

In the area "Design Options" the user is enabled to create a new energy option. As explained an option consists of demands, processes and as the case may be storage systems. Both the heat and electricity demand require hourly distribution data. These can be imported into the database of hourly profiles if they are available as a text file (.txt). Then, the type of energy and the annual demand determine each demand sufficiently. Via the return button the selected option can be viewed again. Now the graphics display in the right upper corner of the window has built the first two blocks of the flow chart of the energy option. For more complex options these blocks can be moved and also the flowchart can be shown in full screen by a double click on the graphics window.

Whereas the model enables to create multiple demands, the demands can not be met solely. This means that a demand allows all appropriate devices regarding energy production to produce for it. Thus, there is no possibility to analyze an energy system consisting of several demands that have to be served individually. Consequently, a scenario consisting of subsystems that is missing a heat grid can not be modeled by the tool. As a result, there are only two scenarios regarding urban districts that result from the prerequisite of thermal and electric connection: one single house and numerous houses connected to a non dissipative heat grid.

Apart from the processes RES, CHP and HP, COMPOSE requires processes that meet possible deficits of electricity and heat. This is necessary because the model only considers the defined processes. It does not calculate deficits automatically. If, for instance, the CHP and the RES electricity production cannot meet the electricity demand, the model is not able to compute the analysis and displays an error message. The electricity scarcity has to be compensated by a further electricity producing process. Contrary, if the demand can be met there is no need for a deficit process. However, it is recommended to create one because deficits usually appear during the analysis. Such a deficit process needs to be designed with high costs in order to prioritize the RES and CHP production. This applies also to the heat production. As a result, the deficit process can be described as the purchase of energy in order meet the demand. These deficit processes already exist as records in the component “process”. They are characterized by a very high capacity, an efficiency of 100%, a continuous operation type and very high costs.

Other important features of processes in COMPOSE are the decisions about allowing internal usage, storing and dumping. The user needs to decide about these possibilities for each efficiency of a process. Thus, multiple energy productions that are characterized by multiple efficiencies as it is the case for the CHP can have different designs. As a result, it is possible to allow a CHP for dumping heat (heat efficiency) but not to dump electricity (electricity efficiency). Allowing internal usage for an efficiency means that the produced energy can serve as the fuel of another process. If a process is selected to consume internal fuels it uses energy of the appropriate energy type that is produced by processes inside the energy system, which are defined to allow for internal usage of their production(CHP, RES).

The RES production is a process with the operation type “must run”. This ensures that the production of RES is unchangeable. The production is determined by the hourly profile and the capacity. The CHP unit can be defined to be either a heat or an electricity type. Its operation type is continuous. The characteristic of the CHP process record is that it comprises two efficiencies: one for heat and for electricity production. Each efficiency is created by defining the percentage and the energy type of the production. Furthermore, the CHP allows for internal usage of its electricity

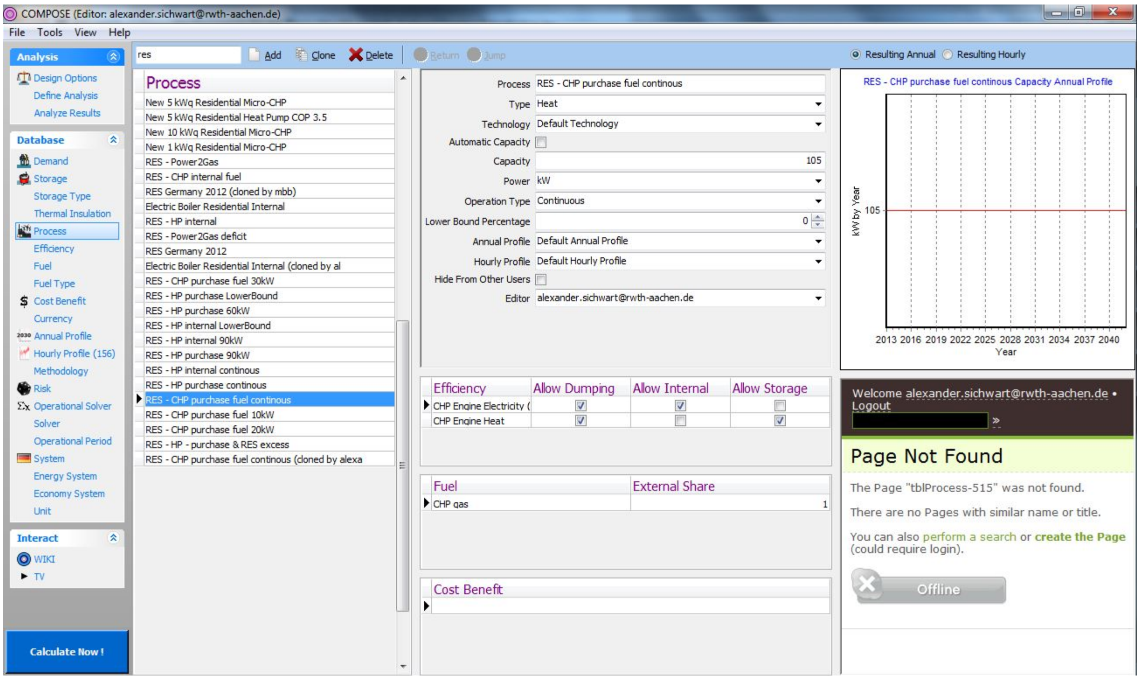

Figure 7.3: COMPOSE - CHP process

production. This ensures that the electricity produced by the CHP can consumed by the HP unit. Additionally, the CHP heat production is allowed to be stored.

The process representing the HP device is created similarly but the HP requires only one efficiency that is used as the COP of the HP unit. The main difference between the design of the CHP and the HP is the number of fuels that are required for each process. Whereas the CHP uses 1 fuel in this case, namely natural gas, the HP seems to require two. The fuels of the HP seem to be internal electricity from RES excess and purchase from the electricity grid. A process in COMPOSE can use multiple fuels with a constant share of each fuel. A constant share of RES excess does not allow to consume as much RES excess as possible, as it is recommended for an optimal usage of the HP unit. However, this feature can be used, for instance, for devices that consume a fixed mixture of fossil and gaseous fuels as it can be the case for CHPs.

Fuel	External Share
Biogas	0,3
Natural gas	0,7

Figure 7.4: COMPOSE - Multiple fuels

For this case an idea could be to establish two identical processes that use different fuels. One process consumes RES excess and the other purchases electricity from the grid. The preference for the process using RES excess results from the difference in costs. Unfortunately, this idea leads to a higher capacity of the HP device because both processes could be used at the same time. An idea could be to use the feature of non concurrent processes that is offered by the model. Whereas this

Process	Non Concurrent Operation	Non Concurrent Operation 2
HP purchase	RES - HP internal	
HP internal		

Figure 7.5: COMPOSE - Non concurrent processes

avoids an increase of the capacity, it evokes a decrease of the capacity and leads to very unrealistic operation modes. A simple situation can illustrate this problem. In a situation of small RES excess and high heat demand, the HP using RES excess is forced to operate but it is not able to meet heat demand completely. The purchasing HP is then not allowed to produce the remaining heat because the concurrent operation of the processes is forbidden. As a result, the HP capacity cannot reach its capacity, which is not a realistic case.

Finally, the solution is a compromise. Only one HP process is installed, which uses only internal electricity. Moreover, only one deficit process for electricity is created. It meets the remaining electricity demand and also allows for internal usage of its electricity production. Thus, it supplies the HP and the demand.

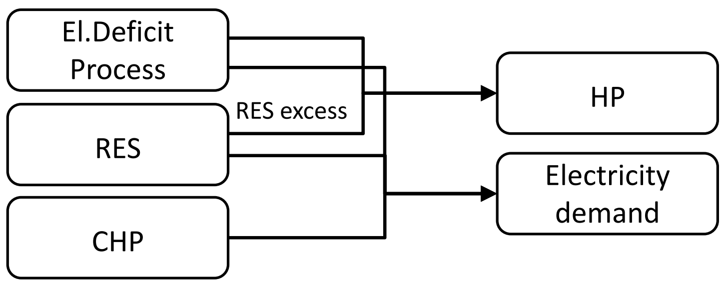

Figure 7.6: 2 electricity deficit processes

Additionally, the efficiency can be dependent on ambient temperature by implementing an appropriate hourly profile. This feature can be advantageous for more precise modeling of an air source HP. However, simplifications have to be taken into account and effort is required. The hourly profile of the temperature must be transformed in order to eliminate negative values. The efficiency can be selected to be a maximum value so that the maximal efficiency is only reached at the highest ambient temperature. As a result, the dependency of efficiency and temperature is linear, which is still a considerable simplification. Due to the complicated procedure and the small advantage, this opportunity needs to be considered carefully.

The storage system can be defined for several energy types (electricity, heat, cooling, fuel). The settings for storage systems are numerous. Especially, the thermal loss is a detailed feature. The user is able to select different thermal insulation materials, the thickness of the insulation and make it dependent to the ambient temperature. However, the thermal loss can also be ignored. The storage capacity of the hot water tank, that is used for this thesis is defined in Liters. The energetic capacity is determined by the input and output temperature. Furthermore, the models offers to impose restrictions on the operation of the storage system (e.g. start with full load, begin and end with empty storage content).

A record of the “Cost Benefit” component is characterized by the type of costs respectively benefits. These are energy production costs, fuel costs, selling prices, investment costs and fixed annual operational and maintenance costs. An extraordinary cost type is the startup cost of a process. This can help to reduce the number of startups, which can be useful for CHPs, for instance. Moreover, each type must be specified to belong to one the three costs categories (economic, financial, fiscal). Finally, a very important feature is that the implementation of an hourly profile provides the opportunity to establish e.g. electricity or fuel spot market prices.

Finally, the designed components are shown in figure 7.7 in the way it is displayed in COMPOSE. On the left side are the selected energy types for the whole system. Right next to them the specific fuels are shown. Afterwards each process is shown next to the fuel that it consumes. On the right side, the demands are shown. In between the HP and the storage are shown, which both only use internal fuels.

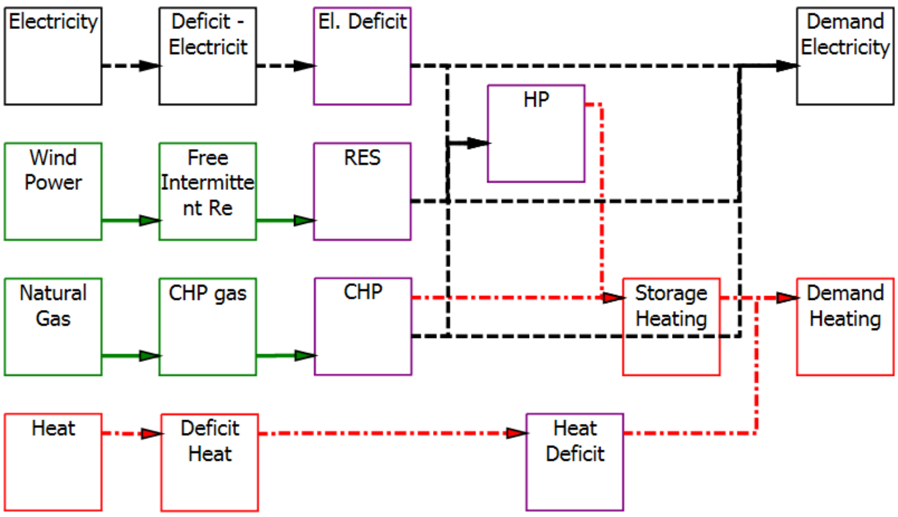

Figure 7.7: COMPOSE - designed components in energy flow chart

7.4 Calculations in COMPOSE

The calculations of COMPOSE are created in the MPL format. For each analysis the model generates a new optimization problem in MPL. These are then calculated by solvers.

The calculation of COMPOSE is mainly structured according to the format of an optimization problem, namely an objective function and constraints. The objective function is to minimize costs. The constraints comprise first the basic technical equations including the equations of thermal and electric productions determined by efficiencies and fuels and secondly the allocation of productions for meeting the demands. The letter part is characterized by the different features and characteristics of COMPOSE as the internal fuel and the possible allowance of dumping produced energy. Hence, the total production of a process is structured as follows:

$$\begin{aligned} p = \quad & p_d + p_{int} + p_{dump} + p_{s,in} \\ \\ p: \quad & \text{total production} \\ p_d: \quad & \text{production for meeting the demand} \\ p_{int}: \quad & \text{production for supplying internal devices} \\ p_{dump}: \quad & \text{overproduction} \\ p_{s,in}: \quad & \text{production for loading a storage system} \end{aligned} \tag{7.1}$$

These different destinations of the production can be served by multiple processes.In general, these different destinations of the energy production consist of the aggregation of appropriate productions regarding the type of energy.

$$d = \sum_{j=1}^{n} p_{d_j} \tag{7.2}$$

$$f_{int} = \sum_{j=1}^{n} p_{int_j} \tag{7.3}$$

$$s_{in} = \sum_{j=1}^{n} p_{s,in_j} \tag{7.4}$$

$$p_{dump} = \sum_{j=1}^{n} p_{dump_j} \tag{7.5}$$

$$\begin{aligned} d: \quad & \text{total demand} \\ f_{int}: \quad & \text{total fuel produced for an internal device} \\ s_{in}: \quad & \text{total storage input} \end{aligned}$$

The optimal allocation from the model's perspective is the one with minimal costs. In the reference case of this thesis, the production concerns heat and electricity.

$$p_{el} = p_d + p_{int} + p_{dump} \tag{7.6}$$

$$p_{heat} = p_d + p_{dump} + p_{s,in} \tag{7.7}$$

Equation 7.6 counts for the RES and the CHP electricity production. Both allow for internal usage and overproduction of electricity. Equation 7.7 is applied to the HP unit and the CHP unit. The heat production does not include any productions for providing an internal fuel due the absence of heat consuming processes in the system. Noteworthy, the overproduction of heat is decided to be allowed but it is kept minimal due to the dump penalty. Regarding electricity, a process, namely the HP unit, exists that consumes internal fuel. In terms of the reference energy system, the internal fuel which is the electricity input for the HP is supplied by the electricity production of the CHP, the RES and the electricity grid (according to equation 7.3).

$$e_{HP} = p_{CHP,int} + p_{RES,int} + p_{el.grid,int} \tag{7.8}$$

The optimization of COMPOSE is always a cost minimization. Thus, if the user wants to design a specific optimization strategy, the parameters to change are the costs. For a technical analysis these costs can just be tendency costs that are used in order to create a priority order for the operation mode. Processes and fuels with low costs are preferred and high costs are used for the worst alternatives. In the reference case, these costs are based on fuel costs. The three fuels are natural gas for the CHP, electricity from the grid for the HP and the remaining electricity demand and heat for the remaining heat demand. The calculation of total costs of the reference system is added below.

$$\begin{aligned} C_{total} = \quad & C_{gas} + C_{el.grid} + C_{heat} + C_{dump} \\ \\ C_{total}: \quad & \text{total costs} \\ C_{gas}: \quad & \text{costs for gas consumption} \\ C_{el.grid}: \quad & \text{costs for electricity import} \\ C_{heat}: \quad & \text{costs for heat import} \\ C_{dump}: \quad & \text{costs for overproduction} \end{aligned} \tag{7.9}$$

Fuel costs are determined by the price and the amount of the fuel.

$$C_{gas} = c_{gas} f_{CHP} \tag{7.10}$$

$$C_{heat} = c_{heat} f_{heat,deficit} \tag{7.11}$$

$$C_{el.grid} = c_{el.grid} f_{el.grid} \tag{7.12}$$

$$\begin{aligned} c: \quad & \text{costs per 1kWh} \\ f_{CHP}: \quad & \text{CHP fuel consumption} \\ f_{heat,deficit}: \quad & \text{amount of imported heat} \\ f_{el.grid}: \quad & \text{amount of imported electricity} \end{aligned}$$

Moreover, the model offers the opportunity to add energy production costs. For instance, these energy production costs can be used for RES production like wind power because the fuel is free but the production causes costs. However, in the case of this thesis, the RES production is free because the operation type “must run” forces the production to draw through the system disregarding any costs. The difference between energy production costs and fuel costs for 1kW of energy production is induced by an efficiency lower than 100%. Regarding the electricity deficit process with an efficiency of 100%, the fuel consumption equals the production.

$$f_{el.grid} = \left(p_{el.grid,d} + p_{el.grid,int}\right) \tag{7.13}$$

For a technical analysis it is irrelevant whether the costs are fuel or energy production costs. The only important criterion is the relation between the different costs in order to instruct the model to prioritize correctly. Due to the preference of CHP and HP operation, the fuel costs are only necessary for the deficit processes. Whereas the electricity for the HP unit causes costs whenever it consumes electricity from the grid (electricity deficit process), the CHP has no cost effects. Low fuel costs do not change the operation mode of the CHP, as long as the production of electricity is cheaper than purchasing it from the grid. The calculation below shows the maximal price for gas, which ensures that the electricity produced by the CHP is cheaper than purchased electricity.

$$\begin{aligned} C_{CHP} &< C_{el.grid} \\ c_{gas} f_{CHP} &< c_{el.grid} f_{el.grid,d} \\ c_{gas} \frac{e_{CHP}}{\mu_{el}} &< c_{el.grid} \frac{e_{el.grid,d}}{1} \qquad , e_{CHP} = e_{el.grid} \\ c_{gas} &< c_{el.grid} \mu_{el} \end{aligned} \tag{7.14}$$

μ_{el} : CHP efficiency of electricity production

Furthermore, the CHP unit and the HP unit are able to operate dependent on the electricity balance resulting from the RES production and the consumption by the electricity demand. As these have fixed hourly values, it is possible to create a cost profile consisting of the difference between the RES production and the electricity demand. As a result, a profile follows that includes positive and negative hourly values. Thus, there are benefits as well as costs. The CHP is supposed to benefit from operating during electricity scarcity, whereas the HP should benefit from consuming electricity excess. Consequently, the HP unit has to be dependent on RES minus demand and the CHP unit has to be dependent on demand minus RES. These costs are recommended to be designed as energy production costs rather than fuel costs in order to avoid the influence of the efficiency.

In the following the opportunity to create the dependency of the HP unit on the electricity balance is disregarded in order to keep a clear overview of the principal calculation. For the same reason the storage system is missing in these calculations. The costs and settings chosen for the system analysis lead the optimization to generate results that have certain characteristics that can also be explained with the help of 2 main equations. These are the heat balance and the electricity balance. With the help of these equations the following section seeks to explain the calculations of COMPOSE.

$$d_{heat} = q_{CHP} + q_{HP} \tag{7.15}$$

$$d_{el} = e_{RES} + e_{CHP} - e_{HP} \tag{7.16}$$

Both equations disregard any deficit or surplus productions. Thus, the equations cannot be applied to situations with a deficit or an excess. However, they can function as the main foundation of the calculations. Noteworthy, this is a simplification made for a better explanation and understanding of the model's optimization. It is not the calculation methodology used by the model. The simplification of the two energy balances reduces the number of variables, which are then the electricity consumption of the HP unit and the fuel consumption of the CHP unit. As a result, the equations can be solved, for instance, for the fuel consumption of the CHP unit.

$$d_{heat} = \mu_{th} f_{CHP} + COP e_{HP} \tag{7.17}$$

$$d_{el} = e_{RES} + \mu_{el} f_{CHP} - e_{HP} \tag{7.18}$$

$$\rightarrow f_{CHP} = \frac{e_{RES} - d_{el} - \frac{d_{heat}}{COP}}{-\mu_{el} - \frac{\mu_{th}}{COP}} \tag{7.19}$$

μ_{th}: CHP efficiency of heat production
COP: HP efficiency of heat production

Afterwards, the HP electricity consumption can be calculated with the help of either the equation 7.17 or 7.18.

Regarding excesses and deficits, there are three cases which have to be considered. Case 1 represents a situation with an RES production that exceeds the electricity demand and a relatively low heat demand. In correspondence to equation 7.19 the fuel consumption is calculated but the resulting value is negative. The already existing electricity surplus cannot be consumed completely by the HP and thus leads to a surplus in the electricity balance. Therefore, there is no need for the operation of a CHP. Consequently, the HP supplies the heat demand solely.

$$f_{CHP} = 0 \qquad \rightarrow d_{heat} = COP e_{HP} \tag{7.20}$$

Whereas the electricity balance equation looses a variable by defining the fuel consumption of the CHP to zero, another variable is added, namely the RES excess production $e_{RES,dump}$. As a result, the electricity balance equation is valid again.

$$d_{el} = e_{RES} - e_{HP} - e_{RES,dump} \tag{7.21}$$

In the second and the third case the RES production is lower than the electricity demand. Moreover, meeting the electricity demand causes either a heat surplus production of the CHP (heat excess allowed) or a purchase of electricity from the grid (heat excess not allowed). Notably, a surplus production is not allowed for the HP. For both cases the calculated CHP fuel consumption according to equation 7.19 leads to a negative electricity consumption of the HP unit, which is not feasible. Therefore, the HP consumption is defined to zero and the calculated fuel consumption of the CHP is disregarded and has to be recalculated. The different cases lead to different CHP fuel consumptions.

The production of heat excess appears whenever the user allows the heat efficiency of a process to dump heat. In this situation the electricity demand is higher than the CHP electricity production resulting from meeting the heat demand. For meeting the electricity demand, the CHP has to produce a surplus of heat. By defining the HP consumption to zero, the fuel consumption of the CHP can be calculated with the help of the electricity balance.

$$e_{HP} = 0 \qquad \rightarrow d_{el} = e_{RES} + \mu_{el} f_{CHP} \tag{7.22}$$

The same situation is operated differently if the heat excess is not allowed. In fact, the electricity deficit process is used to produce the remaining electricity. In order to ensure that the CHP does not produce any heat excess, the CHP fuel consumption is calculated with the help of the heat balance.

$$d_{heat} = \mu_{th} f_{CHP} \tag{7.23}$$

Similar to the first case, the electricity balance is extended by the electricity deficit $e_{el.grid}$. With the help of the calculated CHP consumption and the missing HP consumption, the deficit can be calculated.

$$\begin{aligned} d_{el} = &\quad e_{RES} + \mu_{el} f_{CHP,heatbalance} + e_{el.grid} \\ f_{CHP,heatbalance}: &\quad \text{CHP fuel consumption for meeting the heat demand} \end{aligned} \tag{7.24}$$

Concerning the calculation of the storage system, no structure or procedure could be identified. However, results of the calculation of the storage system reveal that it is operated with the knowledge of the demands i.e. the storage is loaded in previous hours in order to avoid heat shortages later on.

Furthermore, the model considers thermal losses. The storage “losses are calculated on the basis of thermal conduction losses from free standing insulated tanks. Heat losses from radiation and convection are considered to be insignificant and are ignored.”[24]

7.5 Evaluation of the calculations in COMPOSE

The optimization of COMPOSE is always a cost minimization with technical restrictions. Therefore, the parameters are costs on the one hand and technical settings on the other hand. As a result, the model offers a high flexibility regarding the design of the optimization.

For the purpose of a technical analysis, costs are used in order to create a priority order of processes for the optimization. These tendency costs are helpful for designing a variety of different operation strategies i.e. different preferences for processes. The costs can be experimented with for small systems like the reference energy system. Accordingly, a specific range of costs can be identified that ensures a certain preference of a process compared to others. This has been done in equation 7.14. Regarding larger systems including numerous processes, this procedure becomes too complex. Clear preferences have to be used in order to ensure the desired priority order. Especially due to the interdependency of heat and electricity of the CHP and HP, the appropriate selection of costs for a desired priority order is very hard to find for large systems.

On the technical side, the user is able to design the processes. Apart from the efficiencies and capacities, the user is enabled to choose the operation type of a process(must run, continuous or discrete). The “must run” operation type makes the process a top priority with fixed hourly values. Furthermore, the user can choose to allow for surplus production and production for both internal usage and storage. This significant feature of the model leads to different cases in the calculation. Whereas, the HP unit is not supposed to consume electricity for a production of heat excess, the CHP unit offers 4 different variations due to its cogeneration of heat and electricity.

1. do not allow any excess
2. allow only for electricity excess
3. allow only for heat excess
4. allow for both heat and electricity excess

In situations of lower RES production than required for the electricity demand, the first to selections lead to the importation of electricity from the grid, whereas the last two do not import any electricity because the CHP unit is allowed to overproduce heat. The two groups can be divided into the cases explained above: heat excess not allowed (1,2), heat excess allowed (3,4). The different strategies of heat excess and electricity deficit will be illustrated with the help of tables comprising hourly values of such a situation.

Instantly, the RES excess production, which both strategies have in common, is illustrated.

The RES production is higher than the electricity demand. Except for the first hour, the heat demand is low. The first hour is characterized by a high heat demand. Thus, the surplus production of electricity can be compensated easily. The CHP unit is operated for supplying the HP and the heat demand. The HP unit consumes the RES excess and the CHP electricity production in order

hours	$demand_{heat}$	$demand_{el}$	RES	CHP_{el}	HP_{el}	$balance_{el}$	$balance_{heat}$
1	130	18	25	25	32	0	0
2	19	13	23	0	6	4	0
3	14	9	20	0	5	6	0
4	16	9	14	0	5	0	0
5	18	8	11	2	5	0	0

Table 7.1: COMPOSE - RES excess

to meet the remaining heat demand. As a result, the electricity and heat balance is accomplished. The same operational strategy is applied for hour 5, which includes a low heat demand. In the fourth hour the heat demand can be supplied solely by the HP unit, which consumes all the electricity excess. The CHP does not operate because there is no need for more heat or electricity. In the hours 2 and 3 of electricity imbalance the CHP is neither operated. The imbalance results from a low heat demand, which limits the HP consumption of electricity excess. Moreover, the restriction of the HP forbids to consume electricity excess when there is no need for heat. Changes in the design of the technical settings can only lead to different results if the costs are modified, too. If it was allowed to dump heat for instance, it is still cheaper to dump the RES excess than to dump the heat production of the HP, which amounts the triple of the excess. The reason is the common dump penalty. The excess production of electricity should cost more than the triple of the dump penalty in order to overproduce heat with the HP. However, the export of electricity is preferred for this energy system.

The next table shows the situation that is characterized by a low RES production that is not capable of meeting the electricity demand solely. Therefore, the operation of the CHP unit is necessary. Furthermore, the heat demand is relatively low. Whereas the strategy of allowing heat overproduction operates the CHP until the electricity demand is met, the group that forbids heat excess limits the CHP production when the heat demand is arrived and imports the remaining electricity from the grid.

hours	$demand_{el}$	RES	CHP_{el}	HP_{el}	$balance_{el}$	$balance_{heat}$
1	19	5	35	21	0	0
2	15	5	10	0	0	4
3	12	5	7	0	0	1
4	9	5	5	1	0	0

Table 7.2: COMPOSE - allowing heat excess

In the first and last hour the cogenerator and the HP unit succeed in balancing both heat and electricity. During the hours 2 and 3 the CHP supplies the electricity demand because it is allowed to overproduce heat. Therefore, the electricity balance is preferred at the expense of heat excess.

hours	$demand_{heat}$	CHP_{heat}	HP_{heat}	$balance_{heat}$	$balance_{el}$
1	110	47	63	0	0
2	9	9	0	0	-3
3	8	8	0	0	-1
4	9	7	2	0	0

Table 7.3: COMPOSE - no heat excess

Here, the heat excess is not allowed. The CHP is limited in the hours 2 and 3 by the heat demand. Moreover, the HP unit does not operate because there is no electricity available and the heat demand is low. As a result, the electricity has to be supplied by electricity from the grid.

These two strategies have to be considered when deciding about an optimization. The importation of electricity is feasible in an energy system that is connected to the electricity grid. Contrary, it is not appropriate for an island. The strategy of allowing heat excess avoids electricity deficits at the expense of heat overproduction. By implementing a heat storage the surplus of heat can be stored. This is the main benefit of a heat storage. It allows for systems that forbid heat excess to store heat in order to produce electricity autonomously and to reduce electricity deficits. The heat storage in COMPOSE can be operated for decreasing electricity excess and deficit.

The discussed calculations are based on technical and economic settings. Whereas the costs for a few processes can be defined easily in order to instruct the model to prioritize correctly, this can become very complex for large systems including numerous processes. The technical settings offer a wide range of possibilities for the design of the optimization. The results of different optimization designs can be compared in order to find the appropriate strategy for the energy system that is to be analyzed.

8 Comparison

Due to the inapplicable storage system of EnergyPLAN regarding the chosen energy system, the comparison of the operational strategies of COMPOSE and EnergyPLAN focuses only on the calculations of the CHP and HP. However, at the end of this chapter, the calculation of the heat storage made by COMPOSE will be shown. For the following comparison COMPOSE is instructed to forbid any heat excess i.e. it accepts electricity imports rather than dumping heat produced by the CHP in order to avoid an electricity deficit. The reason is the connection of the system to the electricity grid and a missing external heat supply.

The operation mode of the two models are similar except for a few situations in winter time. Situations of heat and electricity balance show the equal operation mode of the models. Regarding the heat and electricity imbalances that the tools have in common, both tools optimize similarly. As mentioned above, both accept electricity imports from the grid rather than meeting the electricity demand with the help of the CHP by overproducing heat. Both accept electricity exports rather than consuming all electricity excess with the help of the HP unit by overproducing heat.

The few different results in winter appear due to one main difference concerning the operational strategy. Whereas EnergyPLAN avoids electricity exports at the expense of a heat deficit, COMPOSE produces electricity excess in order to meet the heat demand. The operational strategies of the tools are briefly summarized in the figure 8.1. Three critical cases show the main similarities and the only difference in the operational strategies. Furthermore, the difference in the operational optimization is illustrated in the heat scheduling of one week in winter by the figures 8.2 and 8.3. Noteworthy, the operation mode of the HP unit is the same for both tools.

In the schedule of COMPOSE a heat deficit appears on the fourth day. It results from the imposed restriction that the CHP is not allowed to overproduce electricity. However, the optimization generates a lot of electricity excess due to the operation of the CHP unit. In detail, the electricity excess is not produced by the CHP but by the RES, which is allowed to dump electricity due to its intermittent production. Thus, the model just circumvents the restriction imposed on the CHP unit. The limitation of electricity excess is then the amount of RES production. This limitation applies to the fourth day. If the CHP is allowed to overproduce electricity, the heat deficit found in this week would be eliminated. For the further comparison and analyses, the CHP of COMPOSE is enabled to overproduce electricity. The resulting heat schedule is shown in figure 8.4.

For the illustration of the different operational strategies the electricity is taken into account. Figure 8.5 shows the electricity demand and the RES production. These profiles are fixed and can be

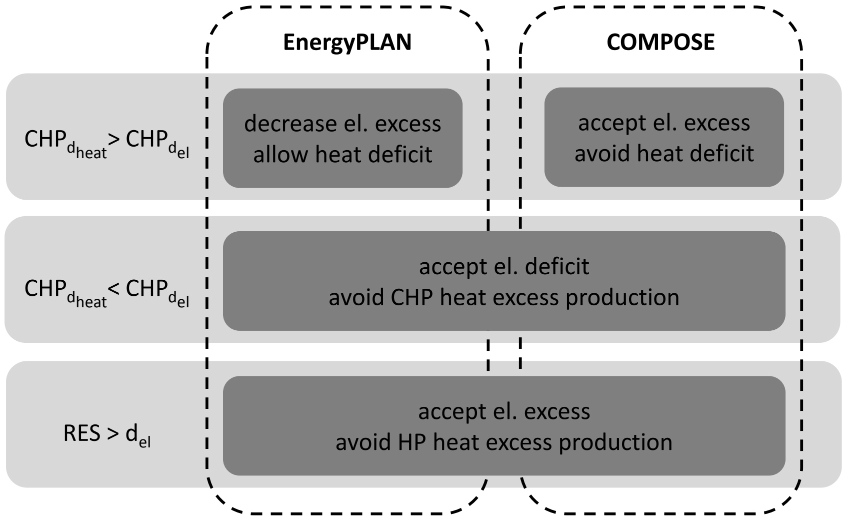

Figure 8.1: Operational strategies in critical situations

interpreted as the electric input of the system. If the two profiles are aggregated to the "Demand minus RES" profile (figure 8.6) the electric imbalance can be viewed. The positive values represent the remaining demand and the negative values represent the excess.

With the help of this electric imbalance the different operation modes of the CHP unit can be illustrated. Figure 8.7 mainly shows the operation schedule of EnergyPLAN. In addition, it shows the difference to the CHP production of COMPOSE, which is either the same or higher than the production of EnergyPLAN. The CHP productions shown in the chart are subtracted by the amount of electricity that is produced for supplying the HP unit (CHP-HP). This means that the internal electricity which is produced and consumed by the internal devices CHP and HP is excluded in this chart. As a result, the visual understanding of the CHP productions is facilitated. Whereas the production of EnergyPLAN is limited by the heat demand, COMPOSE exceeds the heat demand.

Furthermore the HP consumption that exceeds the consumption of electricity produced by the CHP is shown in negative values. Notably, it is also right to say that the HP consumes all RES excess and the resulting excess is produced by the CHP. However, the gap between the shown HP consumption and the electricity excess of the "el. demand minus RES" curve equals the final electricity excess of EnergyPLAN. Regarding the optimization of COMPOSE, the electricity export is higher due to the higher amount of CHP production. The different exports can be seen in Figure 8.8.

Finally, the yearly results of the models are compared in the table 8.1. The values of COMPOSE show the two different strategies that can be chosen for the CHP unit: allow and forbid a surplus production of electricity. The yearly values reveal that the heat deficits can only be avoided by allowing the CHP to overproduce electricity. Concerning the comparison with EnergyPLAN, the preference of EnergyPLAN becomes obvious in the figure 8.9. The different strategies of the two

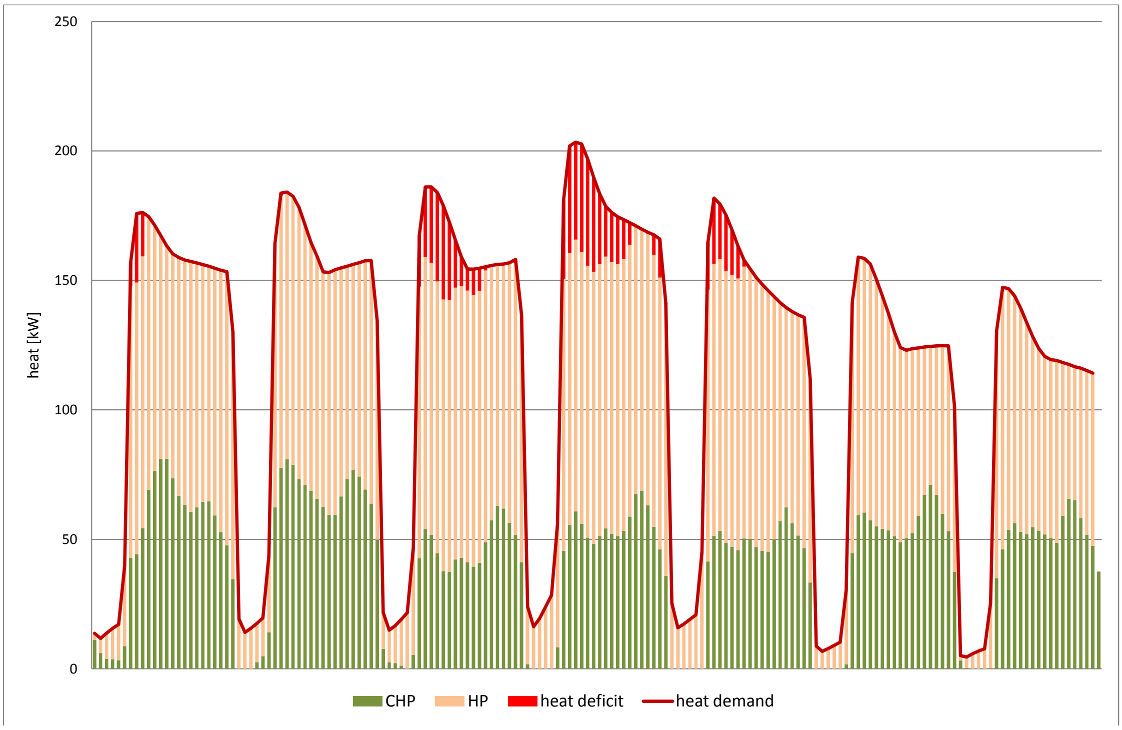

Figure 8.2: week schedule - heat - EnergyPLAN

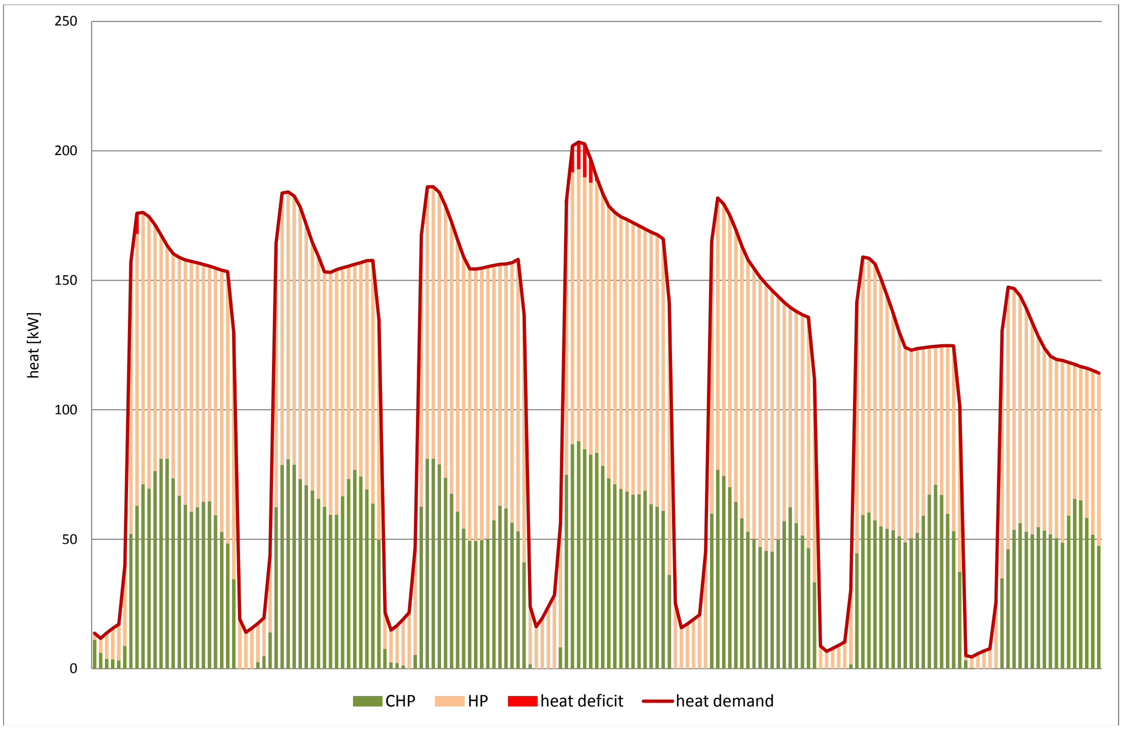

Figure 8.3: week schedule - heat - COMPOSE

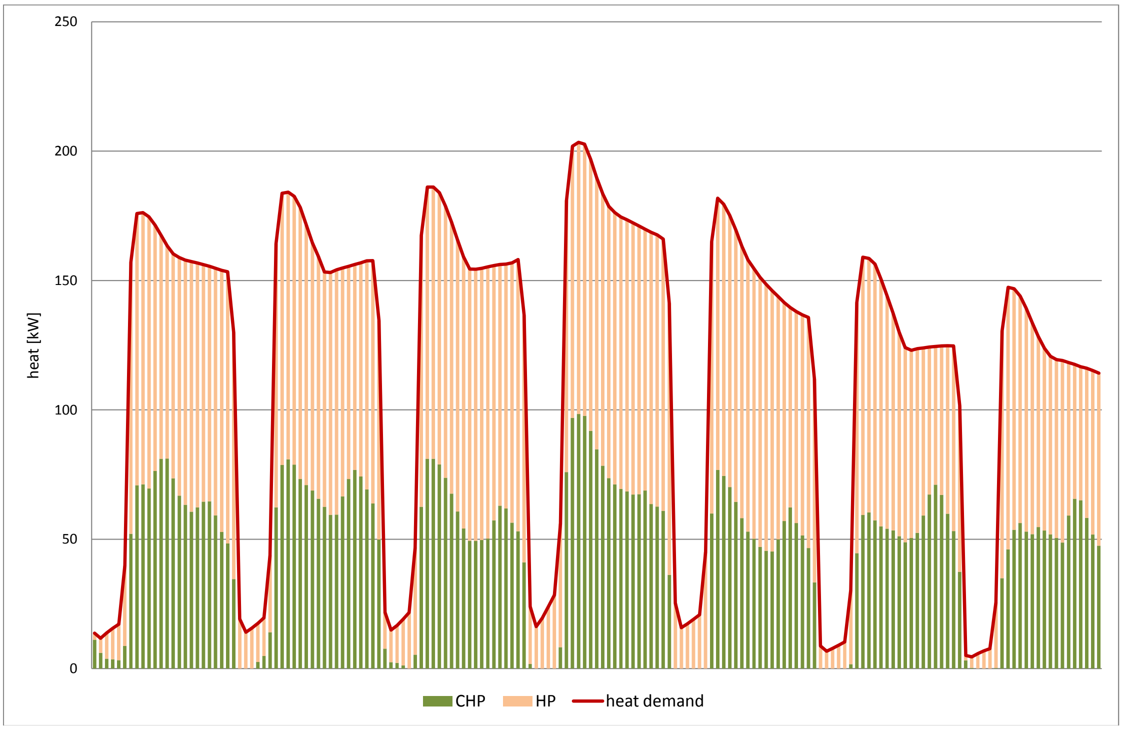

Figure 8.4: week schedule - heat - COMPOSE with CHP elecricity excess

models regarding the decrease of electricity excess are highlighted by shading the EnergyPLAN calculations that are not made by COMPOSE and brightening the strategy of COMPOSE. Whereas COMPOSE seeks to avoid heat deficits because the selected costs are chosen to be very high, EnergyPLAN always prefers heat deficits rather than electricity excesses.

	EnergyPLAN	COMPOSE			
		No CHP el.excess		CHP el.excess	
	[MWh]	[MWh]	change[%]	[MWh]	change[%]
gas consumption	442,1	445,9	+0,9	446,8	+1,1
heat deficit	2,3	0,5	-80,3	0	-100
heat excess	0	0	0	0	0
el. deficit	21,3	21,3	0	21,3	0
el. excess	4,4	5,8	+30,3	6,1	+37,8

Table 8.1: Comparison of yearly results without heat storage

Regarding the operational strategy of COMPOSE that produces heat excess instead of importing electricity from the grid, the differences increase enormously. Especially during warmer days with low heat demand, the different operational strategies become obvious. However, the strategy of producing heat excess is not beneficial for the reference energy system without a heat storage. Indeed, the storage system can be very advantageous for the system due to the flexibility that it

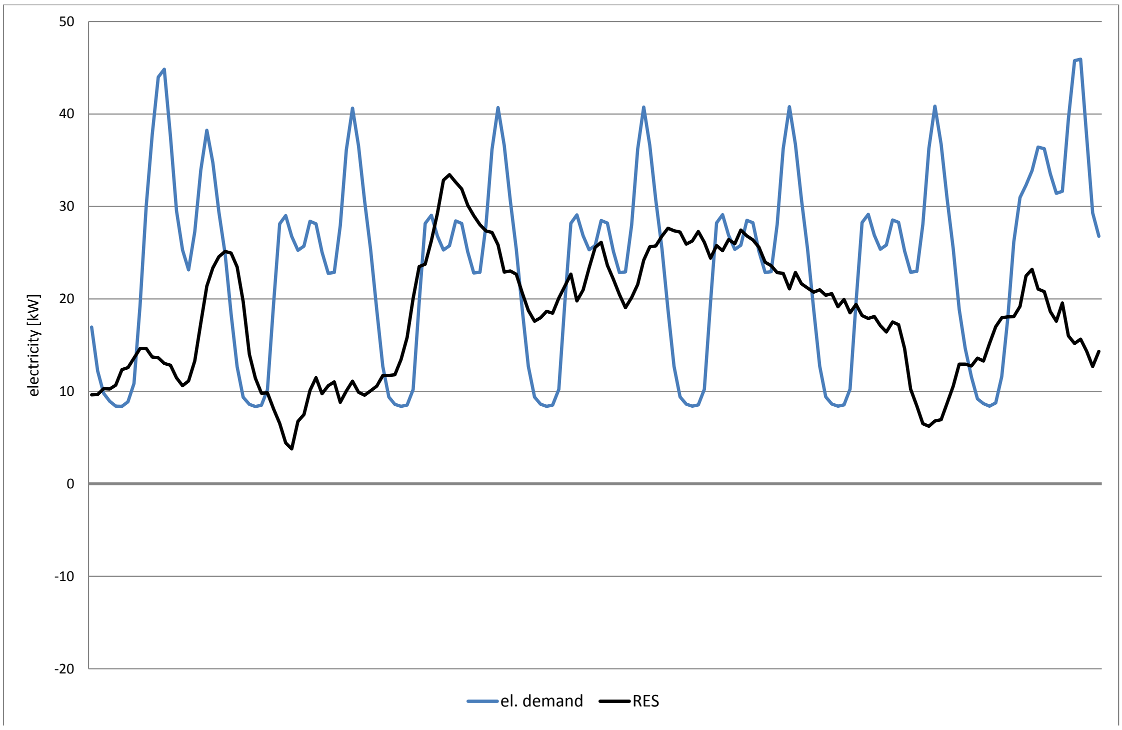

Figure 8.5: week schedule - electricity demand and RES production

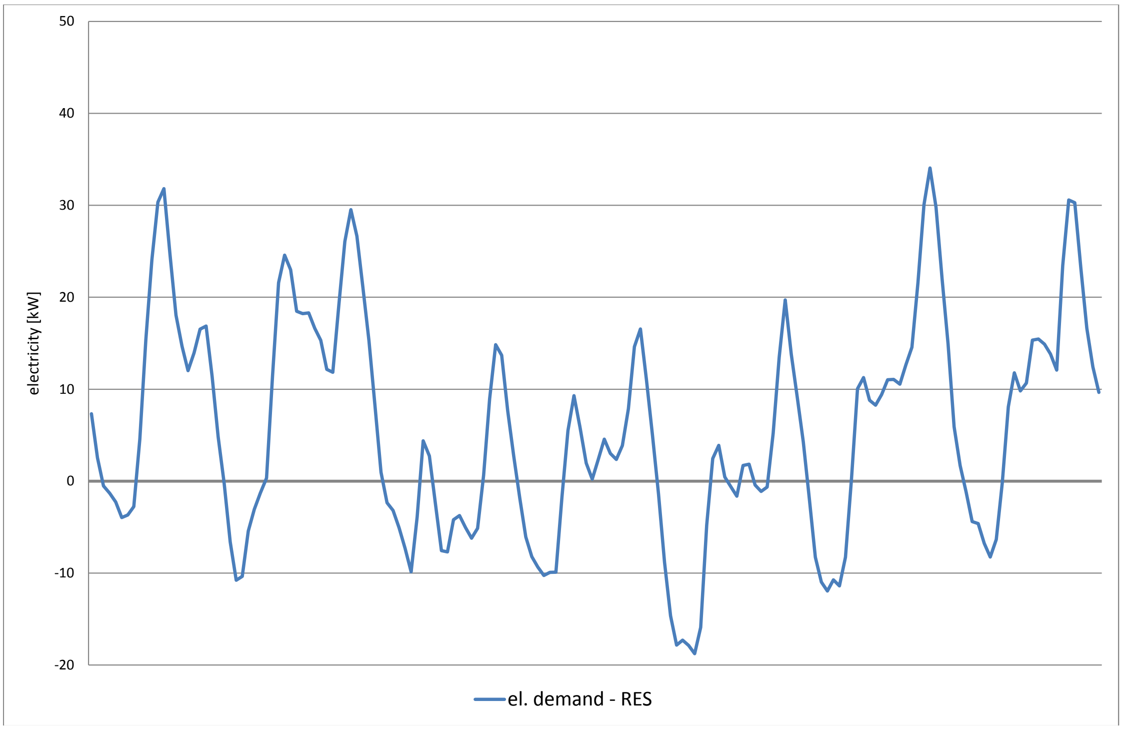

Figure 8.6: week schedule - electricity demand minus RES production

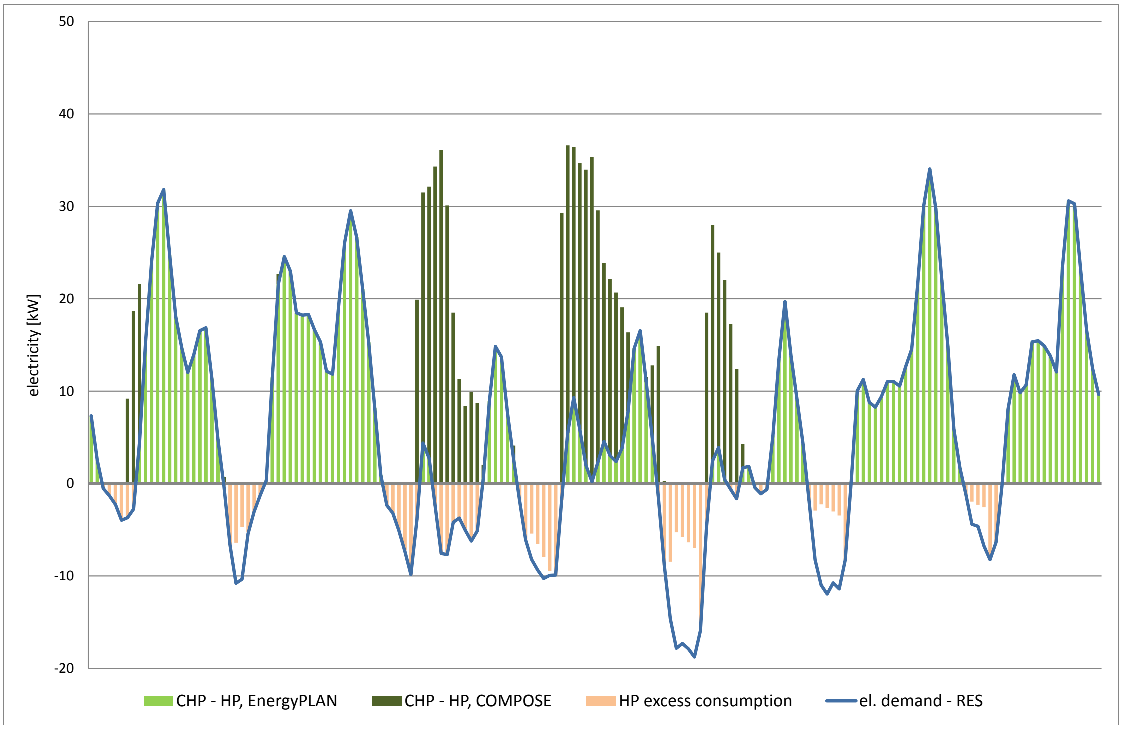

Figure 8.7: week schedule - difference in CHP operation

offers for the cogeneration plant and the heat pump.

Figure 8.10 shows the heat scheduling resulting from COMPOSE. The storage is defined to be empty at the beginning and thermal losses are included. One finding in this scheduling is that the storage is mostly loaded during the evenings. But it is more important to state that an operational strategy cannot be found. For instance, in a few hours the storage is unloaded abruptly, in others the it is unloaded piecemeal.

Finally, in contrast to the storage of EnergyPLAN, which is supposed to only minimize electricity excess, the storage of COMPOSE also allows for the reduction of electricity deficits. This makes the usage of the storage more valuable and thus leads to better results in the electricity balance of a system.

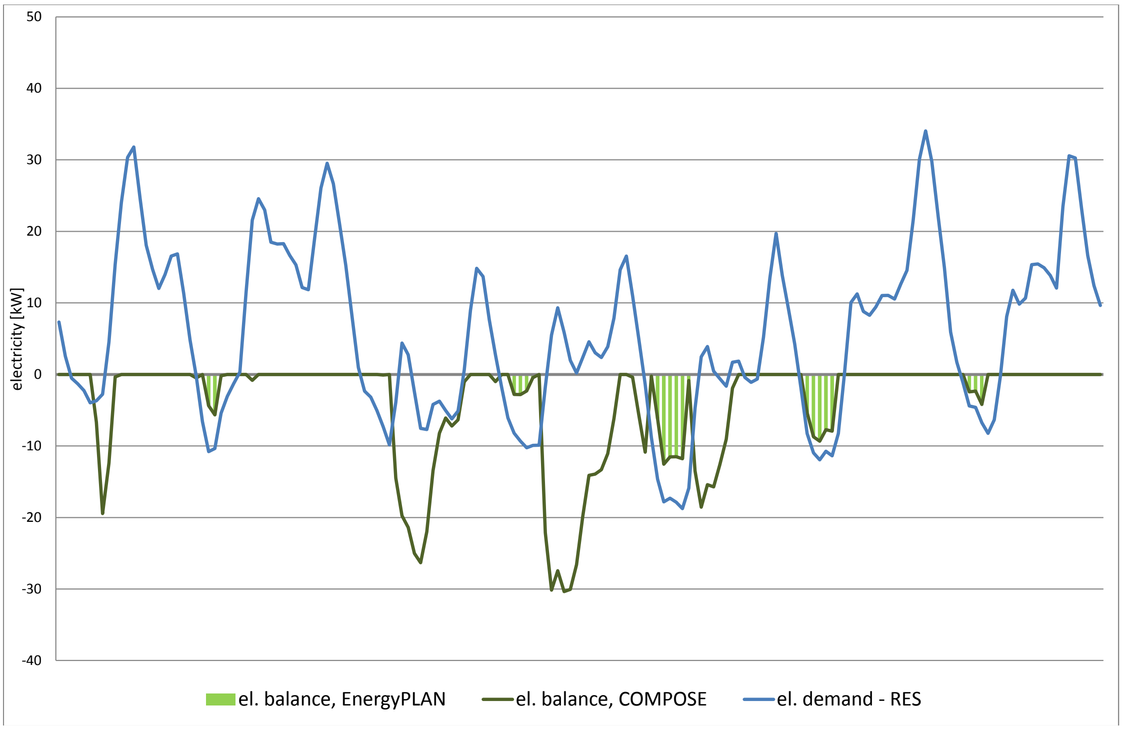

Figure 8.8: week schedule - electricity balance

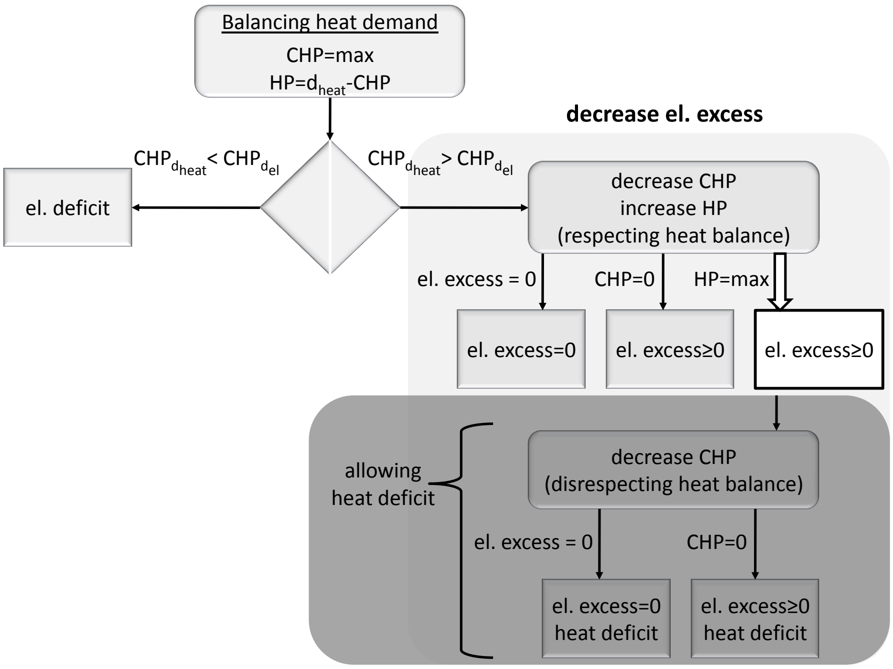

Figure 8.9: Calculation procedure of EnergyPLAN including difference to COMPOSE

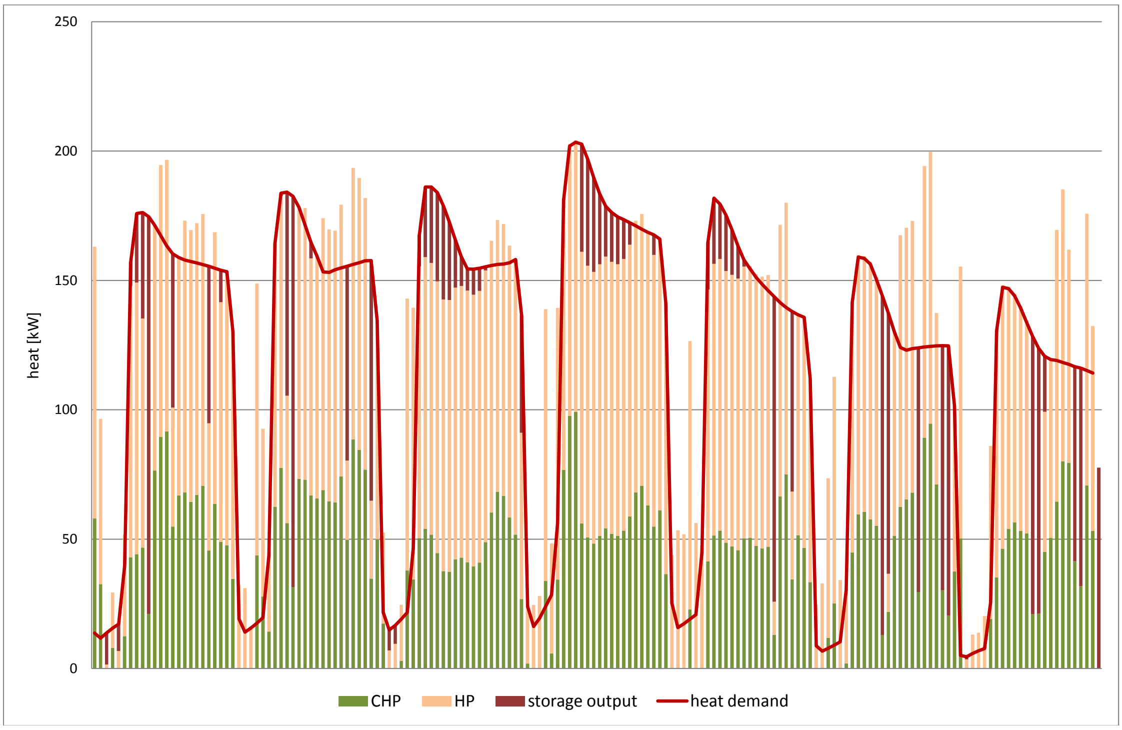

Figure 8.10: week schedule - heat with storage, COMPOSE

9 Application

The analysis of the reference energy system is supposed to illustrate the beneficial usage of energy computer tools. Generally, tools can be used for planning issues on the levels of operation mode, dimension and distribution of a specific energy system. Concerning the planning issues of the reference system, the respective analysis focuses on the dimension level i.e. planning the capacities of the facilities. One reason is the design of the energy system. For instance, the operational level is influenced by the system's connection to the electricity grid. This allows for electricity imports and exports. Moreover, the system is not connected to any heat grid. Heat can only be transfered within the internal heat grid that connects the devices and all residential buildings with each other. Therefore, heat can neither be imported nor exported and thus the devices should neither produce any heat excess nor accept any heat deficits.

Regarding the distribution level, the small size of the system and the thermal and electric connection inside the system allow for one unit of each technology. This is advantageous due to the higher efficiency of large facilities compared to smaller ones. Noteworthy, multiple smaller facilities of the same type can provide more flexibility, when the operation mode is restricted by a minimal operational load. Although, minimal loads for the devices lead to a more realistic analysis, such a restriction is not considered for this analysis. A minimal operational load complicates the analysis enormously. Since the focus of this analysis is put on the illustration of the principal benefits of quick calculations with the help of energy computer tools, it is advantageous to avoid any further factors that increase the complexity of the analysis. These benefits are chosen to be on the dimension level. An investigation on the distribution level is disregarded.

The analysis is made by COMPOSE because it enables to avoid heat deficits which cannot be compensated due to the missing connection to an external heat supply. Furthermore, the model includes the calculation of thermal losses of the hot water tank, which are taken into account for the analysis. The analysis is divided into three parts. The first part demonstrates a quick approach on how to find smaller feasible capacities due to the presence of a heat storage. This includes the improvement of the share of the capacities regarding their total heat production. The second part illustrates the impact of an increasing amount of renewable energy supply on the electricity balance and shows the resulting changes in the optimal shares for the capacities.

The reduction of the CHP and HP capacities can be advantageous because of a correlating decrease of investment costs of the devices. Contrary, a reduction of capacities risks heat deficits in situations of defective storage systems. Thus, a reduction of capacities has to be considered carefully.

However, it is worthwhile to show the influence of implementing a heat storage into the energy system.

In a first step, the size of the storage is fixed to amount 5000 liters. The reference case is that both capacities achieve together the maximal heat demand of 210kW. Additionally, the capacities are selected to be equal as it was done during the previous illustrations of this thesis thus, each heat capacity amounts 105kW. The storage enables to reduce these capacities. This reduction is shown in table 9.1 by running multiple calculations with a decreasing aggregated capacity. The important

CHP and HP capacity	210kW [MWh]	190kW [MWh]	170kW [MWh]	150kW [MWh]
gas consumption	464	465	470	474
heat deficit	0	0	0	2,6
heat excess	5,1	5,1	5,1	5,0
el. deficit	12,0	12,0	12,0	12,1
el. excess	3,7	4,4	6,8	9,9

Table 9.1: Comparison of yearly results dependent on capacities of CHP an HP

result is that the implementation of a heat storage allows to decrease the capacities of the devices without generating any heat deficits. The smallest of the 4 analyzed capacities that succeeds in avoiding heat deficits amounts 85kW. Thus, the aggregated capacity of the CHP and HP devices is 170kW, which is 40kW lower than the maximal heat demand. Noteworthy, the electricity excess increases by reducing the capacities. At this point, a selection of capacities would be based on the preference of either smaller capacities or less electricity excess.

In the following the storage size is increased in order to investigate if a further reduction of the capacities is possible. Figure 9.1 shows the smallest feasible heat capacity of the 4 chosen capacities that can avoid heat deficits. This explains that the capacity is the same for 5.000 and 10.000 liters. The doubling of the storage size allows for a further decrease of the total capacity but it does not achieve the next smallest capacity level.

Until now, the share of each capacity amounts 50%. An interesting question is if changes in the share of the capacities can compensate the increase of electricity excess that correlates with the decrease of the total capacity. For this investigation the storage is defined to contain 5.000 liters. For the decided storage size the table 9.1 can be used in order to select the smallest feasible capacity, which is in this case 170kW. Table 9.2 shows the changes in the results of 3 shares compared to the reference share of 50%.

Importantly, the 4 shares are able to avoid heat deficits. Contrary, the different shares show significant changes regarding the electricity balance. The CHP share of 60% induces an increase of electricity excess of more than 150% without generating any benefits for the system. Thus, a decrease of the CHP capacity seems to be advantageous. The positive effect can be seen in the reduction

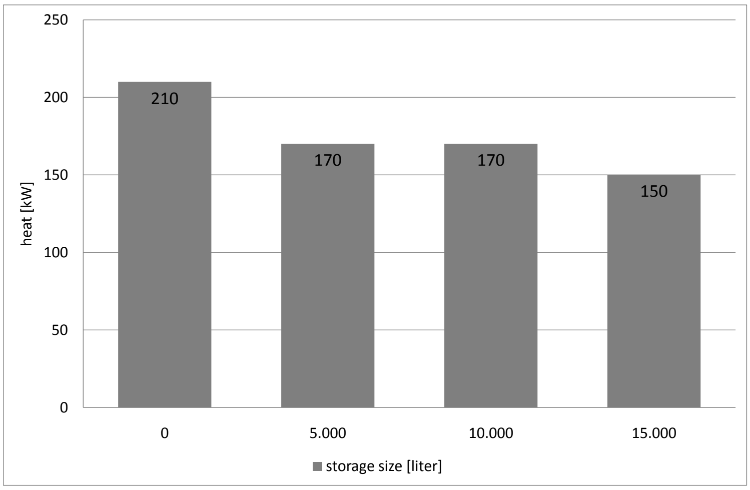

Figure 9.1: Smallest capacity dependent on storage size

CHP heat capacity share	30%	40%	50%	60%
	[%]	[%]	[%]	[%]
gas consumption	-6,9	-1,4	0	+4,4
heat deficit	0	0	0	0
heat excess	-0,9	+2,8	0	+0,2
el. deficit	+110,3	+5,9	0	0
el. excess	-47,4	-41,6	0	+156,3

Table 9.2: Comparison of yearly results dependent on ratio of CHP capacity

of electricity excess. Notably, there is a minimal CHP capacity in order to avoid negative impacts on the electricity balance. This limit is already exceeded at a share of 30%. Here, the electricity deficit has more than doubled compared to the CHP capacity of 85kW. In this case, an advantageous share is 40% because the electricity excess can be reduced by more than 40% at the expense of only small increases of heat and electricity deficit. Notably, the preference can also be to avoid any further electricity deficits, but for this analysis the objective is decided to be a minimal total electricity exchange i.e. sum of electricity imports (deficits) and exports (excesses). The absolute values for the different shares are illustrated in figure 9.2. The columns show that the amount of electricity deficit generally increases when decreasing the share of the CHP capacity. Noteworthy, the electricity deficit increases abruptly at a specific share and is constant for the shares of 50% and 60%. Contrary, the increase of electricity excess correlates with an increase of the CHP share. In the range of the abrupt increase of the electricity deficit the changes in electricity excess are marginal. As a result, the best share, the share with a minimal sum of deficits and excesses, is found before the beginning of the abrupt increase of electricity deficit. As a result, the share of 40% is selected. This results in a CHP heat capacity of 68kW and an HP heat capacity of 102kW.

Concerning the question above, the results show that an improved division of the capacities can reduce the increased electricity excess, induced by the reduction of the total capacity, significantly. A comparison of the reduced and improved capacities with the reference capacities of 105kW in table 9.3 shows that the found capacities generate comparable results by reducing the aggregated capacity from 210kW down to 170kW.

aggregated heat capacity	210kW	170kW	
CHP capacity	105kW	68kW	-35,2 %
HP capacity	105kW	102kW	-2,9%
	[MWh]	[MWh]	[%]
gas consumption	464	463	-0,2
heat deficit	0	0	0
heat excess	5,1	5,2	+2,0
el. deficit	12,0	12,7	+5,9
el. excess	3,7	4,0	+6,7

Table 9.3: Comparison of reduced capacities with start capacities

The illustrated calculations can be described as an quick approach on how to reduce the capacities of the devices. The capacities can still be improved by going more into detail. For this case, further total capacities that are marginally smaller than 170kW are worth to investigate. Additionally, further shares between 30% and 40% could be analyzed in order to reduce the electricity excess. However, this is not the objective. It is rather important to show that the results generated from a few analyses can help to improve the planning of the devices. The shown results of such an approach can be found quickly and ensure an acceptable relation between effort and beneficial results.

Finally, the yearly electricity balance of the different selections of capacities are illustrated in figures 9.3 to 9.5. Notably, the electricity deficit that is constant at 12MWh appears during the summer. The reason is the very low and sometimes even missing heat demand, which represents only space heating. The best results are achieved with the reference capacities of 105kW for each device. Moreover, the decrease of electricity excess for the improved share of the aggregated capacity of 170kW becomes obvious and also the increase of electricity deficit can be seen.

The last part of the analysis focuses on the impact of increasing shares of renewable energy. The share of the total renewable energy production has been 50% of the electricity demand and is added by shares of 75% and 100%. Firstly, the influence on the electricity balance is examined. Therefore, the CHP and HP capacities and the storage size are defined to be fixed. The capacities are chosen like in the reference case with 105kW for each device and the storage size again amounts 5.000 liters.

The table 9.4 shows that the gas consumption and the electricity import is reduced by an increased

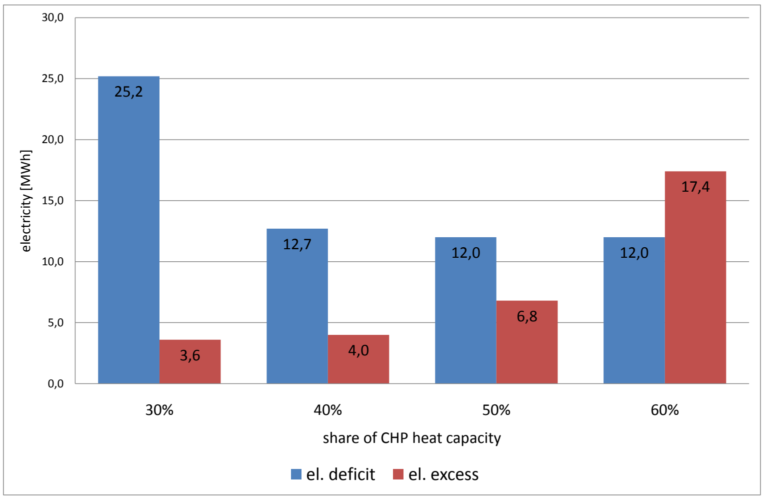

Figure 9.2: electricity deficits and excesses dependent on heat capacity shares

RES share	50%	75%	100%
	[MWh]	[MWh]	[MWh]
gas consumption	464	408	359
heat deficit	0	0	0
heat excess	5,1	5,0	5,0
el. deficit	12,0	8,0	5,8
el. excess	3,7	14,7	31,4

Table 9.4: Comparison of yearly results dependent on shares of RES on electricity demand

amount of RES. As opposed to this advantage, the negative impact is that the electricity excess increases enormously. This can also be seen by comparing the figures 9.6 to 9.8. As it was shown above, an improvement of the share of the capacities of the devices can reduce the electricity excess. This seems logical because an increase of the HP capacity should lead to a higher consumption of RES excesses in order to produce heat. Finding the improved shares of capacities for each RES share is part of the next calculations.

The results shown in figures 9.9 to 9.11 are gained by 12 calculations, namely 4 shares of CHP heat capacity for each of the 3 shares of renewable energy. The differences between these renewable shares can be seen in the total electricity exchange as well as in the electricity imports and exports. Whereas an increasing amount of renewable electricity decreases the import, it increases the export. These changes appear in different scales. Whereas the maximal change of the import is almost 10MWh, the average change between a share of RES of 50% and 100% amounts more than

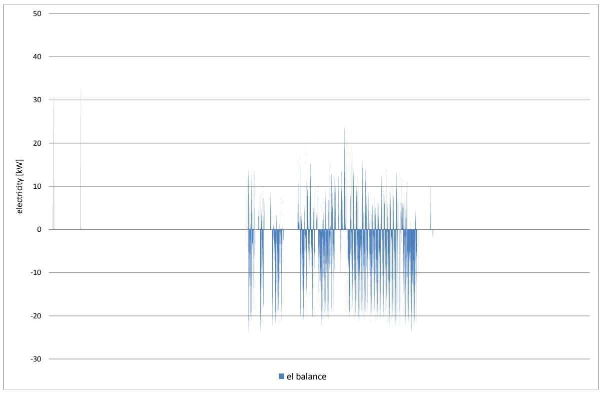

Figure 9.3: electricity balance - 210kW, 50% share

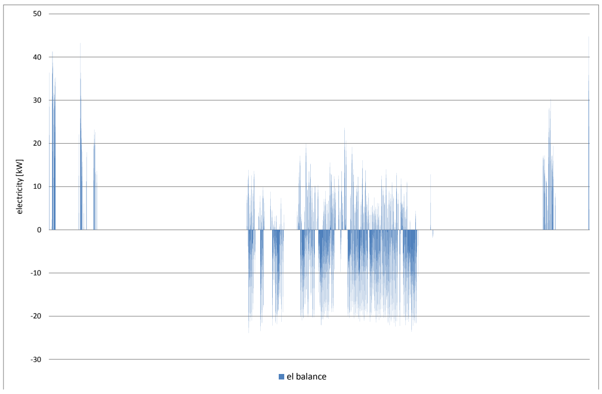

Figure 9.4: electricity balance - 170kW, 50% share

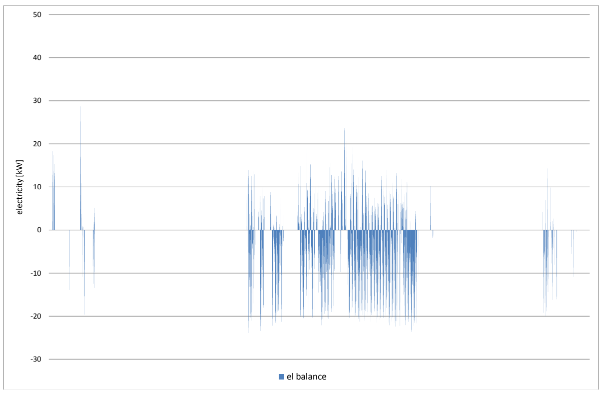

Figure 9.5: electricity balance - 170kW, 40% share

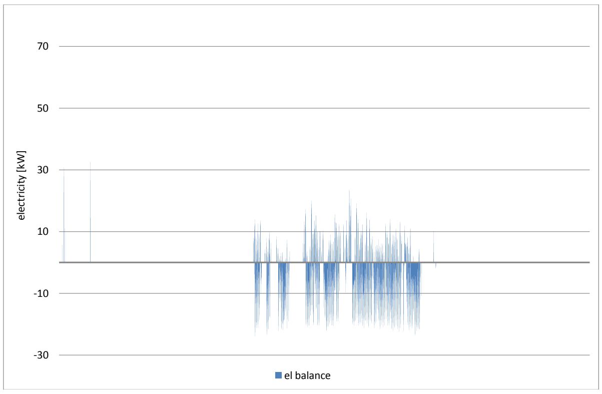

Figure 9.6: Yearly electricity balance with a 50% RES share

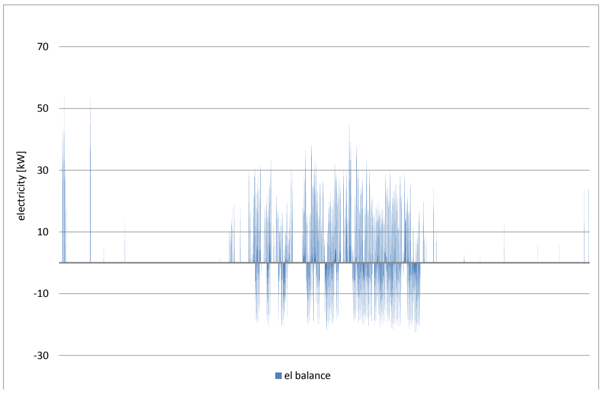

Figure 9.7: Yearly electricity balance with a 75% RES share

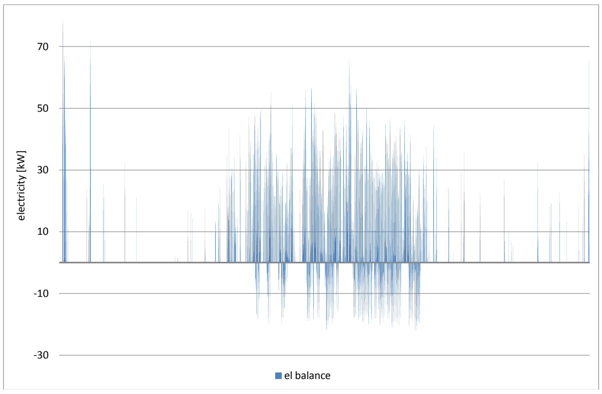

Figure 9.8: Yearly electricity balance with a 100% RES share

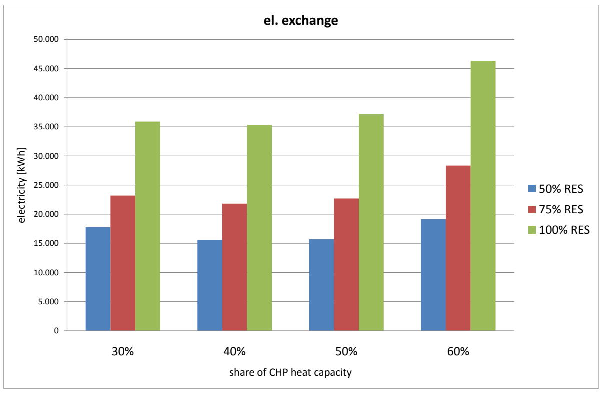

Figure 9.9: Yearly electricity exchange

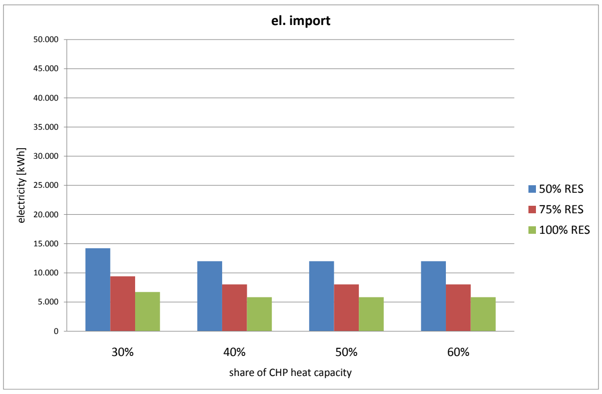

Figure 9.10: Yearly electricity import

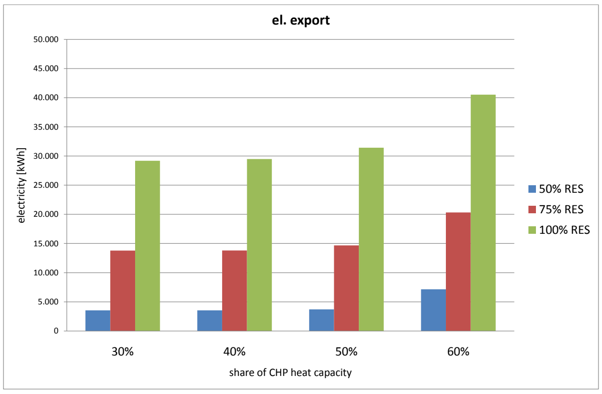

Figure 9.11: Yearly electricity export

25MWh. Especially, the increase of export due to the increase of the RES share from 75% to 100% is very high with an average increase of more than 15MWh. Consequently, the export is the main influence on the total electricity exchange.

Regarding the shares of the heat capacities, the import and the export comport similarly to figure 9.2. Concerning the share with the minimal electricity exchange, the different RES shares show the same characteristics. For all 3 RES shares the minimal electricity exchange can be found for a share of 40% of the CHP heat capacity. This share has also been identified as the share with the lowest electricity exchange for the aggregated capacity of 170kW and an RES share of 50% (figure9.2). As opposed to the results found for 210kW for each share of RES, the results for the reduced aggregated capacity of 170kW are more diverse. The reason is that the share of heat capacity has more influence when the devices do not have much overcapacity. This is shown by figure 9.12. For each of the RES shares the CHP heat production amounts an almost constant share of the heat demand independent from the share of the heat capacity. These values are based on the overcapacity of the devices. The same analysis for an aggregated capacity of 170kW can lead to different shares of heat production. However, from the results of figure 9.12 it can be followed that a certain share of heat production is optimal for each share of RES. Thus, if the reduced capacity of 170kW is calculated with very low and high shares like 30% or 60%, there is not enough flexibility left for the devices in order reach the optimal share of heat production.

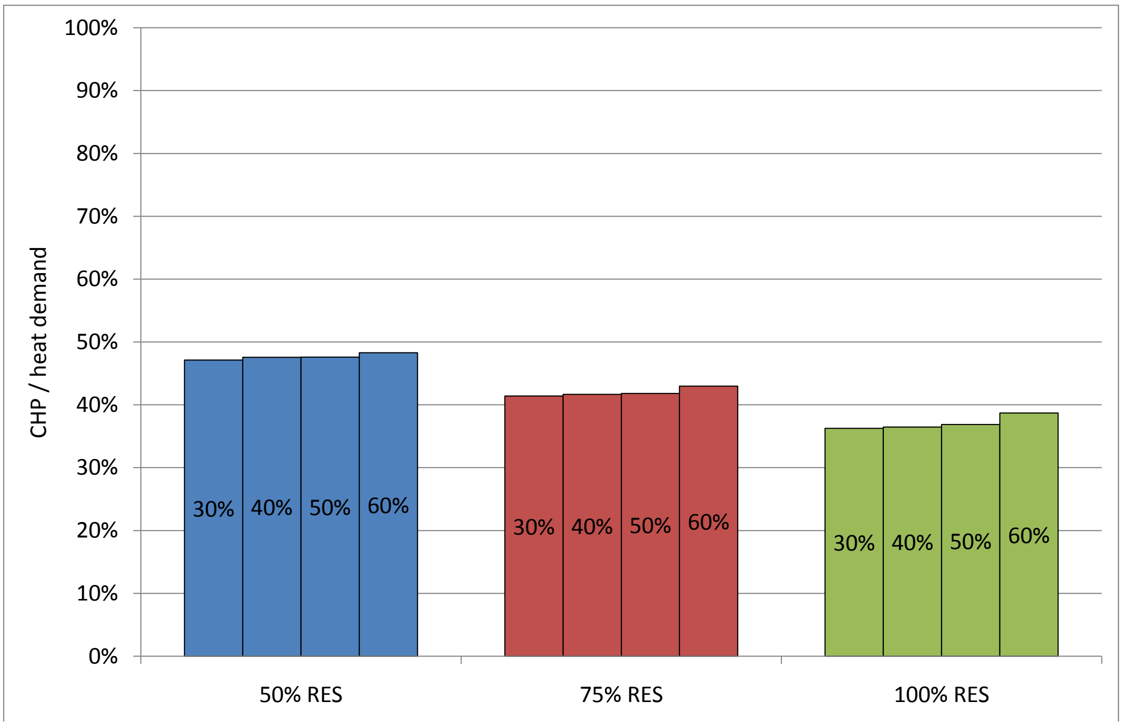

Figure 9.12: Contribution of CHP heat production to total heat demand

This analysis has shown several possible objectives for an analysis with the energy computer tool

COMPOSE. These can be used in order to plan the devices and identify the influences of increasing renewables. In fact, the analysis can be continued, especially by using the storage size as a parameter for further calculations or by going more into detail when choosing certain parameters like the aggregated capacity or the shares of capacities.

10 Application recommendation

Generally, the tools are useful to run simplified analyses in order to gain basic information for testing and planning energy systems. Whereas detailed simulations require a long time, the models calculate on an hourly basis within just a few seconds. For a defined system with demands that have to be specified, different technologies can be investigated by the tools by running multiple analyses.

Both tools can be applied for energy systems that include the heat and electricity sectors. Noteworthy, they only allow for systems that are thermally and electrically connected. Thus, energy systems that include an electricity grid but do not contain any internal heat grid cannot be designed. Although EnergyPLAN allows for separate districts with own demands, the electrical communication between these districts is missing. Furthermore, the systems can include renewable and conventional energy technologies. A comparison of such different technologies within the same system is a possible objective for analyses with the tools. The possible technologies are numerous but very simplified. The efficiencies are fixed and independent on the production rate. Moreover, the devices cannot be instructed to serve only selected demands. Especially, the scope of design of the devices differentiates the tools regarding their applicability. Whereas, EnergyPLAN offers only predefined devices, COMPOSE can be used as a modeling framework that allows to create devices manually. The possibilities offered by COMPOSE include different operational strategies for each device. Thus, a CHP unit, for instance, can be instructed to meet the heat demand even if this means to overproduce electricity. Contrary, the technical optimization of EnergyPLAN defines fixed strategies for the operation of the devices. Hence, CHP units avoid to produce electricity excesses and accept heat deficits. With this predefined operational strategy, EnergyPLAN cannot be used to analyze a system that forces its CHP to meet the heat demand due to no other existent heat supply. Indeed, EnergyPLAN just shows where heat deficits appear when the objective is to minimize the electricity excess. This result can be used to choose a heat producing device that has to be added to the system. As opposed to EnergyPLAN, COMPOSE enables to choose the operational strategy of the devices. This flexibility makes COMPOSE useful for many different energy systems. For instance, a district heating network that is not connected to any external heat supply and which has a fixed number of devices like the reference system can be analyzed with COMPOSE because it allows to avoid heat deficits.

However, the applicability of a model is depends on the energy system that it is supposed to analyze. Energy systems differ in size and complexity. The reference system is designed very small and simple. The benefits of EnergyPLAN regarding complex systems including numerous devices cannot be shown in such small systems. EnergyPLAN is very useful for many different technologies. It offers a wide range of facilities that are included in the input data of the tool and only require a few values to be integrated into the system. EnergyPLAN's focus on electricity balancing becomes obvious not only in its operational strategy but also in its multiple grid stabilization options and the possibility to define stabilization shares. These make EnergyPLAN very useful for national systems.

As opposed to EnergyPLAN, COMPOSE differentiates between the project level and the superordinate system level. The framing system can either be designed very simple when the focus is put on the operational level or it can help to characterize the project's influence on the upper system. The latter leads to results that are different to the results from EnergyPLAN. The results of EnergyPLAN like, for instance, electricity and heat balance equal the results of COMPOSE when the system is designed simply. In fact, thee superordinate system is more like a surrounding framework. The results are single values like the avoided fossil fuel consumption of conventional powerplants due to the replacement of electricity production. Contrary, EnergyPLAN considers the system that is to be analyzed already as the framing system like a national system. However, the simple focus on the devices of the subordinate energy system in COMPOSE can reveal the potential of balancing the incoming intermittent electricity. The analysis of the reference system shows this by scaling production rates from wind power and photovoltaic to the dimension of the urban district. In the case of the reference system the share of the annual renewable energy amounts 50% of the total electricity demand. Analyses of increasing renewable shares can show how much renewable energy the designed system is able to integrate. In terms of integrating intermittent energy, the positive influence of storage systems can be investigated.

As a conclusion regarding possible energy systems for the tools, COMPOSE can be used for each kind of energy system, whereas the fixed operational design does not always meet the characteristics of an energy system. However, very complex systems that include all diverse technologies within a national system show the benefits of the model. Multiple technologies like vehicle to grid or energy sectors like transport are already available and just need to be specified by typing in a few values. Contrary, many technologies in COMPOSE can become too complex to overview and require more effort because each process has to be created manually. Furthermore, the selection of costs for a desired priority of operation becomes too complicated.

Moreover, the planning period of the tools differ from each other. Whereas EnergyPLAN allows only for analyes of one year, COMPOSE can calculate multiple years with changing annual values of renewable productions and demands. Regarding the planning of capacities for a specific planning period, useful information can be gained from the results of multiple analyses. The planning issues concern the three levels of operation mode, dimension and distribution. Concerning the operation of COMPOSE, realistic costs and defined capacities and numbers of devices enable COMPOSE to find the cheapest operation mode. If a certain technical operational strategy is desired, the devices can be designed accordingly. Additionally, the COMPOSE provides the opportunity to define minimal loads for the devices or even to choose a discrete operation of only zero or full load. As opposed to COMPOSE, EnergyPLAN only allows for a linear range of operational loads. The possible restrictions offered by COMPOSE allow also for improvements on the distributional level. Here, it could be of interest to investigate the different influences on electricity balancing of multiple smaller devices with lower efficiency and one or a few devices with higher efficiency. Concerning dimension level, the models can be used according to the bottom up approach. By running several analyses with different capacities the results help to identify the minimal necessary capacity, for instance, to avoid deficits in heat or electricity. Especially for analyses that include storage systems, the analyses reveal how far the storage system allows to decrease the capacities of the devices. For instance, the analysis of the reference case shows how the capacities of the CHP unit and the HP unit can be improved by changing their shares on total heat capacity and also how far they can be decreased without causing heat deficits for the system.

11 Summary and Conclusion

This thesis has dealt with energy modeling software applied to distributed generation on the city district level. The tools considered are EnergyPLAN and COMPOSE, which are both input output tools that use the bottom approach in order to investigate the best chosen inputs for the operation of an energy system. The energy system used for this thesis is characterized by its electricity and heat demands of 10 domestic buildings. The supply is provided by the internal devices CHP, HP and heat storage. In addition, the system has a fixed input of renewable energy, which the 3 mentioned devices have to deal with. Moreover, the system ensures thermal and electric connection between the buildings and the devices. Whereas the system is connected to the electricity grid, there is no external heat supply. Thus, electricity imbalances are acceptable for the analysis of the system. Contrary, heat imbalances cannot be compensated. This restriction has lead to the conclusion that COMPOSE is the more appropriate tool for this system. The investigations of the calculations of the tools have shown that EnergyPLAN accepts heat deficits, whereas appropriate operational strategy can be designed in COMPOSE. Hence, COMPOSE has been used for an analysis that puts the focus on the planning of the capacities of the devices. The analysis consisting of multiple different calculations has illustrated an approach on how to reduce and improve the capacities of CHP and HP. Furthermore, the application of the tool revealed the influence of an increasing amount of renewables on the electricity balance of the system.

However, the results of the comparison of the tools need to be considered carefully due to the following reasons. The chosen energy computer tools EnergyPLAN and COMPOSE embody different capabilities. Noteworthy, they have been tested and evaluated by applying them to an energy system that does not reveal all their individual strengths. In fact a comparison of the tools is made that does not reveal that one tool is better than the other because both have different focuses and key features. Especially, EnergyPLAN shows its benefits for national systems which is not possible for the reference energy system. Otherwise, the characteristics of the technical optimization of EnergyPLAN could be identified. Also COMPOSE offers interesting features that have not been used for the analysis. Especially the discrete operation type is very interesting for further investigations. Moreover, both tools can be used for a realistic economic analysis that includes fixed costs like investment costs as well as variable costs.

As a conclusion, further research of the two tools that focuses on their individual strengths and their further abilities that have not been shown in this thesis is highly recommended. Moreover, I generally recommend to expose the wide field of energy computer models. It is worthwhile to stay updated for new developments in this field. Apart from the ongoing improvement of existing models, many more are developed continuously that fill gaps that have not yet been filled by the existing tools. Consequently, further research seems to be very promising.

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Aachen, 31st March 2014

Alexander Sichwart