Analysing the match between the energy production and consumption of a Net-Zero Energy Building: A multi-physics approach using Modelica

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Abstract
In the light of climate change and CO₂ emissions, energy performance is becoming increasingly more important. This increases the interest in Net-ZEBs. Net-ZEBs are buildings which consume no energy on a yearly basis by balancing on-site produced energy with energy consumption. Therefore, the importance of the methods of accurately predicting the energy performance of these buildings is highly important. This study aims to gain insight into the energy behaviour of Net-ZEBs by analysing the match between energy consumption and production. This analysis is done through the development of a high-resolution Modelica model in which production, storage, consumption and control are integrated. This model is then used to conduct a sensitivity study of some of the key parameters of a Net-ZEB. The sensitivity study showed the mutual interactions between several subsystems. For example, a change in the electric part of the system, can also influence thermal performance of the Net-ZEB and vice versa. Gaining insight into these interactions between subsystems is one of the main advantages of using the Modelica model. Especially making use of the matching indices proved to be a useful approach for analysing the performance of a Net-ZEB. The Modelica model can be used in order to quantify the consequences of design choices. In doing so, it can be useful in the development and testing of concepts of Net-ZEBs or other types of buildings. Also innovative system concepts or components can be tested using the Modelica model. All these can be analysed in great detail.

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<th>Unit</th>
<th>Description</th>
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<td>OEF</td>
<td>[-]</td>
<td>On-site energy fraction</td>
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<tr>
<td>OEM</td>
<td>[-]</td>
<td>On-site energy matching</td>
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<td>OEFc</td>
<td>[-]</td>
<td>On-site electrical energy fraction</td>
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<td>OEFh</td>
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<td>On-site heating energy fraction</td>
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<td>On-site cooling energy fraction</td>
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<tr>
<td>G(t)</td>
<td>[kW]</td>
<td>On-site produced power</td>
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<td>L(t)</td>
<td>[kW]</td>
<td>On-site consumed power</td>
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<tr>
<td>COP</td>
<td>[-]</td>
<td>Coefficient of Performance</td>
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<td>DHW</td>
<td>[-]</td>
<td>Domestic Hot Water</td>
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<td>Sheat_on_on(t)</td>
<td>[kW]</td>
<td>Net on-site produced heat send to on-site heating storage</td>
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<td>[kW]</td>
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<td>[kW]</td>
<td>Thermal energy sold to the heating grid</td>
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<td>[kW]</td>
<td>Net on-site produced cold send to on-site heating storage</td>
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<td>[kW]</td>
<td>Net off-site produced cold send to on-site heating storage</td>
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<td>Scold_off_off(t)</td>
<td>[kW]</td>
<td>Thermal energy sold to the cooling grid</td>
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<td>Gelec_off_eh(t)</td>
<td>[kW]</td>
<td>Off-site produced electricity sent to electrically driven heating machines</td>
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<td>Gelec_on_eh(t)</td>
<td>[kW]</td>
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1. Introduction

In the light of climate change and CO₂ emissions, energy performance is becoming increasingly more important. As a part of this trend, the European Commission requires all new buildings to be Net Zero Energy Buildings (Net-ZEBs) by December 31st 2020 as part of the Energy Performance of Buildings Directive (EPBD)\[^{34}\]. This increases the interest in Net-ZEBs and therefore, the importance of the methods of accurately predicting the energy performance of these buildings. The method of determining the energy performance which is most often used for residential buildings in The Netherlands, is the EPC calculation\[^{46}\]. This calculation determines a buildings energy performance by rating it from ‘A’ to ‘G’. ‘A’ meaning it has a very high energy performance and ‘G’ meaning a very poor energy performance. This approach is based on a simplified calculation regarding the energy consumption of the building. When present, the on-site energy production is also valued in a simplified way. However, the interaction between energy consumption and production is not taken into account. Therefore, the EPC calculation provides no insight into the possible mismatch between the production and consumption of energy.

Such a mismatch occurs when the moment, magnitude or both of on-site energy production differs from that of the energy consumption (see Figure 1). Since a large amount of on-site energy production in The Netherlands is produced by means of PV systems\[^{11}\], the moment and magnitude of the energy production is largely dependent on solar radiation. This dependency results not only in a high unpredictability of the moment and magnitude of the on-site energy production, but also makes it intermittent. Meanwhile, the energy consumption conforms to roughly the same daily profile year round (see ‘Appendix 7.3.6.’). This results in a high probability of a mismatch between energy production and consumption.

This mismatch can be overcome by temporarily storing the surplus of on-site produced energy and using it when the production of energy is insufficient. Currently in The Netherlands, the electricity grid can be used as an off-site energy storage in which the surplus of electricity produced by the PV-installation can be stored. However, restrictions are expected to be imposed on the amount of electricity that can be stored on the grid\[^{1}\]. Also, using the electricity grid as off-site storage can cause large fluctuations due to the unpredictability of the solar radiation which can negatively impact the performance of the grid\[^{1}\]. Understanding of energy balancing on the grid is required to ensure quality and short term security of energy supply\[^{2}\]. Therefore, a higher interest in Net-ZEBs can pose an increased demand on the electricity grid.

The mentioned effects that the increasing number of Net-ZEBs have on the electricity grid, emphasise the importance of self-consumption of renewable energy. Self-consumption can be achieved in various ways. One example is demand management, which decreases the mismatch by shifting the energy consumption to times of the day in which energy production is high. Another example is on-site energy storage, which (partly) replaces the off-site energy storage on the electricity grid. On-site energy storage can be achieved per dwelling or per neighbourhood. Lund et al. (2010) suggests the latter, while the cumulative mismatch of multiple dwellings is levelled out to some degree\[^{3}\]. An additional advantage of self-consumption is being independent from increasing energy prices, which are expected due to shortages in fossil fuels\[^{4}\]. In The Netherlands, the cost of energy is taking up an increasing share of the total housing costs\[^{5}\]. Self-consumption will enable people to gain control over their energy costs. Also, since the Dutch building stock is responsible for 30% of the total Dutch energy consumption\[^{5}\], an increased amount of self-consumption increases the share of renewable energy production, which reduces the amount of CO₂ emissions.

Net-ZEBs can be designed in many different ways with a large range of system topologies. To make better-informed decisions, it is of great importance for various stakeholders to predict energy performance of design options and to analyse the mismatch of a Net-ZEB, as well as the rate of self-consumption, prior to construction. Four major stakeholders can be identified (see Table 1).
Table 1 Stakeholders, their interest and information that is required.

<table>
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<th>Stakeholder</th>
<th>Main interest</th>
<th>Energy prediction needed for</th>
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<tr>
<td>Dutch government</td>
<td>Reduction of CO₂ emissions and as part of that, renewable energy consumption</td>
<td>Policy making</td>
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<td>Home owners</td>
<td>Maintain comfort and reduced utility bill</td>
<td>Decision making on renovation and choice of house</td>
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<td>Energy companies</td>
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<td>Housing corporations</td>
<td>Reduction of capital costs</td>
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In order to accurately determine the mismatch of a Net-ZEB, and in doing so the rate of self-consumption, the EPC calculation is insufficient. For a more detailed energy performance prediction of a residential building, a distinction is made between simulating energy consumption, energy production and energy storage. Firstly, the energy consumption of a building can be simulated using thermal simulation software, for example Vabi Elements[44] or IES-ve[45]. This software simulates the consumption based on, among others, information regarding material, geometry and occupant related inputs. This provides, dependent on the software used, moderately detailed to highly detailed information on the energy consumption. Secondly, the energy production can be calculated or simulated using hand calculations or simulation programs. An example of such a simulation program is PVsyst[46]. This allows for highly detailed, weather dependent energy production predictions. And thirdly, the energy storage can be calculated using a variety of software programs, for example TRNSYS[36] or Modelica[37].

However, simulating the energy consumption, production and storage more accurately, but separate, can cause deviations between the simulation and the actual building behaviour[7]. The dynamic behaviour of a residential building through the interaction of the three must be included in the prediction. Several energy performance prediction models which include all three aspects are present in literature. Either by combining multiple software or by using a single software. Combinations of multiple software in one tool are for example EnergyPlus and TRNSYS[38] or MathCad, Excel and CEM[31]. Examples of models which use one software use, in a majority of cases, TRNSYS or Modelica. These are used to simulate for example Net-Zero Energy Buildings[32][30][13], low energy buildings[41][42], offices[43], hotels[43] or neighbourhoods[56].

Although the examples mentioned simulate energy production, consumption and storage, most do not explicitly derive the performance indicators mentioned earlier from the simulations. In order to gain more insight into the energy performance and the relation between the performance indicators, a model is needed which is able to simulate these indicators.

This study has the goal to gain insight into energy performance of a Net-ZEB with an integrated renewable energy system and the relation between the following performance indicators: CO₂ emissions, utility bill, capital costs, thermal comfort and matching indices. In order to do so, a model is developed from which these indicators can be derived using Modelica. This model can be used to analyse designs, systems and energy management of a residential building. The Modelica-based testbed, created by Al Koussa (2014), will be used as a starting point. This testbed exists of a fully functioning model of a residential building with all systems included, for example heating, ventilation, shading and internal gains[33]. This model also includes PV panels, thermal solar collectors and thermal storage. In this study, the heating system and electrical system of this model will be extended to represent a more realistic system as is used in Net-ZEBs by adding a second thermal storage, an electricity storage, a grid interaction and an interaction between the electricity storage and the thermal storage. It will then be used to simulate a residential Net-ZEB in order to analyse the performance indicators mentioned earlier.
1.1. Goal
The goal of this project is to gain insight into the behaviour of a Net-ZEB and the matching between energy production and consumption. This behaviour will be determined by the following performance indicators: CO₂ emissions, utility bill, capital costs, thermal comfort and matching indices. In order to simulate these performance indicators, a Modelica model is developed from which these indicators can be derived. This model is also used to conduct a sensitivity study in order to further analyse the effect of changing the following parameters: electric energy production, storage and consumption, thermal energy production, storage and consumption and supervisory control.

1.2. Outline of report
In order to outline the transition from a real world Net-ZEB to a simulation of a Net-ZEB, Figure 2 is presented. Firstly, a system description of a Net-ZEB is compiled in which assumptions are made on a real world Net-ZEB (see Figure 2). The assumptions on which components should be present in the system description are stated in the introduction and the interactions between them are shown in Figure 5. Using this system description, an abstraction of a real world Net-ZEB is created, which forms the conceptual model. This includes the development of the Modelica model through the extension of previous work to the current model. This is discussed in Section 2. This conceptual model is then used to create the final Modelica model in Section 3. The final Modelica model is created by implementing the calculation of the performance indicators and by introducing the case study. Also, the setup of the sensitivity study is discussed. Finally, the Modelica model is used to do the sensitivity study and the results are discussed separately for each step in Section 4. General conclusions that are drawn on both the results of the sensitivity study and the Modelica model are presented in Section 5.
2. Model development

In this section, first the previous work in Modelica which forms the starting point for this study will be presented. It consists of a full functioning Modelica model of a residential building. Secondly, the way this previous work is extended to meet the requirements of the current study is discussed. This involves adding components to the model to form a system which is more representative of a Net-ZEB.

2.1. Previous work

In previous work, Al Koussa (2014) created a Modelica-based testbed of a residential building[33]. In this testbed, the thermal energy consumption and the thermal and electrical energy production can be simulated. It consists of three parts, as is shown in Figure 3. The electricity consumption, or plug load, is included using measured values of an actual residential building[33][47]. Figure 4 provides an overview of the connections between the thermal and electrical systems that are shown in Figure 3. As can be seen, the electric and thermal systems are completely separate. This restricts the usability of the testbed to cases where no thermal and electric interaction is present. Especially when considering the increased rate at which PV panels and thermal solar collectors are being installed[11][48], as well as the increasing interest in Net-ZEBs, the possibility of simulating the interaction between the electric and thermal behaviour is becoming more interesting.

2.2. Current work

In the current study, the previously discussed testbed created by Al Koussa (2014) will be extended to represent a more realistic system as is used in Net-ZEBs. This is done by adding a second thermal storage, a heat pump, an on-site electricity storage, a grid interaction and supervisory control (See Figure 5). The supervisory control is separated in the ‘Thermal energy management’-component and the ‘Electric energy management’-component. Also, an interaction between thermal and electric behaviour is added. This
interaction consists of two aspects. Firstly, the possibility of storing on-site produced electricity in the thermal storage by means of a heat pump and secondly, the possibility of the auxiliary heaters to be powered by on-site produced electricity. These added components are discussed in more detail in this section, as well as the way the performance indicators are obtained from the simulations.

The circuit through the thermal solar collector, heat pump and thermal energy management will from here on be referred to as the ‘production circuit’, the circuit through the DHW thermal storage and the thermal energy management will be referred to as the ‘DHW circuit’, and the flow from the thermal energy management to the room heating thermal storage will be referred to as the ‘room heating circuit’.

![Figure 5 Overview of the extended testbed](image)

In this section, the different components which are added to the Modelica testbed are described, including the implementation in Modelica.

### 2.2.1. Heat pump

A heat pump is added to the model of the Net-ZEB in order to be able to convert on-site produced electricity into thermal energy which can be stored in one of the thermal storages. The heat pump considered is air-to-water and it is connected to the electric energy management, from which it receives electricity, and to the thermal energy management, to which it forwards its thermal energy. For information on both energy management components, see ‘Section 2.2.5.’. The amount of energy the heat pump can produce is completely dependent on the electricity it receives from the electric energy management and the COP. The COP depends on the temperature difference between the evaporator, which is at ambient temperature, and the condenser, which is at the temperature of the production circuit. Figure 6 shows the relation between the temperature difference and the COP for heating (COPh) of the heat pump that was selected for this work. The black dots are the values found in literature. The green line is the approximation that is used and implemented in Modelica.
The buildings library\textsuperscript{[49]} of Modelica contains a heat pump component (Buildings.Fluid.HeatExchangers.HeatPumps). This component simulates the behaviour of a heat pump, including the COP. However, in this component, the electricity demand cannot be set as an input, which is necessary to use it in the setup as described earlier. Instead, the electricity demand is an output and the temperature at the condenser-side can be set as an input. This means the heat pump cannot be used directly in the extension of the testbed.

Multiple attempts to change the in- and output parameters of the heat pump component proved unsuccessful. Therefore, a different approach was chosen. A boiler component from the buildings library (Buildings.Fluid.Boilers.BoilerPolynomial) was selected. The inputs of this component are the maximum capacity and the part load ratio. In order to make sure the output of this component would be the same as a heat pump component would have, the following steps were taken. First, the maximum capacity of the boiler was set to the maximum output of the electric energy management multiplied with the maximum COP. Secondly, the part load ratio was set to the output of the electric energy management, which can change per time step, multiplied with the COP, which can also change per time step. This way, the thermal energy added to the production circuit is the same as would be the case when a heat pump component with variable COP was used.

### 2.2.2. On-site electricity storage

In order to simulate the possibility of storing the on-site produced electricity, produced by the PV panels, an on-site electricity storage is added to the testbed in the form of a battery. This battery is connected to the electric energy management (see also ‘Section 2.2.5.’), from which energy is forwarded to and taken from it. There are several types of batteries on the market. In this study, lead acid batteries are chosen, because of the relatively low costs per capacity\textsuperscript{[52]} and the maturity of the technology\textsuperscript{[52]}.

The on-site electricity storage is implemented in Modelica by using a DC battery from the LBNL Districts Library\textsuperscript{[49]} (Districts.Electrical.DC.Storage.Battery). In the battery component, the charge efficiency, discharge efficiency and capacity can be set. This way, more realistic behaviour of the battery can be simulated. A lead acid battery has an efficiency of 85 to 90\%\textsuperscript{[52]}. This is simulated in Modelica by using a 92.5% efficiency for both charging and discharging, which sums up to a total efficiency of a little over 85.5%. The capacity is 10 kWh for the base case, which is based on the information published by Tesla\textsuperscript{[16]}.

### 2.2.3. Electricity grid

In The Netherlands, electricity can either be bought from the electricity grid or sold to the electricity grid. This allows for the possibility of storing the on-site produced electricity on the grid. In order to add this possibility to the model, a second battery component is added of the same type as described in ‘Section 2.2.2.’. This grid component is connected to the electric energy management, similar to the on-site electricity storage. The charging and discharging efficiencies were set to 100%. The capacity of the grid is
considered to be significantly higher than the energy that will be stored or consumed by a single Net-ZEB. Therefore, the capacity of the grid is set to 20,000 kWh. This is selected so that it is considerably higher than the average electricity consumption of a Dutch dwelling, which is roughly 3500 kWh\textsuperscript{[8]}, and will therefore pose no limitations to the operation of the system.

2.2.4. On-site DHW thermal storage
In the testbed of Al Koussa (2014), a thermal storage is present from which thermal energy is taken to meet the DHW demand and the room heating demand (see Figure 4). This thermal storage is ideally kept at 40 °C. In this study, this thermal storage, which will be referred to as the room heating storage, is connected to only the room heating demand. The DHW demand will be met by a second thermal storage, which will ideally be kept at 60 °C. This second thermal storage, which will be referred to as the DHW thermal storage, is added to the flow from the room heating storage to the DHW demand. It receives thermal energy through the room heating storage or directly from the thermal energy management through the DHW circuit (see ‘Section 2.2.5.’) and forwards it to the DHW demand.

In Modelica, the storages are both modelled using stratified water tank components from the LBNL Buildings library\textsuperscript{[49]} (Buildings.Fluid.Storage.StratifiedEnhancedInternalHex). This component consists of a stratified fluid tank with a fluid connector input and a fluid connector output. It also contains an internal heat exchanger with separate input and output connectors. Inputs for this component are volume, height, insulation values, number of volume segments and position of the heat exchanger. The output is the temperatures in the different segments of the volume and the thermal losses. The volume of the DHW thermal storage is set to 150 litres and the temperature of the room in which the storage is placed is set to a constant value of 15 °C in order to determine the thermal losses of the storages.

2.2.5. Energy management
The model includes two energy management components, one thermal and one electric, as is shown in Figure 5. Each functions as an instantaneous control in which the supervisory control is implemented. This controls where to store the on-site produced energy. In this section each will be discussed in detail.

**Thermal energy management**
In the thermal energy management, the thermal part of the supervisory control is implemented, which determines whether to store the on-site produced thermal energy in the DHW storage or in the room heating storage. Therefore, all thermal energy that is produced on-site, either by the thermal solar collector or by the heat pump, is forwarded to the thermal energy management. Also both thermal storages are connected to the thermal energy management (see Figure 5).

The heat pump and thermal solar collectors are connected to the thermal energy management through the production circuit. In this fluid circuit, the thermal energy is transferred to the thermal energy management. Using two additional circuits, the DHW storage and the room heating storage are connected to the thermal energy management as well. In the thermal energy management, these are connected to each other by means of two heat exchangers. These heat exchangers are from the LBNL Buildings library\textsuperscript{[49]} (Buildings.Fluid.HeatExchangers.ConstantEffectiveness). Figure 7 shows a simplified overview of the thermal energy management. The production circuit (1) is shown by the yellow line, which goes through two heat exchangers which are shown in the red squares. The top heat exchanger (hex_1) is also connected to the room heating circuit, which is shown in red (2). The bottom heat exchanger is connected to the DHW circuit, which is shown in orange (2). All temperatures can be manipulated by turning on any of the three pumps, one for each circuit. There is also the possibility to turn off the heat pump and thermal solar collector. This is...
necessary because there is a limited amount of thermal storage capacity. This means that when both thermal storages are at their maximum capacity, there is no need for any further thermal energy and the thermal energy production is turned off.

There are two possibilities for storing on-site produced thermal energy. The first is giving priority to the DHW-storage (60 °C) and storing any surplus of thermal energy, after the DHW-storage is at maximum temperature, in the room-heating-storage (40 °C) (system 1 and 2, see Table 2). The second possibility is the other way around and gives priority to the room-heating-storage (40 °C) (system 3 and 4, see Table 2). This supervisory control takes place by a series of ‘AND’, ‘OR’ and ‘Switch’ components. These components are connected to the temperature sensors of the storages and the production circuit. They are also connected to the switches which turn on and off the pumps which in turn determine the mass flow through all three circuits. By determining the mass flow through the circuits, the temperatures can be manipulated. The way these temperatures influence the supervisory control is described in Table 4 and 5 in ‘Appendix 7.1.’.

**Electric energy management**

In the electric energy management, the electric part of the supervisory control is implemented. It determines whether to store the on-site produced electricity in the on-site electricity storage, in the on-site thermal storage by means of the heat pump, or on the electricity grid. Therefore, the electric energy management is connected to the PV panel (on-site electricity production), the on-site electricity storage and the grid interaction (see Figure 5). Also the plug load and the energy demand from the auxiliary heaters is met through the electric energy management. Therefore, these are also connected to it.

The components that are connected to the electric energy management can be categorized in two groups. Firstly, components which demand or produce a given amount of electricity. There is no decision making involved in this group. These are the PV panel, the auxiliary heaters, the plug load and the pump load. Secondly, there are components from which there is the possibility to send electricity to or take electricity from. These are the on-site electricity storage, the heat pump and the grid interaction. This difference means that the components from the first category are part of the conditions which are set for the electric energy management. Meaning that when on-site produced electricity is insufficient, it must be actively taken from the grid in order to meet the demand. Only in the second category there is the possibility of making decisions. This is where the electric energy management difference from the thermal energy management, which only distributes the available on-site produced energy and receives no conditions for thermal energy. This difference is also visible in Figure 8. The components which form the conditions are shown on the left. The yellow and the pink square are the PV panel and the plug load, respectively. The dark blue arrows below them are the auxiliary heaters and the pump load. On the right, the components of the second category are shown. In the blue squares the on-site electricity storage and the grid interaction are shown. Beneath these, the white arrow shows the heat pump output. All components in the middle, connected by pink lines, form the instantaneous controls of the electric energy management. These operate by using a series of ‘IF’, ‘AND’ and ‘OR’ components. They first add up the required electricity flows, meaning the components from category one. These are the PV panel production and the consumption of the plug load, auxiliary heaters and pump load. If the resulting power is positive, it can be stored in the on-site electricity storage or in the thermal storage by means of the heat pump. If the resulting power is negative, electricity needs to be taken from either the on-site electricity storage or the grid. This way, the electricity requirements of the plug load, the pump loads and the auxiliary heaters is always met.

The way the surplus of electricity can be stored is very similar to the way the thermal energy management operates. Firstly, it can be stored in the on-site electricity storage until this is at full capacity. Any electricity still available after that can be stored in the on-site thermal storage by means of the heat pump (system 1 and 3, see Table 2). Or secondly, the other way around can be used. In which case the surplus of electricity is first stored in the on-site thermal storage until this is at its maximum temperature. Any electricity still available after that will be stored in the on-site electricity storage (system 2 and 4, see Table 2).
The two possibilities for storing electricity and the two possibilities for storing thermal energy mean a preference can be selected. Any surplus of energy after the first choice of storage is at full capacity will be stored in the second storage. Table 2 shows these possibilities. These supervisory control options are also part of the sensitivity study.

### 3. Performance indicators and case study

The stakeholders that are mentioned in the introduction have an interest in knowing the following performance indicators: CO₂-emissions, overheating hours, percentage of renewable energy consumption, utility bill, matching indices and capital costs. How these are simulated and with which assumptions is discussed in this section.

#### 3.1. Performance indicators

##### 3.1.1. Matching indices

In order to quantify (mis)match between energy production and energy consumption, the matching indices are used as formulated by Cao et al. (2013). These exist of the On-site Energy Fraction (OEF) and the On-site Energy Matching (OEM)\(^{[21]}\). Equations 1.1 and 1.2 show how each can be calculated.
Equation 1.1 On-site Energy Fraction (OEF)\ref{21}

\[
OEF = \frac{\int_{t_1}^{t_2} \text{Min}[G(t), L(t)] \, dt}{\int_{t_1}^{t_2} L(t) \, dt}
\]

To explain what each matching index represents, Figure 9 is used. It shows a curve of the on-site produced power and a second curve of the on-site consumed power over one day. It is clear the two curves do not match. To quantify the mismatch, the OEF is used to calculate the part of the on-site consumed energy that is met by on-site produced energy for each time step and integrates this over the period between ‘t1’ and ‘t2’. The OEM on the other hand, calculates the part of the on-site produced energy that is used to meet the on-site consumption for each time step and also integrates this over the period between ‘t1’ and ‘t2’. In Figure 9, this means that the OEF equals 1 during the middle of the graph, where the on-site produced energy is higher than the on-site consumed energy. However, the OEM is lower than one for that part of the day. The OEM will equal one during the beginning and end of the day, where the on-site consumed energy is higher than the on-site produced energy. However, here the OEF will be lower than 1. This illustrates that the OEM and OEF provide insight into the matching of production and consumption of energy when used simultaneously. Using only one of them will provide very little insight into the possible mismatch. In the situation where there is no mismatch, both the OEF and OEM will equal one.

However, there are disadvantages to using these matching indices. Firstly, there is no option of taking into account energy storage. This is necessary to accurately quantify the possible mismatch present in a residential buildings that include energy storage. Secondly, it provides insight into the mismatch of the total dwelling without considering different types of energy\ref{21}. In order to overcome this disadvantage, the OEF and OEM have been extended by Cao et al. (2013) to form the electrical, heating and cooling matching indices\ref{23}. The principle remains the same, however each index focuses only on one of the types of energy (electric, heating or cooling). This way, more insight can be gained into which energy system contributes to a possible mismatch. The OEF for electrical, heating and cooling, or OEF_e, OEF_h, OEF_c, respectively, as well as the OEM for electrical, heating and cooling, or OEM_e, OEM_h, OEM_c, respectively, are calculated using Equations 2.1 through 2.6.

Equation 2.1. On-site Energy Fraction – electric (OEF_e)\ref{21}

\[
OEF_e = \frac{\int_{t_1}^{t_2} \text{Min}[G_{\text{elec, on}}(t) - S_{\text{elec, off}}(t), L_{\text{elec}}(t)] \, dt}{\int_{t_1}^{t_2} [L_{\text{elec}}(t) + G_{\text{elec, off}}(t) + G_{\text{elec, on}}(t)] \, dt}
\]

Equation 2.2. On-site Energy Fraction – heating (OEF_h)\ref{21}

\[
OEF_h = \frac{\int_{t_1}^{t_2} \text{Min}[G_{\text{heat, on}}(t) - S_{\text{heat, off}}(t), L_{\text{heat}}(t)] \, dt}{\int_{t_1}^{t_2} [L_{\text{heat}}(t) + G_{\text{heat, off}}(t) + G_{\text{heat, on}}(t)] \, dt}
\]
By using these extended indices, the contribution of each type of energy to the total mismatch can be calculated. Moreover, each extended index does not only consider the energy production and consumption, but also the energy storage and the energy which is converted into another type, as is the case when electricity is converted to thermal energy by means of a heat pump for example. This allows for a much more complete insight into the energy matching of a building.

A disadvantage of the extended matching indices is that there is no single value which can be used to compare a dwelling to other dwellings. Therefore, the Weighted Matching Index (WMI) is introduced by Cao et al. (2013). It summarizes the extended matching indices to a single value and provides the possibility of weighting one of the indices more than others. This can be useful when one of the indices is considered to be more important than the others for example. When all six weighing factors have the same value of 0.1667 (1/6), meaning there is no weighing involved but only averaging, than this results is referred to as the Average Matching Index (AMI)\[^{30}\].

\[
WMI = w_1 \cdot OEF_c + w_2 \cdot OEM_e + w_3 \cdot OEM_h + w_4 \cdot OEM_c
\]

In this study, the electrical and heating matching indices have been used. Since no cooling is present in the Net-ZEB that is considered, the OEFc and OEMc serve no purpose.

### 3.1.2. Overheating hours

The thermal comfort is a very important performance indicator for home owners. In order to evaluate the thermal comfort, the overheating hours are calculated. To do so, an overheating threshold is used for the living room and the bedroom, based on information found in literature\[^{34}\] (see Figure 10). The interior air temperature of these rooms is compared to the reference ambient temperature (T_{ref}). The radiative interior temperature is assumed to be the same as the air temperature, since this information was not extracted from Modelica. The overheating hours are then calculated as the amount of hours the temperature is above the overheating threshold.
Figure 10: Overheating threshold for living room and bedroom

3.1.3. CO₂ emissions

As part of the 20-20-20 climate and energy package set out by the European Commission, the CO₂ emissions need to be reduced by 20% compared to the 1990 levels\[50\]. This makes knowing the CO₂ emissions very important for governments in order to determine policies.

The total CO₂ emissions are calculated using two CO₂-emission factors. A ‘low’ emission factor and a ‘high’ emission factor. The ‘high’ factor of CO₂ emissions can be contributed to the consumption of electricity taken from the electricity grid. This emits 490 gCO₂eq/kWh\[55\]. The ‘low’ emission factor can be contributed to the energy production of PV panels. This emits 41 gCO₂eq/kWh\[55\]. The CO₂ emissions for which this emission factor is used is the electricity which is produced by the PV panels and is exported to the grid, subtracted from the total electricity which is produced by the PV panels. This amount of electricity is then multiplied with the ‘low’ emission factor of 41 gCO₂eq/kWh\[55\].

3.1.4. Total energy consumption

One of the main goals of the European Union, and because of that the Dutch government, is to reduce the energy consumption of its building stock\[34\]. In order to provide insight into the total energy consumption of a residential building, it is selected as one of the performance indicators in this study.

The total energy consumption is defined as the total energy the residential building consumes, both thermally and electrically. The total thermal energy consumption consists of the thermal demand for DHW, the thermal demand for room heating and the thermal losses of the system. The electric energy consumption consists of the plug load and the pump load. Adding up these four energy demands, results in the total energy consumption of the residential building.

In Modelica, this is implemented using a ‘Sum’-component which adds up the powers in kW of each of these demands. After that an ‘Integrator’-component is used to integrate the power over time to calculate the energy in kJ. In a last step, the energy in kJ is divided by 3600 to compute the total energy consumption in kWh. This final value can be obtained through the component named ‘X_TotalEnergyConsumptionTotal’.

3.1.5. Utility bill

For homeowners, the utility bill is a very important performance indicator. Especially with the increasing prices of energy\[5\]. Also the feed-in-tariff is an important aspect to consider. It is therefore important to include the utility bill as a performance indicator.

In this study, the utility bill exists out of two parts, namely the price of electricity and the return on electricity through exporting it to the electricity grid. In The Netherlands, the price of electricity is made up out of the baseprice, 21% taxes and ‘energiebelasting’. The base price is the price of the electricity, 21% taxes is the tax that has to be paid to the tax collector, and ‘energiebelasting’ is an additional tax which is charged in order to discourage people from using extensive amounts of electricity\[30\]. The base price of electricity is shown in Figure 11\[6\]. This is the hourly variable price of electricity in Scandinavia, which is
assumed to be similar to the Dutch electricity prices. The ‘energiebelasting’, which is 0.1599 euro/kW h \[10\] is added to the baseprice. The tax of 21% is than added to this electricity price. The feed-in-tariff is assumed to be fixed at 0.07 euro/kWh. This amount is based on the feed-in-tariff of several Dutch energy companies \[9\].

In Modelica, the total utility bill is calculated as follows. Firstly, the total power (in kW) that is taken from the electricity grid is integrated over time to compute the total energy taken from the grid. Secondly, the total price of electricity is computed in the way that is previously described. And thirdly, the income from exporting electricity to the electricity grid is calculated using the feed-in-tariff and the total amount of electricity that is exported. These three are results are obtained from Modelica through the components ‘Q_TakenFromGrid’, ‘Q_ElectricityPrice’ and ‘Q_SendToGrid1’.

### 3.1.6. Percentage of renewable energy consumption

When considering the energy performance of a residential building, it is highly important to not only consider the total energy consumption, but also the percentage of it that is produced using renewable energy sources. In order to do so, the percentage of renewable energy consumption is calculated in this study.

To calculate the percentage of renewable energy consumption, two of the following three aspects need to be known. The total energy consumption, the total renewable energy consumption and the total non-renewable energy consumption. Of these three, the total energy consumption is calculated in the model (see ‘Section 3.1.4.’). The other aspect that will be calculated is the non-renewable energy consumption. The reason this aspect is chosen is because it is easier to implement into Modelica. It is the amount of energy that is taken from the grid, since this is the only source of non-renewable energy.

Figure 5 shows, among others, the system boundary of the Net-ZEB. This boundary emphasizes that the grid interaction lies outside the system boundary. The total non-renewable energy consumption is calculated by summarizing the amount of energy that is taken from the grid. This can then be obtained through the component named ‘X_NonRenewableEnergyConsumptionTotal’. Using this result and the total energy consumption, the percentage of renewable energy consumption is calculated.

### 3.1.7. Capital costs

For both the housing corporations and the home owners, the capital costs of a residential building is an important performance indicator. However, since the capital costs of a residential building is highly dependable on for example the type of dwelling and location, this study did not consider the capital costs of
the entire dwelling. Instead, only the capital costs of the system components that are changed in the sensitivity study were considered. This means the capital costs of the PV panels, thermal solar collectors, electricity storage and thermal storage are considered. All other components, such as pumps, heating elements or piping are not considered. For each of the mentioned components, the capital costs is based on multiple sources. For full details on the prices, see ‘Appendix 7.4’.

The capital costs of PV panels is approximated by the red line, as shown in Figure 12. The capital costs of the thermal solar collectors, electricity storage and thermal storage are approximated at 158.4 euro/m$^2$, 453 euro/kWh and 4954 euro/m$^3$, respectively. These values are calculated by taking the average of all prices found in literature.

![Figure 12 Capital costs of PV panels](image)

### 3.2. Case study

#### 3.2.1. Sensitivity study

In order to gain insight into the effect the earlier mentioned parameters have on the performance indicators, a sensitivity study is conducted. For this sensitivity study, a base case is selected and simulated in the Modelica model that is developed in this study. After that, several parameters are changed in order to determine the effect this has on the performance indicators mentioned earlier.

To gain optimal insight into the behaviour of the building and the effects the adjustments of the parameters have, the simulation period would ideally be an entire year. However, due to the long simulation time of roughly 15.5 hours that is required to simulate an entire year, this is not done in this study. Instead, a typical summer period and a typical winter period of 14 days each is selected. The advantage of this choice, is that more simulations can be conducted and in doing so, more information can be gained. The period of 14 days is also long enough to determine the ability of the on-site energy storage to bridge the energy mismatch of a day or a week. However, a disadvantage of this choice is that no insight is gained into the seasonal storage capacities of the dwelling. For this reason, the storage capacities are chosen as such that they are in line with bridging daily or weekly variations in production and consumption, instead of bridging seasonal variations.

In order to choose a representative period of time, the ambient temperature, direct radiation and diffuse radiation are shown in Figure 13. The blue column shows the period that has been chosen as a representative winter period. The red column does the same for the summer period. These periods have been selected because both the temperatures and radiation levels are close to the average for that period of the year.
3.2.2. Definition of base case
The base case will consist of the detached single family house, based on the reference building as published by the Dutch government\textsuperscript{[53]}. The parameters are as follows: the thermal resistance of the walls, roof and floor are 3.5 m\textsuperscript{2}K/W, 6.67 m\textsuperscript{2}K/W and 3.5 m\textsuperscript{2}K/W, respectively; the U-value of the windows is 1.65 W/m\textsuperscript{2}K and the thermal solar collectors have an area of 2.3 m\textsuperscript{2}. Furthermore, the area of the PV panels is 20 m\textsuperscript{2}, the volume of the thermal storage for room heating and DHW are added and are 0.45 m\textsuperscript{3} and 0.15 m\textsuperscript{3}, respectively. Finally, 10 kWh of electricity storage is added, which is sufficient to bridge weekly variations in energy production and consumption according to publications from Tesla\textsuperscript{[16]}.

3.2.3. Varied parameters
The parameters that will be varied in the sensitivity study are summarized in Table 3. The variations were selected based on the results of the base case.

For the thermal demand, the ‘reference’ has the properties from the reference building as published by the Dutch government\textsuperscript{[53]}, as is described earlier. The varied parameter is based on the passive house concept\textsuperscript{[51]}. This concept has the following properties: heat recovery on ventilation of 75\%, thermal resistance of all façades, floors and roof of 6.67 m\textsuperscript{2}K/W, U-value of the windows of 0.8 W/m\textsuperscript{2}K, internal blinds and an air tightness of 0.2. All these properties were implemented in Modelica in the class ‘Level1_NoShad’, in the construction properties. The heat recovery on ventilation, however, is implemented differently. In the original testbed, the ventilation was implemented as an internal heat gain which adds or subtracts energy to or from the room. Therefore, adding heat recovery was implemented as reducing this heat gain by 75\%.

The varied values for the electric demand, which is the plug load, are 25\% lower and higher than the base case, respectively.

The meaning of the variations in the controls is explained in more detail in ‘Section 2.2.5.’.
Table 3 Varied parameters in the sensitivity study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter variations*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal solar collector area [m²]</td>
<td>2.3 – 10 – 20 – 30</td>
</tr>
<tr>
<td>PV panel area [m²]</td>
<td>20 – 30 – 40</td>
</tr>
<tr>
<td>Thermal storage volume [m³]</td>
<td>0.225 + 0.075 – 0.45 + 0.15 – 0.90 + 0.30**</td>
</tr>
<tr>
<td>Electricity storage capacity [kWh]</td>
<td>5 – 10³ – 20</td>
</tr>
<tr>
<td>Thermal demand [-]</td>
<td>Reference – Passive</td>
</tr>
<tr>
<td>Electric demand [kWh]</td>
<td>2800 – 3500³ – 4375</td>
</tr>
<tr>
<td>Control [-]</td>
<td>1 – 2 – 3 – 4</td>
</tr>
</tbody>
</table>

* Bold indicates the base case value
** The first number is the room heating storage, the second is the DHW storage

4. Analysis of simulation results

Each step in the sensitivity study will be discussed separately in this section, starting with the base case. For each step, only the most important or significant results are shown. See ‘Appendix 7.3.’ for the complete results.

4.1. Base case

Using the parameters as stated in ‘Section 3.2.2.’, the base case scenario is simulated. The performance indicators are calculated as is explained in ‘Section 3.1.’.

Figure 14 shows the matching indices for a summer and winter period. The OEF during summer equals 1, which means all of the electricity consumption during the summer is produced using the PV panels. The OEM of less than 1 means more electricity is produced than needed. This is also apparent by the negative utility bill for the summer period, which means electricity is sold to the electricity grid (see Figure 15). Figure 16 shows the exact time at which this electricity is sold to the grid, namely on the 19th of July. Also the electricity which was taken from the grid on the 21st of July is visible in Figure 16. Additionally, it can be seen that the on-site electricity storage (green line) is charged during the day and discharged during the night. It seems that the capacity of 10 kWh is enough during most of the simulation period for the base case.

Figure 14 shows that the OEFh is less than 1 during the summer period. This means that not all thermal consumption is met using on-site produced thermal energy. Also the OEMh is less than 1 during the summer. This means that not all the on-site produced thermal energy is used on-site. It is expected that at least one of these equals 1. The reason this is not the case is because the temperature of the production circuit is below the required temperatures of the storages. Figure 17 shows the temperature of the production circuit and of both thermal storages. It can be seen that the temperature of the production circuit (orange line) is not always above 60 °C, which means it is unable to keep both storages on their required temperatures of 40 °C and 60 °C, despite the fact that thermal energy is produced. This explains why both the OEMh and OEFh are below 1 during the summer.
4.2. Production

In this section, the sensitivity of the production of on-site energy is discussed. The parameters that are varied are the PV panel area and the solar thermal collector area.

4.2.1. Thermal

The thermal solar collector area is varied from 2.3 m$^2$ through 30 m$^2$. The influence this has on the matching indices is shown in Figure 18. It shows that any increase in thermal solar collector area above 20 m$^2$ has very little effect on the matching indices. The reason for this can be found in the temperatures of the thermal storages and production circuit. These are shown in ‘Appendix 7.3.1.’. In this appendix, Figure 25 shows that the temperatures of the thermal storages can only be increased by the production circuit, when the temperature of the production circuit (orange graphs) exceeds the thermal storage temperatures. Also, the temperature of the production circuit increases with increasing thermal solar collector area. However, above 20 m$^2$ of thermal solar collector area, the capacity of thermal storages become the limiting factor. This means all thermal energy produced from additional solar thermal area cannot be harnessed. This explains the stabilizing matching indices in Figure 18.
4.2.2. Electric

The PV panel area is varied from 20 m\(^2\) through 40 m\(^2\). Figure 19 shows the matching indices over the PV panel area. As can be seen, the PV panel area has very little influence on the matching indices. Figure 26.1 in ‘Appendix 7.3.2.’ provides insight in the reason for this. In the summer period, 20 m\(^2\) of PV panel is sufficient to meet the electricity demand of the Net-ZEB. This can also be seen in Figure 19, since the OEF\(e\) is 1. Increasing the PV panel area to 30 m\(^2\) or 40 m\(^2\) changes only the amount of electricity that is sold to the grid. This means there is a surplus of electricity in summer. However, in the winter period, the 20 m\(^2\) of PV panel is not nearly enough to meet the electricity demand of the Net-ZEB. An interaction with the grid is needed for large periods of the winter. Even when the PV panel area is increased to 40 m\(^2\), it is still not enough to meet the electricity demand. This means there is a large lack of electricity in the winter period.

The large surplus of on-site produced electricity in summer and the large shortage of on-site produced electricity in winter suggest that the PV panel area is not optimized for the summer period, nor is it optimized for the winter period. When considering an entire year in which there is a large surplus of electricity in summer and a large shortage of electricity in winter, seasonal electricity storage is needed. Since no seasonal storage is present in the current model and the matching indices are calculated over 14 days, instead of a full year, multiple matching indices have a value less than one.

Additional simulations are needed in order to determine the optimized PV panel area for either the summer or winter period. In order to optimise the PV panel area for the entire year, a simulation of one year needs to be conducted.
4.3. Storage

In this section, the sensitivity of the storage of on-site energy is discussed. The parameters that are varied are the electric storage capacity and the thermal storage volume.

4.3.1. Thermal

The total volume of the on-site thermal storage is varied from 0.3 through 1.2 m$^3$. The ratio between the room heating storage and the DHW storage is assumed to be 3:1 in all cases. Figure 20 shows the matching indices as a function of the total thermal storage volume. The matching indices hardly change when changing the thermal storage volume. The reason for this is related to the on-site thermal production (see Figure 27.1 in ‘Appendix 7.3.3.’). The temperature of the DHW storage will be used to illustrate how the thermal storage capacity is related to the on-site thermal production. Figure 27.1 shows that the temperature of the DHW storage gradually reduces during the summer period when the temperature of the production circuit is below the DHW storage temperature. Increasing the volume of the DHW storage decreased the slope with which the DHW storage cools down. However, this decrease in temperature is highly dependent on the amount of days that the DHW storage can be charged. Especially since each day that charging is possible, the DHW storage is charged to its maximum temperature of 60 °C. When considering the winter period in Figure 27.1, it can be seen that the DHW storage has an initial value of 60 °C. However, the temperature of the production circuit is such that it cannot charge the DHW storage. Therefore, the DHW storage cools down at a rate which depends on its size. It is therefore advisable to optimise the size of the on-site storage to the amount of the on-site energy production in order to make optimal use of the storage capacity that is present.

![Figure 20 Matching indices over total on-site thermal storage volume](image)

4.3.2. Electric

The capacity of the on-site electricity storage is varied from 5 kWh through 20 kWh. Figure 21 shows the influence this has on the matching indices. As can be seen, the matching indices do not change when changing the capacity of the on-site electricity storage, with the only exception being the OEFe during the summer period. The reason for this can be found in the grid interaction, which is shown in Figure 28.1 in ‘Appendix 7.3.4.’. It shows that when the on-site electricity storage has a capacity of 5 kWh, electricity is taken from the grid during most of the simulated days. This results in the OEFe being less than 1 (see Figure 21). However, when the capacity of the on-site electricity storage is increased to 10 kWh, no electricity is taken from the grid, which results in an OEFe of 1 (see Figure 21). This confirms the statement of Tesla that 10 kWh of on-site electricity storage is sufficient to overcome weekly variations in PV production$^{[16]}$. Increasing the capacity of the on-site electricity storage even further does not result in any additional increase in the matching indices.
During the winter period, the on-site electricity production is not nearly enough to meet the electricity demand of the building, as is discussed in ‘Section 4.2.2.’. For this reason, there is very little surplus of electricity that can be stored on-site. Therefore, increasing the capacity of the on-site electricity storage serves no purpose when there is no on-site electricity to store. In order to better understand the advantage of the on-site electricity storage during the winter period, additional simulations need to be conducted in which the amount of on-site produced electricity is increased.

![Figure 21 Matching indices over on-site electricity capacity](image)

### 4.4. Consumption

In this section, the sensitivity of the consumption of on-site energy is discussed. The parameters that are varied are the thermal consumption of the building, by applying the Passive House Concept (see ‘Section 3.2.3.’) and the electric consumption, by varying the plug load.

#### 4.4.1. Thermal

The thermal consumption is varied by changing the building from the reference building as published by the Dutch government[53] to a building which meets the requirements of the Passive House concept[51]. The exact building descriptions are given in ‘Section 3.2.3.’.

Figure 22 shows the matching indices of the reference building and the Passive house concept. It can be seen that the OEFh during the summer increases, while the OEMh decreases. This occurs because the increased thermal insulation reduces the thermal consumption, while the thermal production remains the same. This results in the fraction of on-site produced thermal energy that is used directly increases and the fraction of the on-site consumed thermal energy that is used directly decreases. The same is true for the winter situation, in which the thermal energy production is not sufficient to meet the on-site thermal consumption. When this thermal consumption is reduces by making use of the Passive house concept, the fraction of the on-site thermal consumption that is met using on-site produced energy increases, resulting in an increased OEFh.

Another aspect that is apparent in Figure 23 is that all indicators shown decrease by roughly 50% during the winter period. This can be explained as follows: during the winter period, the on-site produced energy is insufficient to meet the consumption. It is therefore necessary to use energy from the electricity grid, which results in non-renewable energy consumption, CO$_2$ emissions and an utility bill. By adapting the Passive house concept, the total thermal energy consumption during the winter is reduced, which in turn reduces the non-renewable energy consumption, CO$_2$ emissions and a lower utility bill.
4.4.2. Electric

The electric consumption, or the plug load, is varied from 2800 kWh/a through 4375 kWh/a. These values are chosen as they represent a 25% variation on the average Dutch plug load of 3500 kWh/a\[8\]. Figure 30.1 in ‘Appendix 7.3.6.’ shows the distribution of the plug load for all three cases for a winter and summer period.

The plug load is part of the internal heat gain of the building. Therefore, an increased plug load will increase the temperature in the building. Since there is no cooling present in the Net-ZEB that is studied, this increase in temperature can result in overheating. Figure 30.2 shows the interior temperature in the living room and bedroom. The peaks are increased slightly with increasing plug load. This is more clear when considering the overheating, shown in Figure 30.3. The amount of overheating increases with increasing plug load in both the living room and the bedroom, during both the winter and summer period.

4.5. Control

As is explained in ‘Section 2.2.5.’, it is important to store the on-site produced energy as efficiently as possible and there are 4 setups in which the energy can be stored on-site (See Table 2). In order to determine which is the most efficient, all four are part of the sensitivity study.

The results show very little difference for all performance indicators, except for the utility bill (see Figure 24). In case of the utility bill, it is more efficient to use setup 1 or 3. These are the setups in which the on-site produced electricity is first stored in the on-site electricity storage. Only when that is at full capacity, the energy will be stored in the on-site thermal storage by means of the heat pump. This setup provides an utility bill of roughly 0 euro for a 2 week summer period, while the other two setups provide a utility bill or roughly 2 euro for the same period. For the winter period, the results show no significant difference. This can be explained by the fact that room heating is not used in the summer period. This means the energy stored
in the on-site thermal room-heating-storage will most likely not be used during the summer. Therefore, any energy stored in this storage will not be used and will gradually be lost due to thermal losses in the thermal storage. When this energy is sold to the grid, this provides income because of the feed in tariff.

The difference in utility bill during the summer period is also apparent in the state of charge (SOC) during the summer period (see Figure 31.1 in ‘Appendix 7.3.7.’). The SOC in setup 1 and 3 are much higher than the SOC of setup 2 and 4. This results in an higher change of the on-site electricity being at full capacity, which in turn allows for the on-site produces electricity to be sold to the grid.

4.6. Discussion on the Modelica model

The Modelica model that is developed in this study has many advantages. However, there are also some disadvantages. Both will be discussed in this section.

One of the major advantages of the Modelica model is that it is able to simulate a Net-ZEB including all aspects of the building, by integrating the production, storage, consumption and control of a building. This integration provides a complete insight into the behaviour of the system. This behaviour can then be analysed by looking at the different subsystems, which are all simulated in a high level of detail. This has the advantage of being able to investigate the interaction between the different subsystems. Being able to analyse this interaction of subsystems in a high level of detail, as well as being able to simulate all aspects of a Net-ZEB, allows the Modelica model to provide information on performance indicators prior to construction. This is of great interest for the stakeholders that are involved.

However, because of the high level of detail the model provides, detailed information of the building is required in order to simulate it. Therefore, using this model in the early design phase might prove to require many assumptions. Also, the simulation time to simulate an entire year is roughly 15.5 hours. This prevents the model from being used to simulate many different cases. Also, a certain level of expertise is required to use the Modelica model.

5. Conclusions and recommendations

In this study, a Modelica model is developed in which a Net-ZEB can be simulated, including all aspects and subsystems. This model was then used to conduct a sensitivity study of the parameters in order to gain insight into these parameters. In this section, the conclusion on the Modelica model and the sensitivity study are presented separately.

5.1. Conclusion on the Modelica model

The Modelica model includes the integration of the production, storage and consumption of energy, as well as supervisory control. The system and all its subsystems are simulated at a high level of detail. The combination of the mentioned aspects and the high level of detail allow the model to be used to analyse the interaction between several subsystems. This combination of aspects and the way the performance indicators are derived from the simulation, can be of great importance for stakeholders of future Net-ZEBs. It can provide detailed insight into the behaviour of a Net-ZEB, as well as quantify the consequences of the choices that are made prior to construction. Especially making use of the matching indices proved to be a useful approach for analysing the performance of a Net-ZEB.

Due to the detailed input information that is required by the model, using it in the early design phase might prove to require many assumptions. The Modelica model will most likely prove to be of most benefit in two situations. Firstly, it can be used in order to quantify the consequences of design choices in general cases. In doing so, it can be useful in the development and testing of concepts of Net-ZEBs or other types of
buildings. Also innovative system concepts or components can be tested. All these can be analysed in great detail, including their robustness. This way, the Modelica model can help to provide insight into the behaviour of buildings with on-site energy production and storage and in doing so, provide information which can be used to upgrade the EPC calculation by adding energy storage to the calculation.

Secondly, the Modelica model can be of great benefit to stakeholders who are in later stages of design, when many aspects of the design are already decided upon. It can then be used to determine the amount of on-site production, storage and consumption of energy that can be expected of the design, as well as the aspects that influence this. Meaning it provides detailed insight into the self-consumption of a building and in doing so, the model can help to make well-informed decisions on the system sizing of the design. Especially when the focus lies more and more on self-consumption and energy neutral buildings.

5.2. Conclusion on the case study
The sensitivity study that is conducted in this study provides insight into the performance indicators and the effects that varying certain parameters have on them. Also, it showed the mutual interactions between several of the results. For example, the sensitivity study showed that a change in the electric part of the system, can also influence thermal performance and vice versa. In that sense, the sensitivity study proved the potential of the Modelica model.

Advantages of the sensitivity study as it is conducted in this study is that it provides insight into the effect of a single parameter, because only one parameter is changed in every simulation. In doing so, this parameter and the result of changing it can be studied in detail. However, due to the interdependencies in the results, as mentioned earlier, changing a single parameter proved to be a too simplistic approach. Rather than changing a single parameter, it would provide more useful results when multiple parameters were changed simultaneously. For example, increasing both the on-site production and storage of electricity would provide more useful results.

To fully understand and possibly optimise the relationships between the different forms of on-site production, storage and consumption of energy, many more simulations need to be performed. Also, one of the main conclusions is that there is a major difference between the thermal and electrical demand for the summer period and the winter period. In order to overcome this, seasonal storage is required. However, to fully understand the behaviour of the system, a yearly simulation needs to be conducted.

Also, an aspect which is very important to take into account is the initial value of for example the thermal storages and the electricity storage. This can influence the results to a large extent, especially when the simulation period is short. When the initial values that are chosen are very different from the average values that will occur in the simulation, this influence increases.

5.3. Recommendations
There are several aspects of the Modelica model that can be improved. These are listed below.

- The simulation time of the model makes yearly simulations very time consuming. It is therefore recommended that work is done on reducing the simulation time.

- The mass flow though the production circuit, DHW circuit and room heating circuit is not yet optimized. Therefore, there are days that the production circuit does not reach the temperature of 40 °C which is required to store thermal energy in the room heating storage. By reducing the flow through the solar collector and heat pump, this temperature can be increased and in doing so, more energy can be transferred to the thermal storages. A optimisation is required to improve this.

- In the current model, the heat pump is implemented using a boiler-component (see ‘Section 2.2.1.’). This can be improved by using an heat pump component from the LBNL Buildings library\(^{[49]}\).

- The PV panel which is implemented in the current model is not thermally connected to the building. This is something which can prove to be of interest, especially when PV panels are integrated into the roof, instead of placed on top of the roof. The PV component that is used in this study
(Districts.Electrical.DC.Sources.PVSimple) does not provide this option. This component should be extended in order to include this option.

- The financial performance indicators that are used in the current model are the utility bill and the capital costs. In which the capital costs are limited to the capital costs of energy production and storage. These performance indicators can be added to form the life cycle costs, which would increase the usability of the model by further including financial aspects. This would require yearly simulations and taking into account reduction of efficiency of for example the PV panels.
6. References


[32] Sun, Y. (2014) *Sensitivity analysis of macro-parameters in the system design of net zero energy building.* City University of Hong Kong


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### 7.2. Electric energy management setup for decision-making

Table 5 Overview of decision-making in the electric energy management

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7.3. Full results of sensitivity study

7.3.1. Production – thermal

Figure 25: Temperatures of thermal storages and production circuit over varying thermal solar collector area.
7.3.2. Production – electric

Figure 26.1 Grid interaction and on-site storage interaction over varying PV panel area

- 20 m² (base case) (summer)
- 20 m² (base case) (winter)
- 30 m² (summer)
- 30 m² (winter)
- 40 m² (summer)
- 40 m² (winter)

Legend:
- stored on-site
- grid interaction
Figure 26.2 State Of Charge (SOC) of on-site electricity storage over varying PV panel area
7.3.3. Storage – thermal

Figure 27.1 Temperatures of production circuit and thermal storages over varying thermal storage volume

- 0.225 + 0.075 m³ (summer)
- 0.225 + 0.075 m³ (winter)
- 0.45 + 0.15 m³ (base case) (summer)
- 0.45 + 0.15 m³ (base case) (winter)
- 0.9 + 0.3 m³ (summer)
- 0.9 + 0.3 m³ (winter)

Legend:
- production circuit
- room-heating-storage
- DHW-storage
- room-heating-storage (goal)
- DHW-storage (goal)
Figure 27.2 Thermal losses of thermal storages over varying thermal storage volume
7.3.4. Storage – electric

Figure 28.1 Grid interaction and on-site storage interaction over varying capacity of on-site electricity storage
Figure 28.2 State Of Charge (SOC) of on-site electricity storage over varying capacity of on-site electricity storage
7.3.5. Consumption – thermal

Figure 29.1 Temperatures of living room, bedroom and ambient and horizontal direct radiation

- Reference building Dutch government (base case) (summer)
- Reference building Dutch government (base case) (winter)
- Passive House concept (summer)
- Passive House concept (winter)

Legend:
- bedroom
- livingroom
- ambient
- direct hor. radiation
Figure 29.2 Overheating of living room and bedroom
7.3.6. Consumption – electric

Figure 30.1 Plug load variation
Figure 30.2 Ambient, living room and bedroom temperature
Figure 30.3 Overheating in living room and bedroom
7.3.7. Supervisory control

Figure 31.1 Grid interaction and on-site storage interaction
Figure 30.2 Temperatures of production circuit and thermal storages
Figure 31.3 State Of Charge (SOC) of on-site electricity storage
7.4. Capital costs

Figure 32.1 Capital costs of PV panels

Figure 32.2 Capital costs of thermal solar collectors
Figure 32.3 Capital costs of electricity storage

Figure 32.4 Capital costs of thermal storage