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Analysing the Energy-flow of a Residential Building utilizing a Combined Heat and Power Unit (CHP) considering economical Appeal

Master´s in Mechatronics

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Abstract

Analysing the Energy-flow of a Residential Building utilizing a Combined Heat and Power Unit (CHP) considering economical Appeal

This master's thesis provides an overview of a more efficient, future-oriented living concept in Dornbirn, Austria. The use of a combined heat and power unit (CHP), in combination with a thermal storage, as a heating system is specifically investigated. In order to make this heating system more attractive for the consumer, the sale of the generated electricity from the CHP is considered. The more efficient use of energy for heating increases the attractiveness by a minimisation of the living space. This master's thesis aims to draw attention to the issue and to achieve a rethinking in the planning of future living space. For the research and elaboration of this thesis, statistics and trustworthy literature were used, and physical modelling was applied. This Master's thesis can be assigned to the fields of energy technology, mechatronics, architecture and civil engineering. It contributes for students, researchers, and other interested person in these sectors.

Keywords: *combined heat and power unit (CHP), residential building, tiny living, modelling, heat energy, electricity sale*

Kurzreferat

Analyse des Energieflusses eines Wohngebäudes mit einem Blockheizkraftwerk (BHKW) unter Berücksichtigung wirtschaftlicher Aspekte

Die vorliegende Masterarbeit gibt einen Überblick über ein effizienteres, zukunftsorientiertes Wohnkonzept in Dornbirn, Österreich. Untersucht wird explizit der Einsatz eines Blockheizkraftwerks (BHKW), in Kombination mit einem thermischen Speicher, als Heizsystem. Um dieses Heizsystem für den Endverbraucher attraktiver zu gestalten, wird der Verkauf des vom BHKW produzierten Stromes vorgesehen. Die Steigerung der Attraktivität beinhaltet zudem den effizienteren Einsatz der Energie für das Heizen, was folglich zu einer Minimierung des Wohnraumes führt. Durch diese Masterarbeit soll Aufmerksamkeit auf die Thematik gelenkt und ein Umdenken in der Planung des zukünftigen Wohnraumes erreicht werden. Zur Recherche und Ausarbeitung dieser Arbeit wurden Statistiken und vertrauenswürdige Literaturquellen verwendet, sowie die physikalische Modellbildung angewandt. Diese Masterarbeit kann den Fachbereichen Energietechnik, Mechatronik, Architektur und Bauwesen zugeordnet werden. Sie bietet vor allem für Studierende, Forschende und Interessierte aus diesen Bereichen einen Mehrwert.

Keywords: *Blockheizkraftwerk (BHKW), Eigenheim, kleiner Wohnraum, Modellbildung, Heizenergie, Stromverkauf*

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1. Approach to the Issue

Climate change is advancing and humanity urgently needs to do something in order to stop it. Without solutions, our world will become more and more uninhabitable and can lose its diversity of life. The progress of climate change can be counteracted in many different areas. Private households are responsible for a third of the used energy and about 40% of the associated emissions worldwide [1]. One advantage of this high portion is that everyone can participate in decrease the problem within their own home. Every person should contribute in order to achieve the common goal.

The carbon footprint of a household is dominated by its heating [2]. In order to keep this dominating part as low as possible the house should be designed to be thermally efficient. All components should be combined in such way that the heating runs as advantageously as possible.

Various heating devices can be considered in the choice of the appropriate heating system. However the use of a combined heat and power unit (CHP) has a particularly advantage. In addition to thermal energy the CHP also produces electrical energy. This electrical energy can be used by the homeowner himself or get sold. The case of selling can support the electricity grid at critical points when it is controlled correctly. This is a huge advantage for both the house owner and the electricity provider. Another advantage is that the CHP can supply electricity at desired times. This property is particularly important for stabilising the electrical grid. In return, the owner gets a higher selling price insofar as the prices are based on the electricity stock exchange. The problems with stability become more and more apparent as more renewable power sources feed into the grid. This is a positive aspect of this heating system.

Considering the economic situation for the owner, the sale is currently very lucrative. The electricity price has been rising sharply since mid-2021. Due to the resurgence of the economy prices for gas and oil have reached peak levels. As a result of these high prices, the associated electricity price is also catapulted upwards. [3]

The price of electricity for 1 kW h has temporarily topped 70 euro cents on the stock exchange. [4].

A glimpse into the future shows that the use of these heating systems can serve as a component for future Smart Grids [1]. This future solution requires many flexible power generators so that the targeted properties can be achieved.

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[1] An intelligent electrical network that can communicate with all consumers and producers in order to satisfy the required amount of electricity and protect the distribution grid [5].

In order to consider the efficiency of the system the individual components must be described and linked together. One method to realise this is the use of a dynamic simulation, which is particularly suitable for the case. It allows the reaction on individual peak values. Without the usage of a dynamic model only the average values could be considered.

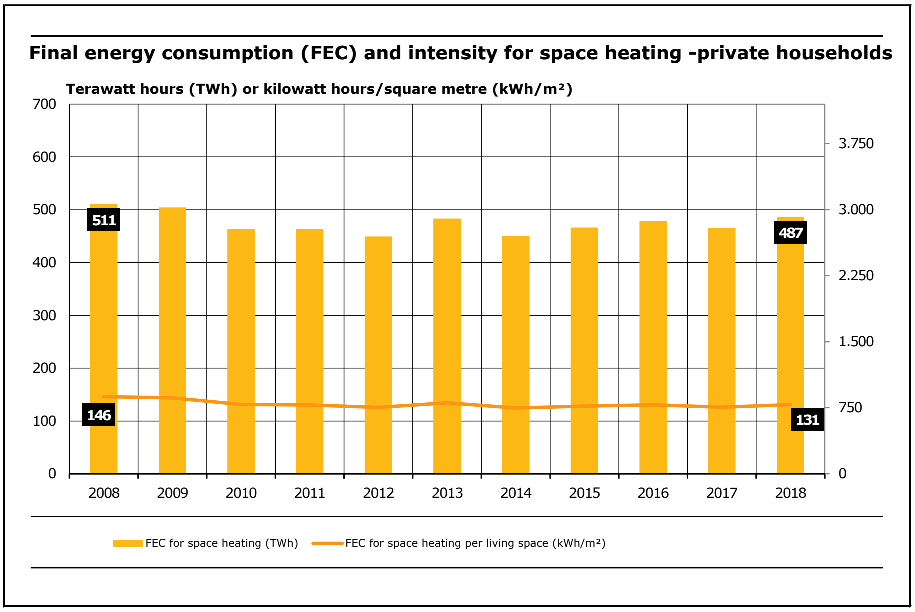

Figure 1.1.: Final Energy Consumption for Space Heating customised illustration based on [6]

As illustrated in the Figure 1.1, the demand for heating energy has decreased slightly. This reduction should continue to be pursued in the future. New concepts are constantly appearing to minimise the heating energy consumption and the resulting impact on climate change. Due to this the first tiny houses came onto the market. Living in a Tiny House reduces the per capita emissions by up to 70 % [1]. It can be concluded that the size of the living space has a strong influence on energy consumption and the associated emissions.

This problem can be formulated in a question and can serve as an incentive to conduct this research. The research question is:

Which constellation can provide the heat energy for a residential building in a financially attractive way with an electricity price-controlled combined heat and power unit - taking into account the hourly values of electricity prices?

1.1. Structure of Thesis

The thesis is divided in seven chapters and introduces with an approach to the issue and the research question to be clarified. The purpose of this chapter is that the readers should know the background of the execution. They they are informed about the problem in order to understand the following solutions.

The next chapter contains the state of the art of the heating system and the smart grid. This chapter brings the reader up to date on the key components and their use.

In the following chapter are the used methods and sources explained. It specifically describes where and why certain sources have been chosen and also why the simulation method was chosen.

The fourth chapter contains the description and implementation of all required components of the system to be modelled. All components are explained with the reason for consideration, the functionality, the chosen simplifications and the final implementation.

In the fifth chapter the cases to be simulated are defined at first. The results are then structured and prepared for analysis in the following chapter.

The sixth chapter contains the analysis of the results of chapter five. The individual scenarios as well as the comparison with each other are discussed.

The last chapter contains the summary of the thesis. The findings of the results and the modelling approach of the concept. In addition, the further work steps and suggestions for improvements are discussed.

2. State of the Art

2.1. CHP - Combined Heat and Power Unit

Functionality

A combined heat and power unit is a technology that produces electricity and thermal energy. This process runs at high efficiencies while using various kinds of fuels. The high efficiency is due to the fact that the gained heat is used additionally to the electricity production. In most other electricity production processes the generated heat is not used [7]. The efficiency for a CHP powered by an internal combustion engine is about 90 percent [8, p. 11].

In most cases, CHP units are powered by an internal combustion engine or a steam turbine. The combustion engine uses natural gas, oil or biogas as fuel. When a steam turbine is used, the first step is to generate steam, which is used to drive the turbine in the next step. In this thesis, a CHP with an internal combustion engine is used. For this reason, only this concept is explained in more detail.

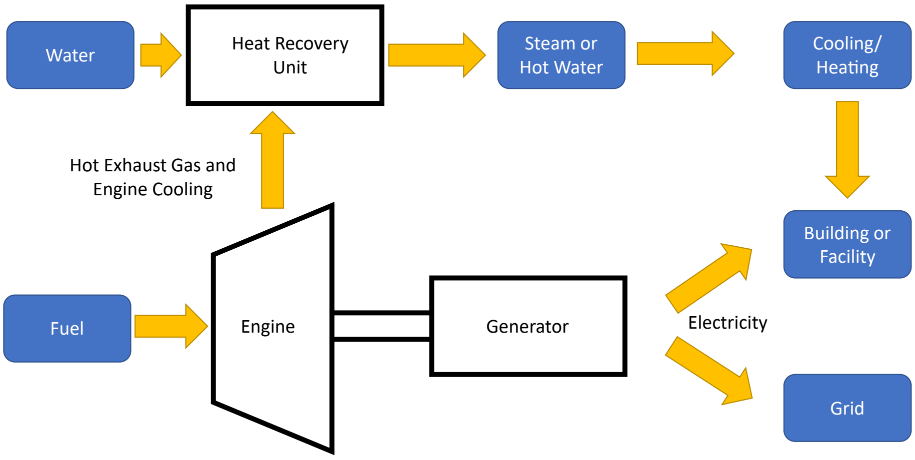

Figure 2.1.: CHP Overview
source: [7]

As illustrated in Figure 2.1 the CHP unit uses the fuel to run the combustion engine, which drives the generator. The generator produces electricity that can be used for own consumption as well as for feeding into the grid. The generated heat from the engine is fed into a heat recovery system.

This heat consists of the heat stored in the engine's cooling medium and the hot discharged exhaust gases. These are combined for further consideration. [8]

This system transfers the heat to the desired storage medium. This stored heat can then be used to heat the building.

Usage of a CHP

CHPs are used in various buildings as electricity-producing heaters. In order to check the suitability of a CHP unit, a number of factors must be taken into account. These factors are the operating hours of the CHP unit, the thermal energy demand of the building and the tariffs for fuel and electricity. This is the only way to ensure a technically correct and also economic use. The buildings that are suitable for such a system are usually very large. Examples of a building heated with CHP would be industrial buildings, hotels and large apartment buildings [7].

CHPs can be divided according to their size. Some manufacturers also offer smaller systems that are designed for the use in single-family homes. These systems are called nano or micro CHP and have a nominal electrical output of up to 1000kW h per year.

The future of the use of a CHP in a single-family house is uncertain. Developments in the technology of the system speak in favour of its use as investment costs are becoming lower and lower. However, the decreasing heat demand of residential buildings, due to more thermally efficient building materials in the future and thus the ever shorter period of use of the CHP argue against it [9].

The statistic shows that the use of CHP units with a maximum output of 2 kW is increasing again. This increase started in 2017 and has surpassed the peak before the decline that started in 2014 (Figure 2.2).

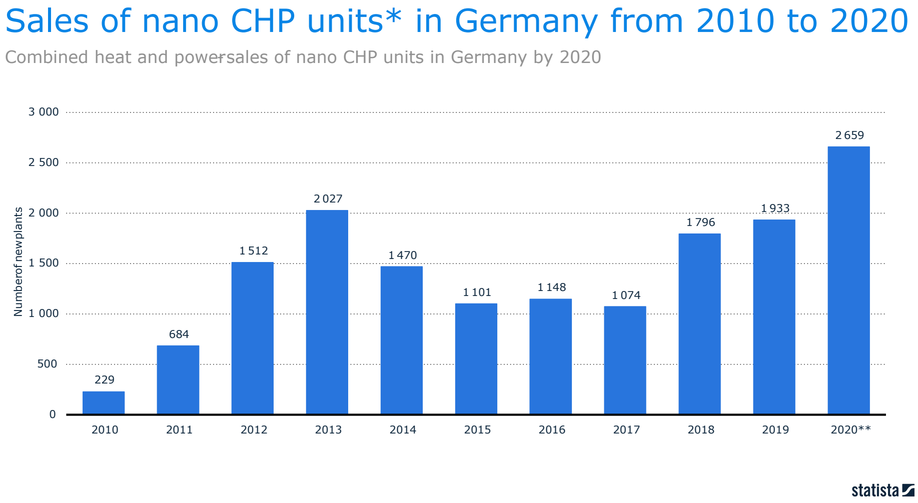

Figure 2.2.: Statistic Sales of Nano CHP in Germany
customised illustration based on [10]

Thermal Storage

Heating with a thermal storage goes back into the past very far. The tiled stove, for example, which was once widespread in Austria, was invented in 1767 by Carl Johan Cronstedt and Fabian Wrede. Their idea was to store the heat generated by the fire in a brickwork. In this process, the smoke of the fire slowly passed through the brickwork via a long winding channel before leaving the house through the chimney [11].

The use of a thermal storage tank has several advantages. These advantages include increasing the generation capacity, shifting the energy purchase to times with low fuel costs and allowing the operation of CHP plants. [12, pp. 89-90]

CHP units are usually operated in order to supply the demand for the required heat load. Operation at times of low electricity consumption often results in a surplus of generated electricity. By integrating a thermal storage unit, the system can be operated at any time and does not only have to be geared to the required heat. [12, p. 89]

2.2. Domestic Electricity Production

The positive image of traditional energy production is steadily declining among the population. The result is that many of the conventional generation methods have an expiration date. And in return, governments have pushed ahead with the energy turnaround. In 2017, around 38.5% of the energy in Germany was already generated with renewable energy sources. The renewable energy sources are owned by private persons, farmers or financial investors in most cases. Consequently, there is also a big change among electricity providers. More and more new competitors are entering the market. Some of these competitors offer to distributing the generated electricity of the owners of small power plants. The usual consumption-oriented, centralised electricity production is shifting more and more towards generation-oriented, decentralised electricity production. [13, pp. 115-116]

2.3. Modelling Components

Each component to be modelled is described fundamentally at the beginning of its sub chapter in chapter 4. The mode of operation as well as the state of the art of each component is discussed. Only the components CHP and the thermal storage have a more detailed consideration, as they serve as key components of the system.

3. Methods

3.1. Modelling Approach

Mathematical models can be used in order to avoid problems at an early stage, even before an experiment has been carried out. These models must map the behaviour of the reality as accurately as necessary. The use of a mathematical model is usually justified when statements have to be made about a system that has not been realised yet. The required statements are for example a feasibility study or various estimates that are needed for the development of a prototype. In a model the parameters can be modified without much effort. This makes it possible to simulate all desired scenarios. Modifications in real experiments are often very expensive or not possible at all. As already mentioned, this characteristic helps to avoid errors at an early stage. In general, the use of a model usually leads to a better understanding of the complex technical processes. [14, p. 4]

Casually there exist two different methods to obtain a dynamic model of a real system [14, p. 5] :

Physically Modelling

This method is also called theoretical modelling. The modelling process is based on physical laws. [14, p. 5]

Experimental Modelling

The model is created by system identification, experimental identification, which is based on observations and experiments of the real system. [14, p. 5]

For the elaboration of this master thesis the physical modelling is applied. The physical modelling is implemented with the application of object oriented modelling language. The language used is *Modelica* [1].

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[1] *Modelica* is a programming language used to represent cyber-physical systems. It makes the the causal and a-causal linking of parts that are controlled by mathematical equations possible, which makes modeling from scratch easier.[15]

3.2. Used Software - Dymola

Multi-physical dynamic systems can be effectively modelled and simulated using *Dymola*. *Dymola* is a *Modelica* based solution. It quickly solves complicated multidisciplinary system modeling issues that may combine mechanical, electrical, thermal or process-oriented features and components for example. [16]

The possibilities of implementing the modelling as well as the multidisciplinary model libraries favour the use of *Dymola* in this work.

3.3. Declaration of the SHAC Concept House

This concept was set up by Markus Hager, from *SAEM GmbH.* This proposal is currently just a first draft that will hopefully get further development.

In this concept, a residential house is designed for two occupants. The floor area of this residential house is 35 m^2 and is limited to one floor. The building material of the house is wood and the insulation was done according to the guideline [17]. The total window area is 5 m^2 and is divided by 2 m^2 each on the south and west sides and by 1 m^2 on the east side. So far, the concept does not include the use of an automated ventilation and air conditioning system. The air exchange and cooling is only provided by the windows. The house is heated by a central thermal storage tank made of stone. This storage tank has the dimensions 2.4 x 2.3 x 0.5 m and is heated by the exhaust gases and the heated cool medium of the CHP. This CHP has a total output of 3 kW (2 kW thermal and 1 kW electrical). The CHP is driven by a gas engine. The used gas consists to 20 % of bio gas. The price is assumed to be constant for the whole year, as this is common in the region to be used. The generated electricity is sold in two defined time windows. The first time window is in the morning and starts at 7 am. The second one is in the evening and starts at 5 pm. Both time windows are active for 4 hours. The electricity price is listed hourly.

3.4. Literature

Material Parameters

The physical parameters used for the various materials during the development are taken from the textbook *Heat and Mass Transfer* by Yunus Çengel [18]. Factors that come from another source are marked by a source.

Environmental Data

All data of the environment for the entire year 2021, are provided by the website *Solcast* [19].This page offers a limited, free access for students and researchers, which is sufficient for all the necessary data for the elaboration of the thesis. The data set is split hourly throughout the year and contains fifteen different variables. Not all variables are needed for the elaboration.

Functionality Components

For the modelling of the physical processes of the used components, preferably German-language sources are used. The authors of the literature refer to a comparable environment, with consequently similar environmental factors. This means that the results of the examples can be used as reference values.

4. Modelling

This chapter describes all modelled components. Each of these descriptions begins with the reason for the consideration before describing the general function. This is followed by the application and the associated simplifications in this thesis. The next section provides a brief insight into the implementation in *Dymola*. The descriptions are concluded by a small insight into the results of the respective models.

The described components can be seen in Figure 4.1.

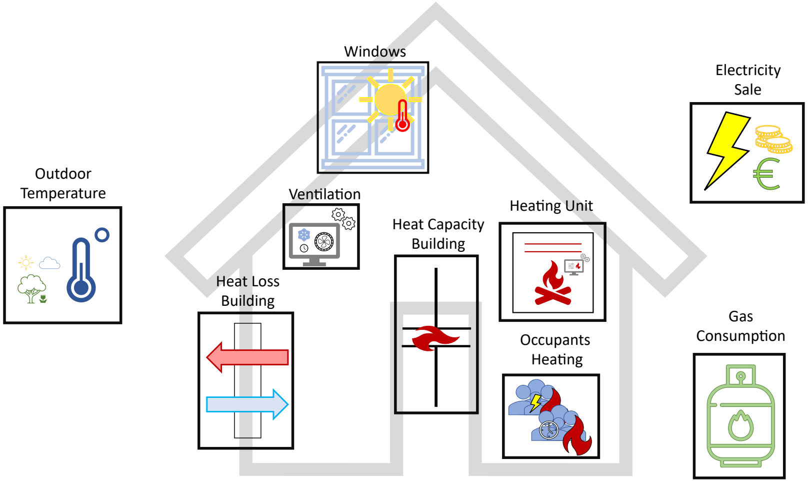


Figure 4.1.: Components Overview

4.1. Entire Model

The entire model consists of the components shown in Figure 4.1. These components are related to each other as follows.

The *Outdoor Temperature* is used as an input value for the *Windows*, *Ventilation* and *Heat Loss Building* components. The output values of these three models and the output values of the *Heating Unit* and *Occupants Heating* describe the thermal energy flow into and out of the *Heat Capacity Building*. Furthermore, the data of the *Heating Unit* is required by the *Gas Consumption* and *Electricity Sale* models for their tasks.

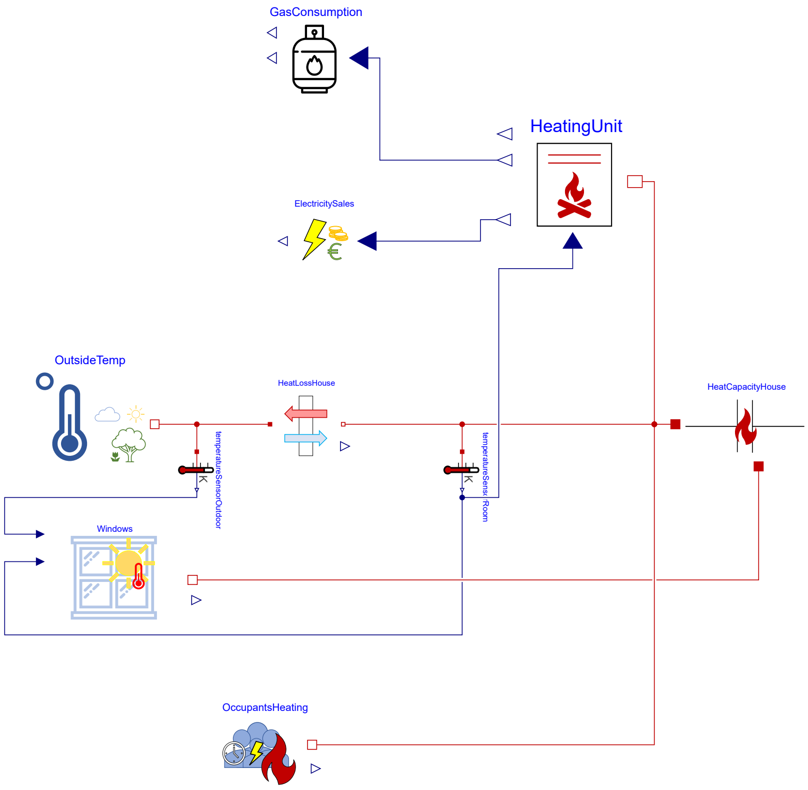


Figure 4.2.: Entire Model

Figure 4.2 shows the implemented model in *Dymola*.

4.2. Outdoor Temperature

Purpose and Functionality

The thermal conduction of the exterior surfaces is usually the largest amount of thermal energy loss in a house. In this loss, the outdoor temperature is a main factor and consequently the most important parameter for the calculation of the associated heating power.

The annual course of the outdoor temperature for Dornbirn for the calendar year 2021 is included in the environmental data. The table has two columns and 8760 rows, of which each row represents one hour. The first column shows the time and the second the corresponding temperature.

Implementation in Dymola

This table is imported into *Dymola* using the *CombiTimeTable* block. The type of data is Real and the unit for the temperature values is degree Celsius. Additionally, the output of the table is converted into Kelvin using the *from_ degC* block. Finally, the *PrescribedTemperature* block is used to act as an infinite reservoir that can absorb or generate as much energy as is required to maintain the temperature of the input (Figure 4.3).

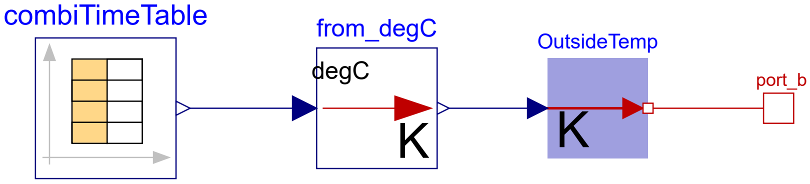


Figure 4.3.: Outdoor Temperature Model

Results

The result of this model is the following hourly recorded temperature curve of the outdoor temperature (Figure 4.4). A larger version of this graphic is included in the appendix subsection A.1.

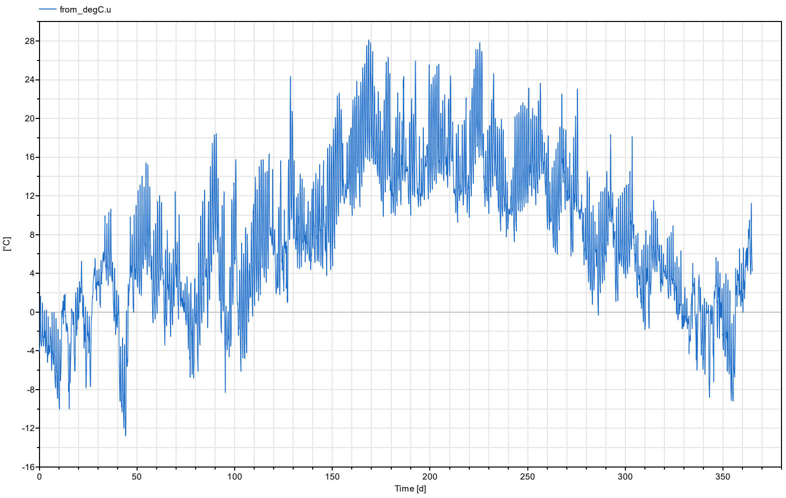


Figure 4.4.: Outdoor Temperature Dornbirn 2021

4.3. Heat Capacity of the Building

Purpose and Functionality

The heat capacity of a body is essential for the consideration of the heating and cooling process of it, as well as for the associated heat storage. Its value indicates how much energy is needed to achieve a temperature increase of one degree.

In order to calculate the heating capacity, the shape as well as the material parameters must be known. The heat capacity is calculated with references to Equation 4.1.

$$C = c \cdot m = c \cdot V \cdot \rho \tag{4.1}$$

Where C is the calculated heat capacity in $\frac{J}{K}$, c is the specific heat capacity in $\frac{J}{kg \cdot K}$ of the material, V is the volume of the body in m^3 and ρ is the density of the material in $\frac{kg}{m^3}$.

Application and Simplification

In the considered model the individual heat capacities of the solids are evenly heated by the same source. Consequently, these individual heating capacities can be summed up. Therefore, the house can be split in two different types of heat capacities: the heat capacity of the indoor air on the one hand and of the solids on the other hand (Figure 4.5).

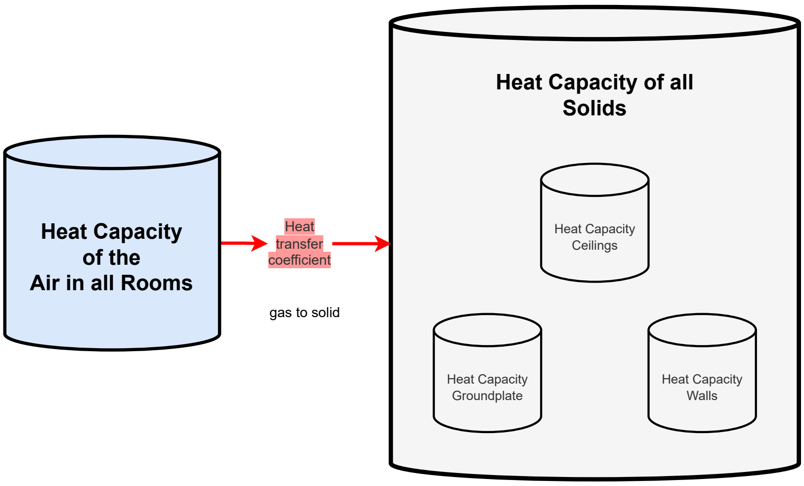


Figure 4.5.: Heat Capacity Overview

As illustrated in Figure 4.5, the summarised capacity of the solids includes the individual capacities of the walls, of the ground plate as well as of the ceiling. The heat capacity of the indoor air comprises the air in the entire living space. These two heat capacities are connected via the heat transfer coefficient (gas to solid). To ensure that the heat capacity is not only designed for a special case, the calculation must be carried out using specified and modifiable parameters. The user must enter the following parameters, as shown in Table 4.1, to find the result for the desired housing complex. Additional deductions relating to furniture or stairs are not taken into account.

Table 4.1.: Customisable Parameters for Heat Capacity Calculation

Material	Design
Density Wall - ρ_{wall}	Total Living Area - A_{total}
Density Ceilings - $\rho_{ceil.}$	Length of House - l
Density Ground Plate - $\rho_{gp.}$	Width of House - w
Specific Heat Capacity Wall - $c_{p_{wall}}$	Height of Walls - h_{wall}
Specific Heat Capacity Ceilings - $c_{p_{ceil.}}$	Thickness of Walls - t_{wall}
Specific Heat Capacity Ground P. - $c_{p_{gp.}}$	Thickness of Ceilings - $t_{ceil.}$
	Thickness of Ground P. - $t_{gp.}$
	Numbers of Floors - n_{floor}

The user-defined dimensions of the building are illustrated in Figure 4.6. The object represents the cross-section of a house with 2 floors.

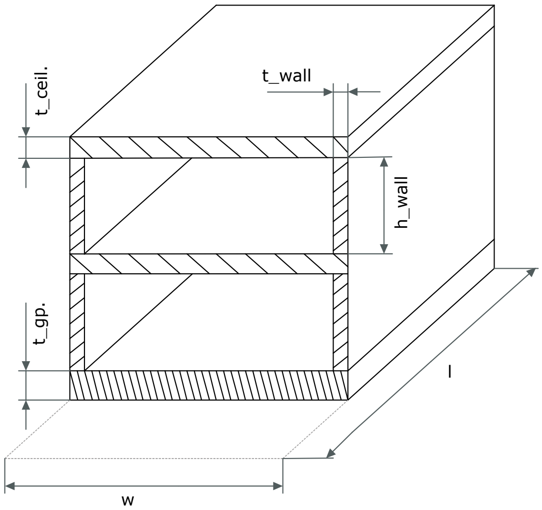


Figure 4.6.: Design Parameter Building

A simplification of the design of the house is that each room has only exterior walls. Considering multiple walls would limit the model too much.

After specifying the customisable parameters the heat capacity of the air inside the house is calculated. As can be seen in the Equation 4.1, the calculation of the heat capacity always requires the mass of the body and its specific heat capacity. The parameters of Table 4.1 and the properties of the air allows to calculate the volume inside the house, the mass of the air and the resulting heat capacity. (Equation 4.2)

$$C_{air_{ins}} = c_{air} \cdot m_{air_{room}} = c_{air} \cdot A_{floor} \cdot h_{wall} \cdot n_{floor} \cdot \rho_{air} \tag{4.2}$$

For the calculation of the heat capacity of the solids the components must be considered separately, subsequently they can be combined to the total heat capacity of the solids. The parameters required for this come from Table 4.1. The openings for doors and windows in the walls are not taken into account. The heating capacity of the solids is thus slightly higher. Previous simplifications reduce the volume of the solids, thus a consideration of the doors and windows in the detailing grade of this work is not necessary.

Again, the first step is to calculate the volumes of the various solids. The volume of the ground plate can be calculated from the living area A_{floor} and the thickness of the plate $t_{gp.}$ (Equation 4.3). The area A_{floor} is the living area per floor (Equation 4.4).

$$V_{gp.} = A_{floor} \cdot t_{gp.} \tag{4.3}$$

$$A_{floor} = \frac{A_{total}}{n_{floor}} \tag{4.4}$$

The next volume is the volume of the ceilings. It depends on the living space A_{total}, their thickness $t_{ceil.}$ and the amount of floors n_{floor}. (Equation 4.5)

$$V_{ceil.} = A_{floor} \cdot t_{ceil.} \cdot n_{floor} \tag{4.5}$$

The third volume is that of the walls. This can be calculated with the length l and the width w of the floor area A_{floor}, the height h_{wall} and the thickness t_{wall} of the walls. (Equation 4.6)

$$V_{wall} = (l + w) \cdot 2 \cdot h_{wall} \cdot t_{wall} \cdot n_{floor} \tag{4.6}$$

The next step is to calculate the masses with the previously calculated volumes and the corresponding densities.

To calculate the heat capacities of these three solids, the masses have to be multiplied by the specific heat capacity of the respective materials.

The final step is to summarise the heat capacities of all solids to get the resultant C_{solid} Equation 4.7.

$$\begin{gathered} C_{solid} = C_{gp.} + C_{ceil.} + C_{wall} \\ C_{solid} = c_{gp.} \cdot V_{gp.} \cdot \rho_{gp.} + c_{ceil.} \cdot V_{ceil.} \cdot \rho_{ceil.} + c_{wall} \cdot V_{wall} \cdot \rho_{wall} \end{gathered} \tag{4.7}$$

The heat transfer coefficient between the air and the solids of the house $G_{AirToWall}$ is the result of the multiplication of the heat dissipation capacity by convection and the surface in contact. (Equation 4.8)

$$G_{AirToWall} = \alpha_K \cdot A_{transfer} \tag{4.8}$$

The unit of the heat dissipation capacity is $\frac{W}{K \cdot m^2}$ and it can be calculated with reference to Equation 4.9. [20, p. 75]

$$\alpha_K = 2 + 12 \cdot \sqrt{v} \tag{4.9}$$

The *DIN* standard of *thermal environment ergonomics* [21, pp. 20-21] does not specify the case of a living space, so the most suitable room type must be used. Based on the vertical temperature difference and the operative temperature, the living space must be classified in category A. This results in a maximum average air velocity for the cooling period in summer of $0.12\frac{m}{s}$ and $0.10\frac{m}{s}$ for the

heating period in winter. For the calculation, a maximum average air velocity of $0.11\frac{m}{s}$ is assumed.Therefore, the heat dissipation capacity is $5.97\frac{W}{K\cdot m^2}$.
The transfer surface $A_{transfer}$ contains the surfaces of the solids that are in contact with the air. These surfaces can by calculated with the given parameters of Table 4.1.

Implementation in Dymola

The implemented model consists of two *HeatCapacitor* blocks and a *Thermal-Conductor* block, which describes the transfer of heat between the air inside the house and the solids. The values of the two heating capacities and the thermal conductance are calculated according to the equations stated above (Equation 4.2 and Equation 4.7).

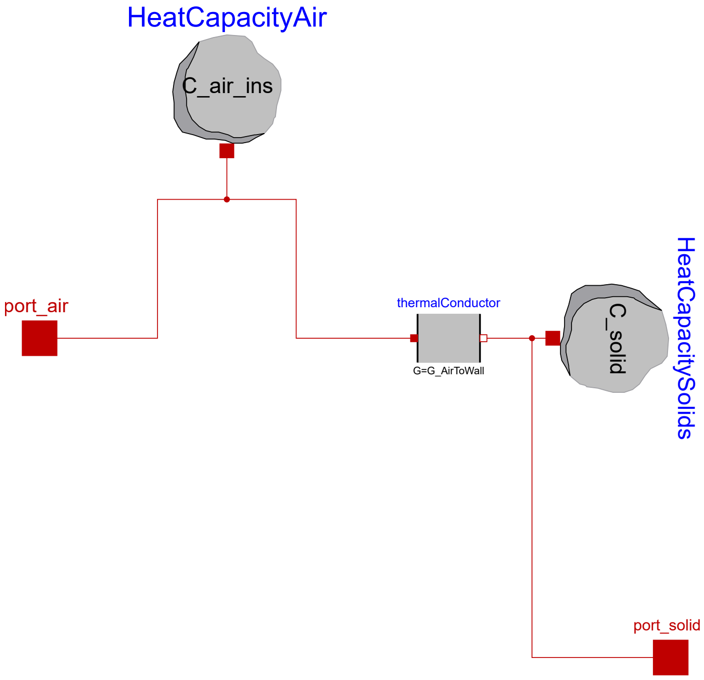


Figure 4.7.: Heat Capacity Model

Results

A house based on the idea of SHAC has a heat capacity of $1.48 \cdot 10^7 \frac{J}{K}$. For comparison, a container filled with water which has the same heat capacity as the house must have a volume of approx $3500l$.

4.4. Heat Loss of the Building

Purpose and Functionality

The heat loss of a house consists mainly of the heat conduction through the exterior walls and through the top ceiling. In the cold months this loss describes the heat energy leaving the house, which in turn must be brought back into the building by the heating system. The heat loss is required for the dimensioning of the heating.

This heat loss depends on the heat transfer coefficient of the material to be passed through u, the surface A_{ext} and the temperature difference between the respective surfaces.

$$\dot{Q}_{loss} = A_{ext} \cdot u \cdot (T_{indoor} - T_{outdoor}) \tag{4.10}$$

As the heat transfer coefficient has a significant influence on the heat loss the goal is to make it as low as possible. The higher the value of the heat transfer coefficient, the more heat energy passes through the material at the same temperature difference. The coefficient in the application is reduced by adding layers of insulating materials to the top of the base material.

According to the Austrian Institute for Building Technology [17, pp. 5-6], the heat transfer coefficient of an exterior wall in a new building shall not exceed the value $0.35 \frac{W}{m^2 \cdot K}$. The value limit for a ceiling that borders on the outside air is $0.2 \frac{W}{m^2 \cdot K}$.

Application and Simplification

This heat loss component provides the connection between outdoor and indoor air. Heat conduction through the ground plate into the soil has been neglected. No data is available for the temperature of the earth underneath the ground plate.

The corresponding areas for the different heat coefficients can be calculated with the geometric parameters of the house and the window areas. The area of the ceiling is calculated by the length and width of the house and the number of floors.

To calculate the area of the walls, the floor plan of the building and the number of floors are also required, as well as the wall height. The sum of the window areas is subtracted in the last step. The reason for this is that the heat loss of the windows is discussed in section 4.5.

At the end the two thermal conductances, the products of the heat transfer coefficients and the corresponding areas, are added together.

Implementation in Dymola

This model connects the outside air (input) with the air inside the house (output). The model is based on the thermal domain for the representation of heat flow and temperature. The *ThermalConductor* block serves as a link between the two interfaces and has the value as described above. The *HeatFlowSensor* is used to integrate the heat flow in order to get the total heat loss. The data type is Real (Figure 4.8).

The model *Ventilation* finds place in the *HeatLoss* model, but is described in section 4.7.

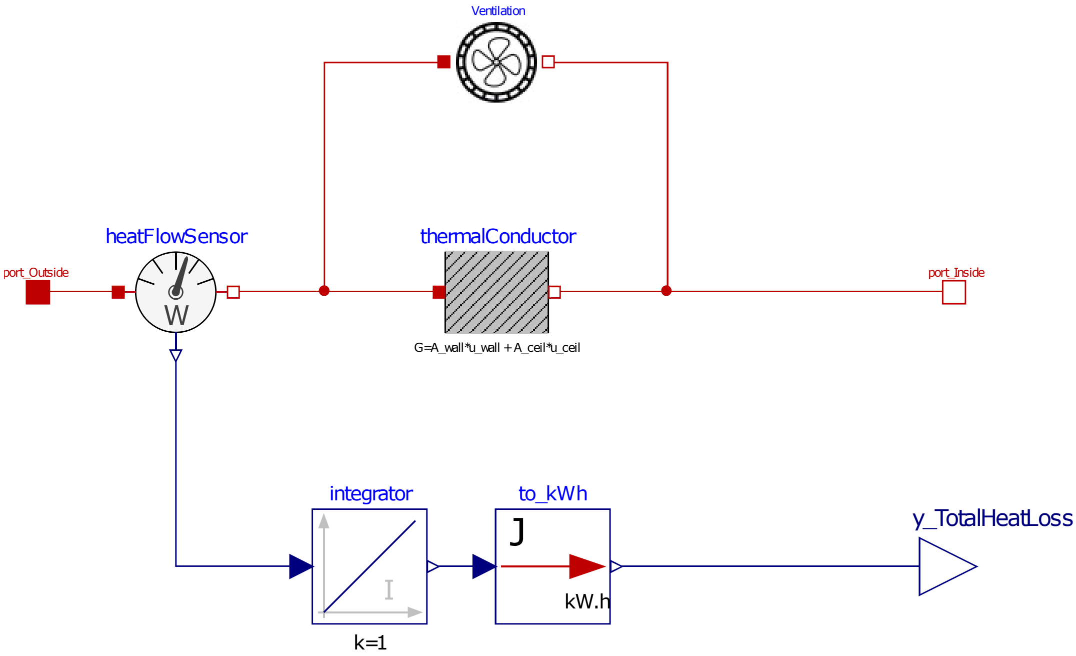


Figure 4.8.: Heat Loss Model

Results

The total heat loss for the year 2021 for the concept house *SHAC* is 4567 kW h. The negative sign in Figure 4.9 is cased by the fact that in most cases the heat flow is from the inside to the outside.

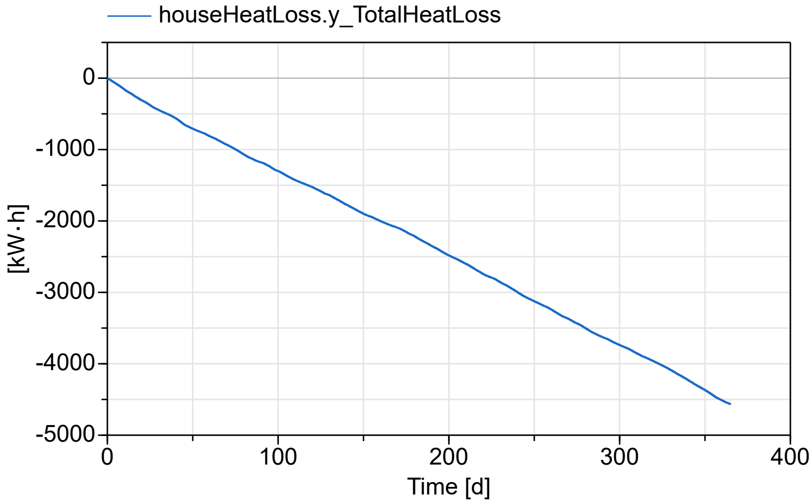


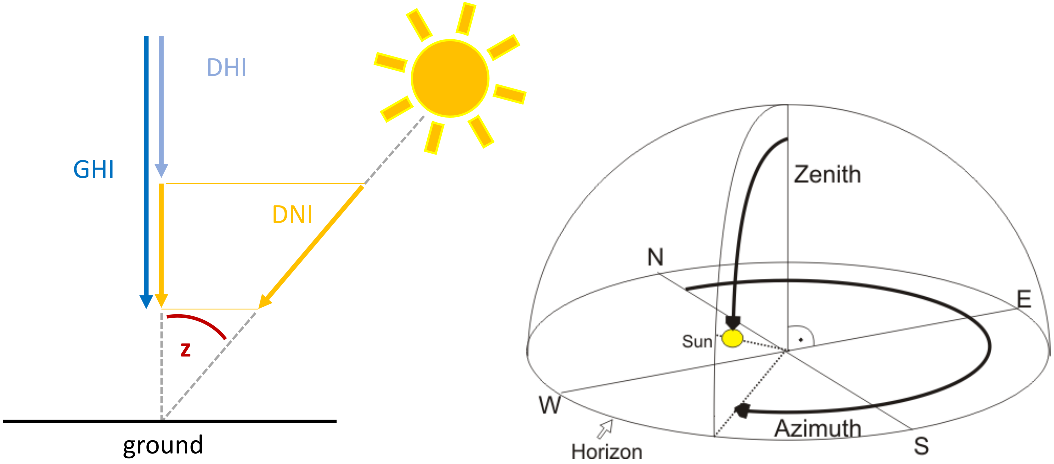
Figure 4.9.: Total Heat Loss SHAC

4.5. Windows

Purpose and Functionality

On sunny days there is a heat gain as a result of the solar radiation. This heat gain can relieve the heating system on cold days, but also heat up the house to unpleasant room temperatures on warm and sunny days. Therefore, this value will be very important for the simulation.

The environmental data [19] contain the solar radiation values direct normal irradiance (DNI), diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI), as well as the current angles of the sun (Figure 4.10).



(a) Solar Radiation (b) Angles Sun, source: [22]

Figure 4.10.: Sun Parameters

The radiation GHI consists of the DHI and the vertical amount of the DNI (Equation 4.11). The angle z is called zenith.

$$GHI = DHI + \cos(z) \cdot DNI \tag{4.11}$$

The direction of the GHI is vertical. Since the windows are perpendicular to the horizontal, this value cannot be used. Thus an alternative value must be found.

Application and Simplification

The total radiation striking a window must be composed of diffusive and direct radiation. Diffusive radiation is not directional.

The existing values of the data set can be used after adjusting the tilt of the window surface. The thesis assumes that all windows are vertical. This results in 50 percent of the measured value for the occurring diffuse radiation [23, p. 324].

The direct radiation to the window can be calculated via the angles azimuth and zenith. The zenith is taken into account first and then with this new value for the DNI the azimuth is taken into account.

The consideration of the zenith is the same throughout the day. If the angle is higher than 90°, the sun is under the horizon and its dark. The DNI is multiplied by the sine of the zenith (Figure 4.11).

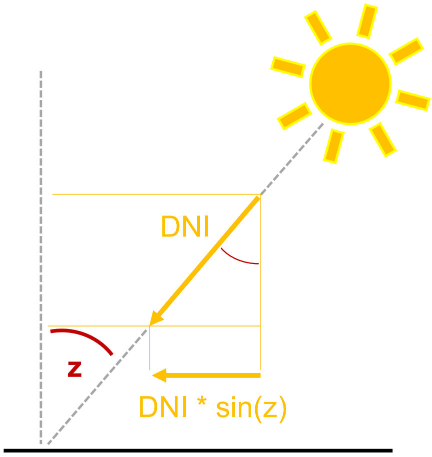


Figure 4.11.: DNI Zenith Angle

This results in the following value for the direct radiation, DNI_z, after considering the zenith angle (Equation 4.12).

$$DNI_z = DNI \cdot \sin(z) \tag{4.12}$$

This value is now used for further consideration according to the azimuth. The azimuth angle ranges from 0° to 360° during the day and each cardinal direction is written once on the angle (Figure 4.12).

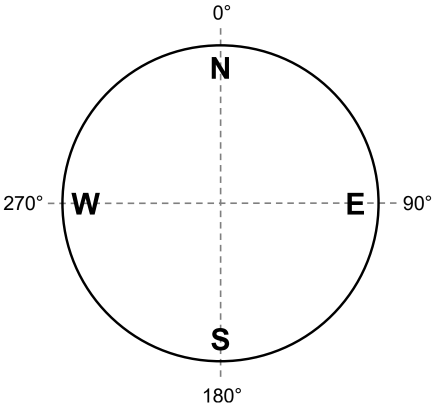


Figure 4.12.: Azimuth related to Cardinal Direction

A house has four facades in which windows can be installed. Using the azimuth angle, the DNI can be assigned to the respective facades. The irradiation range is always 180° and begins 90° before the respective direction is reached.

In the observation of the east direction the beginning is at 0°, the peak at 90° and the end at 180°(Figure 4.13).

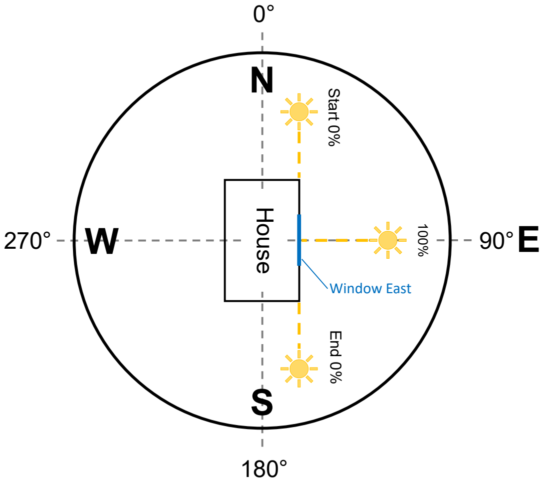


Figure 4.13.: Azimuth Distribution East Facade

The result of the sine from the azimuth angle can be used as the percentage distribution over this range, with the value 0 at the beginning and the end and the value 1 in the middle. To create this range, the sine of the azimuth must only be limited between 0 and 1. Negative values of the sine make no sense, as the radiation cannot be negative (Figure 4.14).

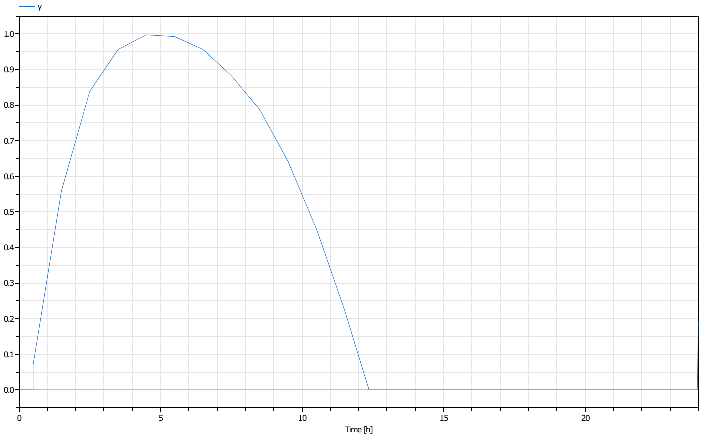


Figure 4.14.: Limited Sine Azimuth

For the east direction the distribution fits without an offset angle. Each other direction is adjusted in the calculation so that it has the same orientation as the east. This consideration is only correct if the house is perpendicular to the cardinal directions, but in most cases the house is not exactly aligned to this. In addition the angle of the house β is added to the required alignment displacement (Figure 4.15). This results in the following displacement values for the azimuth angle:

- East: $0 + \beta$
- South: $90 + \beta$
- West: $180 + \beta$
- North: $270 + \beta$

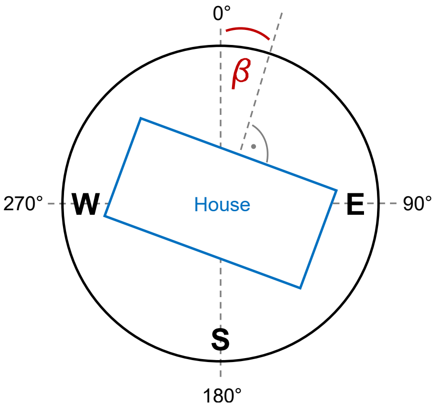


Figure 4.15.: House Angle β

The azimuth is now adjusted for each cardinal direction and the house angle β, then the sine of this new angle is calculated and limited. This gives four signals that are used for the further calculation.

The direct radiation is divided through the azimuth and zenith angle and can now be summed up with the adjusted DHI component for each direction. As an example, the calculation of the solar radiation for the south side (Equation 4.13).

$$
\begin{aligned}
G_s &= DNI \cdot sin(z) \cdot sin(a_s) + 0.5 \cdot DHI \\
a_s &= a + (90 + \beta)
\end{aligned}
\tag{4.13}
$$

$$
\begin{aligned}
z &\; ... \; zenith \\
a &\; ... \; azimuth \\
a_s &\; ... \; azimuth\ south
\end{aligned}
$$

The windows must be divided according to the sides of the house. As an example, the east window is the one where the peak of the cardinal direction East is normal to its surface. The user enters his window sizes for each direction.

In addition to the main factors of quantity of solar radiation and size of the window area, the solar heat gain also depends on factors that describe the properties of the window [24, pp. 330-331]. These factors for the window are the solar factor (total solar energy transmittance factor) g and the heat transfer coefficient U_F, which describes the thermal losses to the environment. To describe this loss, the outside temperature as well as the inside temperature is required. The solar factor g and the heat transfer coefficient U_F for the windows can be found in [25]. These parameters must be entered by the user before using the model.

$$
\frac{\dot{Q}_n}{A_F} = U_F \cdot (T_i - T_o) - g \cdot G \tag{4.14}
$$

The available solar heat gain $\dot{Q}_n$ can be seen in Equation 4.14. It consists of the sum of gains from solar radiation and thermal loss. In the model, all four cardinal directions are calculated separately and are summed up at the end.

To prevent the house from overheating on days with high solar radiation and a warm outdoor temperature, a darkening system can be integrated. This darkening system observes the inside temperature of the house as well as the amount of DNI. If both upper limit values are exceeded, the radiation is completely blocked. In all other cases, the value is calculated as in Equation 4.14. This output value of the darkening defines the heating power of the sun through the windows.

Implementation in Dymola

The *Windows* model consists of different sub-models as seen in Figure 4.16.

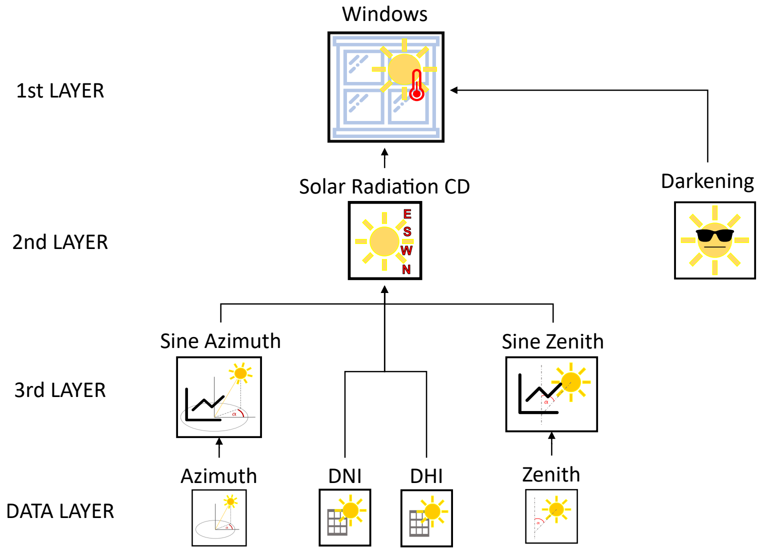


Figure 4.16.: Solar Heat Gain Model Structure

DATA

The parameters for the sun, the two angles (zenith and azimuth), as well as the radiation values DNI and DHI all come from the source section 3.4 and are implemented using the *CombiTimeTable* block. The angles are converted from degrees to radians.

Sin Zenith

This model computes the sine of the zenith angle. The sine is limited between 0 and 1. The data type is Real (Figure 4.17).

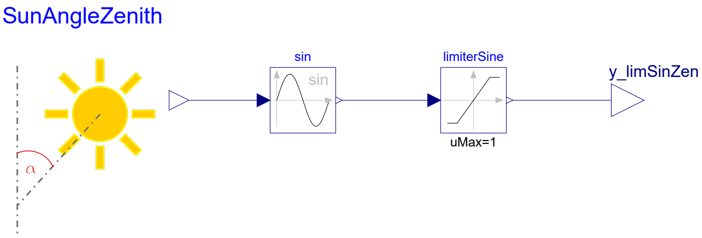


Figure 4.17.: Sin Zenith Model

Sin Azimuth

This model has an input and an output. The input delivers the angle, which includes the displacement of the cardinal direction and the rotation of the house (as described above). Furthermore, the azimuth angle is imported. This model has the task of creating the limited sine wave for each cardinal direction. This is done with the math blocks from *Dymola*. The blocker at the end cuts off the signal from 23:30 until 00:30, as the data set is incomplete at this point. This has no effect as there is no solar radiation at this time on any day of the year (Figure 4.18).

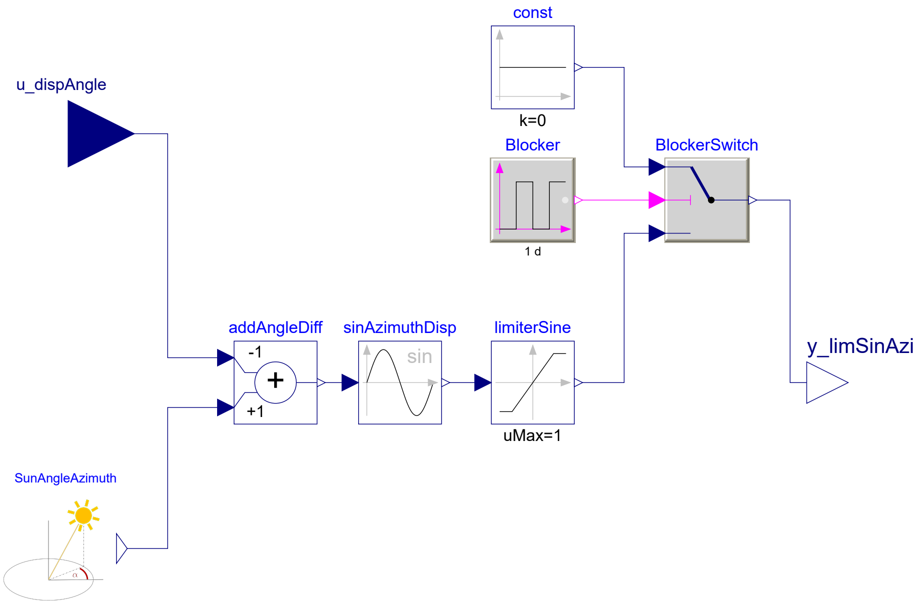


Figure 4.18.: Sin Azimuth Model

Solar Radiation Cardinal Direction (CD)

This model has the task of calculating the actual solar radiation for each cardinal direction. For this, three further components, *Sin Azimuth* and *Sin Zenith*, and the sun parameters are needed. The calculation is done according to Equation 4.13 by using the maths blocks of *Dymola*. The output of the model is the resulting radiation of the sun for each direction, which results in four outputs of the model. The data type is Real.

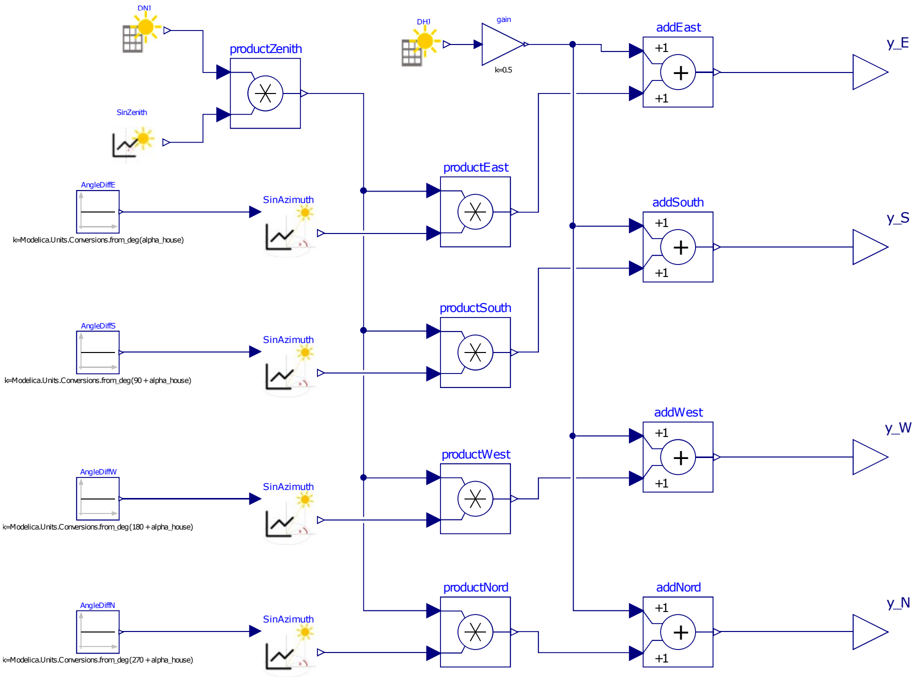


Figure 4.19.: Solar Radiation CD Model

Darkening

The *Darkening* model has two inputs and one output. Its task is to check the indoor temperature and the DNI. Both upper limits must be reached to set the *And* block to True. Then, by the *Not* and *booleanToReal* blocks, you get the number 0 for darkening or 1 for not darkening. The data type of these values is Real, so that they can now be multiplied by the solar power (Figure 4.20).

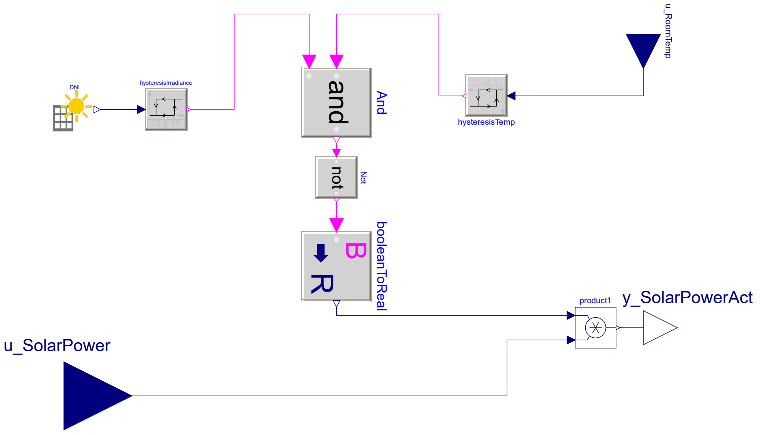


Figure 4.20.: Darkening Model

Windows

The model has two thermal connectors (air outside and air inside the house) and one Real output. The user has to define the heat transfer coefficient U_F and the energy transmittance g of the window, as well as the surfaces separately according to their orientation (A_{east}, A_{south}, A_{west} and A_{north}). The heat loss of the windows is implemented with a thermal conductor. The thermal conductance is calculated with the the heat transfer coefficient and the total window area. The solar heat gain is calculated according to Equation 4.14 and is output. The model is displayed in Figure 4.21.

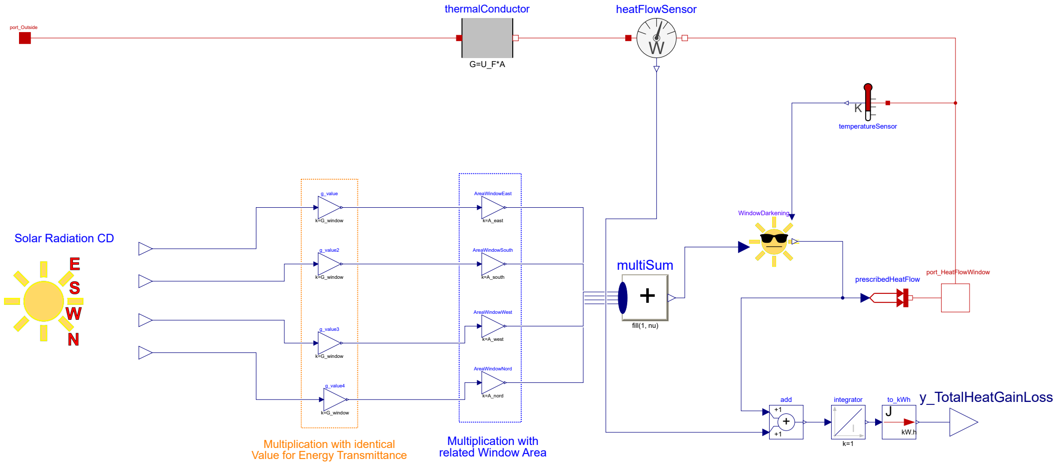


Figure 4.21.: Windows Model

Results

For the year 2021 the solar radiation per square metre for the buildings south side is 780 kWh/m^2. This radiation and the parameters of the window (u=0.54 and U_F= 0.706 W/m^{2}K [25]) result in a solar heat gain of 398 kWh/m^2. (Figure 4.22).

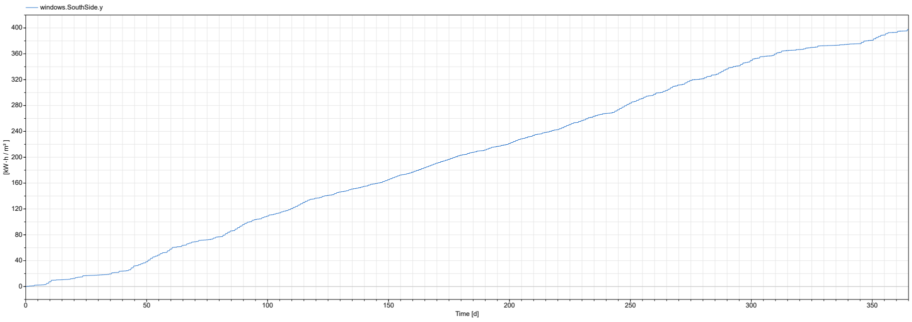


Figure 4.22.: Solar Heat Gain South Side per m^2

The total solar heat gain without darkening for the year 2021 is 1141 kWh/m^2. Taking darkening into account, a value of 371 kWh/m^2 remains. Both values refer to per square metre of window area per side and are illustrated in Figure 4.23.

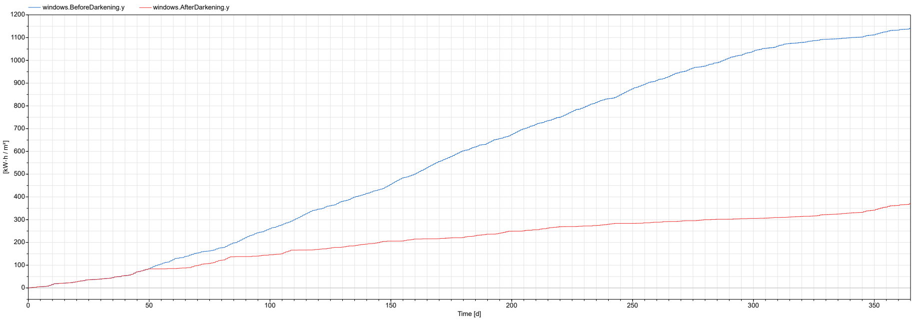


Figure 4.23.: Solar Heat Gain before Darkening

4.6. Heating Unit

The *Heating Unit* model consists of three submodels. The heating control, the heating (CHP) and the thermal storage (Figure 4.24). These models are connected in the order previously listed. The *Heating Unit* model has one input for the room temperature. The output values of the model are the heat flow and the data of the CHP-run. These data are the electric and the total power of the CHP and the total heat energy (integrated heat power of the CHP). These values are mandatory for further calculations.

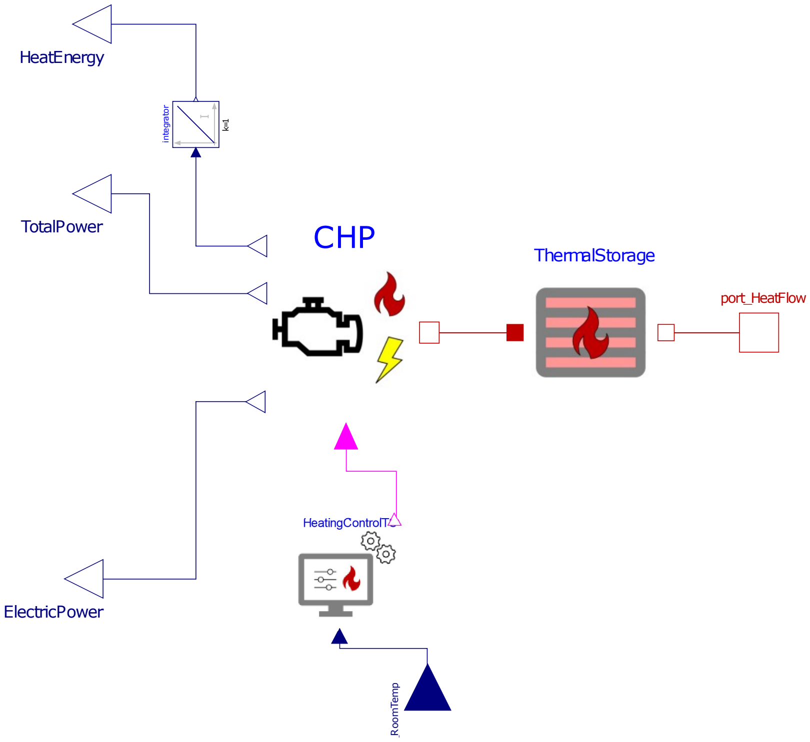


Figure 4.24.: Heating Unit Model

Heating Control

Purpose and Functionality

The task of the heating control is to switch the connected heating on and off. It is possible to define the time window for the heating period. For this task it is necessary to have the information of the house. The room temperature is the most important input.

Application and Simplification

The heating control has the task of controlling the heating so that the desired room temperature is reached in two predefined heating windows with a constant heat power. The two heating windows and the target room temperature must be predefined by the user. In the case of this thesis the heating is a CHP. Thus the defined time window also limits the electricity production and the associated sales.

The following conditions must be fulfilled for the heating control in order to send the signal to switch the heating on. On the one hand, the room temperature must be below the lower limit of the desired room temperature. On the other hand, the actual time must be in one of the two heating time windows. If only one of the two is given, the heating continues off or turns off. An example for switching off during a running heat process could be reaching the maximum temperature or heating over the end of the predefined time window.

Implementation in Dymola

The model has an input where the room temperature is entered of the data type Real. The output is the heating status (ON/OFF) as a Boolean value. The time windows that restrict the heating are implemented with two *BooleanPulse* blocks, two *Constant* blocks, an *Or* and a *Switch* block. The pulse signals are *true* if the time window is active and *false* if not. If one of these windows is reached the OR also results in *true*.

In order to implement the temperature comparison a *Hysteresis* block, a *Not* block and a *BoolToReal* block are required. The actual room temperature is compared to with the desired temperature using the hysteresis. The heating process starts when the temperature of the room is below the lower temperature limit and ends when the upper limit is reached. This output value describes exactly the opposite of the heating requirement. Therefore the output of the hysteresis must be negated. The output value of the *Not* is of type Boolean and must be converted to type Real for the following product. The subsequent product between the two checks gives the value 1 for heating and 0 if not. The heating is only active if both checks are correct. The output of the heating status is of the Boolean data type which is again transformed. (Figure 4.25)

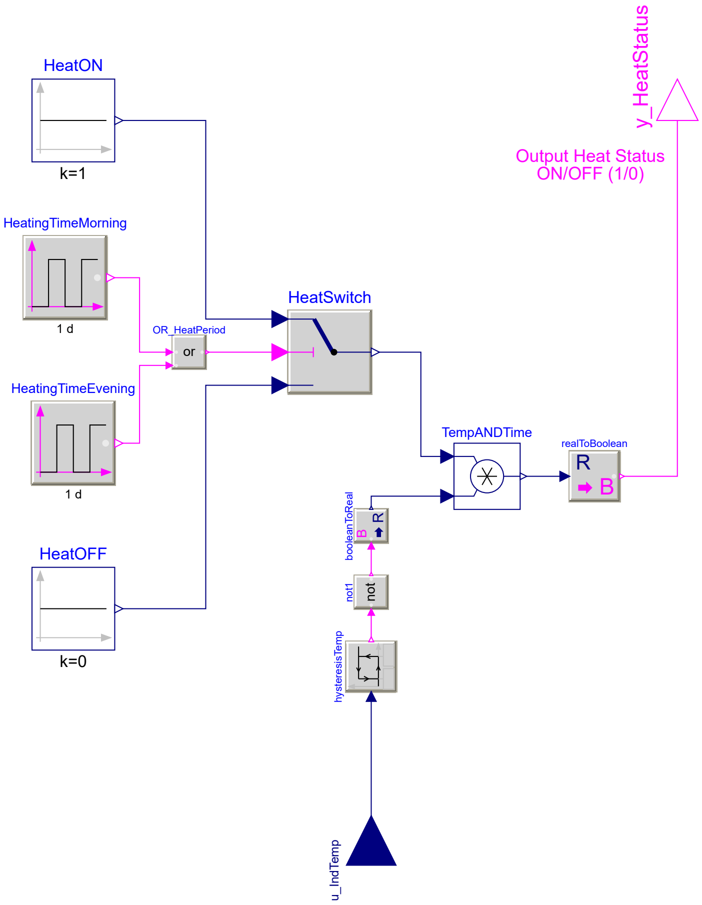


Figure 4.25.: Heating Control Model

Results

The January 2$^{\text{nd}}$ 2021 is used as an test day to show the signal of the heating status. The modelled house is the SHAC concept house. On this day the outdoor temperature was between $0\ °C$ and $-5\ °C$.

The graph (Figure 4.26) shows the status when no heat time window is prescribed. The heating must be switched on and off eleven times. The heating times range from a few minutes to several hours.

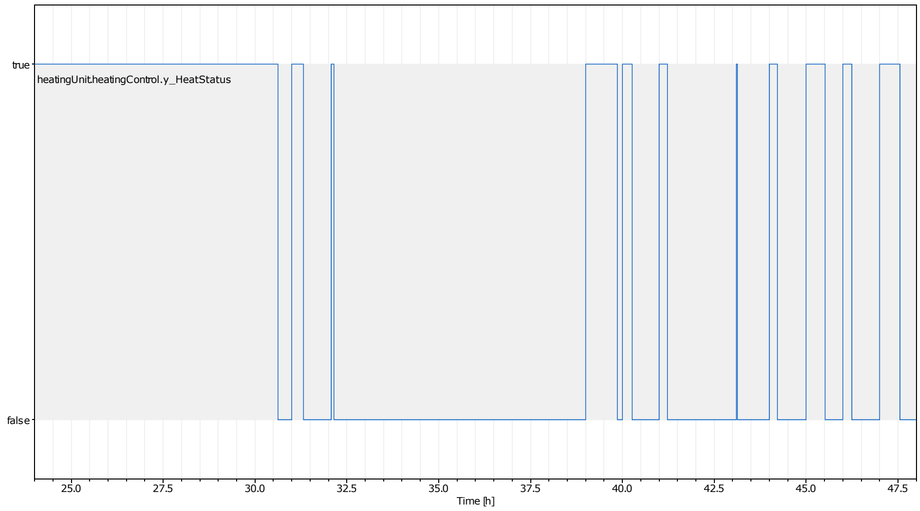


Figure 4.26.: Heating Control Heat Status without prescribed Heat Time Window

If the control unit has two prescribed time windows the many switching processes can be reduced to one. As a result the CHP runs for a longer time (Figure 4.27).

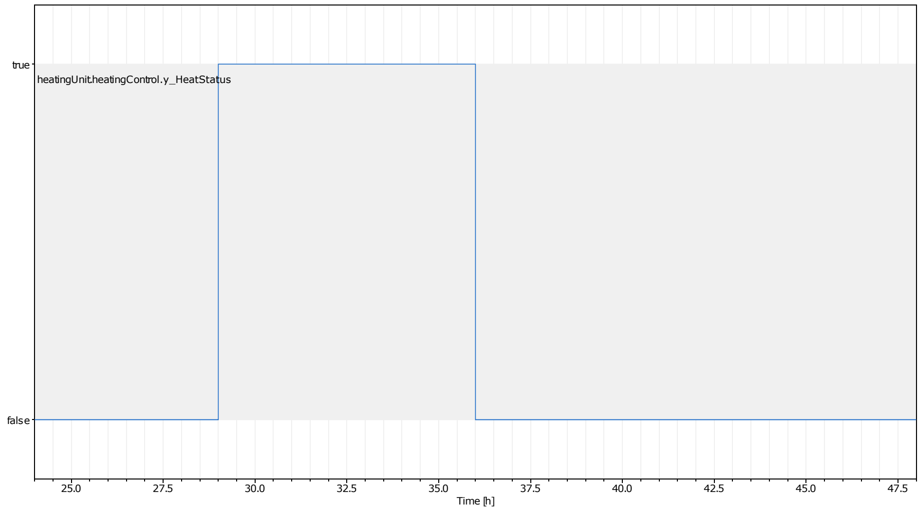


Figure 4.27.: Heating Control Heat Status with prescribed Heat Time Window

CHP

Purpose and Functionality

The CHP is the component of the heating system that creates the heat. The CHP is a machine that also generates electricity besides heat. More details about the functionality of this component are described in section 2.1.

Application and Simplification

In this work the heat power of the CHP is defined by the user. The reason for this is that the system is oriented towards the heat demand. The resulting total power as well as the electrical power are defined based on the entered heat power. The electrical power is half the heat power and the total power is the sum of these two. The value for the efficiency comes from the source cited in section 2.1. A simplification that is realised is that the machine always runs with a constant power.

Implementation in Dymola

The model gets the heating status as from the heating control. The data type of this value is Boolean. In addition, the model has three outputs of the type Real where the information regarding the different powers and consequently generated energies is sent out. Another output delivers the thermal heat flow in the thermal domain. For further processing of the input signal a conversion to the data type Real must take place by using the *BoolToReal* block. This is followed by the calculation of the thermal and electrical actual power by considering the efficiency of the machine. For the calculation of the gas consumption the total power must be used, because it indicates the target power. In addition to the output of the Real power values the thermal power is fed to a *prescribedHeatFlow* block in order to obtain the actual heat flow (Figure 4.28).

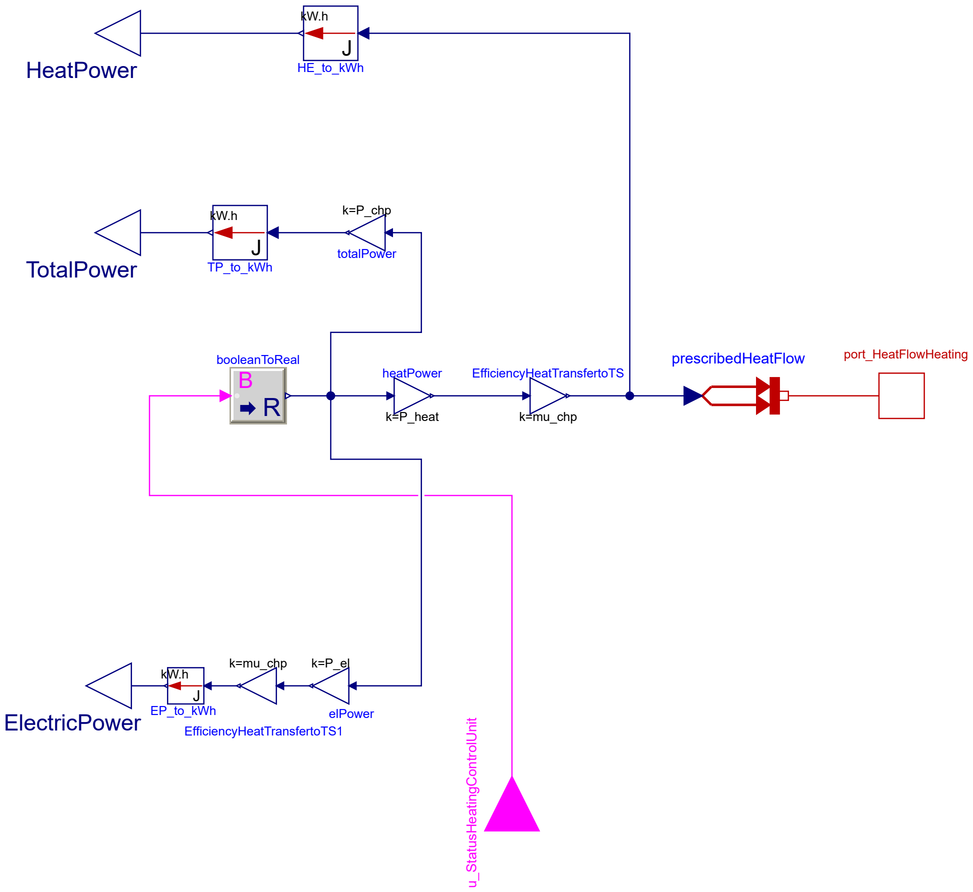


Figure 4.28.: CHP Model

Thermal Storage

Purpose and Functionality

The use of a thermal storage for heating goes back for many years and has also been very common in Austria and especially in Vorarlberg (section 2.1). A thermal storage stores the thermal energy of a heating device. This storage can be designed in different ways. The decisive factor is the heat capacity. This describes how much energy can be stored. The heat capacity depends on the volume and the material in which the thermal energy is stored.

Application and Simplification

The thermal storage is a solid cuboid. The dimensions (length, width, height) and the material are adjustable in order to maintain the flexibility of the model. With these parameters entered the heat capacity must be calculated according to formula Equation 4.1. The thermal storage is placed in the middle of the house. It is connected to the heat capacity of the house Figure 4.8 via the port of the heat capacity of the air. The heat transfer between the thermal storage and the room air is via convection. The so-called *tiled stove constant* [20, p. 76] is used as the heat transfer parameter. This constant describes the heat emission of tiled stoves and other flat space heaters.

Implementation in Dymola

The input is connected to the output of the CHP model and the output of the *Thermal Storage* model is the one of the parent model, the *Heating Unit*. The heat capacity of the storage tank is represented with the block *HeatCapacitor*. The transfer conductance (*tiled stove constant*) has been implemented by the block *ThermalConductor*. The entire model is implemented in the thermal domain (Figure 4.29).

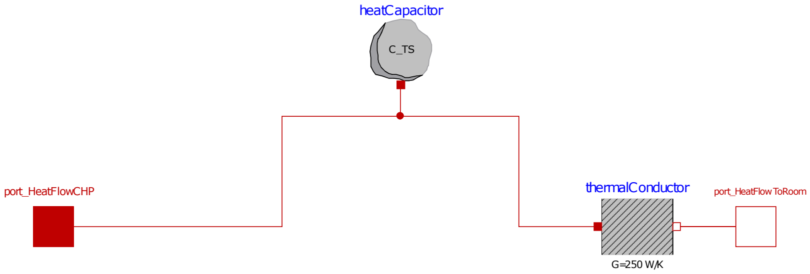


Figure 4.29.: Thermal Storage Model

Results

The thermal storage of *SHAC*'s concept has a heat capacity of 6.35×10^6 J/K. To compare this solid-state thermal storage with a water tank, the tank would have a volume roughly 1500 l for an equivalent heat capacity.

4.7. Ventilation

Purpose and Functionality

The main reason for the implementation of the ventilation process is to show the associated heat dissipation to the outside air.

Ventilation of an occupied room is an essential process. The consumption of fresh air depends on the number of people present in the room and the activities they are performing. A person needs a fresh air supply of $25 - 36\frac{m^3}{h}$ in the living room during normal activities [26, p. 2]. This required amount of fresh air must be constantly returned to the room, otherwise the air becomes too much polluted and has a harmful effect on the people. There are many methods to ventilate ranging from simple ventilation by open windows to complex automated ventilation systems. Another function of ventilation is the remove of the humidity.

Application and Simplification

For the further design of the process the amount of fresh air supply is set at $36\frac{m^3}{h}$. The ventilation in this thesis is realised by using the windows. The removal of humidity is not considered. Therefore, the most suitable method for ventilation is shock ventilation [27, pp. 17-23]. In order to determine the required ventilation time per hour the volume flow must be known. An assumption is that the windows are fully opened. The windows must be swivelled in order to open them. In addition the volume flow also depends on the temperature difference between the inside and the outside air. In this case the range in which the volume flow is as follows [28, p. 5] :

$$\begin{aligned} \Delta T = 5K \quad &\rightarrow \quad \dot{V} = 380\frac{m^3}{h} \\ \Delta T = 20K \quad &\rightarrow \quad \dot{V} = 760\frac{m^3}{h} \end{aligned}$$

As already mentioned the ventilation process involves a heat flow in addition to the air exchange. This heat flow always moves in the direction towards the higher temperature. As a result in winter heat is released to the outside and in summer heat is let into the room. Therefore it is important to keep ventilation times as short as possible. Due to the fact that this work deals with the thermal behaviour of the house the ventilation time will be based on the winter values. A further simplification is that a constant volume flow, $\dot{V} = 700\frac{m^3}{h}$, is assumed.

The subsequent required ventilation time results from the volume flow and the fresh air demand, which is derived from the number of persons and consumption per person (Equation 4.15).

$$t_{vent} = \frac{n_{pers} \cdot 36\frac{m^3}{h}}{700\frac{m^3}{h}} \cdot 3600s \tag{4.15}$$

This results in a ventilation time per person of $185s$ per hour.

The heat dissipation is described by free convection. The heat dissipation capacity α_K depends on the medium and its velocity. The unit of α_K is $\frac{W}{K \cdot m^2}$. Shock ventilation occurs in the medium air and the outside velocity is assumed to be $0\frac{m}{s}$. This results in a heat dissipation capacity of $2\frac{W}{K \cdot m^2} - 10\frac{W}{K \cdot m^2}$ [20, p. 75]. The mean value $6\frac{W}{K \cdot m^2}$ was chosen for the model. This value is now multiplied by the open window surface and the result is the thermal conductance of the open windows. The user must enter the total surface of all windows and the percentage that should be opened in order to calculate this value.

The simplified implementation is that during ventilation the entire heat flow moves through the open windows and the heat loss through the walls and ceiling is eliminated. This process is represented by a thermal resistance which is connected parallel to the *HeatLoss.ThermalConductor* (Figure 4.8). The ventilation resistance has two different values. During ventilation the value is calculated as the reciprocal from the thermal conductance of the open windows. And on the contrary the value is infinitely high so that the heat flow goes through the walls and ceiling again.

This work has no other component for cooling provided. But the ventilation with the windows can also remove the heat from the rooms on warm days. The temperature in the room is monitored in order to control the temperature. When the limit is reached and it is cool enough outside the opened windows bring fresh and cool air into the room.

Implementation in Dymola

The *Ventilation* model is located in the *HeatLoss* model (Figure 4.8). The control of the ventilation times has been outsourced to a sub-model. This model is called *VentilationControl*.

Ventilation Control

The model has two inputs where the temperatures are input. The output of the model is the status for the window opening as a Boolean variable. There are two cases: cooling and ventilation.

In order to implement the shock ventilation a *BooleanPulse* block, *ShockVentilation*, is needed. The pulse duration per hour is calculated according to Equation 4.15.

For cooling the two temperatures are converted and checked in the *Hysteresis* blocks. One if the room is too warm and the other one if it is cold enough outside for cooling. If both cases occur the conditions of the *andTempLimits* are fulfilled. The second *BooleanPulse* block, *CoolingVentilation*, limits the period of the cooling processes at the night. The reason for this is that there is no overlap during the darkening. The *andTempTime* is active when there is a need for cooling during night.

The output value is *true* if at least one of the two cases is active (Figure 4.30).

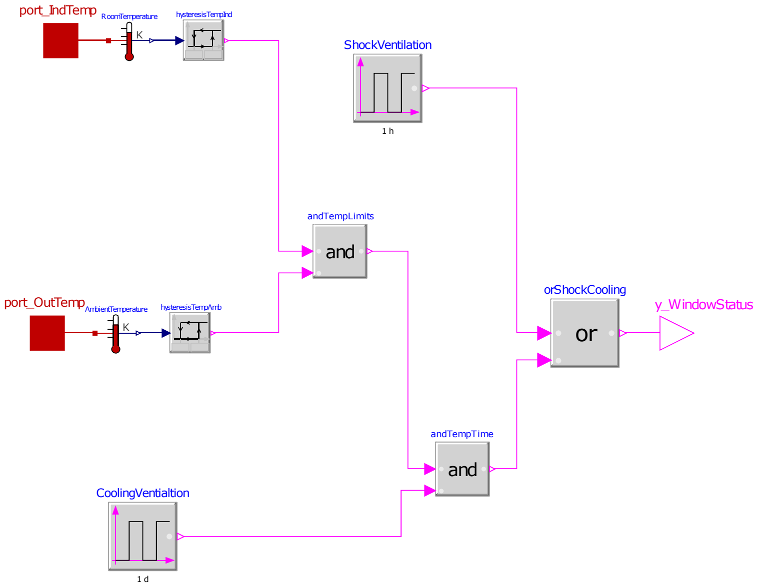


Figure 4.30.: Ventilation Control Model

Ventilation

The model has an input and an output that connects it to the room and the outside air. These two ports are connected to the *VentilationControl* which delivers the ventilation status after processing. This signal and a *Switch* are used to change between two *Constant* blocks. The value R_{thW} is the resistance of the open window and was calculated with the entered window area and α_K. The other value is used for the closed state. It was chosen very high so that the heat flow does not pass through this model. The component that requires these values is a *ConvectiveResistor* that describes the resistance between $port_{Outside}$ and $port_{Inside}$ (Figure 4.31).

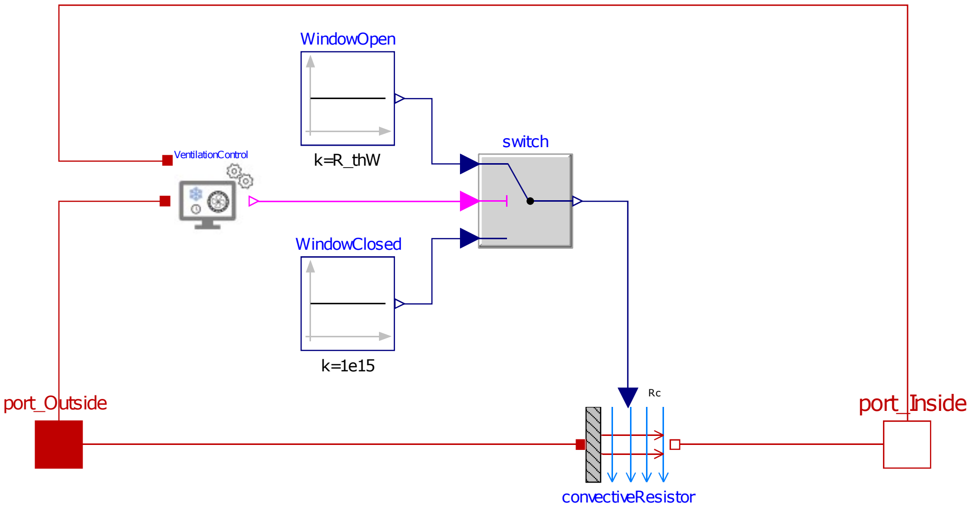


Figure 4.31.: Ventilation Model

Results

The room of the *SHAC* house cools by approximately 0.3 °C in 5 minutes of ventilation while the outside temperature is -2.5 °C. At this point, no heating is running; the subsequent heating is provided by the heat stored in the walls, ceilings and the thermal storage tank (Figure 4.32). A larger version of this graphic is in the appendix subsection A.2.

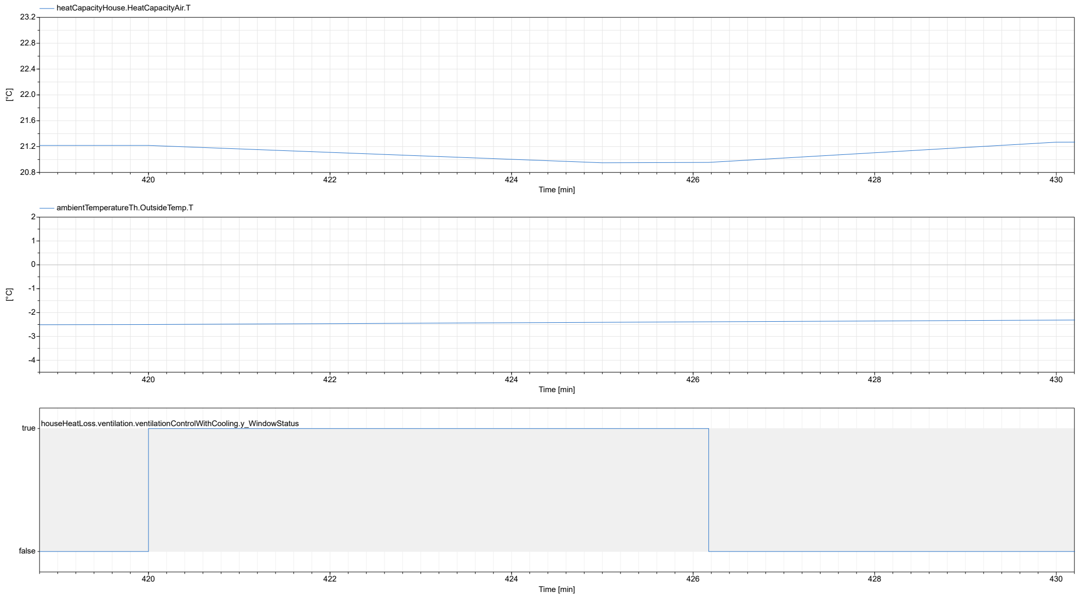


Figure 4.32.: Ventilation Result

4.8. Occupants

Purpose and Functionality

The occupants deliver a significant part of the thermal energy brought into the system. One person has a heat power of 120 W just by being present [29, pp. 321-322]. In addition to the presence the electrical consumption of the people also contributes to the heat output. The annual value of consumed electrical energy per person living in a single house is 2500 kW h when the hot water is produced electrically. This value does not increase proportionally to the number of residents. Each additional person requires 1000 kW h [30]. The added electric energy amount is divided by the days using the H0 profile [31]. The annual consumption of the profile is normalised to 1000 kW h.

Application and Simplification

The user enters the number of occupants and the typical time period while they are at home. With these data the heat power is calculated. This is determined by the occupants presence and their electrical consumption.

The heating portion due to presence is calculated with a per person heating capacity of 120 W . This power is multiplied by the number of occupants and the time period of their presence. The result is a temporal curve of the heat power due to presence.

The heating portion due to the electrical consumption can be calculated after the user entered the numbers of residents. The value for the annual consumption is calculated like 2500 kW h plus 1000 kW h times number residents minus one. Then the H0 profile is adjusted to this calculated annual value by a multiplication with the factor which describes the difference between the calculated per year consumption and the reference value of the H0 profile.

These two daily courses can now be added up to a resulting one. This resulting curve describes the heating capacity of the occupants at each point in time.

Implementation in Dymola

The implementation is done with two subordinate models. One for the calculation of the power of the presence, the *OccupantsPresenceHeating* and the other one for the calculation of the power caused by the electrical consumption, the *OccupantsElectricityConsumption*. The output values of these two models are summed and fed to a *prescribedHeatFlow* block. This provides the required heat flow in the thermal domain which is put out at the thermal port. The second output gives the value of the total heat energy after integrating the power and subsequent unit conversion (Figure 4.33).

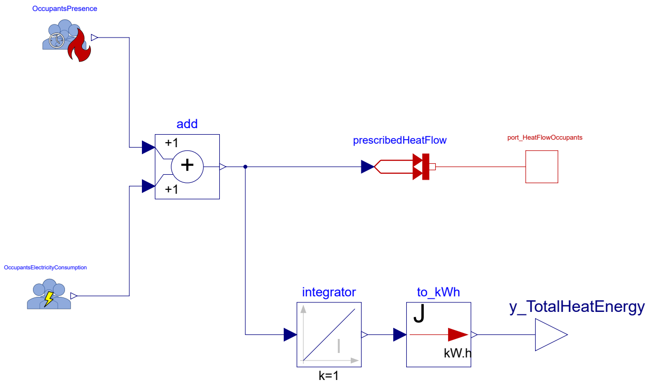


Figure 4.33.: Occupants Model

Occupants Presence Heating

In this model a *BooleanPulse* block is used to specify the time window of presence. Based on its output the *Switch* changes between two constants. One constant is 120 W and describes the power that a person heats with. The second constant is zero and it is used for the case of absence. The output value of the switch is multiplied by the number of residents. The result equals the output $y_{PowerPresence}$.

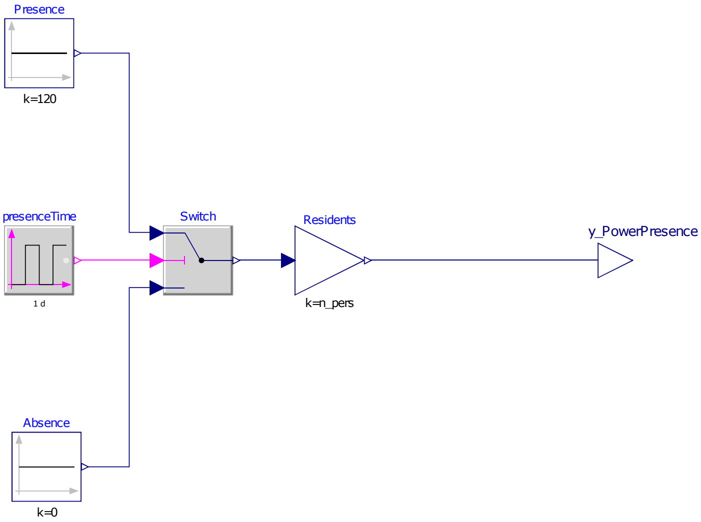


Figure 4.34.: Occupants Presence Heating Model

Occupants Electricity Consumption

This model gets the H0 profile as input using the *CombiTimeTable* block. This table must be multiplied by a factor of $1e3$ to convert the values from kW to W. Then the values are multiplied by a factor of 2.5 in order to adjust them to the actual annual electric consumption. Furthermore, a constant of 114 is needed to add the value for each additional person. The value 114 is the power calculated with the annual energy value $1000kWh$. This constant is multiplied by the value: number of persons minus one. This power value is now added to the adjusted H0 profile and is given out at the output $y_{PowerElecConsumption}$ (Figure 4.35).

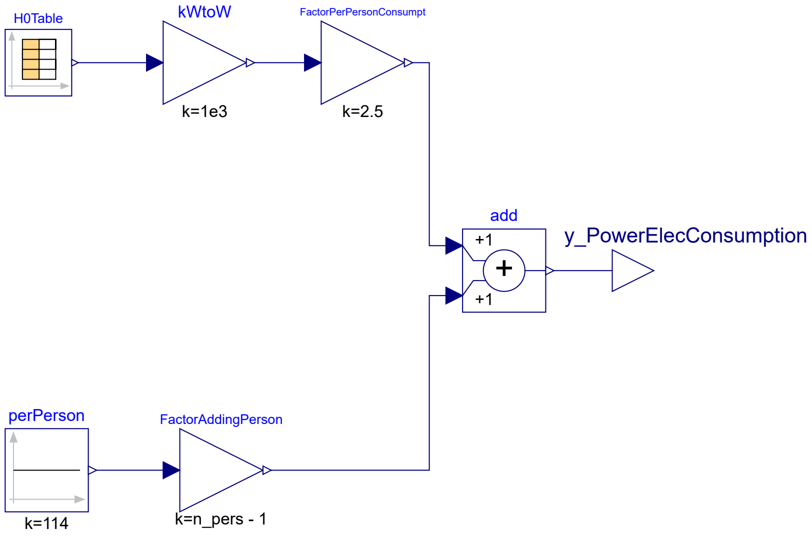


Figure 4.35.: Occupants Electricity Consumption Model

Results

The heating energy that one person contributes to the household amounts to 2977 kW h per year (Figure 4.36).

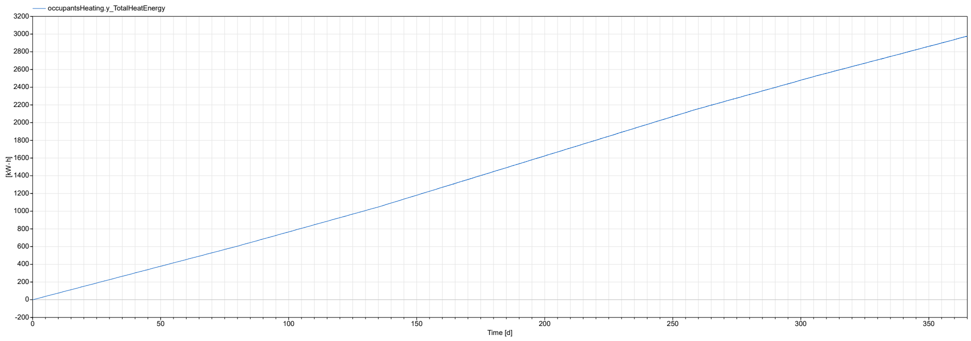


Figure 4.36.: Occupants Total Heat Energy

4.9. Gas Consumption

Purpose and Functionality

The inclusion of the gas consumption in this thesis has the following reasons. One is that the gas price of the required gas is needed for the consideration of the financial aspect. Another one is that an indication of the volume of the consumed gas is advantageous for the planning of a house. It can be used in order to calculate the size of a tank or the number of deliveries, insofar as the gas is not purchased from the grid.

Application and Simplification

The gas price is assumed to be a constant value for the whole year and is entered by the user. The gas prices used in this work are obtained from the website of the city of Bregenz [32]. The concept of *SHAC* favours the use of 20 percent bio gas. The price for one kW h is 6.62 euro cents.

In order to calculate the volume of consumed gas the user must enter the calorific value of the gas. This value indicates how many kW h are contained in one m^3 of gas.

Implementation in Dymola

The model receives the total power of the CHP as input. In order to calculate the value of the used energy the power must be integrated. This energy is used in order to calculate the price of the used gas and the required volume. Both values result from a multiplication. The price is calculated by the gas price and the volume with the calorific value. Both values generate the output to the model (Figure 4.37).

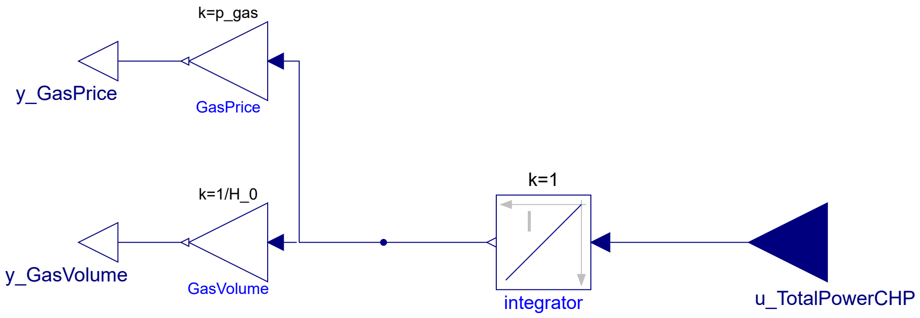


Figure 4.37.: Gas Consumption Model

Results

The *SHAC* concept house requires 962 kW h of gas for the year 2021. This amount of gas costs just under 400 € (Figure 4.38).

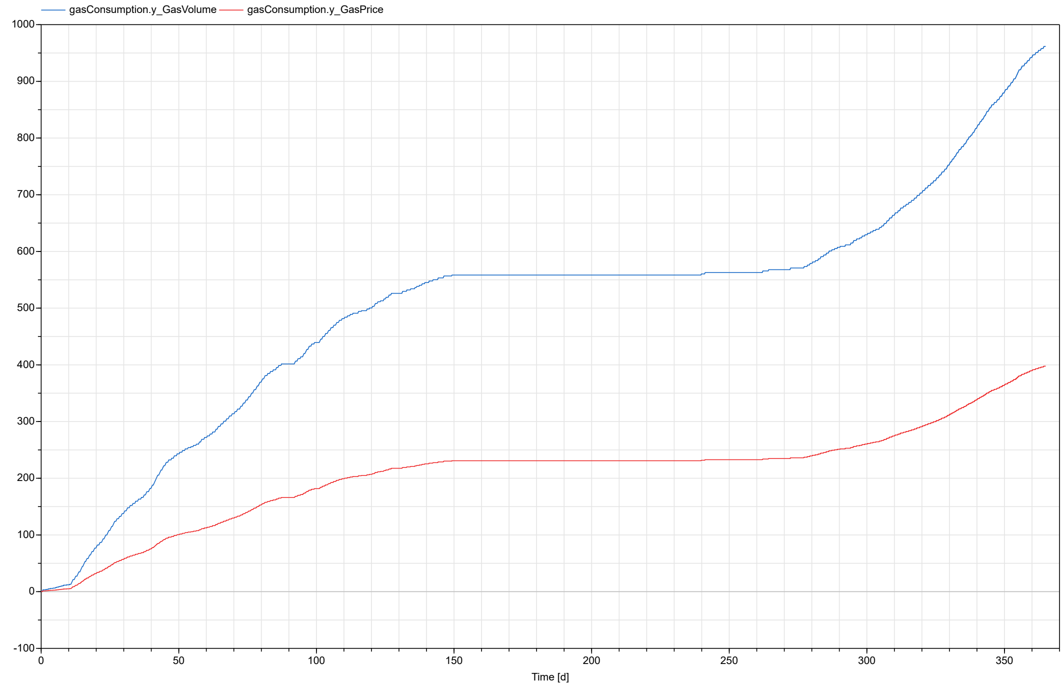


Figure 4.38.: Gas Consumption Results SHAC 2021

4.10. Electricity Sale

Purpose and Functionality

In addition to thermal energy, the CHP also generates electrical energy. The heating system is controlled by the price of electricity and is designed to sell the electrical energy. The electricity price is traded on the stock exchange and has fluent values throughout the day.

Application and Simplification

When considering the price of electricity there are two possibilities. On the one hand the electricity price can be assumed to be a fixed value. This value is an average value of a defined period. This can be the case when a fixed price has been agreed on by the electricity supplier. The other possibility is to use the daily course of the electricity price. This curve is freely accessible [4]. The assumption that one gets the same price for one's own produced electricity is a strong simplification. Both cases are considered in this work.

Implementation in Dymola

The model has two inputs. On the one hand the electrical power of the CHP is imported. On the other hand the daily course of the electricity price is entered into the *CombiTimeTable* block. There is also a constant that represents the price of electricity when the value is fixed. The Boolean variable can switch between these two (*true* = variable price, *false* = constant price). The user must decide between the two. The calculation of the earnings is a multiplication of the price and the electrical power. This amount is integrated in order to determine the total profit of the electricity sale. The profit is the output of the model (Figure 4.39).

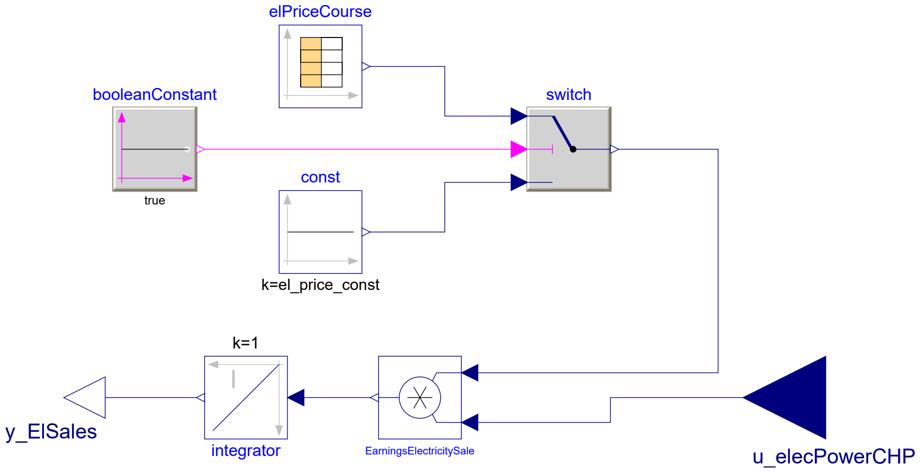


Figure 4.39.: Electricity Sales Model

5. Simulation

This chapter shows the advantages of the SHAC concept compared to other residential buildings. All concepts use a CHP in combination with a thermal storage as heating. A traditional house from the Vorarlberg region is used as a concise example at the beginning. Due to the condition of the house, for example no or a poor insulation of the walls, it is obvious that an enormous heat energy is needed to keep the house at the desired temperature of 24°. The resulting gas demand is correspondingly high, as are the associated energy costs. In the next step, this house is renovated to demonstrate the improvements to the previously simulated unchanged house. In a further simulation, the room temperature is reduced from 24° to 22.5°. Again, the effects on the required heat energy and the energy costs become apparent.The final simulation reflects *SHAC*'s concept and consequently the greatest savings. The potential of the idea becomes evident.

This chapter includes the results of the simulations. The comparisons of the results can be found at the beginning of the next chapter.

5.1. S1: Traditional House

This use case describes a traditional house from the Vorarlberg area. These buildings do not only consist of living space, because a large part is used purely for agricultural purposes. The part that is used for living and consequently is heated is limited to the right half in the example house in Figure 5.1. As one can imagine, this scenario describes the most inefficient case of all simulation applications, since those kind of houses neither have well isolated walls nor insulated windows and doors.

Figure 5.1.: Example Traditional House in Vorarlberg
source: [33]

The parameters for the model of this house are listed in Table 5.1. The parameters of the heat transfer coefficients are taken from the document of *Energie Tirol* [34].

Table 5.1.: Parameters of the Case "Traditional House"

Parameter	Value	Unit	Description
General			
n_{pers}	2		Number of occupants
T_{goal}	24	°C	Desired room temperature
Design building			
A_{total}	200	m^2	Total living area
n_{floor}	2		Numbers of floors
u_{wall}	2	$\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$	Heat transfer coefficient walls
$u_{ceiling}$	1	$\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$	Heat transfer coefficient ceiling
	Softwood		Material of the walls and the ceiling
h_{wall}	2	m	Height of the walls
t_{wall}	0.25	m	Thickness of the walls
$t_{ceiling}$	0.2	m	Thickness of the ceiling
	Concrete		Material of the ground plate
$t_{groundplate}$	0.2	m	Thickness of the ground plate
Windows			
g	75	%	Energy transmittance windows
U_F	2.5	$\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$	Heat transfer coefficient windows
A_{win}	$5 + 5 + 5 + 5 = 20$	m^2	Window area (East/South/West/North)
Heating System			
P_{heat}	35	kW	Heat power CHP
	Concrete		Material of the thermal storage
l_{TS}	2.4	m	Length thermal storage
w_{TS}	2.3	m	Width thermal storage
h_{TS}	1.5	m	Height thermal storage
Prices			
p_{gas}	0.0062	€ / kWh	Gas price

The graphs of the provided heat energy of the CHP, the heat energy generated by the occupants, the thermal energy of the windows and the total heat loss to the outside are shown in Figure 5.2. Furthermore, the costs for the purchased gas and the earnings from the sale of electricity are plotted. A larger version of this graphic is included in the appendix subsection B.1.

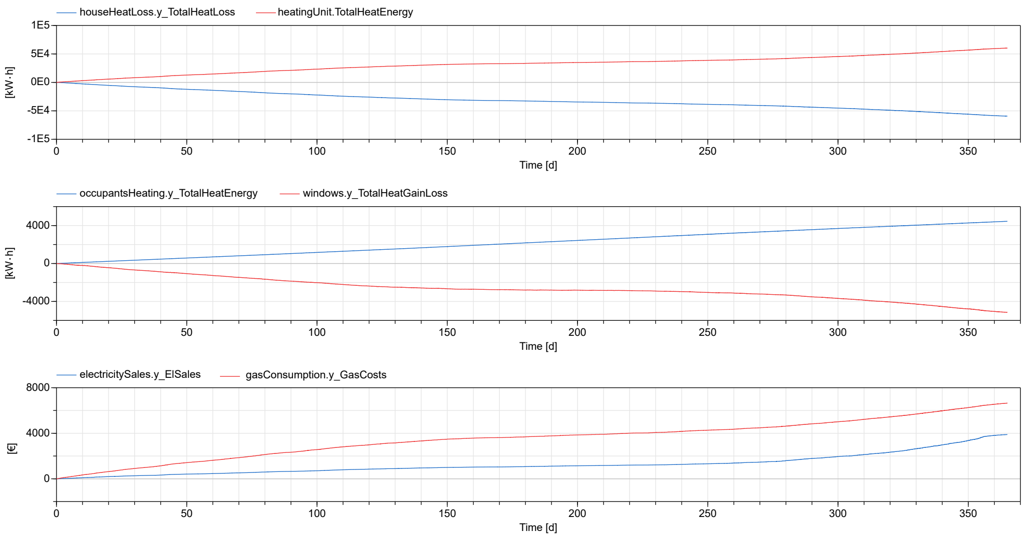


Figure 5.2.: Results Traditional House

The required heat energy for the year 2021 is 60 264 kW h. This amount and the living space of the building result in a final energy consumption for space heating per square metre of 301 kWh/m^2.

As can be seen in Figure 5.3 the system can maintain the desired indoor temperature for the first simulation scenario.

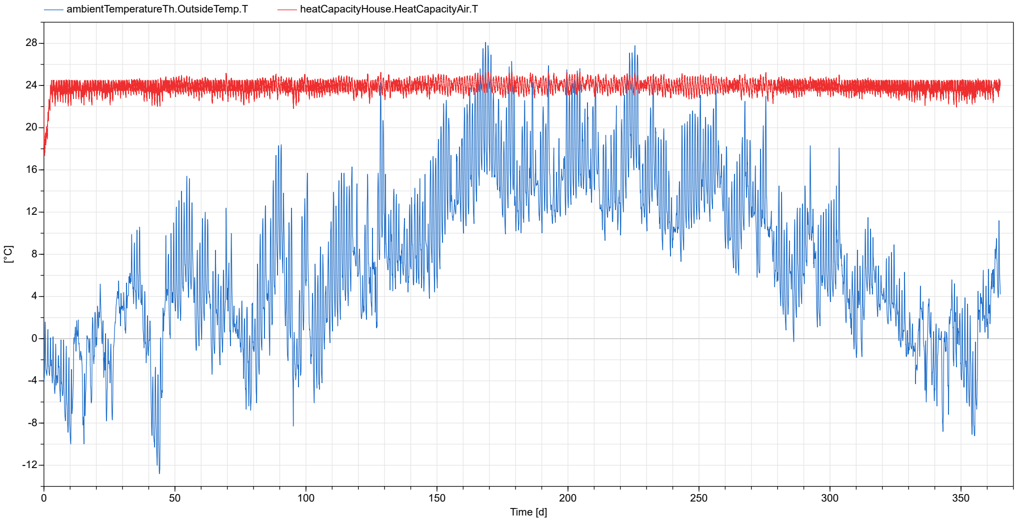


Figure 5.3.: Indoor Air Temperature Traditional House

At the beginning, the room temperature drops because the first ventilation interval starts at 00:00 and the heating cannot run at this time. The first heating interval does not start until 07:00 in the morning.

The run time of the CHP can be calculated using the required heat energy and the thermal power of the CHP. For this scenario, the heating system must run about 1722 hours. The corresponding heating status is shown in Figure 5.4.The heating has to run almost every day, even if it's not really cold outside.

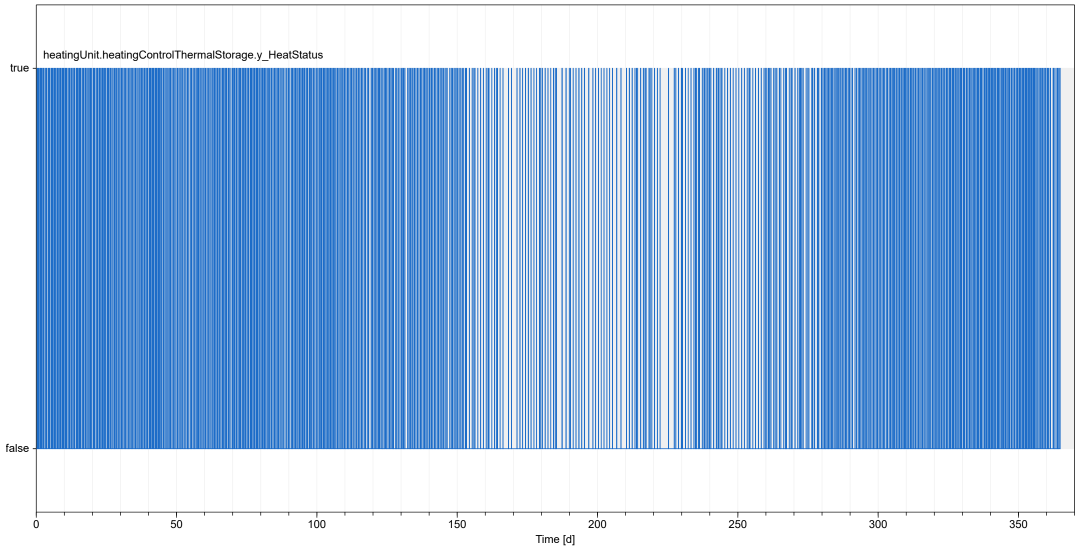


Figure 5.4.: Heat Status Traditional House

5.2. S2: Renovated Traditional House (T24)

This use case describes a renovated traditional house from the Vorarlberg area. In this scenario all windows and the entire insulation of the walls and the top ceiling have been brought up to date. The heat transfer coefficients for the walls and ceiling are taken from the guideline [34].

The "T24" in the name represents the desired indoor temperature, which has not changed from the previous scenario. Renovation is not uncommon and can have a price advantage over new construction in certain cases.

The parameters for the model of this house are listed in Table 5.2.

Table 5.2.: Parameters of the Case "Renovated Traditional House (T24)"

Parameter	Value	Unit	Description
		General	
n_{pers}	2		Number of occupants
T_{goal}	24	°C	Desired room temperature
		Design building	
A_{total}	200	m^2	Total living area
n_{floor}	2		Numbers of floors
u_{wall}	0.35	$\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$	Heat transfer coefficient walls
$u_{ceiling}$	0.2	$\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$	Heat transfer coefficient ceiling
	Softwood		Material of the walls and the ceiling
h_{wall}	2	m	Height of the walls
t_{wall}	0.25	m	Thickness of the walls
$t_{ceiling}$	0.2	m	Thickness of the ceiling
	Concrete		Material of the ground plate
$t_{groundplate}$	0.2	m	Thickness of the ground plate
		Windows	
g	51	%	Energy transmittance windows
U_F	0.7	$\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$	Heat transfer coefficient windows
A_{win}	$5 + 5 + 5 + 5 = 20$	m^2	Window area (East/South/West/North)
		Heating System	
P_{heat}	35	kW	Heat power CHP
	Concrete		Material of the thermal storage
l_{TS}	2.4	m	Length thermal storage
w_{TS}	2.3	m	Width thermal storage
h_{TS}	1.5	m	Height thermal storage
		Prices	
p_{gas}	0.0062	€ / kW h	Gas price

The results of this simulation scenario are shown in Figure 5.5. The same six sizes are illustrated again. A larger version of this graphic is included in the appendix subsection B.2.

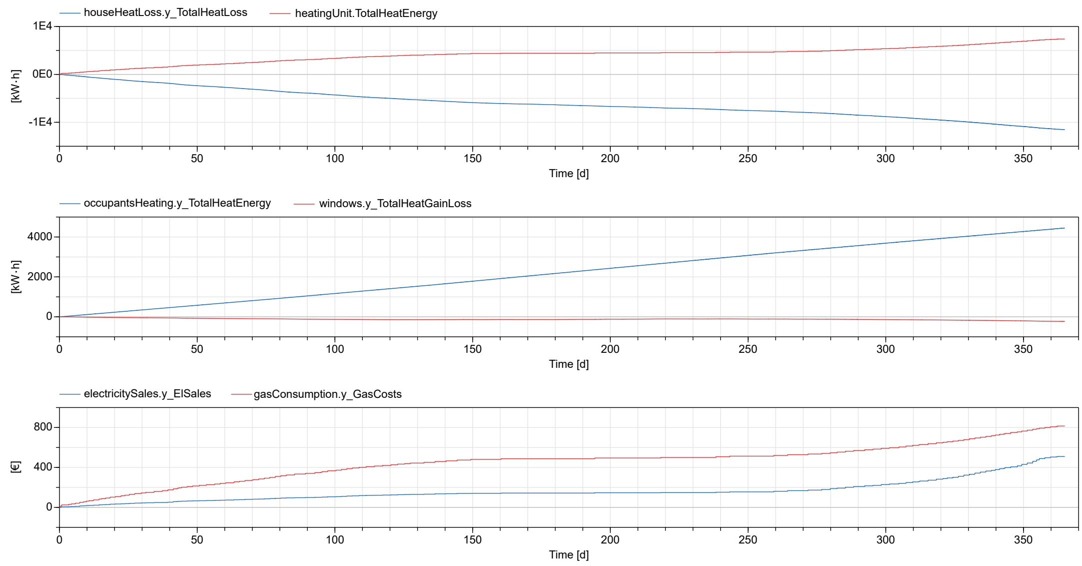


Figure 5.5.: Results Renovated Traditional House (T24)

The required heat energy for the year 2021 is 7383 kW h. This amount and the living space of the building result in a final energy consumption for space heating per square metre of 37 kWh/m^2.

In general, the thermal storage needs a higher temperature than the air inside the house to achieve and keep the desired temperature. The temperature of the thermal storage can be seen in the Figure 5.6. At the beginning, the temperature rises very sharply. The reason for this is the same as the one that causes the temperature drop at the beginning and is explained in the previous scenario.

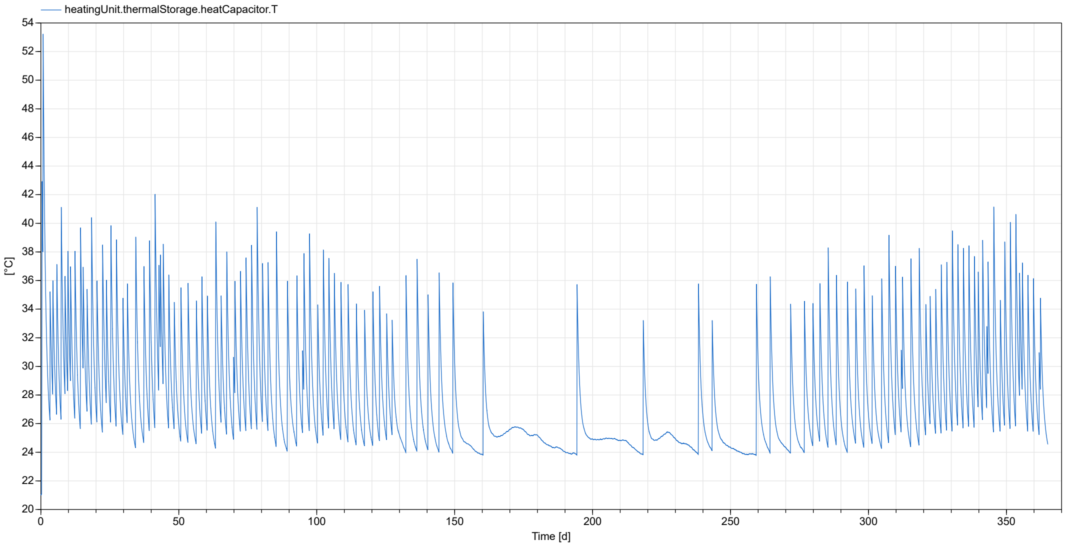


Figure 5.6.: Thermal Storage Temperature Renovated Traditional House (T24)

A larger version of Figure 5.6 is included in the appendix subsection B.3.

5.3. S3: Renovated Traditional House (T22)

In this scenario, the temperature has changed from 24 °C to 22.5 °C in comparison to the previous scenario. This scenario is intended to show the influence of a too high room temperature regarding the required heating power.

The parameters for the model of this house are listed in Table 5.2, expect the temperature.

The variables to be compared are shown in Figure 5.7. A larger version of this graphic is included in the appendix subsection B.4.

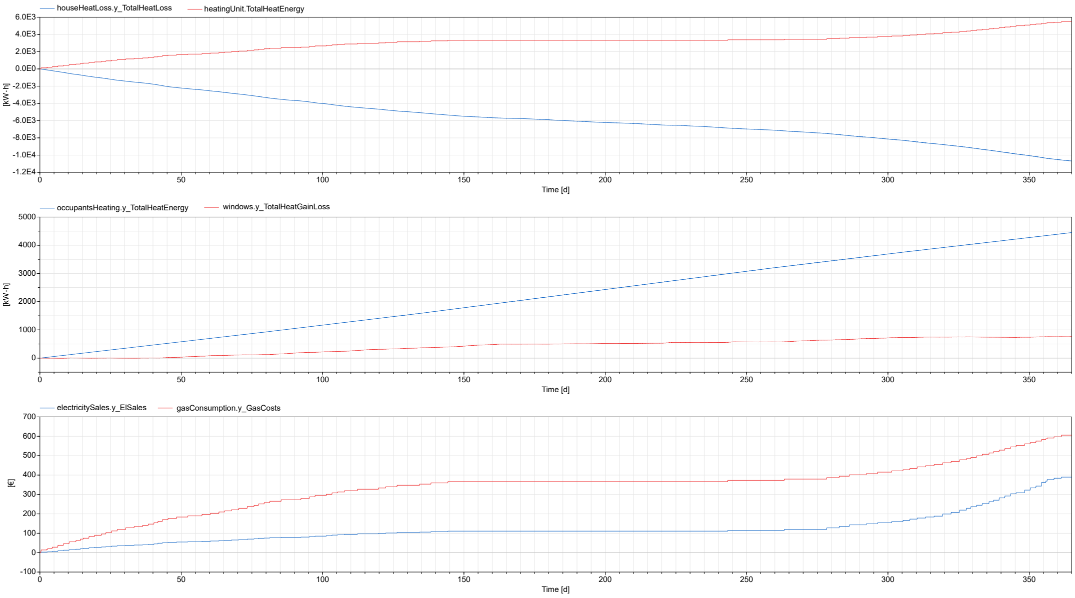


Figure 5.7.: Results Renovated Traditional House (T22)

The required heat energy for the year 2021 is 5490 kW h. This amount and the living space of the building result in a final energy consumption for space heating per living space of 27.5 kWh/m^2.

The decrease of the required total heat energy results that the heating does not have to run so often. The heat status can be seen in Figure 5.8.

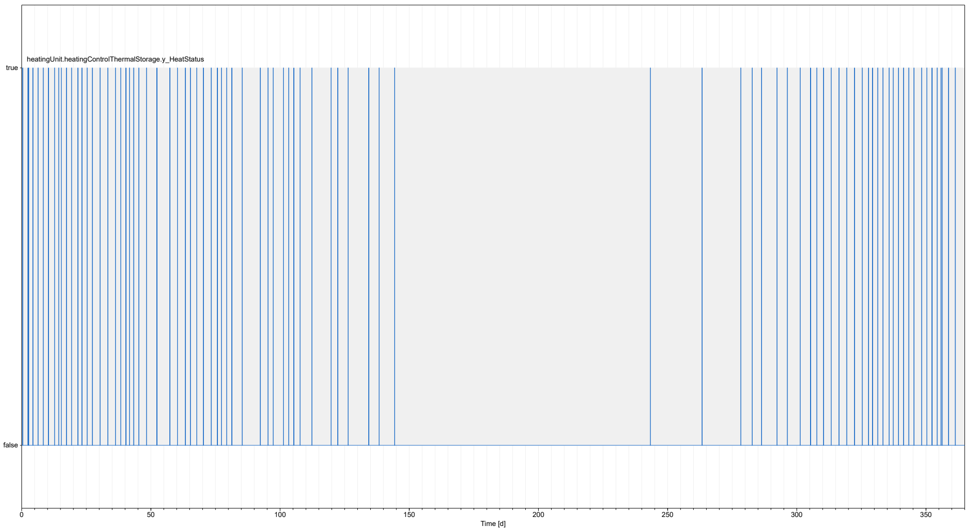


Figure 5.8.: Heat Status Renovated Traditional House (T22)

5.4. S4: SHAC Concept House

This scenario represents the concept created by the *SHAC*. A detailed description of the concept can be found in section 3.3. The aim is to show how much energy can be saved with this concept.

The parameters for the model of this house are as listed in Table 5.3.

Table 5.3.: Parameters of the Case "SHAC Concept House"

Parameter	Value	Unit	Description
General			
n_{pers}	2		Number of occupants
T_{goal}	22.5	°C	Desired room temperature
Design building			
A_{total}	35	m^2	Total living area
n_{floor}	1		Numbers of floors
u_{wall}	0.35	$\frac{W}{m^2 \cdot K}$	Heat transfer coefficient walls
$u_{ceiling}$	0.2	$\frac{W}{m^2 \cdot K}$	Heat transfer coefficient ceiling
	Softwood		Material of the walls and the ceiling
h_{wall}	2.9	m	Height of the walls
t_{wall}	0.15	m	Thickness of the walls
$t_{ceiling}$	0.15	m	Thickness of the ceiling
	Concrete		Material of the ground plate
$t_{groundplate}$	0.2	m	Thickness of the ground plate
Windows			
g	51	%	Energy transmittance windows
U_F	0.7	$\frac{W}{m^2 \cdot K}$	Heat transfer coefficient windows
A_{win}	$1 + 2 + 2 + 0 = 5$	m^2	Window area (East/South/West/North)
Heating System			
P_{heat}	2	kW	Heat power CHP
	Concrete		Material of the thermal storage
l_{TS}	2.4	m	Length thermal storage
w_{TS}	2.3	m	Width thermal storage
h_{TS}	0.5	m	Height thermal storage
Prices			
p_{gas}	0.0062	€ / kW h	Gas price

The result of the simulation is represented with the same six variables as in the three simulation scenarios before and are shown in Figure 5.9. A larger version of this graphic is included in the appendix subsection B.5.

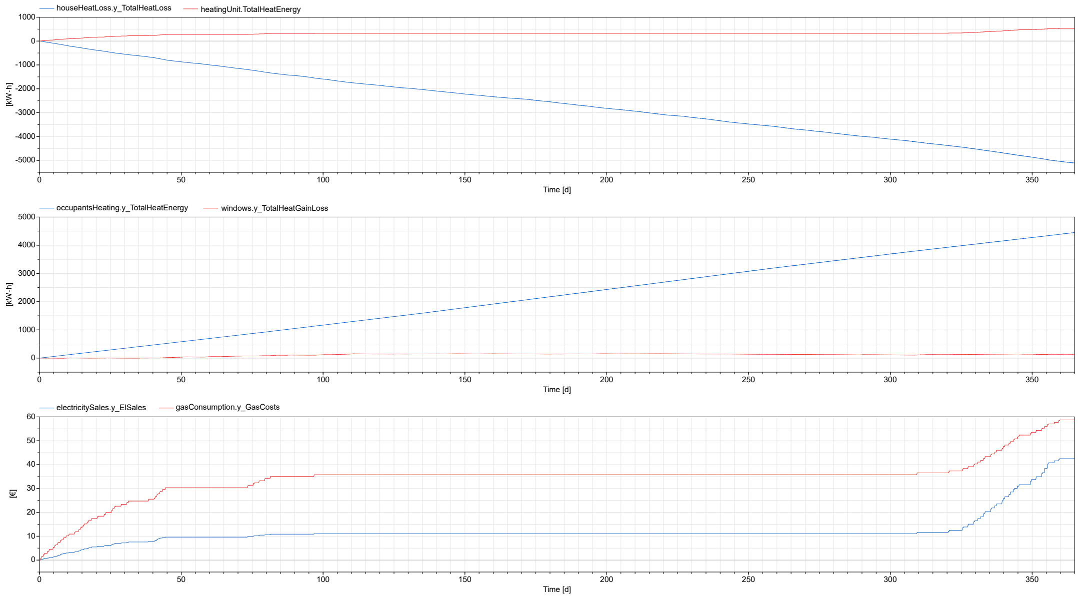


Figure 5.9.: Results SHAC Concept House

The required heat energy for the year 2021 is 533 kW h. This amount and the living space of the building result in a final energy consumption for space heating per living space of 15.5 kWh/m^2.

The second graph shows the temperatures of the air of the inside, the solids and the thermal storage of the *SHAC* concept house Figure 5.10.

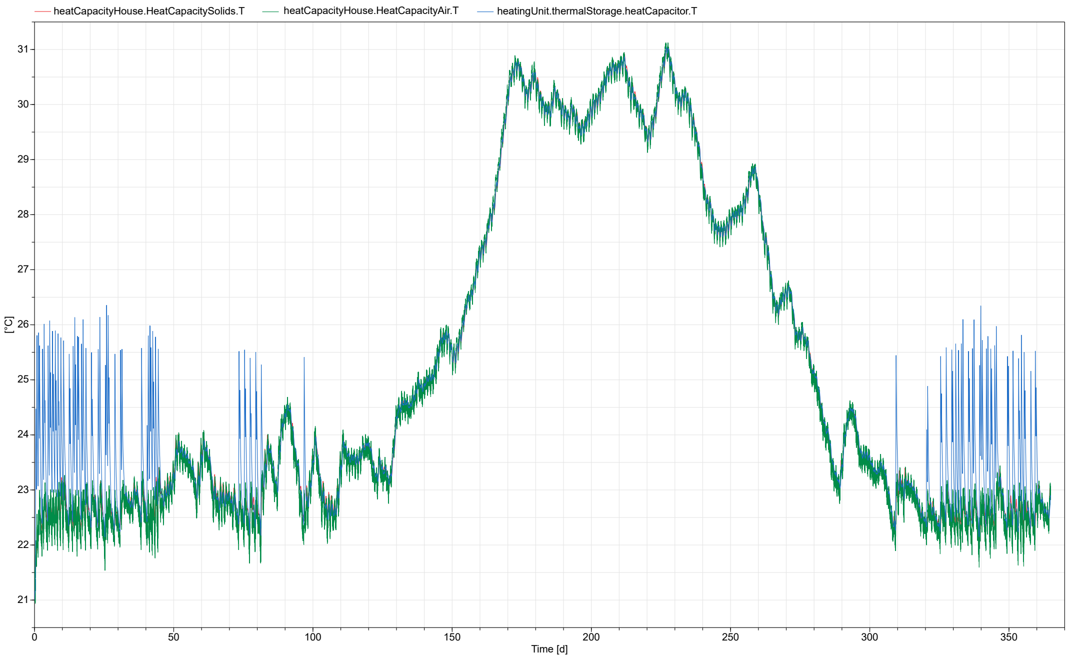


Figure 5.10.: Temperatures SHAC Concept House

A larger version of this graph is available in subsection B.6.

6. Analysis of the Simulation Results

This chapter is divided into two parts. The first part compares the results of the four simulation scenarios from chapter 5. The second part discusses individual and more detailed results from the simulation model.

6.1. Comparison of Simulation Scenarios with each other

The following naming in the graphs are from the previous chapter, e.g. S1 represents the first simulation, S2 the second one, etc.

6.1.1. Final Energy Consumption for Space Heating

The first compared value is the total energy consumption required for heating per square metre per year. The individual values can be seen in Figure 6.1.

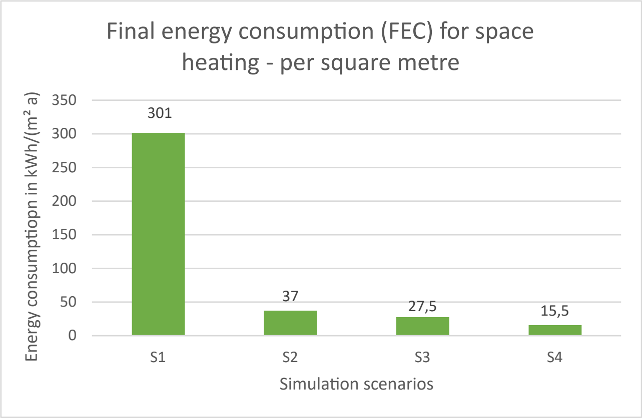


Figure 6.1.: Comparison Final Energy Consumption for Space Heating

From scenario 1 to scenario 2 there is a reduction of 264 $\mathrm{kWh/m^2a}$. This is a reduction of 87.7% of the energy used in case 1. The reduction is achieved by adjusting the values to a renovated house that has new windows and insulation to today's standards.

The difference between scenario 2 and scenario 3 is the lowering of the room temperature from 24 °C to 22.5 °C. This lowering brings an energy reduction of 9.5 kWh/m^{2}a, i.e. 25.7%.

Between scenario 3 and scenario 4, the size of the building has changed. This results in a reduction of 12 kWh/m^{2}a, i.e. 43.6% of the previously required energy. In this comparison, it becomes apparent that the internal gains by occupants, that is the influence of each person living in the house has on the energy consumption, has a disproportionate effect on the living space. This aspect is discussed in more detail in subsection 6.2.5.

Compared to the average value of the final energy consumption for space heating per square metre and per year of 2018, that is illustrated in Figure 1.1, the following reductions or increases in consumption are shown in Figure 6.2.

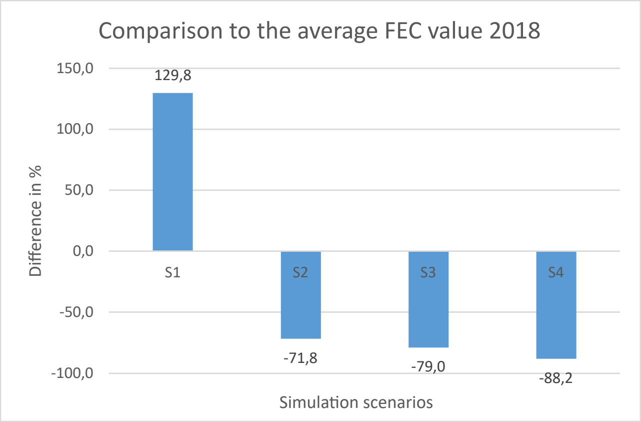


Figure 6.2.: Comparison FEC with Average Value 2018

6.1.2. Operation Costs CHP

The costs shown in Figure 6.3 reflect the actual costs for the operation of the CHP per year. These costs result from the expenditure of the required gas minus the income from the sold electricity.

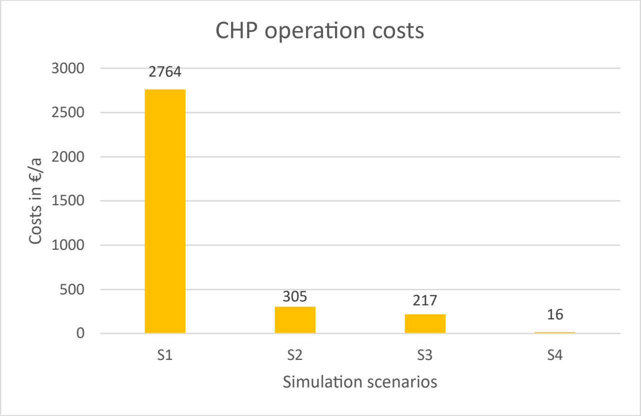


Figure 6.3.: Comparison CHP Operation Costs

In conclusion, based on the findings of this chapter, the use of a CHP in a small housing concept can be ruled out. This finding reflects part of the nature of the development process.

6.2. Further Simulation Results

6.2.1. Temperatures and Heating Status

This section considers the different temperatures of the simulation in combination with the corresponding heating status. All of them are included in Figure 6.4.

It can be seen that the thermal storage has a higher temperature in the cold months than the air inside the house and the solids. In addition it is visible that the air inside the house is too warm between days 150 and 280. A possible solution of the problem is described in section 7.

Another insight is that the heating is only active at the times, when the thermal storage is warmer than the air inside the house and the solids. The CHP unit must run for about 266.5 h to reach and keep the desired room temperature for the year 2021.

The typical number of full load hours for a CHP plant is about 4,000 per year. This value serves as a guideline for making a statement about the economic efficiency of the system. [35]

In order to achieve more full load hours, it would be possible to reduce the power of the CHP unit.

A more detailed examination shows that the CHP needs to run at the beginning and at the end of the year. It is evident that no operation is necessary between day 45 and 72. Between these days, the outdoor temperature was rather high before dropping again after day 72.

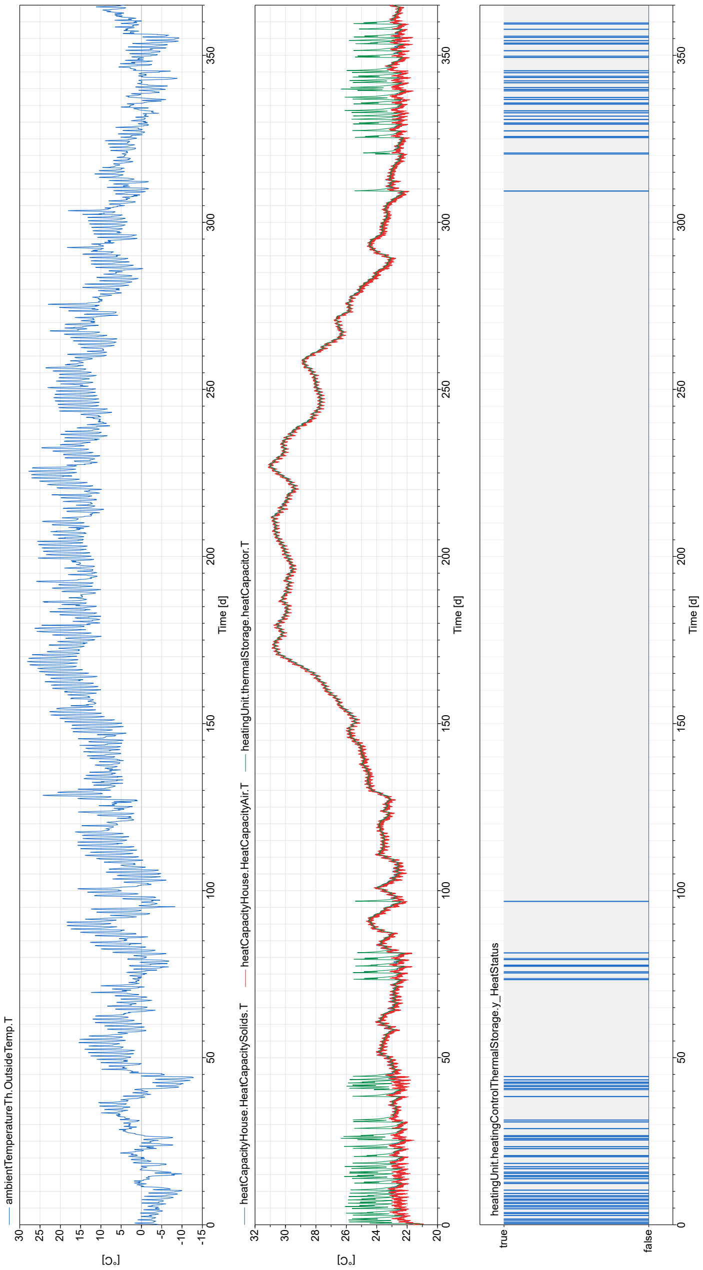


Figure 6.4.: SHAC Concept House - Temperatures and Heating Status 2021

6.2.2. Constant vs. variable Electricity Price

In the initial situation of this thesis, the use of the variable electricity price is assumed. The reason for this is that the electricity price is very high at certain times of the day and very low at others. Figure 6.5 represents the electricity price profile of a day in the beginning of December 2021. It can be seen that the price is highest at 9 am and at 5 pm and very low during the night.

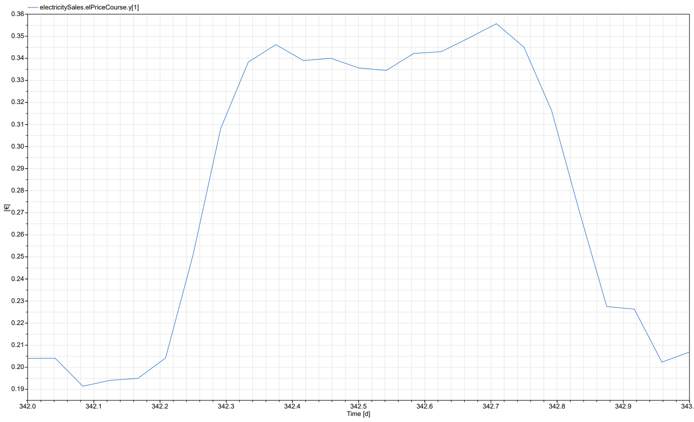


Figure 6.5.: Electricity Price Day Profile Dec.2021

Since the electricity price has generally increased significantly since mid-2021, the annual profile of 2021 cannot be used for a meaningful prediction, as can be seen in Figure 6.6. Therefore a further case is examined to investigate the result of an average price of 40 euro cents per kW h. The value represents an average price for the first half of the year 2022.

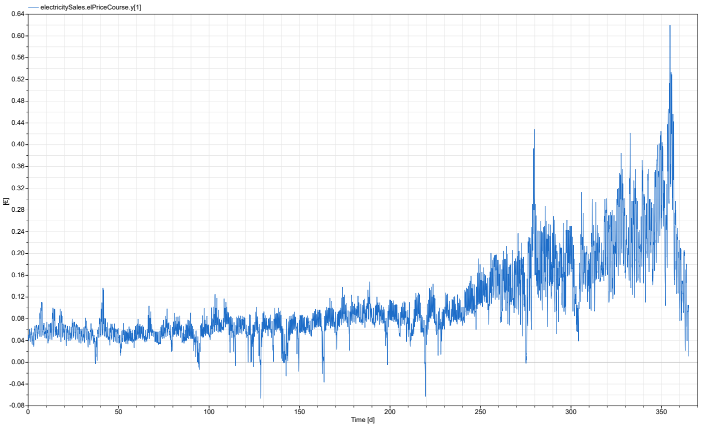


Figure 6.6.: Electricity Price 2021

The two cases, variable price and constant price, are quite different. With the constant price, a total amount of €106.44 is achieved for selling the produced electricity. The variable price only achieves an amount of €42.48. Furthermore, the derivative of the curve is significantly different at the beginning of the year and almost identical towards the end of the year due to the increase of the electricity price (Figure 6.7). For a limited future outlook, the assumption of a constant price is sufficient, but for a more accurate statement, a further consideration, which is explained in section 7, must take place.

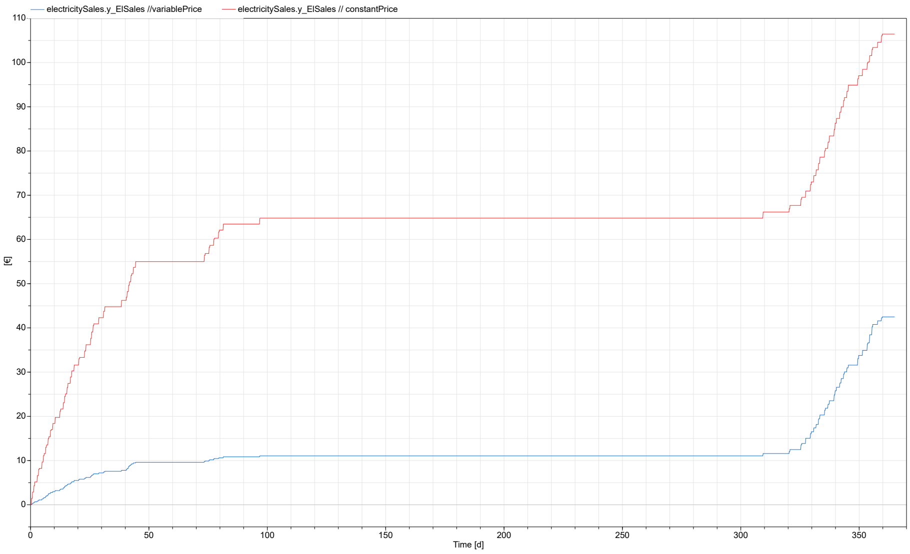


Figure 6.7.: Constant vs. variable Electricity Price 2021

6.2.3. Ventilation

Ventilation is carried out through the windows in the model. On warm days, the ventilation has to provide a cooling function in addition to the hygienic air exchange. The following diagram shows how often the window is opened in one day (Figure 6.8). The 190th day in 2021 is used for the consideration.

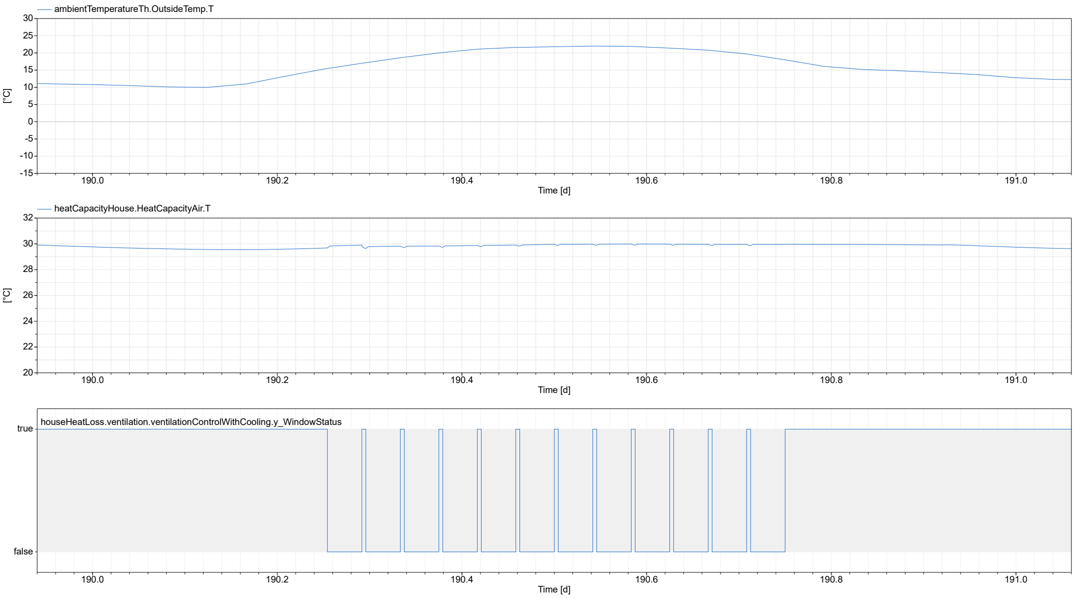


Figure 6.8.: Ventilation Window Status Day 190

It is evident that the window is open continuously at night, when people are present and the outside is cooler. During the day, only the required air is supplied to the room at the defined intervals.

6.2.4. Gas Volume

The *SHAC* residential building requires 133 m^3 of gas to heat the living space with the CHP unit for the year 2021.The increase in gas consumption can be seen in Figure 6.10. As a comparison, if one stores the required gas in a tank, the tank with the necessary size looks like the one shown in Figure 6.9.

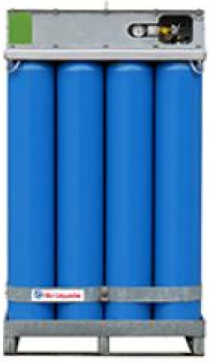


Figure 6.9.: Gas Cylinder Bundle 143.2 m^3
source: [36]

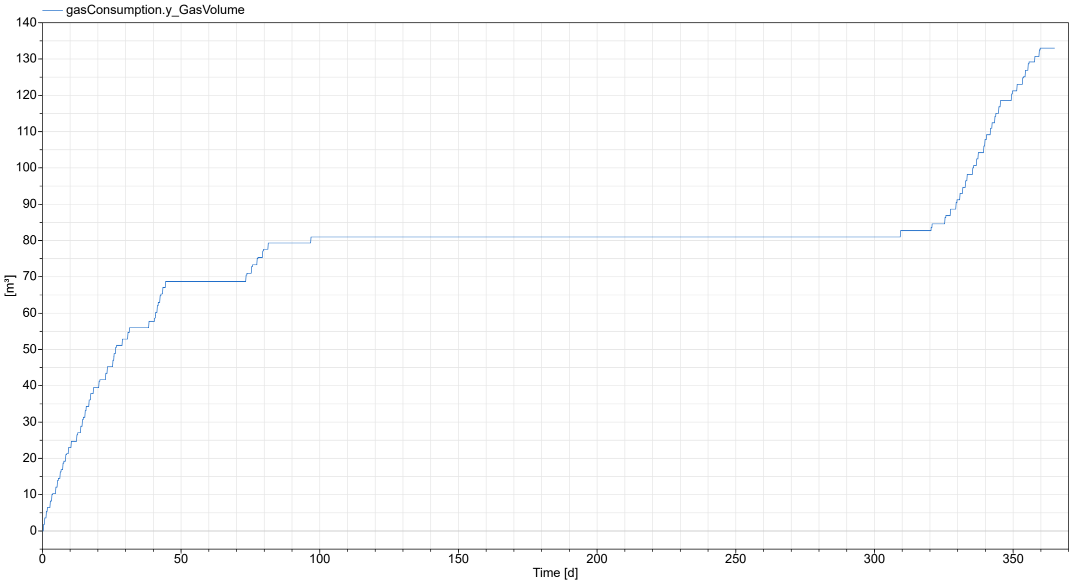


Figure 6.10.: Gas Consumption SHAC Concept House 2021

6.2.5. Heat Energy of Occupants in Relation to Living Space

The following two illustrations show that the internal heat gain of the occupants have a disproportionate influence on the heat energy of the CHP. This effect emerges at a minimum size of living space (approximately 20 m^2 per person). Thus, in Figure 6.11 the heat loss decreases normally, while in Figure 6.12 the heat energy decreases strongly. The reason for this is that the percentage of internal gains caused by occupants related to the heat loss rises sharply. In the last case, the 20 m^2, the heating is therefore only required at certain peak values.

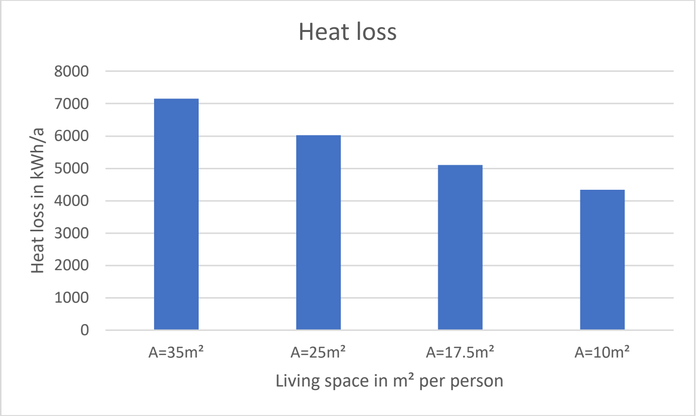


Figure 6.11.: Heat Loss - Different Size of Living Space per Person

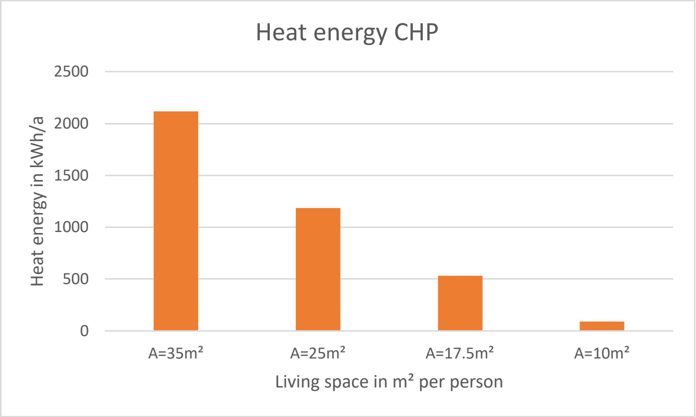


Figure 6.12.: Heat Energy CHP - Living Space

7. Conclusion and Further Work

Conclusion

The goal of this Master's Thesis was to investigate the use of a CHP in a small and thermally efficient house. In order to realise this analysis, a dynamic simulation model was implemented in the object-oriented programming language *Modelica* in *Dymola*. This model consists of nine components, which are all developed in the process of this work. The development of these individual components, as well as the linking to a complete model, was documented in chapter 4.

In order to realise the verification of the use of a CHP unit with a linked thermal storage, four different residential buildings were simulated (see chapter 5). The results of the simulations were compared with each other in order to answer the research question according to the findings of the comparison. It was shown that a house with windows and insulation of the modern standard is not suitable for the use of a CHP unit due to financial aspects. The considered factors were the revenue from the sale of electricity and the expenses for the required gas, which in total did not result in the expected high profit (see chapter 6). In addition to these two factors, the purchase costs of the heating system were not even considered in this work, as the size of a profitable system clearly exceeds that of a normal residential house.

As a result of the available findings, there is no constellation of components that can guarantee a financially attractive generation of heat energy with a CHP unit. Unfortunately, a residential house only becomes financially attractive when it has a high heat loss. This can be caused by an enormously large living area but also by poor insulation. Due to the constantly improving insulation materials and the trend towards building smaller houses, the heat loss will decrease in the future.

One possibility that produces a higher amount of electricity with a small and thermal efficient house is to feed several of these housing units with a centrally placed CHP unit. In any case, it is clear that in reality it is very difficult to implement such a concept.

The most important insight besides answering the research question is, that with a living space of $20\,\mathrm{m}^2$ per person, the heat energy, at our latitudes, plays only a secondary role. This is because the heat generated by the used electrical energy and the occupants presence has a disproportionate effect on the system. The result is that the required heat energy per square metre, in combination with a very well insulated house, falls sharply (see chapter 6).

In general, the simulation results and the associated concept depend heavily on the exact location. There are many uncertain factors when considering solar radiation. For example, months of shade from mountains or surrounding tall buildings/plants can cause an interruption of the internal energy gains from solar radiation. The concept would also have to be verified using a real building with a known location, which is a future step for *SHAC*.

Nevertheless, an intelligent control of a CHP similar to the simulation model can be financially attractive for already existing CHPs in hotels or large houses/facilities as well as for new projects with a high energy demand.

Further Work

Most of the following further work steps are directed towards the development of the concept from *SHAC*. Some of the steps serve as general improvements and are not only based on the *SHAC* concept.

Air Conditioning

On warm, sunny summer days, the temperature rises into intolerable ranges (Figure 7.1). The heat input from the occupants and from solar radiation is too high that the ventilation by windows could compensate it, when it is also warm outside. The adaptation of an air conditioning system increases the electricity demand and leads to a change in the total energy demand. The *SHAC* system does not provide any air-conditioning so far, as it assumes the simplest case. Further consideration should definitely include air conditioning to reach most realistic results.

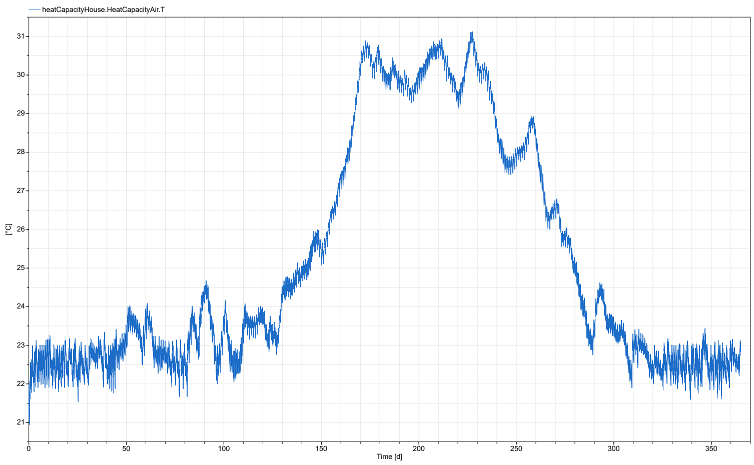


Figure 7.1.: Indoor Air Temperature SHAC Concept House

According to Kain, the use of air conditioning in Austria increases annual electricity consumption by about 15% on average. Of course, this value depends on the house. [37] Especially in *SHAC*, very small and thermally efficient house, this value is likely to be significantly below average.

One possibility to implement an air conditioning system in *Dymola* would be to add a negative heat flow to the system using the *PrescribedHeatFlow* block. The negative heat flow is defined with the power of the air conditioner and a control that turns on the air conditioner when the temperature of the air inside the house reaches the maximum limit of the desired temperature.

Energy Performance Certificate Austria

The energy certificate is the central instrument for optimising the energy performance of a building. It is used for new buildings, conversions or renovations and provides a detailed calculation of the energy performance indicators of a building and its energetically effective sub components. The energy demand is calculated by means of energy gains and losses. Its function is to provide information about the overall efficiency of the building. Thus, there are the four parameters: heating demand (HWB), primary energy demand (PEB), equivalent carbon dioxide emissions ($CO2_{eq}$) and energy performance factor (f_{GEE}) displayed in a well-structured graphic on the first page (Figure 7.2). This graphic provides a useful insight into the present building. The values in the certificate correspond to an example used by the author and have no relationship with this work. Once issued by an authorised person, this certificate is valid for 10 years. [38]

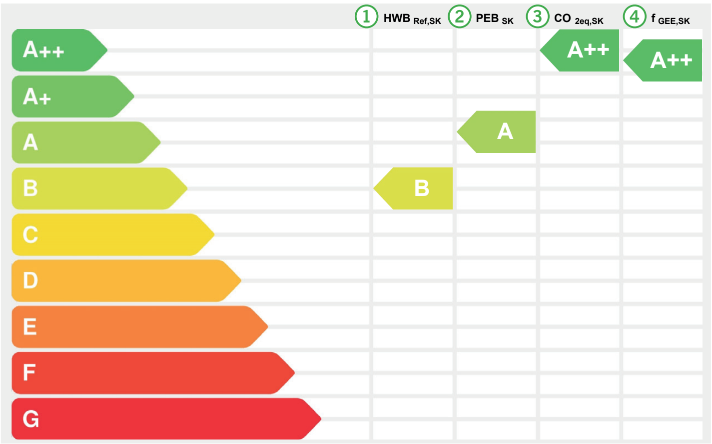


Figure 7.2.: Values Energy Performance Certificate Austria
source: [38]

The energy certificate is a proven way to compare the results of the simulations of new concepts. A closer look at this certificate and the associated compilation of the values seems to be very useful. Subsequently, the required values can be output, calculated or transformed from the simulation results.

Heat Loss to the Soil

The heat loss through the floor of the residential building in the direction of the soil is not considered because required temperature data is missing. It would be interesting, insofar as the required data is available, to investigate this loss. Whether and how significant this heat loss has an influence on the required heat energy.

Variable Price 2022

Since the electricity price has been rising sharply since mid-2021 and remains at this high level in 2022, considering the complete year 2021 is inappropriate for the current and future position. For a more accurate future forecast, the model must be used to look at the first half of 2022.

Bibliography

[1] R. H. Crawford and A. Stephan, "Tiny house, tiny footprint? the potential for tiny houses to reduce residential greenhouse gas emissions," *IOP Conference Series: Earth and Environmental Science*, vol. 588, no. 2, p. 022 073, Nov. 2020, Publisher: IOP Publishing, ISSN: 1755-1315. DOI: `10.1088/1755-1315/588/2/022073`. [Online]. Available: `https://doi.org/10.1088/1755-1315/588/2/022073` (visited on 08/16/2022).

[2] G. Dubois, B. Sovacool, C. Aall, *et al.*, "It starts at home? climate policies targeting household consumption and behavioral decisions are key to low-carbon futures," *Energy Research & Social Science*, vol. 52, pp. 144–158, Jun. 1, 2019, ISSN: 2214-6296. DOI: `10.1016/j.erss.2019.02.001`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2214629618310314` (visited on 08/16/2022).

[3] C. F. Alvarez and G. Molnar. "What is behind soaring energy prices and what happens next? – analysis," IEA. (), [Online]. Available: `https://www.iea.org/commentaries/what-is-behind-soaring-energy-prices-and-what-happens-next` (visited on 08/17/2022).

[4] "DAY-AHEAD PREISE," apg.at. (), [Online]. Available: `https://markttransparenz.apg.at/de/markt/Markttransparenz/Uebertragung/EXAA-Spotmarkt` (visited on 08/07/2022).

[5] A. Kylili and P. A. Fokaides, "European smart cities: The role of zero energy buildings," *Sustainable Cities and Society*, vol. 15, pp. 86–95, Jul. 1, 2015, ISSN: 2210-6707. DOI: `10.1016/j.scs.2014.12.003`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2210670714001383` (visited on 08/16/2022).

[6] S. Wilke. "Energieverbrauch privater Haushalte," Umweltbundesamt. Publisher: Umweltbundesamt. (2020), [Online]. Available: `https://www.umweltbundesamt.de/daten/private-haushalte-konsum/wohnen/energieverbrauch-privater-haushalte` (visited on 08/22/2022).

[7] O. US EPA. "Combined heat and power (CHP) partnership." (Jun. 11, 2015), [Online]. Available: `https://www.epa.gov/chp` (visited on 08/18/2022).

[8] ASUE, *BHKW - grundlagen*, 2010.

[9] A. Wurm. "Die Kraft-Wärme-Kopplung im Einfamilienhaus: Vielversprechende Zukunftstechnologie?" dein-heizungsbauer.de. (), [Online]. Available: `https://www.dein-heizungsbauer.de/ratgeber/bauen-sanieren/kraft-waerme-kopplung-einfamilienhaus/` (visited on 08/18/2022).

[10] "Absatz von Nano-KWK in Deutschland bis 2020," Statista. (), [Online]. Available: `https://de.statista.com/statistik/daten/studie/461644/umfrage/absatz-von-nano-kwk-in-deutschland/` (visited on 08/18/2022).

[11] K. Horn, "Manual for dismantling, documenting and rebuilding historic tiled stoves — sustainable heritage report no. 3," 2012.

[12] İ. Dinçer and M. Rosen, *Thermal energy storage: systems and applications*, 2nd ed. Hoboken, N.J: Wiley, 2011, 599 pp., ISBN: 978-0-470-74706-3.

[13] O. D. Doleski, Ed., *Realisierung Utility 4.0 Band 2: Praxis der digitalen Energiewirtschaft vom Vertrieb bis zu innovativen Energy Services*, Wiesbaden: Springer Fachmedien Wiesbaden, 2020, ISBN: 978-3-658-25588-6 978-3-658-25589-3. DOI: `10.1007/978-3-658-25589-3`. [Online]. Available: `http://link.springer.com/10.1007/978-3-658-25589-3` (visited on 08/20/2022).

[14] T. L. Schmitt and M. Andres, *Methoden zur Modellbildung und Simulation mechatronischer Systeme: Bondgraphen, objektorientierte Modellierungstechniken und numerische Integrationsverfahren*, ser. Lehrbuch. Wiesbaden [Heidelberg]: Springer Vieweg, 2019, 643 pp., ISBN: 978-3-658-25088-1.

[15] "Modelica language — modelica association." (), [Online]. Available: `https://modelica.org/modelicalanguage.html` (visited on 08/22/2022).

[16] D. Brück, *Dymola referential*, 2021.

[17] Ö. I. für Bautechnik, *OIB-330.6-026/19 - OIB Richtlinie 6 - Energieeinsparung und Wärmeschutz*. 2019.

[18] Y. A. Çengel and A. J. Ghajar, *Heat and mass transfer: fundamentals & applications*, Fifth edition. New York, NY: McGraw Hill Education, 2015, 968 pp., OCLC: ocn870517093, ISBN: 978-0-07-339818-1 978-1-259-17330-1 978-981-4595-27-8.

[19] "Solcast - solar forecasting & solar irradiance data," Solcast. (), [Online]. Available: `https://solcast.com/` (visited on 04/14/2022).

[20] O. Zirn and S. Weikert, *Modellbildung und Simulation hochdynamischer Fertigungssysteme: eine praxisnahe Einführung ; mit 33 Tabellen*. Berlin Heidelberg: Springer, 2006, ISBN: 978-3-540-25817-9.

[21] D. D. I. für Normung e.V., *DIN EN ISO 7730 - Ergonomie der thermischen Umgebung – Analytische Bestimmung und Interpretation der thermischen Behaglichkeit durch Berechnung des PMV- und des PPD-Indexes und Kriterien der lokalen thermischen Behaglichkeit (ISO 7730:2005); Deutsche Fassung EN ISO 7730:2005.* 2006.

[22] "Beckhoff information system - TS3900 | TwinCAT 2 solar position algorithm." (2011), [Online]. Available: `https://infosys.beckhoff.com/index.php?content=../content/1031/tcplclibspa/11172726283.html&id=4600675470280830559` (visited on 08/29/2022).

[23] I. Yahyaoui, *Advances in renewable energies and power technologies.* Amsterdam: Elsevier, 2018, ISBN: 978-0-12-812959-3.

[24] U. Eicker, *Solare Technologien für Gebäude: Grundlagen und Praxisbeispiele*, 2., vollständig überarbeitete Aufllage, ser. Studium. Wiesbaden: Vieweg + Teubner, 2012, ISBN: 978-3-8348-1281-0.

[25] "Baubook ökoBauKriterien." (), [Online]. Available: `https://www.baubook.at/oea/` (visited on 04/21/2022).

[26] P. Tappler, *Innenraumluft-info. luftmengen - luftfeuchte.*

[27] H. Künzel, *Richtiges Lüften in Wohnungen*, 6., überarbeitete Auflage. Stuttgart: Fraunhofer IRB Verlag, 2019, 23 pp., ISBN: 978-3-7388-0248-1.

[28] J. Seifert, R. Gritzki, and M. Rösler, *Bestimmung des realen luftwechsels bei fensterlüftung aus energetischer und bauphysikalischer sicht*, 2003.

[29] L. Davis, *Body Physics: Motion to Metabolism.* 2018.

[30] A. Weißbach and L. Wagener. "Stromverbrauch im haushalt," stromsiegel. (), [Online]. Available: `https://www.stromspiegel.de/stromverbrauch-verstehen/stromverbrauch-im-haushalt/` (visited on 08/07/2022).

[31] "Lastprofile, Temperaturtabellen," ED Netze. (), [Online]. Available: `https://www.ednetze.de/geschaeftspartner/lieferanten/lastprofile-temperaturtabellen/` (visited on 08/07/2022).

[32] "Produkte / Preise - Stadtwerke Bregenz GmbH," Stadtwerke Bregenz. (), [Online]. Available: `https://www.stadtwerke-bregenz.at/erdgas-biogas/produkte-preise` (visited on 08/07/2022).

[33] Z. VN, "Vorarlberg Einst und Jetzt. Ammann-Haus in Lustenau," *Vorarlberger Nachrichten | VN.at*, 2015. [Online]. Available: `https://www.vn.at/vorarlberg/2015/11/02/vorarlberg-einst-und-jetzt-ammann-haus-in-lustenau.vn` (visited on 08/19/2022).

[34] B. Oberhuber, *Bauteile & u-werte - die richtige planung für mein haus*, 2017. [Online]. Available: `https://www.energie-gemeinde.at/uploads/tx_bh/energie_tirol_detailinformation_bauteile_u_werte.pdf` (visited on 08/24/2022).

[35] "WBZU - blockheizkraftwerke." (), [Online]. Available: `http://www.wbzu.de/seminare/infopool/infopool-bhkw` (visited on 08/30/2022).

[36] "myGAS portal | technische gase online finden & kaufen." (), [Online]. Available: `https://mygas.airliquide.de/catalog-gas-products/arcal--force/arcal-force-bundel-v12*50l-200-bar/i2506v12r2a001` (visited on 08/26/2022).

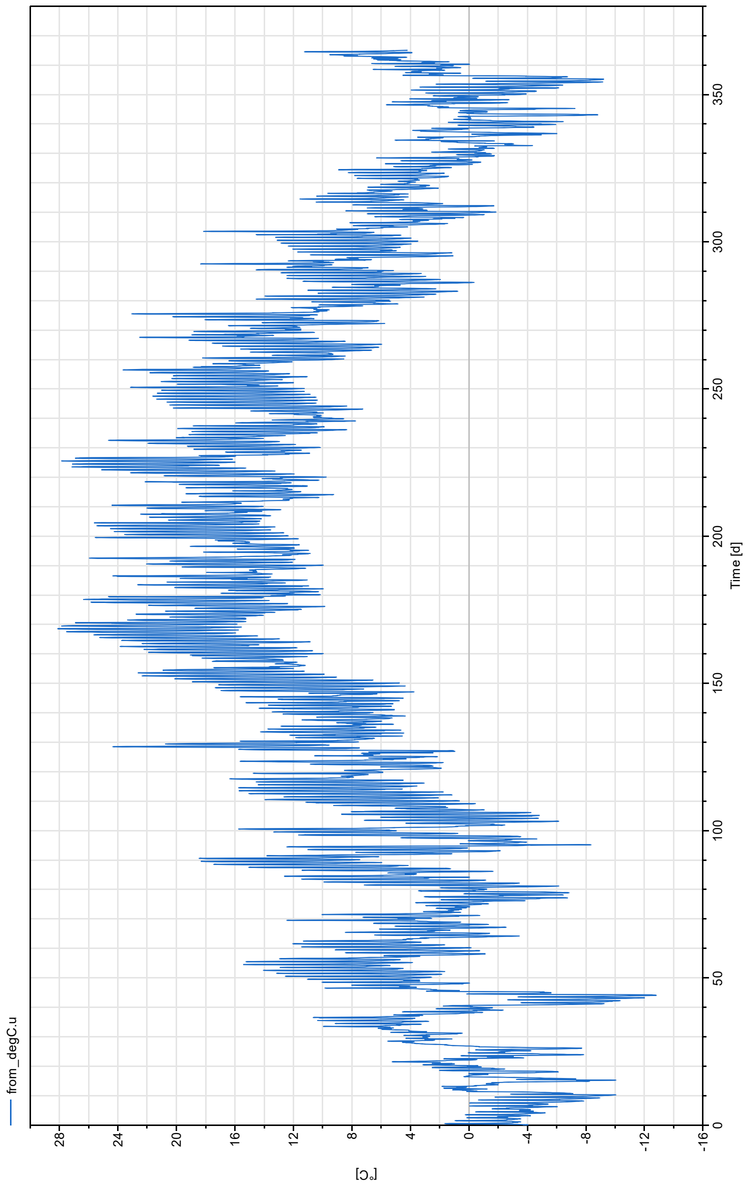
[37] C. Kain. "Stromfresser Klimaanlagen und Ihre Alternativen," Selectra. (), [Online]. Available: `https://selectra.at/energie/tipps/energiesparen/klimaanlage-stromfresser` (visited on 08/25/2022).

[38] *ENERGIEAUSWEIS für gebäude in oberösterreich - energieeffizienz steigern & transparenz erhöhen.* [Online]. Available: `https://www.energiesparverband.at/fileadmin/esv/Broschueren/Energieausweis.pdf` (visited on 08/25/2022).

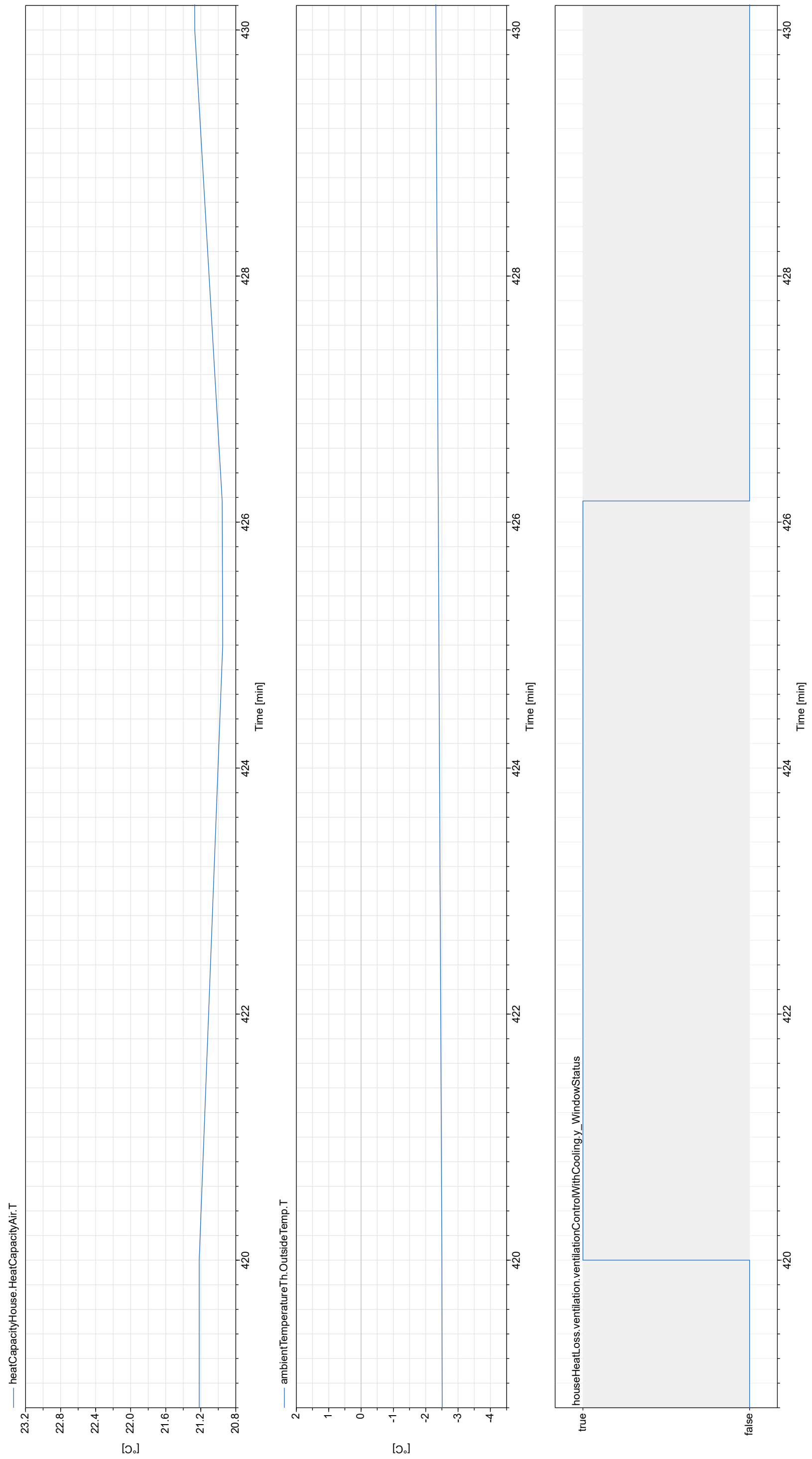
Appendix

A. Modelling Results

A.1. Outdoor Temperature Dornbirn 2021

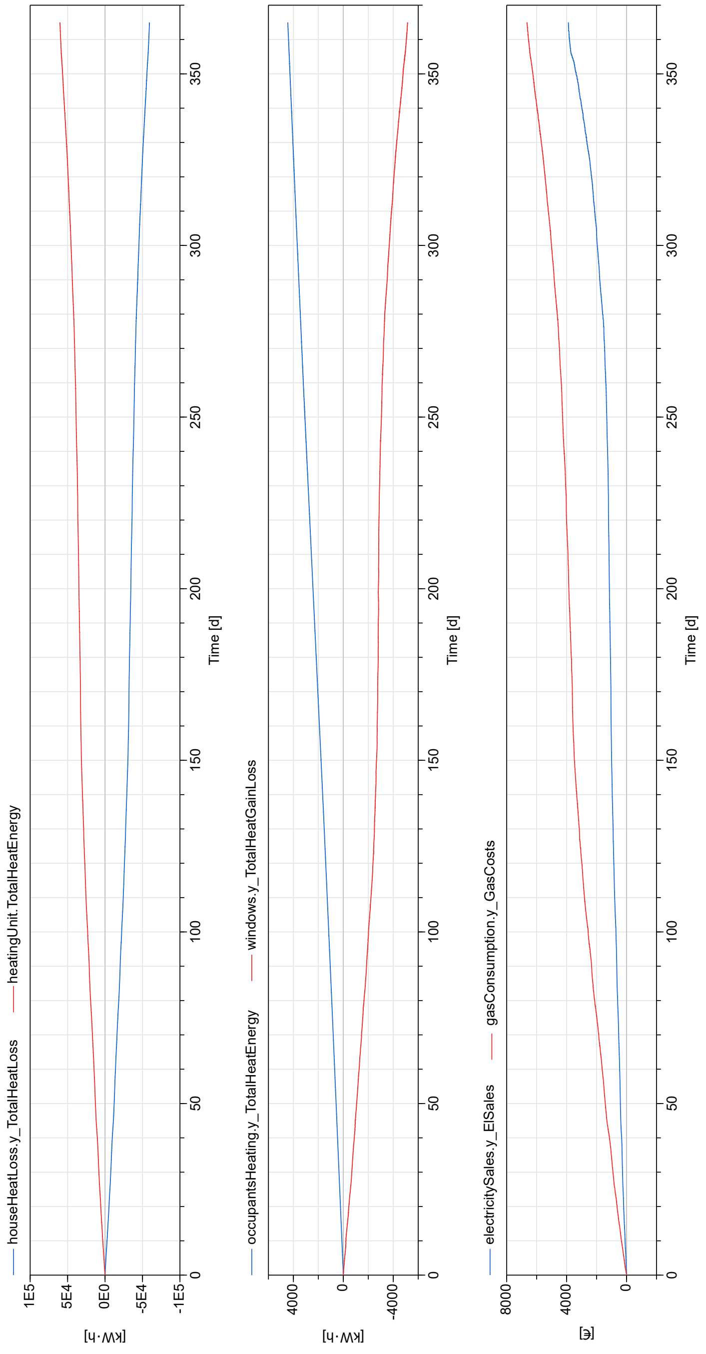


A.2. Ventilation Results

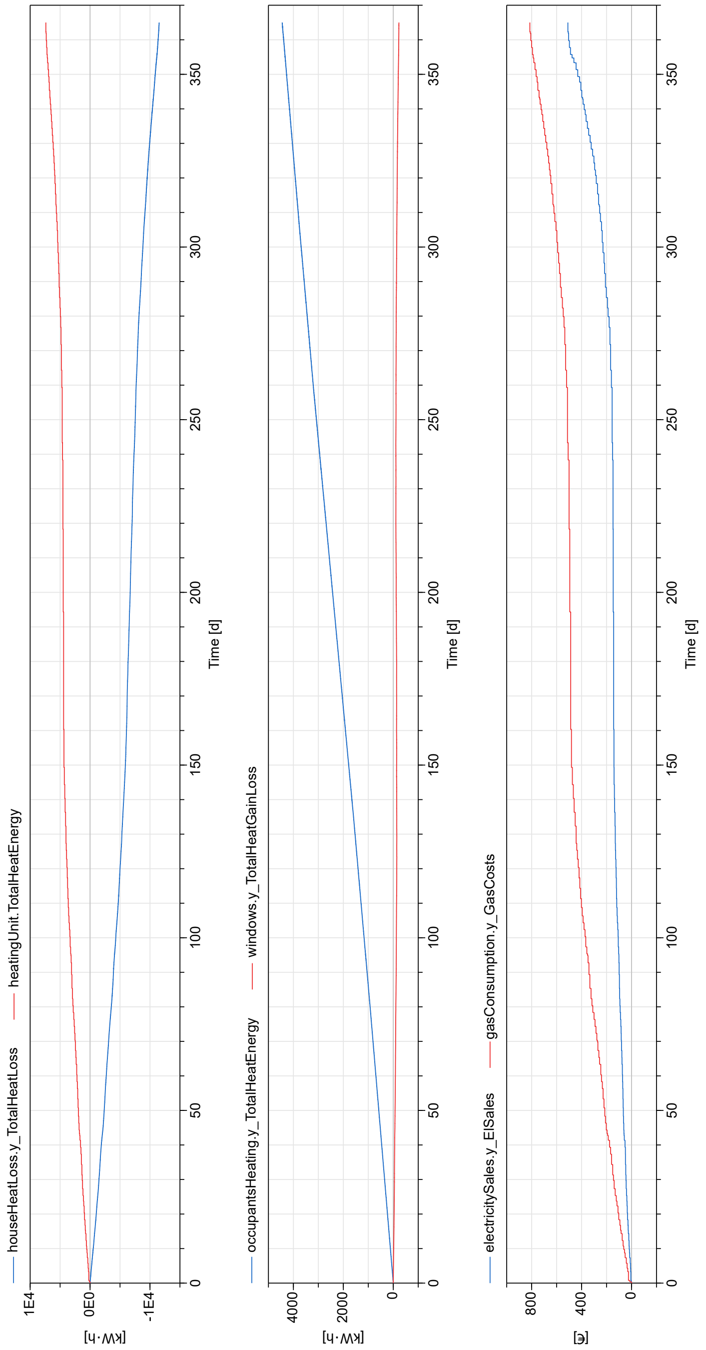


B. Simulation Results

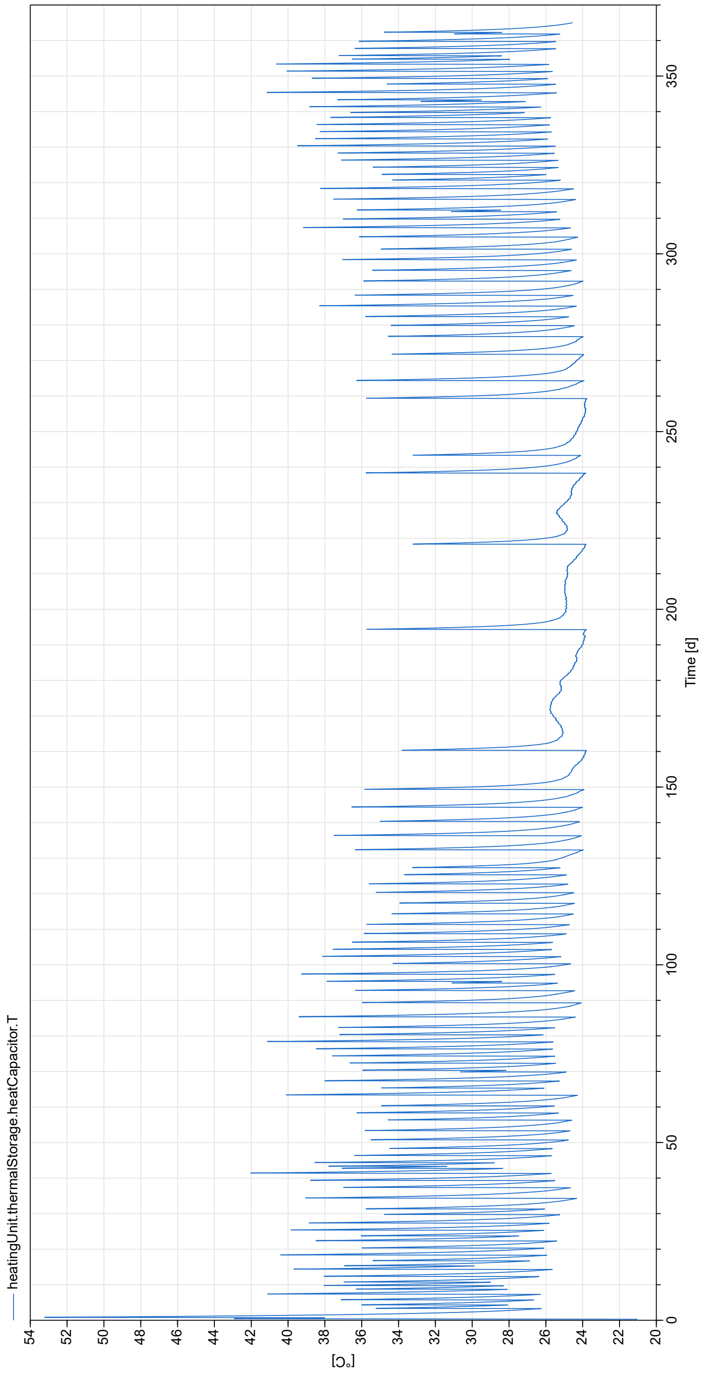
B.1. Traditional House



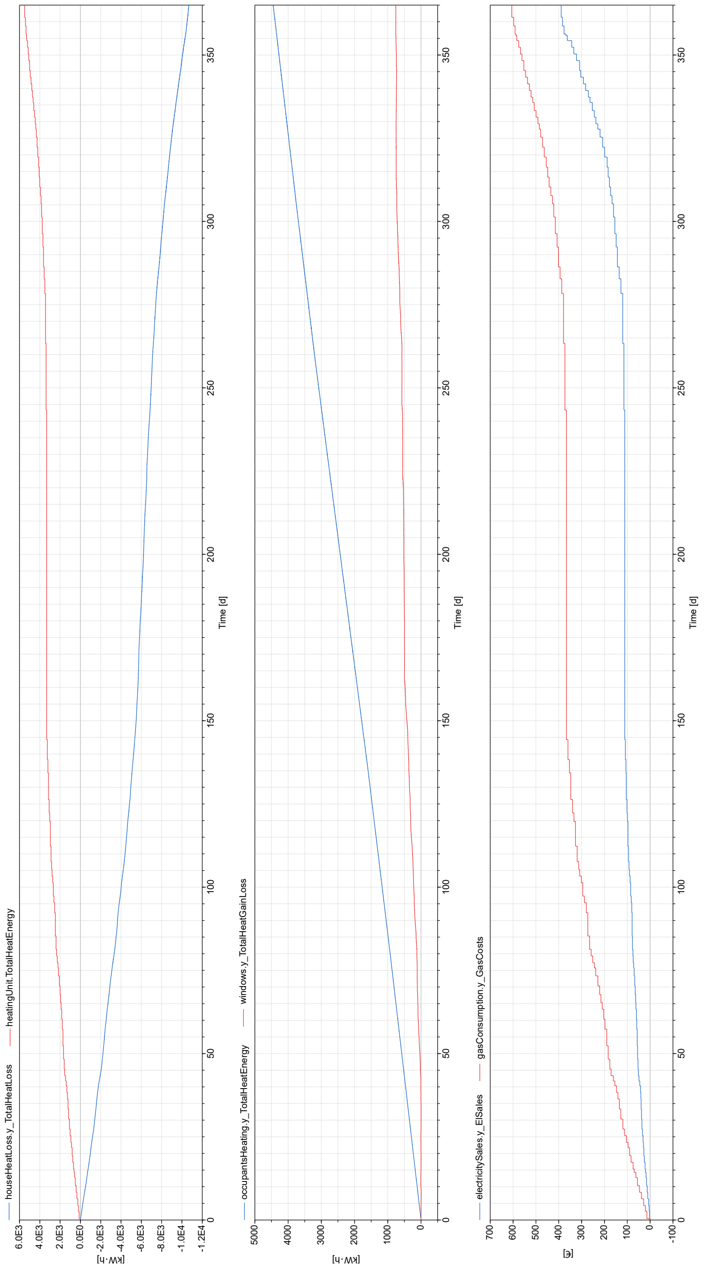
B.2. Renovated Traditional House (T24)



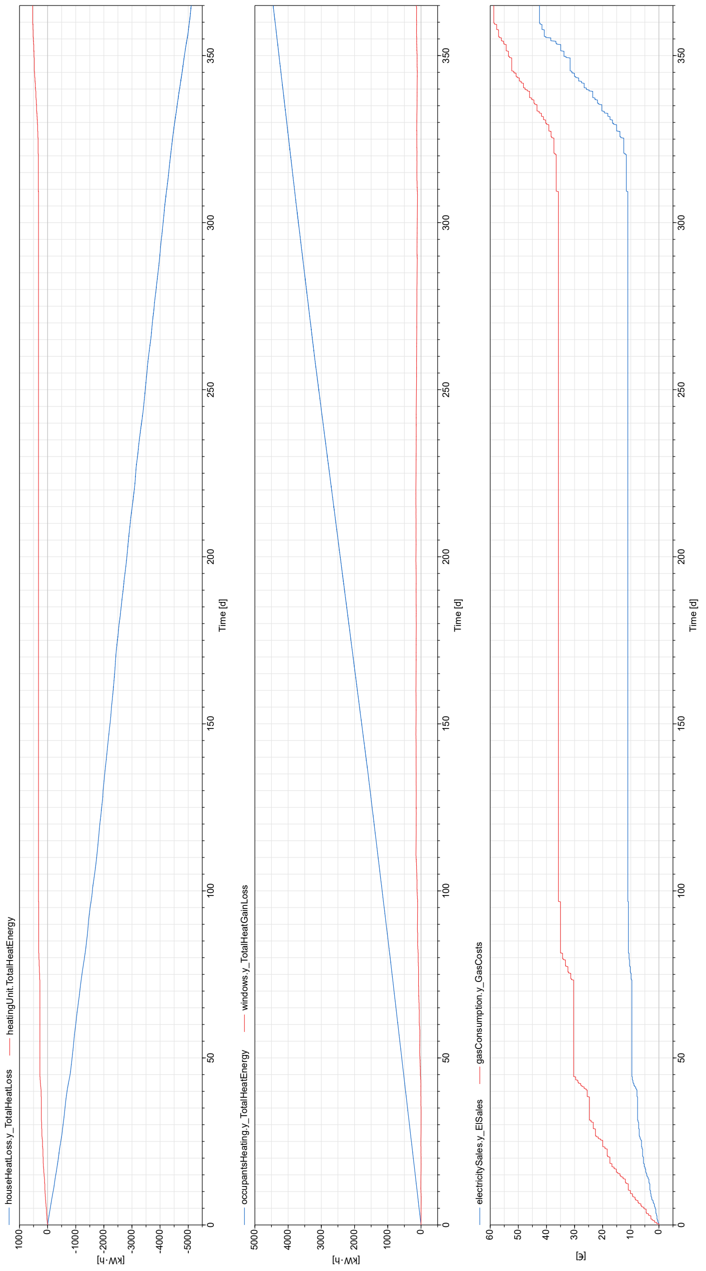
B.3. Renovated Traditional House (T24) Temperature Thermal Storage



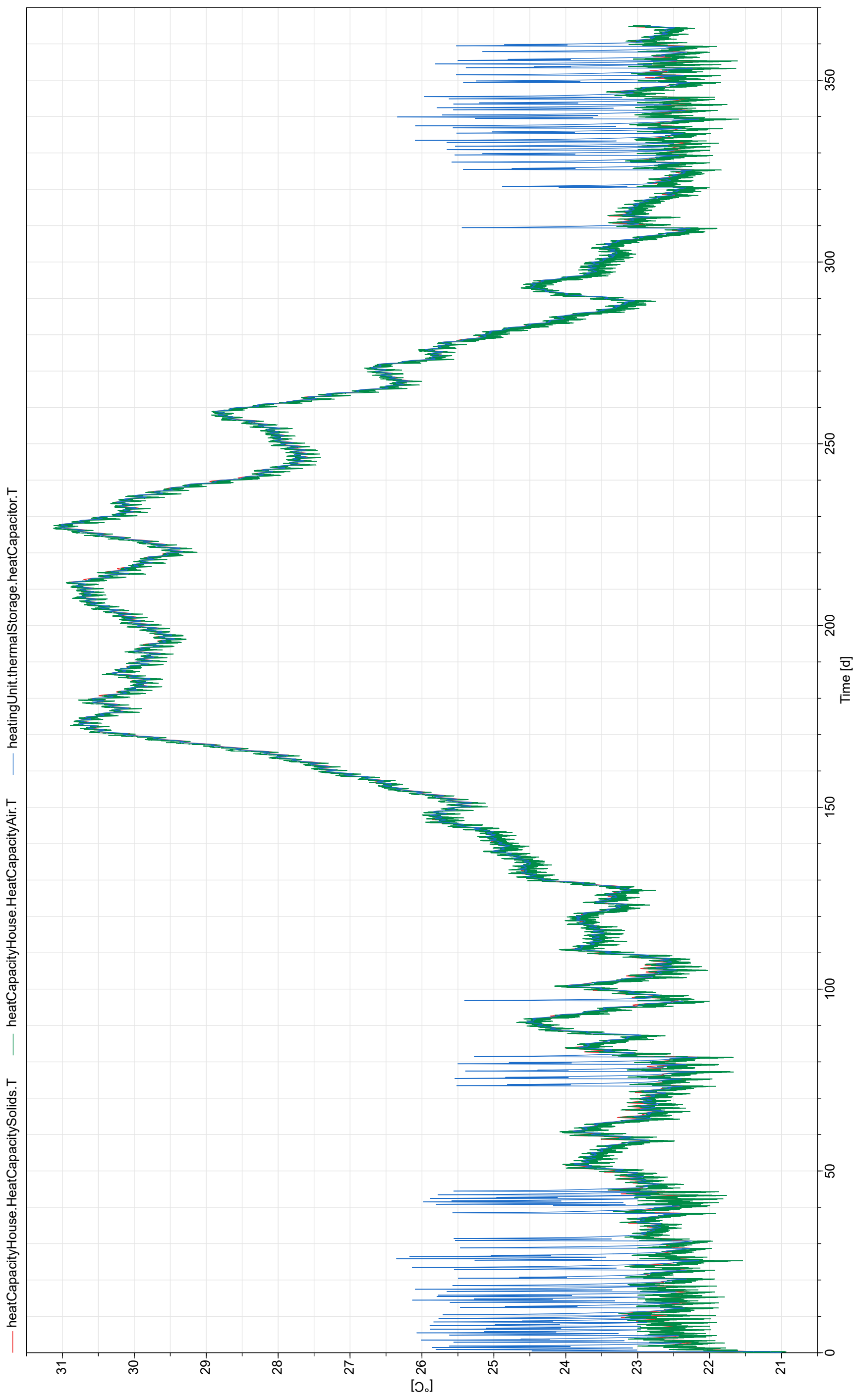
B.4. Renovated Traditional House (T22)



B.5. SHAC Concept House



B.6. SHAC Concept House Temperatures



Sworn Declaration

I hereby declare under oath that this master's thesis is the product of my own independent work. All content and ideas drawn directly or indirectly from external sources are indicated as such. The thesis has not been submitted to any other examining body and has not been published.

Ich erkläre hiermit an Eides statt, dass ich die vorliegende Masterarbeit selbstständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus fremden Quellen direkt oder indirekt übernommenen Stellen sind als solche kenntlich gemacht. Die Arbeit wurde bisher weder in gleicher noch in ähnlicher Form einer anderen Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht.

Maximilian Pauritsch, Dornbirn, August 30, 2022