Hydrogen as seasonal energy storage for Floriade:

The implications of hydrogen in the built environment as part of an energy system

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Abstract

Hydrogen is known for a variety of applications and is often associated with The Energy Transition. This thesis aims to explore the possibilities of applying hydrogen as a seasonal buffer of renewable energy. The research is applied to the case study Floriade, which is a neighborhood currently under development and set to be completed in 2022. The research consists of four parts, each of which contributes the integral design of an energy system that incorporates hydrogen as a seasonal buffer.

The first part focusses on the design of the energy system and the elements that are part of an energy system. Multiple energy system designs, including systems without hydrogen incorporated are evaluated. A multiple criteria analysis is undertaken in order to come to a design with an optimal configuration of elements.

The system layout and components are dependent on the energy demand and the production potential of the neighborhood. The energy demand and the production capacity is calculated with an energy model, which is described in the second part of the research. Multiple software packages are used to calculate and validate data necessary for the research. The consumption and production data are used to make up the balance of energy consumption and production.

The energy balance is used to calculate the efficiency of the energy system. The efficiency determines the feasibility in terms of energy losses and gains. This is described in the third part of the thesis. The overall system efficiency are calculated and the added value of storing renewable energy as hydrogen is evaluated.

To minimize energy losses by means of transport all system components for making and storing hydrogen are located in one building in a central location. The final part of the thesis describes the design of this energy hub. The design of the building is based on safety measures that should be taken into account when introducing hydrogen in the built environment.

The research results in the design of an energy system in which hydrogen is applied as a season buffer for renewable energy. The aspects of both energy system design as well as the application of hydrogen in de built environment are evaluated to draw conclusions on the opportunities and challenges of applying hydrogen as a seasonal buffer.

Contents

1 Introduction

1 Introduction

1.1 Background

The Paris agreement (UNFCCC. Conference of the Parties (COP), 2015) states the importance of recognizing the climate change as an urgent threat to human societies. The world population is growing and with it, the demand for energy grows. The vast majority of this energy is obtained from non-renewable sources such as fossil fuels. Technological advances in the field of sustainable energy production are being made. However, its introduction into the energy system is not progressing fast enough.

Energy production from non-renewable sources results in high carbon dioxide (CO_2) emissions, which contribute to the climate change. For this reason, the European Union is committed to reducing greenhouse gas emissions by 80-95% (Council of the European Union, 2009). Furthermore, the increase in the global average temperature should stay well below 2°C above pre-industrial levels according to the Paris Agreement. Figure 1 shows the carbon budget of the Intergovernmental Panel on Climate Change (IPCC) (The Carbon Brief, 2014). A carbon budget is the cumulative amount of carbon dioxide (CO2) emissions permitted over a period of time to keep within a certain temperature threshold (Sussams, 2018).

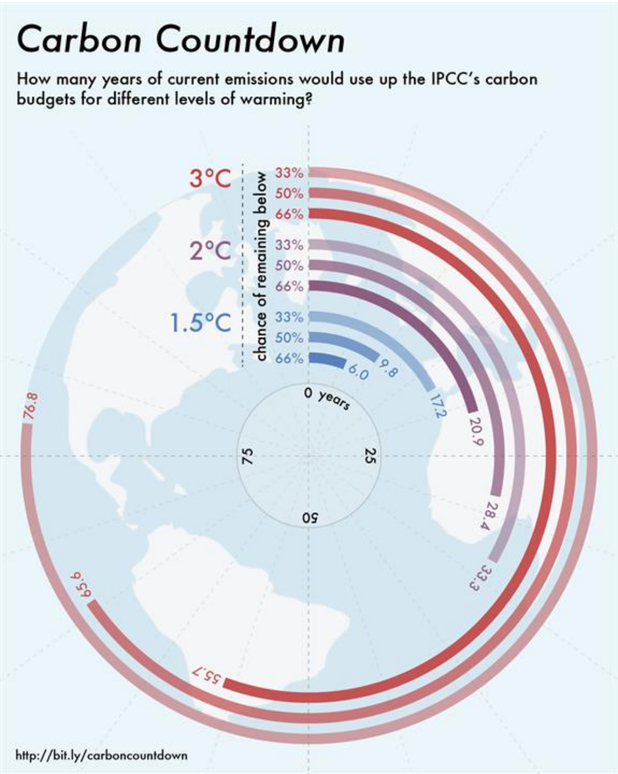


Figure 1: Carbon countdown; retrieved from https://www.carbonbrief.org/six-years-worth-of-current-emissions-would-blow-the-carbon-budget-for-1-5-degrees

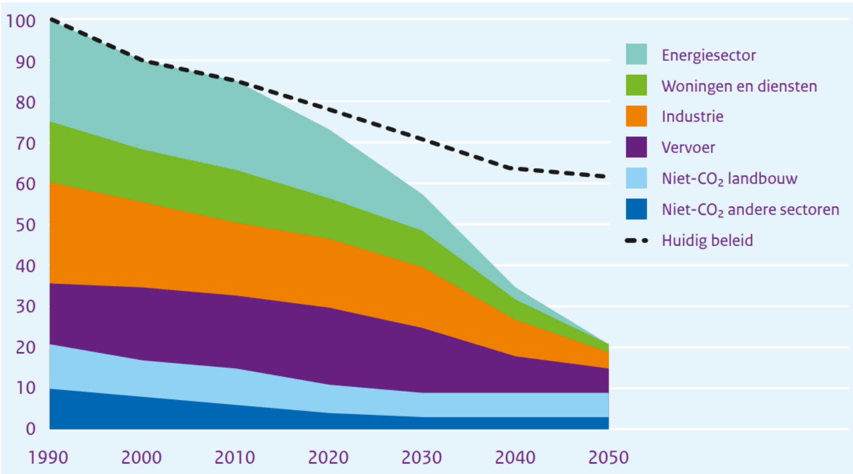


Figure 2: Route map to a low-carbon economy; retrieved from https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/documenten/rapporten/2016/01/18/energierapport-transitie-naar-duurzaam

Great effort is being put in reducing or even mitigating carbon emissions. Alternatives for fossil fuels offer possibilities to reduce the emission of greenhouse gasses. In the Netherlands, the amount of energy produced from renewable sources (hydro power, wind power, solar power, biomass, waste incineration, biogas) increased from 11.793 mln kWh in 2014 to 16.654 mln kWh in 2017 (CBS StatLine, 2016), as can be seen in figure 2. This increase of about 40% shows that the technological advances in the field of renewable energy contribute to achieving the 2050 climate goals (European Union, 2012).

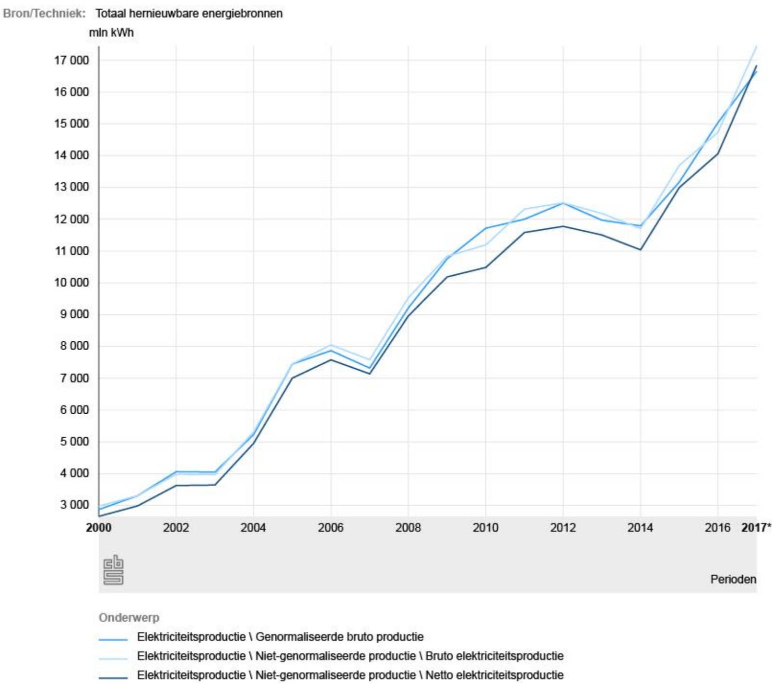


Figure 3: Total energy production from renewable sources in the Netherlands; retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82610ned/line?ts=1528885281637

Achieving the climate goals by reducing the carbon dioxide emissions aids in stopping global warming. The world's primary source of energy are currently fossil fuels, including oil, coal and natural gas. These products are non-renewable and therefore finite. Besides the negative impact they have on the environment, there is also a limit to their stock. So, at some point in the future, the energy system needs new feedstock. The process of switching to a new energy system with renewable energy as source is called the energy transition.

Wind- and solar power are considered the most promising sources of renewable energy. The technology to transform it into electricity, and even heat in the case of solar collectors, is very well developed. The worlds' energy demand (556 EJ = 155.000 TWh) is only a fraction of the amount of energy that the sun and wind provide to earth. If 10% of Australia's land area would be covered in PV panels, or if 1.5% of the Pacific Ocean would exist out of windfarms enough energy would be produced to power the world (van Wijk, 2018).

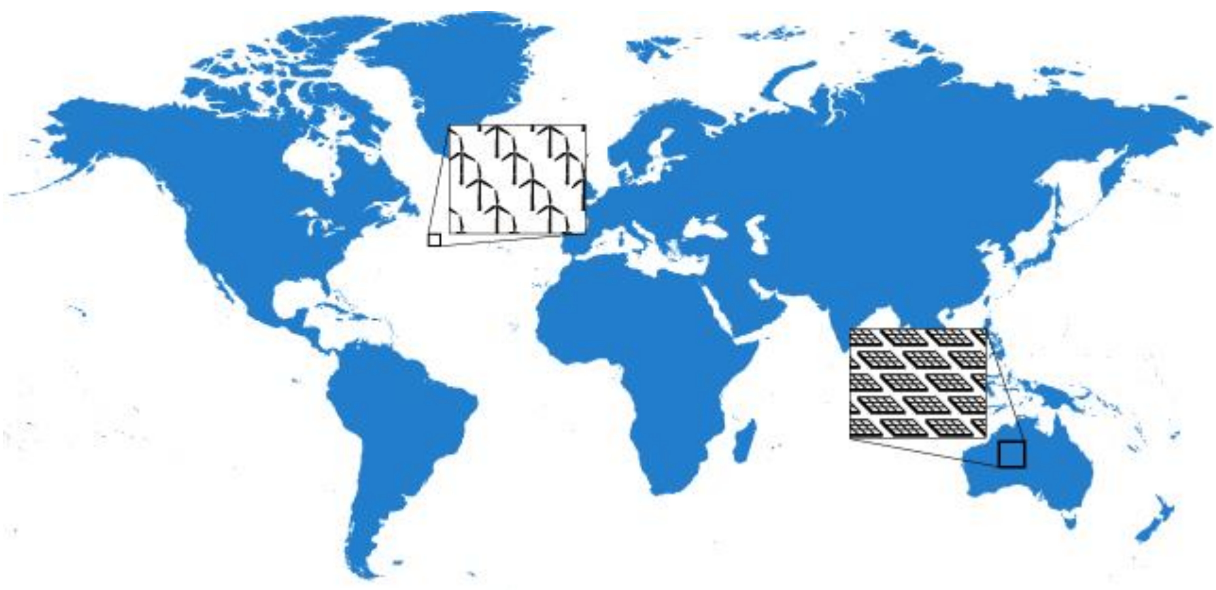


Figure 4: Visualization of surfaces required for energy production, based on van Wijk, 2018

1.2 Problem statement

The Hydrogen Council states that the energy transition needs to overcome five major challenges (Hydrogen Council, 2017).

1. Using more variable renewable energy in the power sector will unbalance supply and demand.
2. To ensure security of supply, global and local energy infrastructure will require major transformation.
3. Buffering of the energy system through fossil fuels will no longer be sufficient to ensure smooth functioning of the system.
4. Some energy end uses are hard to electrify via the grid or with batteries, especially in transport but also in other sectors.
5. Renewable energy sources cannot replace all fossil feedstocks in the (petro)chemicals industry.

Before explaining how hydrogen can contribute to tackling these challenges, some more details on the impact of these challenges are given.

Using more variable renewable energy in the power sector will unbalance supply and demand.

Solar power is generated by PV cells, which transform solar energy to electricity. Wind power is generated by wind turbines, which transform kinetic energy from rotating blades to electricity. So evidently, you need sun or wind before being able to produce electricity from the sun or wind. These sources are not continuously available, as the sun does not shine during the night and less during the winter and it is not always windy. An energy system which is based only on variable sources is not reliable as the source of energy is not always guaranteed.

This results in a disbalance in the energy system. During windy and sunny days the supply may be higher than the demand and during windless, sunless days, demand may be higher than the supply. For this energy system to be reliable, either a back-up source or a buffer is required. Hydrogen can fulfill the role of the back-up source and the buffer.

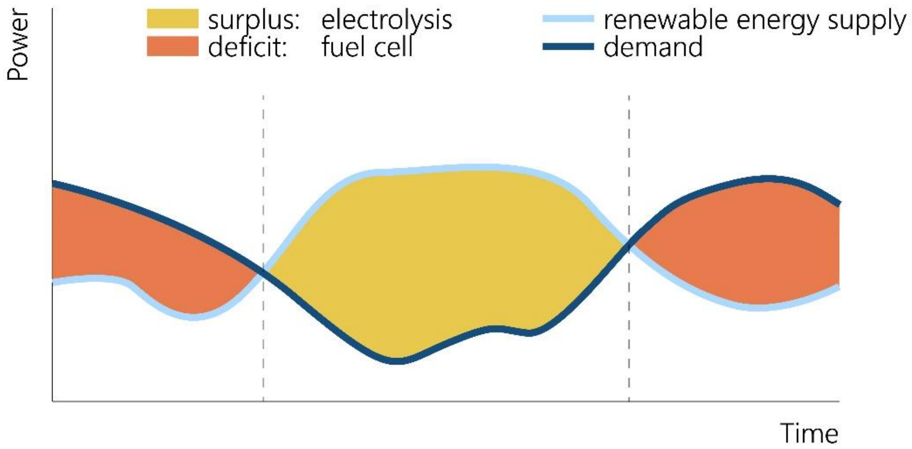


Figure 5: Difference in demand and supply of energy

To ensure security of supply, global and local energy infrastructure will require major transformation.

To cope with the increasing energy production from variable sources, the energy network needs to undergo a transformation. TenneT, the national electricity transmission system operator of the Netherlands confirms this in its vision document for 2030 (TenneT, 2016). The scenarios "Groene Revolutie" (Green Revolution) and "Duurzame Transitie" (Sustainable Transition) involve energy storage system to be able to integrate all the power generated by wind and sun into to energy system. In figure 6, the expected production of energy and the demand is displayed. RDT shows the expected production in the "Towards Sustainable Transition" scenario, CK shows "Central Climate Action" and DK "Decentral Climate Action". Other scenarios that are considered in this document are not evaluated in this report because there is no relation to hydrogen.

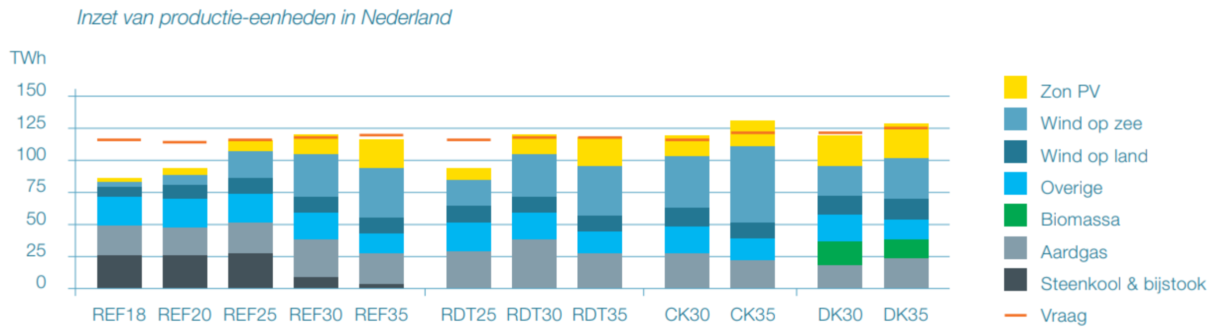


Figure 6: Expected production power TenneT; retrieved from https://www.tennet.eu/nl/nieuws/nieuws/groei-van-zonne-en-windenergie-en-betrouwbaarheid-elektriciteitsvoorziening-vormen-uitgangspunten-v/ on 13-06-2018

Buffering of the energy system through fossil fuels will no longer be sufficient to ensure smooth functioning of the system.

As described in the previous challenge, energy systems that solely rely on variable sources need a back-up and a buffer to form a reliable system. This buffering can be done by connecting the energy system to the grid so the grid can feed energy to the system. In case not enough energy is supplied by sun and/or wind, energy from the back-up grid is used. It is not unlikely that the sources of this back up grid are fossil fuels.

At some point in the future, the fossil fuels will run out of stock. An alternative for storing and buffering energy has to be found in order to maintain a reliable energy network.

Some energy end uses are hard to electrify via the grid or with batteries, especially in transport but also in other sectors.

Direct electrification can in some cases be economically and technologically challenging. Heavy-duty transport, non-electrified trains, overseas transport and aviation, but also some energy intensive industries are more difficult to electrify (Hydrogen Council, 2017). The transport sector plays an important role in the energy transition, but is beyond the scope of this report.

Renewable energy sources cannot replace all fossil feedstocks in the (petro)chemicals industry.

Fossil fuels used for the production of, e.g., plastics will cause (carbon dioxide) emissions at the end of their life cycle when burned in incinerators (Hydrogen Council, 2017). As with the transport sector, the (petro)chemicals industry in not considered in this report.

1.3 Research Objectives

To give direction to the research, an objective and a research question with corresponding sub-questions have been formulated.

1.3.1 Objective

The goal of this thesis is to research the implications of applying hydrogen in the built environment and to design an energy system that incorporates hydrogen as seasonal storage. This objective is considered on different scales, ranging from neighborhood to building scale. Eventually, the report will give a clear overview of what an energy network that includes hydrogen as seasonal storage looks like, how this network fits in a newly developed neighborhood and the design of a production and storage facility. After establishing the consumption profiles of the buildings and calculating the production potential of PV arrays on the roofs of the buildings, an energy balance is composed. For the hydrogen storage and production an energy hub is designed.

The design exercise consists of four elements: energy system design, energy model including consumption and production, energy balance and the design of the energy hub. These elements depend on and influence each other. Figure 7 gives an overview of the elements of the research and the steps taken.

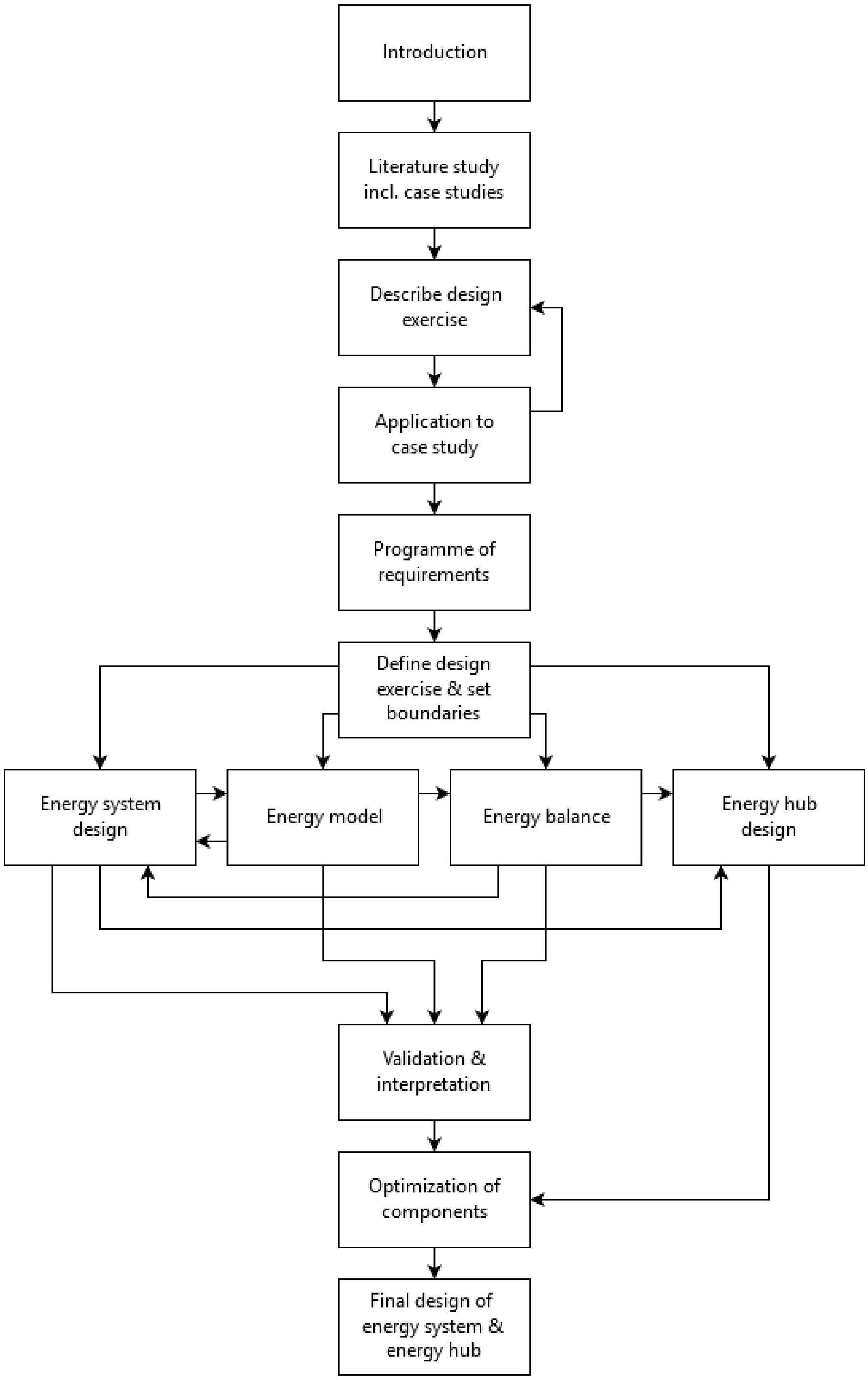


Figure 7: Flowchart of the research

1.3.2 Research question

What does an energy system with hydrogen incorporated as seasonal buffer for a newly built residential area look like and what are the implications of the application of hydrogen in the built environment?

1.3.3 Sub questions

General

- What are the properties of hydrogen?

Energy system design

- What are the options when designing an energy system?
- How can energy be transported in a neighborhood
- What is the role of hydrogen in the energy system?
- Which components are included in an energy system?

Energy model

- How is the data collected, processed and validated?
- What is the energy demand of the neighborhood
- What is the production potential of a photovoltaics array on the case study location

Energy balance

- How is the energy balance calculated?
- What is the energy surplus?
- How much hydrogen can be produced
- How much hydrogen can be stored
- What is the efficiency of the energy system

Energy hub

- What are the design boundaries of the energy hub
- What are the implications of applying hydrogen in the built environment

1.4 Relevance

It has been established that the energy system needs to undergo a transition to be able to deal with the increasing amount of energy produced from renewable and variable energy sources. An important aspect of this transition is the storage and buffering capacity of the energy system. This is the result of a disbalance in the demand and supply. The surplus of energy that is produced by renewable sources can be stored in hydrogen and used at times when the demand is higher than the supply.

The high efficiency of the conversion of renewable energy to hydrogen and the fact that it can be produced and used without emitting greenhouse gasses, makes it an attractive storage medium. Although it has been used as a component of the gas that was used to heat buildings in the Netherlands in the past, it has an image problem due to its explosive nature. This research aims, among other things, to establish hydrogen as a safe energy source and by doing so, making it acceptable to use in the built environment. Furthermore, it can set an example of how to transform energy systems and neighborhoods to run on hydrogen. Eventually, the combination of the production site, the energy hub, the energy network and the design boundaries for the housing in the neighborhood becomes a display of technology and innovation.

2 Literature research

2 Literature research

To get a sense of state of the art of hydrogen in the built environment, this research started with a literature research. This chapter gives background information on hydrogen and explains the relevance of the research. An introduction to hydrogen is given, the energy-related properties are described and the possible applications of hydrogen in the built environment are discussed.

2.1 The basic properties of hydrogen

Hydrogen is a chemical element with symbol H and has an atomic mass of 1.008. This makes it the lightest element on the periodic table. It is the most abundant element in the universe and has an estimated availability as long as the existence of humans. Hydrogen does not occur as a single atom on earth, but as two atoms bound together (H_2) (Fuel Cell & Hydrogen Energy Association, 2018). Because it readily forms covalent compounds with nonmetallic elements, most hydrogen on Earth exists in molecular forms bonded to e.g. oxygens (H_2O) and carbons (CH_n). So, to obtain hydrogen, it must be extracted from other sources. In its purest form and at standard temperature and pressure it is a non-toxic, colorless, odorless, tasteless gas (Desert, 2001). A, for this research, very relevant property of hydrogen gas is its high combustibility. Table 1 shows the properties of hydrogen (Mazloomi & Gomes, 2012).

Property	Value	Unit
Name, symbol, number	Hydrogen, H, 1	-
Category	Nonmetal	-
Atomic Weight	1.008	-
Density (gas)	0.089	g/l
Density (liquid)	0.07	g/cm^3
Liquid to gas expansion ratio	1:848	atm. conditions
Higher Heating Value (HHV)	142	MJ/kg
Lower Heating Value (LHV)	120	MJ/kg
Flammability range in air	4-75	%
Laminar flame velocity	3.06	m/s
Flashpoint	-253	°C
Autoignition temperature	585	°C

Table 1: Properties of hydrogen

Energy content: the amount of energy that is released when the fuel reacts with oxygen. It is quantified by a High Heating Value (HHV) and Low Heating Value (LHV). These values represent the amount of energy required to vaporize a liquid fuel into a gaseous fuel. The LHV is the HHV subtracted with the energy required to vaporize water

Energy density: describes the amount of energy for a given volume of fuel.

Flammability range in air: the range within the hydrogen can ignite in a mixture with air.

Laminar flame velocity: the speed at which a flame propagates through unburnt reactants

Flashpoint: the temperature at which the fuel produces enough vapors to form an ignitable mixture with air at its surface.

Autoignition temperature: the lowest temperature at which a substance spontaneously ignites.

2.2 Hydrogen as carrier of energy

The energy content per mass of hydrogen is 143 MJ/kg, which is about three times more than liquid hydrocarbon based fuels (Mazloomi & Gomes, 2012). Table 1 shows that in the gaseous state, hydrogen has a very low density. As a liquid, the energy content is much higher, but liquifying hydrogen is an energy consuming process, which makes it less attractive to use as a fuel. Table 2 shows the energy density of hydrogen compared to common fuels. It should be mentioned that the energy density of natural gas may vary, dependent on its origin.

Material	Energy per kg [MJ/kg]	Energy per liter [MJ/l]
Hydrogen (liquid)	143	10.1
Hydrogen (compressed, 700 bar)	143	5.6
Hydrogen (atm. pressure)	143	0.0107
Methane (atm. pressure)	55.6	0.0378
Natural gas (liquid)	53.6	22.2
Natural gas (compressed, 250 bar)	53.6	9
Natural gas (atm. pressure)	53.6	0.0364

Table 2: Volumetric and gravimetric energy density for common fuels

Hydrogen can be used as feedstock for turbines, internal combustion engines and fuel cells. On a smaller scale it can be used for kitchen ovens and heaters. The fact that some of these consumers contain no moving parts, results in a high mass to energy conversion. Furthermore, its life span and efficiency is much higher than that of conventional devices. Shown below, is a gas turbine produced by GE which has an efficiency of 60%.

Most importantly, the consumption of pure hydrogen does not emit greenhouse gasses. When combusted it reacts with oxygen, forming water. Hydrogen can also be added to other fuels to form fuels that contain energy. Hydrogen, or hydrogen mixtures can be used as a fuel for engines that are designed to use them. Its high flammability range (table 1) makes for an easily controllable engine power.

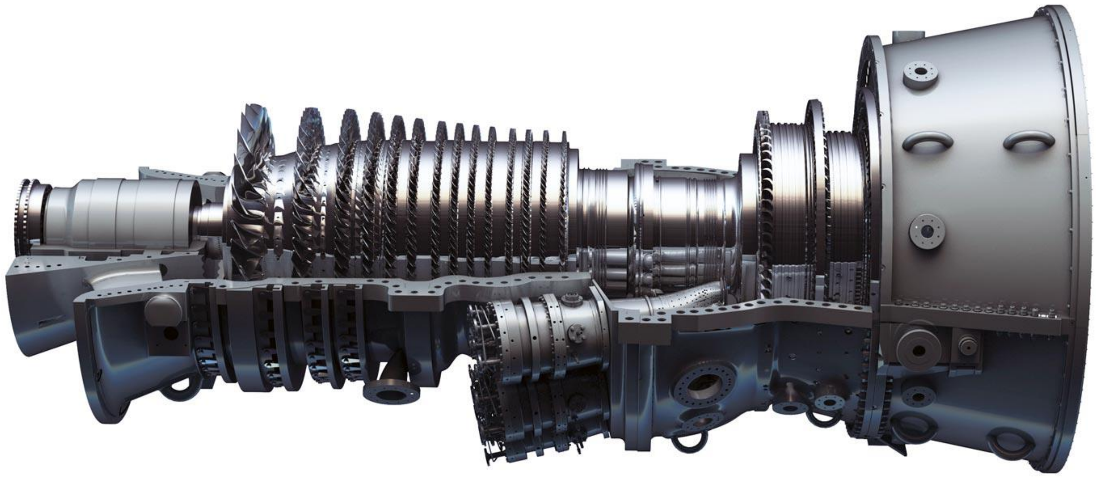


Figure 8: 7F gas turbine produced by GE; retrieved from https://www.ge.com/power/gas/gas-turbines/7f-05 on 13-06-2018

Fuel can only be burnt in a gaseous or vaporized state. The flashpoint of a material defines the temperature at which the fuel produces enough vapor to form an ignitable mixture with air. The flashpoint of hydrogen is relatively low and with the low flashpoint come some advantages. A lower flashpoint requires less complex ignition equipment, making it easier to combust even in “difficult” circumstances. Next to this, the range in which hydrogen combined with air is combustible is relatively high as shown in table 3.

Fuel	Flammable Range [%]
Hydrogen	4-75
Methane	5.3-15
Propane	2.2-9.6
Methanol	6-36.5
Gasoline	1-7.6
Diesel	0.6-5.5

Table 3: Flammability range of common comparable fuels

2.3 Hydrogen production

Hydrogen can be produced from multiple sources. At the moment, the main resource used during the production of hydrogen is still fossil fuel. The main reason for this is costs, but also the fact that these resources are easy to use in production machines. Advances in technology have made it possible to reduce the amount of carbon that is emitted into the atmosphere when producing hydrogen from fossil fuels, but alternatives where no carbon is emitted have presented themselves in the last years. An overview of the production techniques is given.

2.3.1 Fossil fuels

Producing hydrogen from fossil fuels with a process called Steam-Methane-Reforming (SMR) is considered the most economical method (Balat, 2008) and makes up for 48% of global hydrogen production. Coal (30%) and oil (18%) have the second and third place in this ranking (Mazloomi & Gomes, 2012). SMR has the largest share in hydrogen production globally (Minet & Desai, 1983) and uses different resources to produced hydrogen: biomass, coal, gasoline, oil, methanol and methane. The reaction that takes place during SMR is given by the equation:

$$H_2O + CH_4 \rightarrow CO + 3H_2 \qquad (1)$$

Fossil fuels offer the possibility of mass producing hydrogen at a reasonable price. However, during this process, high amounts of CO, CO_2 and other greenhouse gases are emitted (Granovskii, Dincer, & Rosen, 2007). These carbons can be captured and stored underground with a process called Carbon Capture and Storage (CCS). Hydrogen produced from fossil fuels is called grey hydrogen, if CCS is applied during the production process it is called blue hydrogen.

2.3.2 Electrolysis

The technique described in the previous section produces, besides hydrogen, also carbon dioxide which counts as a major drawback for this technique. A more sustainable way of producing hydrogen is by means of electrolysis, which unfortunately accounts for only 4% of the global hydrogen production (Mazloomi & Gomes, 2012). This technique splits water atoms into hydrogen and oxygen. Simply put, the production of hydrogen by splitting is given by the equation:

$$H_2O \rightarrow ½H_2 + O_2 \qquad (2)$$

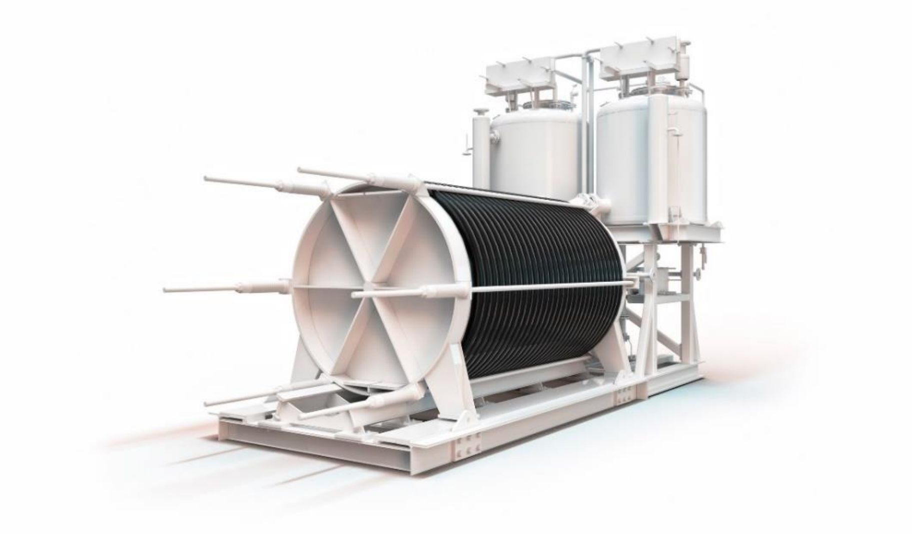


Figure 9: An alkaline electrolyser fabricated by Nel; retrieved from http://nelhydrogen.com/product/electrolysers/#a-range-title on 13-06-2018

During the process of electrolysis, water is subjected to an electrical current which forces molecules to decompose. The half reactions that take place at the electrodes are described by equation (Mazloomi & Gomes, 2012):

Cathode: $2H^{+} + 2e \rightarrow H_2$ (3)

Anode: $2OH^{-} \rightarrow \frac{1}{2}O_2 + 2e$ (4)

If the feedstock used to produce hydrogen by means of electrolysis comes from renewable sources, green hydrogen is produced. It is also possible to produce green hydrogen from biomass by a variety of methods such as gasification or fermentation. Renewable energy systems such as wind or solar power energy show zero or minimal emission of GHGs during the conversion of energy (Khan, Hawboldt, & Iqbal, 2005). Another unique quality of producing hydrogen from wind or solar power is that it can be produced anywhere around the world, because it only requires water and electricity (which can be supplied via solar or wind power). The CO_2 footprint that is mentioned below only considers the CO_2 that is liberated during the production process of hydrogen and does not take into account CO_2 emissions caused by the production of the equipment for hydrogen production.

	Grey	Blue	Green
Feedstock	fossil fuels	fossil fuels	renewables
CCS/CCU	no	yes	not necessary
CO2 footprint [kg/kg H2]	9	0.9-1.35	0
Costs [€/kg]	1.0 - 1.5 (year 2018)	2.0 - 3.0 (year 2020-2025)	2.0 - 3.0 (year 2020-2025) 1.0 (year >2030)

Table 4: Comparison of grey, blue and green hydrogen

2.4 Carbon capture and storage

Carbon capture and storage is a technology that captures CO_2 that is liberated as a by-product during the production of hydrogen from fossil fuels (The Carbon Capture & Storage Association (CCSA), 2016b). This technology is not limited to hydrogen production but can also be used to capture carbon from the normal atmosphere. During the generation of electricity and industrial processes, up to 90% of the emitted carbon is captured before entering the atmosphere. After being captured, it needs to be transported and stored.

The first step is capturing the CO_2 before is enters the atmosphere when fossil fuels are burnt. The CO_2 is separated from the gasses that are released during the generation of electricity. Capturing the CO_2 can be done during three phases of the energy production: pre-combustion, post-combustion and oxy-fuel combustion.

Pre-combustion captures the CO_2 before it is combusted. The syngas is produced by combining pure oxygen with fuels in a gasifier. Combining the syngas (hydrogen, carbon monoxide, carbon dioxide and water) with steam in a shift reactor, converts it in hydrogen and carbon dioxide. After this, the CO_2 is captured from the gas stream, compressed, dehydrated, transported and stored.

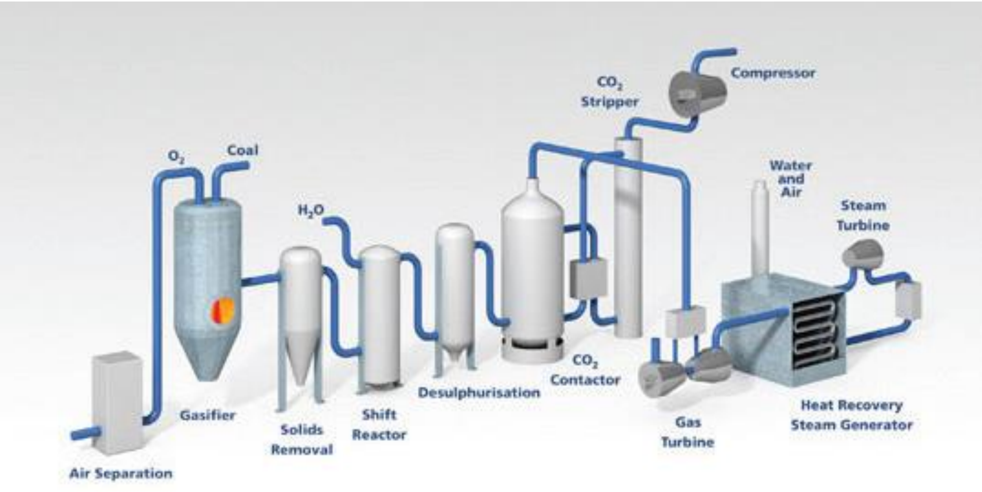


Figure 10: Pre combustion capture system overview; retrieved from https://www.costain.com/what-we-do/oil-gas/decarbonisation/carbon-capture-and-storage-ccs/ on 13-06-2018

Post-combustion captures the CO_2 after it is combusted and can be applied to either new or existing power plants. The steam that is generated by injecting fuel into a boiler and combust it with air, is used to power turbines. The flue gas that is released from the boiler exists of carbon dioxide, nitrogen and water. The gas passes through a chemical wash which captures the CO_2, which is stored after being compressed and dehydrated.

Figure 11: Post combustion capture system overview; retrieved from https://www.costain.com/media/596752/gas-carbon-capture-oct15-2pp-size-747kb.pdf on 13-06-2018

Oxy-fuel combustion is a process that uses pure oxygen instead of air to burn fuel. Pure oxygen is obtained by taking the oxygen out of the air with an air separation unit. The combustion of fuel with oxygen takes place in a boiler, which produces steam that is used to power turbines and generate electricity. The flue gas (carbon dioxide and water) is recirculated to control the temperature in the boiler. The captured CO_2 is, again, compressed, dehydrated, transported and stored.

Figure 12: Oxy fuel combustion system overview; retrieved from https://www.costain.com/media/596752/gas-carbon-capture-oct15-2pp-size-747kb.pdf on 13-06-2018

After capturing the carbon dioxide, it is transported by ship or pipeline to a location where it can be stored. Typical locations for storing CO_2 are geological formations below ground, salt caverns or depleted oil and gas fields. The carbon dioxide is injected under pressure, where it moves upward until it reaches a layer of rock which is impenetrable for carbon dioxide, thus locking it below ground (The Carbon Capture & Storage Association (CCSA), 2016a). This type of storage is called structural storage and is the most often applied form of storage.

Besides storing the carbon dioxide, it can also be used as it is a source of carbon. This can be used during the manufacturing process of fuels, carbonates, polymers and chemicals. The technology to use the carbon dioxide as raw material is called Carbon Capture and Utilization and currently in the phase of development to demonstration (TRL 5-6) (European Commission, 2016).

2.5 Hydrogen networks

Hydrogen networks can be considered on different scales, ranging from neighborhood to city. An overview is given of case studies of different scales.

2.5.1 Case study: H21 Leeds City Gate

The goal of this project is to study the feasibility from both a technical and economical viewpoint of converting the existing natural gas network of one of the largest cities in the UK to 100% hydrogen (Leeds, 2016). This project is used as the basis for the literature research on hydrogen networks. The study focused on a range of subjects in order to come to a conclusion on the feasibility of transforming the energy system of the city. The following conclusions are relevant for this report.

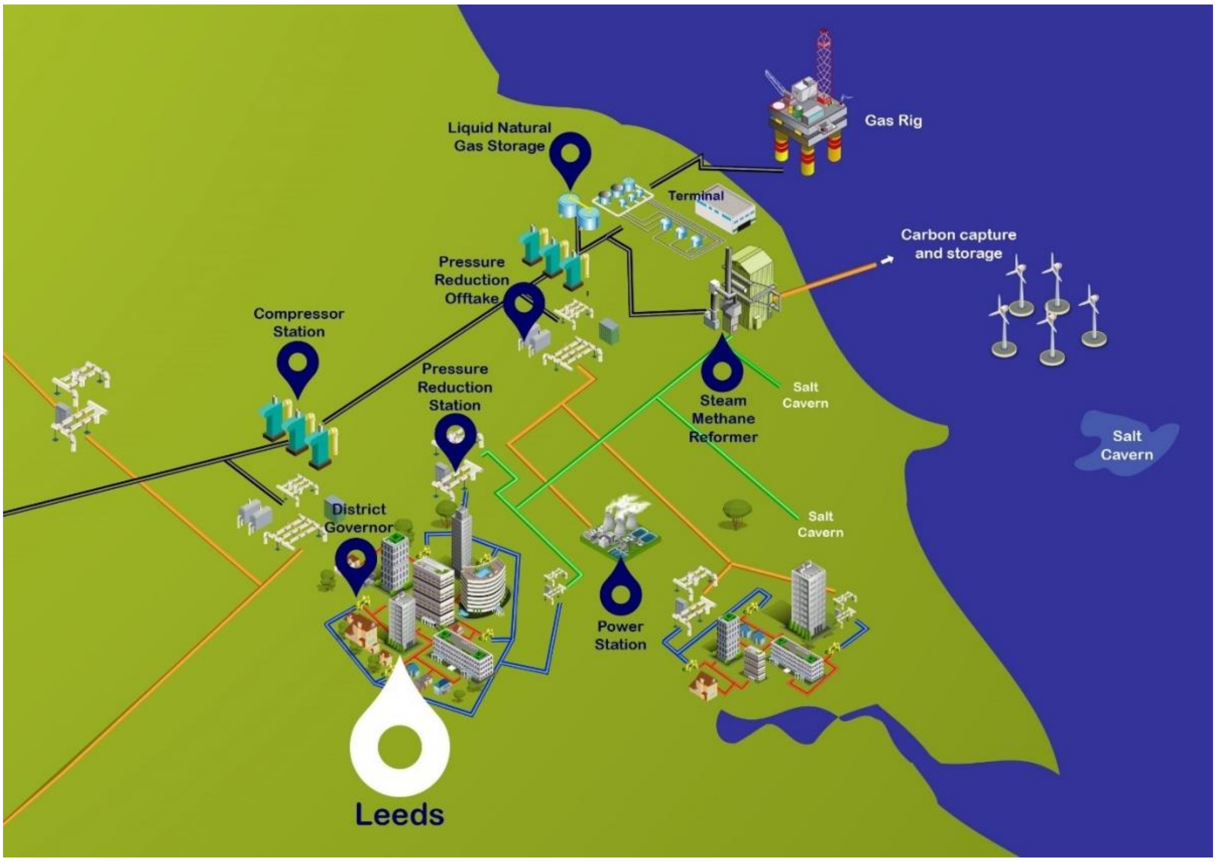


Figure 13: Leeds City Gate system overview; retrieved from https://www.globalccsinstitute.com/news/institute-updates/hydrogen-and-ccs-support-uk-decarbonisation

Network capacity

It can be assumed that the capacity of the gas network is sufficient to be converted to hydrogen. As part of a national program (Iron Mains Replacement Program) the national gas transmission network is already receiving an upgrade. If it is decided to move forward with the introduction of hydrogen in the distribution system, the required adjustments can be incorporated with the IMRP with minimal cost impact.

Network Conversion

An appropriate solution would be to divide the city into zones of about 2.500 homes where the natural gas can be disconnected and appliances can be converted or replaced. As a result, it is expected that those homes will be disconnected from the gas network for 1-5 days. With minimal modification, it is possible to convert the city to hydrogen. Planning, site surveys, upfront enabling works and comprehensive strategy development are essential in order to make the conversion successful.

Transmission system

The pipes that are part of the hydrogen network transport the hydrogen. The hydrogen transmission system consists of pipelines that connect the point of production to the point of demand or the point of storage. More information on hydrogen storage is given in 2.6. A new transmission pipeline will be required to connect the storage sites to the SMR. Associated equipment such as block valves, inspection facilities and pressure reductions stations are part of the transmission system.

2.5.2 (Inter)national scale

The first ever built hydrogen pipeline is operative since 1938 and connects Rotterdam to the Rhein-Ruhr area in Germany (Töpler, 2006). In Venlo, near the German border, the pipeline is split into two parts: one northbound and one southbound.

With a total length of about 1.600 km, Europe has the largest hydrogen pipeline network in the world (Perrin & Steinberger-Wilckens, 2007). The larger pipelines are operated in the Netherlands, Belgium, Luxembourg, Germany and France. Smaller pipelines are operated in the UK, Italy and Sweden. The pipelines are operated by Air Liquide, Linde (BOC), Air Products (Sapio), Stenungsund (Sweden) and Ineos (Wilhelmshaven Germany). The diameter of most of these pipelines is 100 mm and have a working pressure of up to 100 bar.

Figure 14: The AirLiquide pipeline network in Europe (hydrogen is marked red); retrieved from https://www.airliquide.com/industry/supply-modes

2.6 Hydrogen storage

Hydrogen can be stored in a gaseous or a liquified state, but also many chemical storage, (i.e. metal hydrides, formic acid) solutions are available. Its low volumetric density and flammability make it difficult to store. Each storage method has its advantages and disadvantages, a selection of these methods are elaborated on in the next paragraphs.

2.6.1 Liquid form

In liquid form, hydrogen has a much higher energy capacity than when stored in compressed or gaseous state as can be seen in table 2 (Mazloomi & Gomes, 2012). As a result, it has a high density under low pressure, which makes for compact, lightweight storage and efficient transport.

However, in order to liquify hydrogen, extra steps need to be added to the production process. The temperature at which hydrogen changes phase from gas to liquid at 1 bar (atmospheric pressure) is -252.87 °C (20.28 K) (Durieux, 1970). This means that a lot of energy (30%) has to be added to the production process. This has a negative effect on the net energy storage capacity of liquid hydrogen. Furthermore, the addition of liquefiers to the production chain adds more complexity. As a result, the costs of liquid hydrogen is 4-5 times higher than gaseous nitrogen, while the energy density is about 2 times higher, 10.1 MJ/liter for liquid hydrogen and 5.6 MJ/liter for gaseous hydrogen compressed at 700 bar.

Figure 15: Liquid hydrogen storage tanks at NASA's Kennedy Space Center; retrieved from https://www.nasa.gov/content/liquid-hydrogen-the-fuel-of-choice-for-space-exploration on 13-06-2018

2.6.2 Gaseous form

The least complex method to store hydrogen in gaseous form, is storing it in high pressure cylinders (Ananthachar & Duffy, 2005). It is the most energy and time efficient method, but the low achievable density counts as a big disadvantage for this method. It is predicted that in the future, this approach will become less popular.

On a larger scale, hydrogen can be stored in depleted natural gas fields and salt caverns. In the paper Debrining prediction of a salt cavern used for compressed air energy storage (Wang, Yang, Wang, Ding, & Daemen, 2018) the importance of energy storage infrastructures is emphasized. Especially in China, where the production sites are far away from the sites of demand, a lot of energy is lost during the transport of energy as electricity. Here, but also in the northern part of The Netherlands, salt caverns offer the possibility to store the energy below ground. Salt caverns used for natural gas can also be used for underground compressed air and hydrogen gas energy storage purposes (Ozarslan, 2012).

Figure 16: Hydrogen storage tanks and the truck that transports it; retrieved from https://www.airliquide.com/industry/supply-modes on 13-06-2018

J. Kepplinger has studied the present trends in compressed air energy storage (CAES) and hydrogen storage (Kepplinger, Crotogino, Donadei, & Wohlers, 2011). The study has found that storing energy in hydrogen in salt caverns is a viable solution. So far, the disadvantage of this option is the relatively low efficiency, which is about 40%. However, there is a great advantage compared to other options such as pumped hydro power plants (gravitational potential energy: water is pumped from a reservoir to a higher elevation and released through turbines in the case of energy demand) and CAES (compressed air stores heat, which is released when decompressed). The advantage lies in the volumetric storage density which is 0.7 kWh/m^3 for hydro power plants, 3.0 kWh/m^3 for CAES and 170 kWh/m^3 (after losses occurred during power generation) for hydrogen storage plants. In this context, hydrogen is a favorable storage option

The hydrogen gas can be stored in caverns, and if there is a demand for energy the hydrogen can be withdrawn again. The storage system exists of three components:

- The electrolyser which produces hydrogen and oxygen from water;
- Gas installation facility with a compressor that fills or withdraws the cavern with hydrogen;
- The storage cavern.

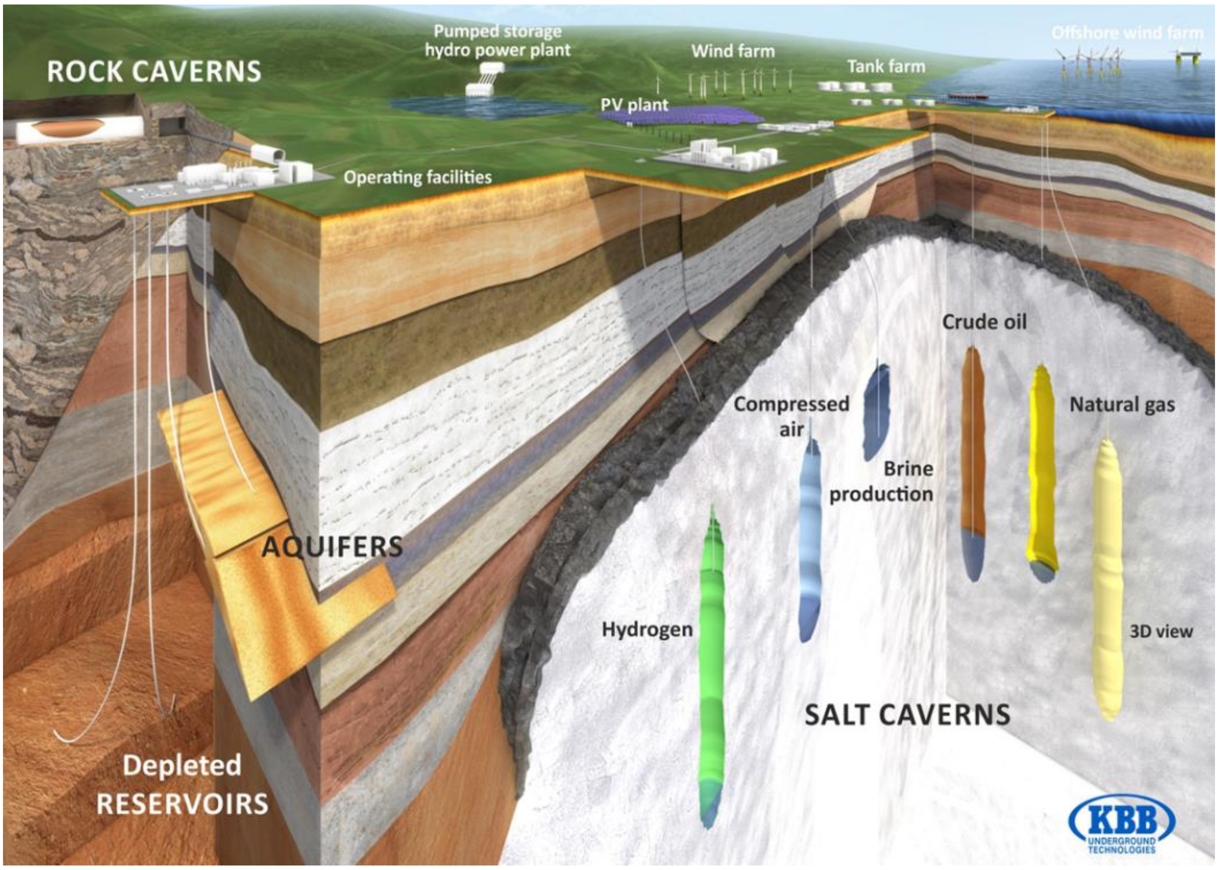


Figure 17: Salt cavern storage overview; retrieved from http://forschung-energiespeicher.info/en/wind-to-hydrogen/project-list/project-details/74/Wasserstoff_unter_Tage_speichern/ on 13-06-2018

It should be taken into account that the hydrogen gas may be saturated with water vapor when it is extracted from the cavern. In this case, the hydrogen needs to be dried. Typical dimensions for salt caverns are 500.000 m^3, the pressure inside ranges from 60 to 180 bar, which offers a storage capacity of 4.200 metric tons. Salt caverns can be designed with flexibility, so it can be made suitable for the location bound conditions.

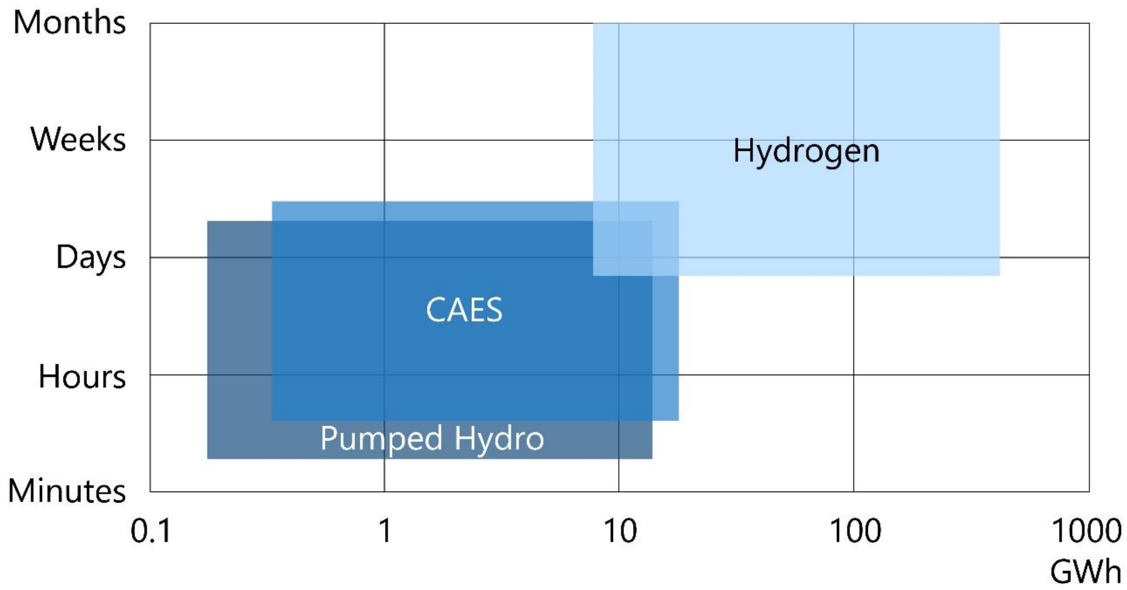


Figure 18: Large scale energy options. based on Ozarslan, 2012

2.6.3 Hydrides

Metal hydrides can be formed between some metals and alloys (Sakintuna, Lamari-darkrim, & Hirscher, 2007). These hydrides offer solid state storage under moderate temperature and pressure. This gives these hydrides an important advantage in the area of safety if compared to liquid- or gaseous state storage. Furthermore, in the solid state they have a higher hydrogen storage density, making it a volume efficient storage method. Because this storage method requires extensive knowledge of scientific principles of storage and chemistry, it is not further considered for this research.

2.7 Safety

As it is described in chapter 2.1, hydrogen is not toxic. In the area of safety, one might argue that its high flammability is a disadvantage. Due to its light volumetric mass, its buoyant and laminar burning velocity is very high. In other words: the hydrogen flows away fast. A pure hydrogen fire lasts about 10-20% of the time compared to a fire that involves hydrocarbons, e.g. methane or gasoline. Because hydrogen is non-toxic, odorless and gives water as sole reaction product, it is completely harmless to inhale the fumes and smoke from a hydrogen fire, and the risk of suffocation is minimal.

To determine what happens in case of an accidental combustion of a car, a study was performed. It has compared the results of a hydrogen and gasoline fire. Figure 19 shows a timeline of the results of the tests. The car on the left is powered by hydrogen and the car on the right is powered by gasoline.

0min, 0 sec | 0min, 3 sec (ignition) | 1min, 0 sec | 1min, 30 sec

Figure 19: Comparison of a carfire with a hydrogen tank and a gasoline tank; retrieved from http://evworld.com/article.cfm?storyid=482 on 14-06-2018

These photographs show that the hydrogen powered car initially displays a large flame. Due to the high pressure in the storage tank, the hydrogen is released with a high velocity, causing a big flame. After one minute, the pressure is reduced and the hydrogen disperses quicker in the air, causing the flame size to reduce. When the tank is empty, the flame is extinguished automatically. No explosion takes place, the car is barely damaged and the temperature inside the car never got above 67 °C (EV World, 2003).

The gasoline powered car is in a worse condition. After the gasoline leaks out of the tank, it forms a puddle on the floor. This puddle ignites and the whole car is set on fire, leaving a total loss car.

Another advantage is relatively high auto ignition temperature. This means that hydrogen gas can be ignited without any source of ignition, other than the ignition temperature, which is 585◦C. Because of its wide range of flammability it can ignite easily in a mixture with air. It should be mentioned that in this case, the hydrogen will flow away easily because of its low volumetric weight. The next paragraph described what the consequences of the safety measures are in a building.

2.7.1 Case study: HyHouse

A study was performed by Kiwa gastec to investigate the safety issues of hydrogen as an energy vector (Crowther, Orr, Thomas, Stephens, & Summerfield, 2015). During the research, a leakage in a house is simulated with different gasses and compositions. The gasses that were used in the simulation were:

- 100% Natural gas
- 100% Hydrogen
- 3% Hydrogen/ 100% Natural gas
- 10% Hydrogen/ 90% Natural gas
- Town gas (50% hydrogen, 25% CO_2, 25% Natural gas)

In the report it is concluded that the concentrations of hydrogen in an environment that simulated a leakage were not as high as originally expected. Because of the low caloric value of hydrogen, a hydrogen leakage was simulated by injecting 340% more hydrogen than injected when simulating a natural gas leakage. This is explained by looking at the numbers for energy density per liter: 0.0364 MJ/liter for natural gas and 0.0107 MJ/liter for hydrogen, as is shown in table 2. However, this is not reflected by the concentrations inside the house. This can be explained by the low volumetric weight of hydrogen and the resulting buoyancy effect. During a low rate leakage, the hydrogen will disperse before reaching concentrations and conditions at which it is flammable. If the hydrogen is injected suddenly and at a high rate, dangerous concentrations could be formed. However, this is only expected in case of damage to the fuel system of a hydrogen vehicle, and even these risks can be reduced.

If hydrogen is dispersed, it will not form explosive mixtures. But because hydrogen rises, it can accumulate at the ceiling of a building in case of leakage. Extensive ventilation of areas with in increased risk of hydrogen leakage, is therefore essential. Preferably, this is done with natural ventilation so there is no risk of system failure. In case natural ventilation is not possible and mechanical ventilation is applied, a back-up system should be in place.

Another important aspect of hydrogen safety is the detection of the gas. The gas can be detected by sensors, more conveniently it would also be detectable by humans by sense of smell. Natural gas and hydrogen are odorless, so in order for it to be detectable by smell, a smell should be added to the gas. For natural gas, this is done by adding mercaptan to the gas mixture. Unfortunately for hydrogen, adding a smell to hydrogen gas reduces its purity. Most end users require 100% purity, so the addition of a smell is not favorable.

3 Case study: Floriade

3 Case study: Floriade

3.1 Introduction

Floriade is the international horticultural exhibition exposition which will take place in 2022 in Almere, the Netherlands. Guided by the theme "growing green cities", the exposition will focus on cities of the future. These cities face challenges in different areas associated with global urbanization. In this context, the main theme is accompanied by four sub themes:

- green: parks and green structures which make the cities more attractive;
- food: food production, safety and food security solutions;
- health: the effect of green structures on a healthy living environment, as well as on the physical and metal vitality of city inhabitants;
- energy: sustainable energy solutions, as well as the effect of green spaces on the vitality of the city

The exposition is promoted as "the ultimate green event" with an inspiring line-up of events and festivities. During the six-month event workshops, pop-ups, art installations, meet-and-greets and cultural events will take place. Cities from around the world are invited to give their vision of a green city, they will be hosted in pavilions on the Floriade terrain. (Floriade Almere 2022, 2018b)

Figure 20: Impression of the Floriade terrain with a view over the water and a residential tower. Copyright Design(ed) by Erick van Egeraat

3.2 Location

The terrain for the exposition is situated in the center of the municipality Almere, conveniently located next to highway A6. Because it is so close to the highway, the city center of Amsterdam is only 25 minutes away by car and 45 minutes by public transport. Future improvements of public transportation and the discouragement of using cars will make traveling to Floriade by means of public transportation even more attractive.

The total area of the Floriade terrain is about 50 hectares, of which the vast majority is situated to the north of the A6 highway. Currently, a camping, a small harbor and an aquatics rental company make use of the wooded area on the border of lake Weerwater. The green area makes for a perfect location for a horticultural exhibition.

With respect to the existing afforestation, a master plan is developed by Dutch architecture firm MVRDV. The global layout of the master plan exists of a grid with plots with an area of 1008 m^2 (50 x 32 m). The plot boundaries are offset by 4 meters to make room for the public arboretum, resulting in building plots of 592 m^2 (42 x 24 m). Each plot is separated by roads 5 meter wide roads.

The outer four meters of each plot offer space to a green city arboretum. This will serve as a model for green structure development in cities. The arboretum will be planted in alphabetical order with 3000 different types of plants and trees that contribute to a green, healthy and sustainable city (Floriade Almere 2022, 2018a).

Figure 21: Impression of the Floriade terrain with a view over the water and apartment buildings. Copyright Design(ed) by Erick van Egeraat

3.3 Building programme

Initially, the site will be developed for the six month lasting exhibition. Afterwards the site will be further developed and redeveloped as a residential area for 660 dwellings. The exact building programme and the exact location of each type of building is still under development. For the purpose of this research, one master plan is considered as the basis and further developments and changes are not taken into account. The research is focused on ground based dwellings for consumption and the roof surface of all residential buildings for energy production.

Different building typologies will be built, ranging from apartments in towers to detached houses in a forest. The design for the buildings is made by Erick van Egeraat. The building typologies are highly relevant for the typical energy profiles of the dwellings. This will be elaborated on in paragraph 3.5.

The newly developed residential area will feature state-of-the-art houses with highly efficient building installation and services. This, combined with modern building materials such as phase change materials and high quality insulation, will make for houses that comply with future building regulations and set an example for other housing projects. The houses will have a very low heat demand for space heating because they are very well insulated.

3.4 Ambitions & opportunities

The theme and subthemes of Floriade give room to sustainability and innovation. This combined with the international exposure makes for a perfect project to display opportunities that hydrogen has to offer. This research will show the possibilities of hydrogen in the built environment and by doing so, it can contribute to achieving sustainability goals of the neighborhood while at the same time prove a principle.

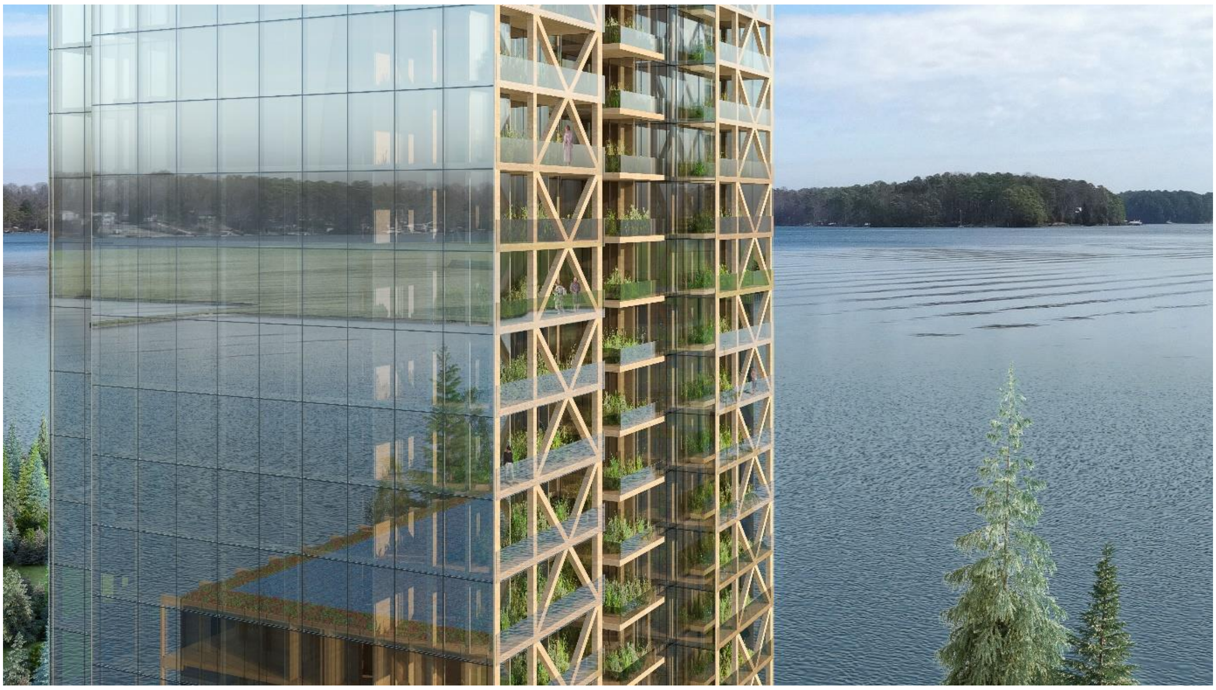


Figure 22: View of a residential tower with a glass façade. Copyright Design(ed) by Erick van Egeraat

3.5 Building typology

As the master plan is constantly under development, a basis is taken for the housing programme of the neighborhood. Table 5 shows the total amount of buildings that are taken into account for this research, 6 building typologies can be distinguished.

Name	Amount	GFA [m^2]
6/plot	24	133
8/plot	50	162
10/plot	4	130
12/plot	28	147
14/plot	56	119
16/plot	64	110
Total	226	

Table 5: Overview of building types and the gross floor area

Building type 14/plot is used as reference building for this research, the layout of the building is shown in figures 24 and 25. The other buildings will also be simulated, but an in depth analysis of these buildings is not necessary. The construction method and building properties (except geometry) are the same for every building.

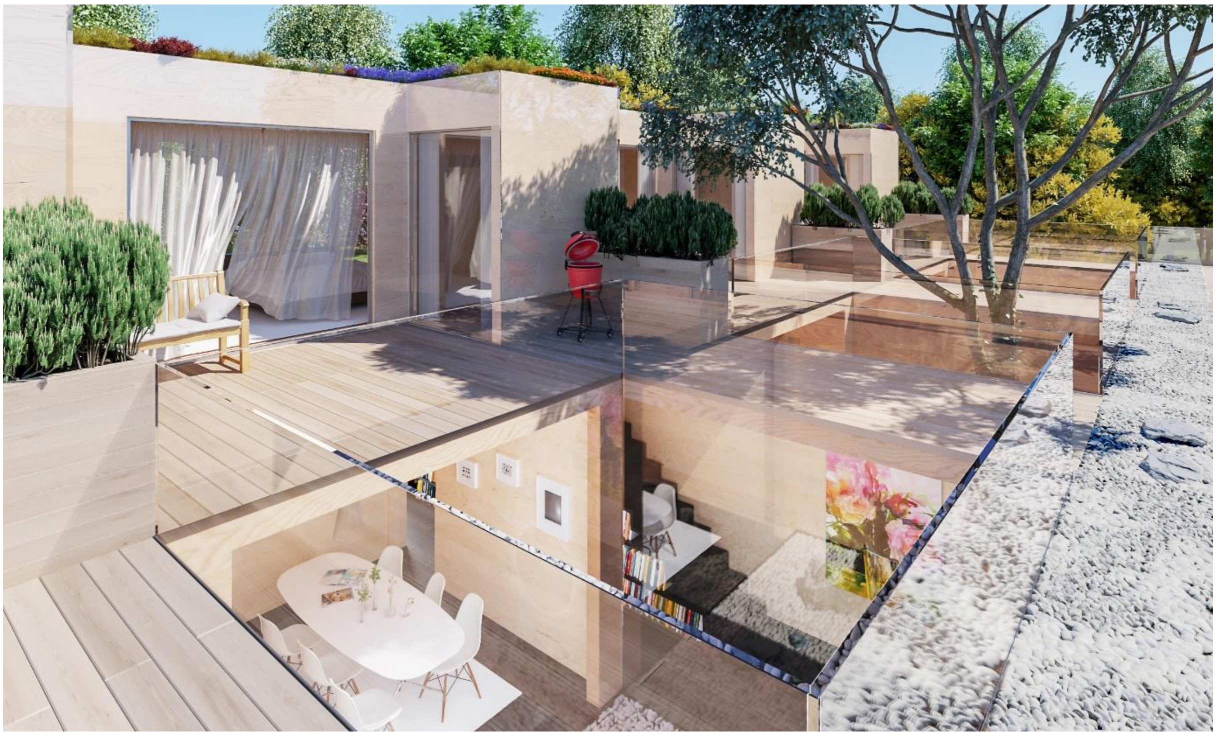


Figure 23: View on roof terraces of building type 14/plot. Copyright Design(ed) by Erick van Egeraat

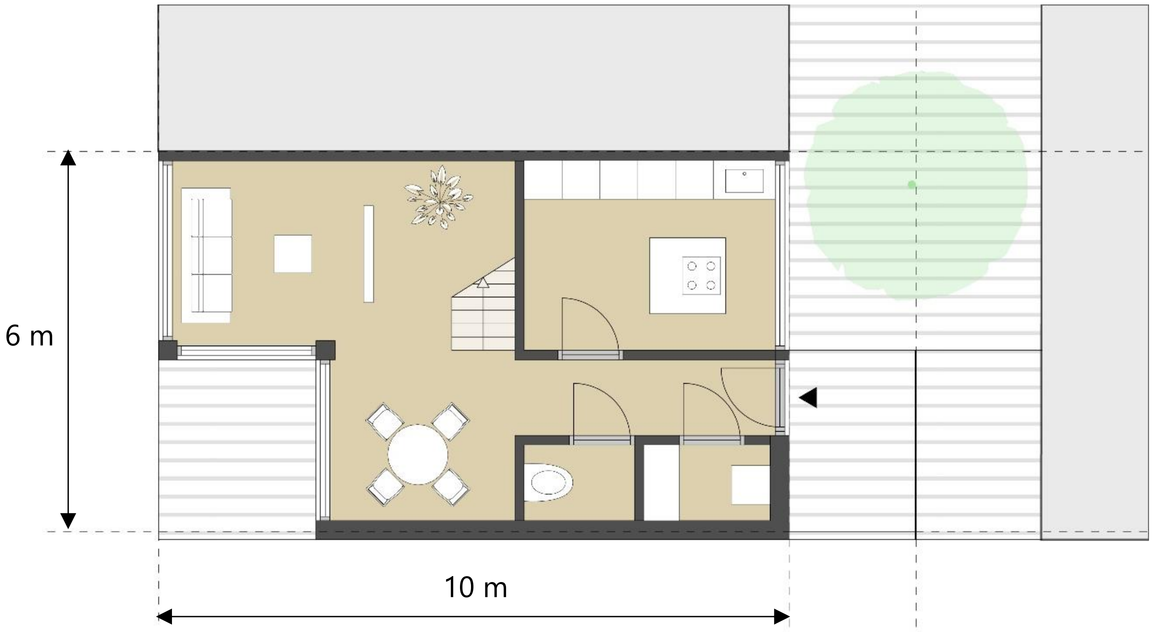


Figure 24: Plan view of the ground floor of building type 14/plot

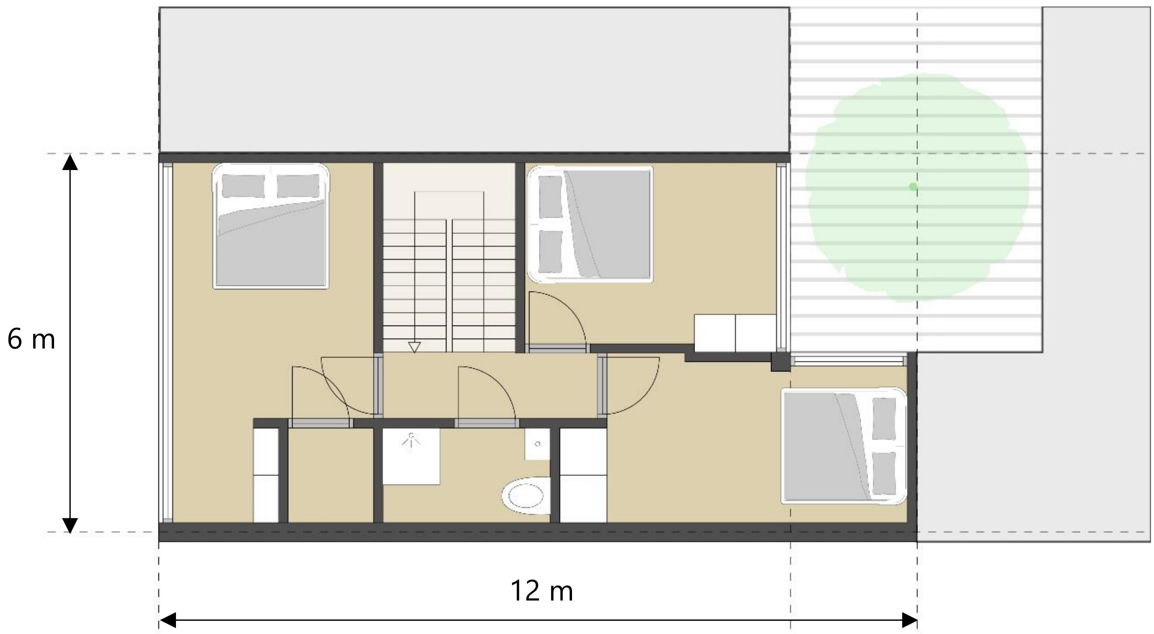


Figure 25: Plan view of the first floor of building type 14/plot

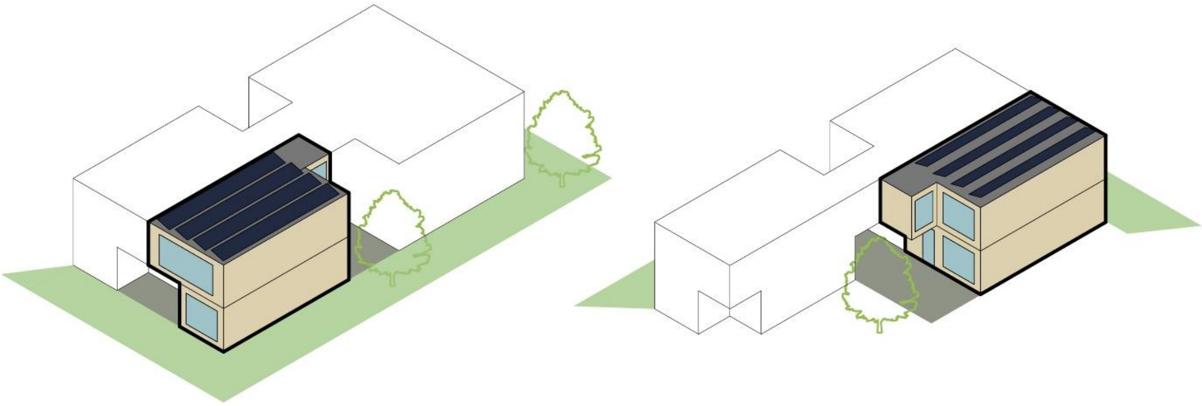


Figure 26: Isometric views of the reference house

Figure 27: View of the shared space between houses. Copyright Design(ed) by Erick van Egeraat

Hotel

The hotel that is described in the master plan plays an important role in the energy system because the heat produced by the fuel cell is recovered with a heat exchanger to produce domestic hot water for hotel guests. Figures 28 and 29 are impressions of the hotel made by the architect. Heat recovery for DHW production for the hotel is described in paragraph 7.3.1.

Figure 28: Impression of the hotel. Copyright Design(ed) by Erick van Egeraat

Figure 29: Impression of the hotel at the border of the Floriade terrain. Copyright Design(ed) by Erick van Egeraat

4 Energy system design

4.1 Design goals & boundaries

4.2 Alternatives

4.3 Energy system selection

4.4 Energy system components

4.5 Energy system layout

4.6 Impact

4.7 Conclusion energy system design

4 Energy system design

The first part of the research focuses on the energy system design of Floriade. This chapter describes the design of an energy system with hydrogen integrated as seasonal storage component. Before going into the design of the system, the goals and the boundaries of the system are described. After the boundaries and goals are clear, some system variants are researched in order to come to one system that is most suitable for this case study. The selected system and its components are described before coming to a conclusion about the energy system. It should be mentioned that the energy system is designed with knowledge of the Building Technology track and its associated boundaries.

4.1 Design goals & boundaries

The design of the energy system for Floriade starts by setting its design goals. In this context, starting points are formulated to give direction to the research.

Distribution of locally produced renewable energy

Transportation and storage of energy results in energy loss. Locally produced energy should be used locally to reduce transportation losses.

Reduce load on national grid

Additionally to the previous goal, the load on the national electricity grid operated by TenneT can be reduced if the produced energy is consumed locally. This aligns with the unbalance on the national grid caused by the intermittent character of renewable energy. At a certain point, a surplus of energy on the national grid will exist, which will lead to switching of PV panels. It is too expensive to stop and restart a power plant so priority will be given to energy produced by these power plants.

The street profile is already crowded as it is

The many innovations that will be displayed at Floriade take up most of the subterranean space available. This becomes clear from the street profiles, which are determined by the municipality. Due to the limited space, it is undesirable to make the infrastructure even more complex by adding a pipeline to the already complex subterranean infrastructure. The street profile, as shown in figure 30, displays the location of cables, pipes and drainage system. This combination is the basis for a street profile. Innovations in the neighborhood, such as adaptive street lighting, may ask for more space in the street profile, making it even more crowed.

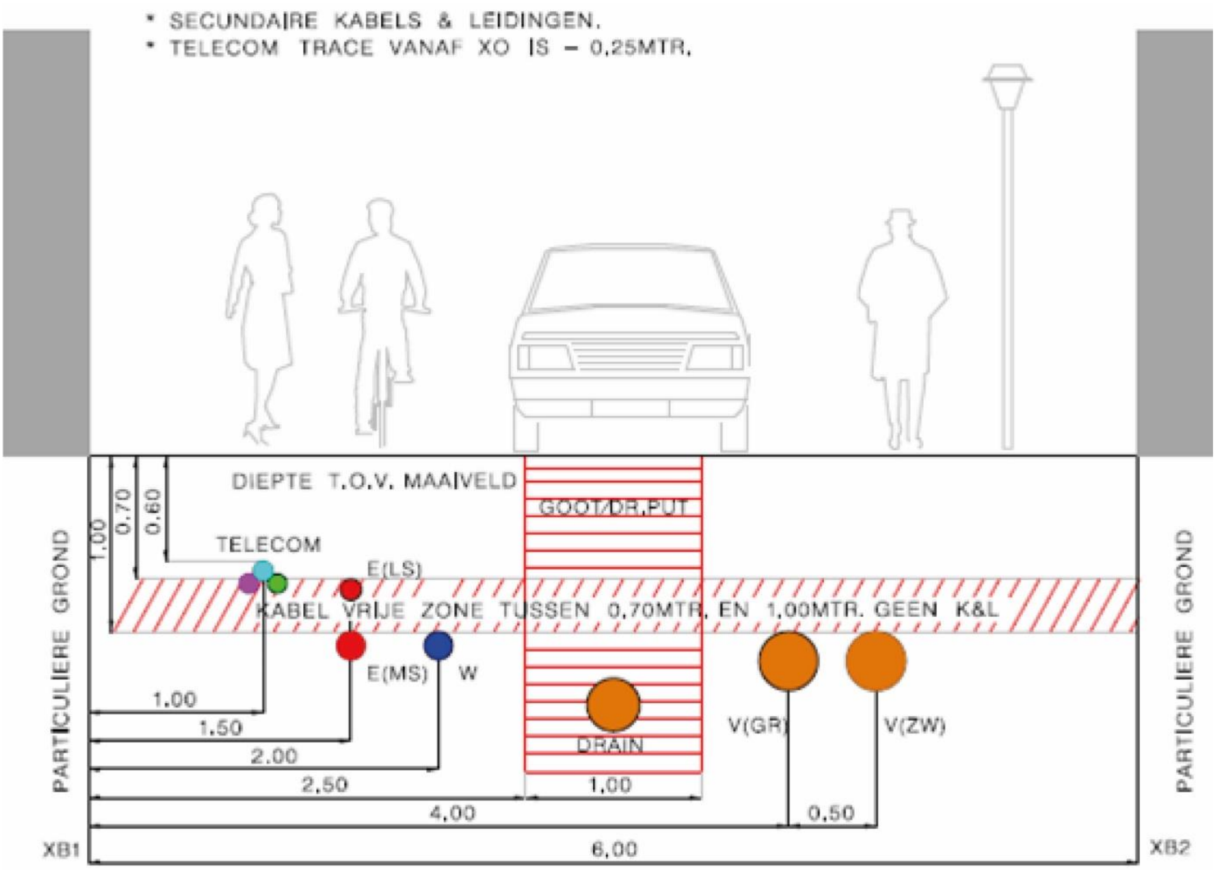


Figure 30: Basic lay out of the street profile for a typical street on the Floriade terrain

Subterranean infrastructures demand high investments

Adding another pipeline to the street profile will not only make it more crowded but also requires additional investments. Without going into the business case of the energy system, it can be assumed that an investor needs to be found to pay for the addition to the street profile.

Optimal use of hydrogen

As part of the research hydrogen should be used in the most optimal way. It should not be a goal to force hydrogen onto the project, but rather to investigate what role hydrogen can play in the energy system. Additionally, it should become clear to what extend the hydrogen can contribute to the themes as described in the introduction of this chapter:

Display hydrogen technology in the context of the built environment

The international exposure of Floriade is a great opportunity to show how hydrogen can be applied in the built environment and on this scale. Hydrogen has not yet been applied in this manner and on this scale. The role of hydrogen on Floriade should become a display of technology to make visitors and residents of the area aware of its potential. Beside showcasing the technology, it should also make people aware of the energy flows in the area.

4.2 Alternatives

Before elaborating on the final design, a variety of alternatives is researched and described. These alternatives will be aligned with the design goals, evaluated and rated on multiple criteria to see if it is suitable for Floriade and if it fits within the scope of this research. The alternatives are discussed on building scale and neighborhood scale. This has to do with either the installations on a building scale or the installations on neighborhood scale. Due to the large amount of system components, an extensive amount of configurations can be considered. For this research, nine system configurations are researched and described. First an overview of the system components and a selection of the different types are given.

System component	acronym
Heating/cooling combination	
Individual heat pump ground/water	HP-ind-gnd
Individual heat pump air	HP-ind-air
Collective heat pump on block level	HP-col-blk
Collective heat pump on neighborhood level	HP-col-nbh
Heating	
HR boiler	BL-hr
Hydrogen boiler	BL-h2
Micro CHP	mCHP
Electricity	
Smart grid	E-grid
Storage	
Building level battery	BT-ind
Block level battery	BT-blk
Neighborhood level battery	BT-nbh
Building level hydrogen storage	H2-ind
Block level hydrogen storage	H2-col-blk
Neighborhood level hydrogen storage	H2-col-nbh
Domestic Hot Water	
HR boiler	BL-hr
Hydrogen boiler	BL-h2
Heat recovered from fuell cell in storage tank	DHW-HR
Booster heat pump	DHW-BST
Photovoltaics	
Individual PV installation	PV-ind
Block-shared PV installation	PV-blk
Neighborhood-shared PV installation	PV-nbh

Table 6: Overview of system component alternatives

4.2.1 System 1: stand-alone

Heating/cooling	Individual heat pump air
DHW	Booster heat pump
Electricity	Electricity grid
Photovoltaics	PV panels on the roof of the house
Storage	Individual storage in a battery

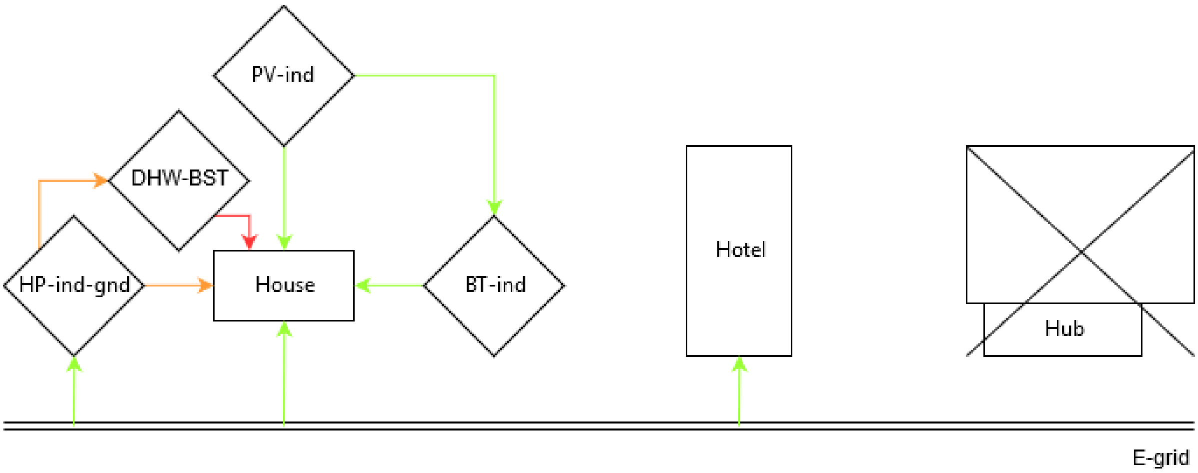


Figure 31: Schematic of system 1: stand-alone

System 1	Stand alone
Amount of installations per building	-
Sense of community	--
Display of hydrogen	--
Subterranean infrastructure	++
Off-grid operation (Electric) building level	++
Off-grid operation (Electric) neighborhood level	N/A

Table 7: Rating of system 1 according to multi-criteria-analysis

In this variant, every building operates independent of other buildings. Heating and cooling is supplied to the building by an air based heat pump and DHW is prepared by a booster heat pump. It is an all-electric building since all electricity comes from the electricity grid. The building generates its own electricity with PV panels on the roof of the building, surplus energy produced by the PV installation can be stored in a home battery, e.g. a Tesla Powerwall. This Powerwall can store enough energy for the building to operate autonomously for approximately one day. Each building has its own PV system, inverter and battery, which creates a high level of individuality and increases the amount of installations in the building.

4.2.2 System 2: Block level collective

Heating/cooling	Collective heat pump ground/water
DHW	Booster heat pump individual
Electricity	Electricity grid + micro-grid
Photovoltaics	Collective PV installation for the block
Storage	Collective storage in a battery

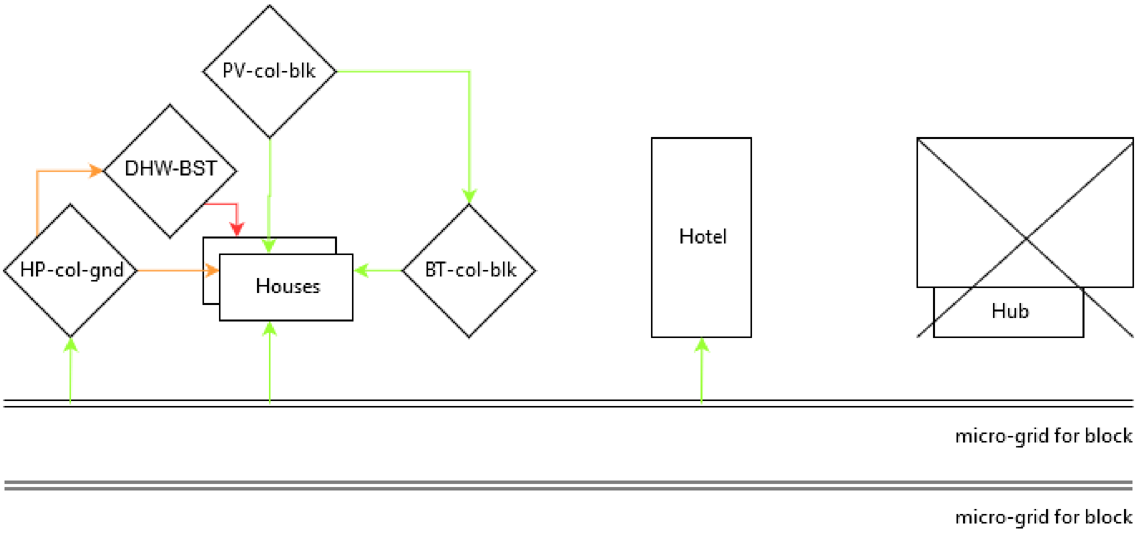


Figure 32: Schematic of system 2: block level collective

System 2	Block level collective
Amount of installations per building	0
Sense of community	++
Display of hydrogen	--
Subterranean infrastructure	+
Off-grid operation (Electric) building level	+
Off-grid operation (Electric) neighborhood level	N/A

Table 8: Rating of system 2 according to multi criteria analysis

This variant is similar to variant 1 except that the residents of one block share the heat pump and the PV installation. Collectively produced energy is stored in one block battery. Domestic hot water is still produced individually because there might be a big contrast in DHW consumption per dwelling. Electricity is less dependent on the user of the building because every house has a basic use of electricity e.g. lighting and equipment such as a refrigerator. To evenly divide stored energy, the block could have its own micro-grid to which certain equipment is connected. The sense of community is strong because energy is consumed and produced together and the amount of installations is much lower because the electrical energy installations are shared with the entire block.

4.2.3 System 3: Block level collective with hydrogen

Heating/cooling	Collective heat pump ground/water or individual air
DHW	Booster heat pump individual
Electricity	Electricity grid + minigrid
Photovoltaics	Collective PV installation for the block
Storage	Collective storage in hydrogen

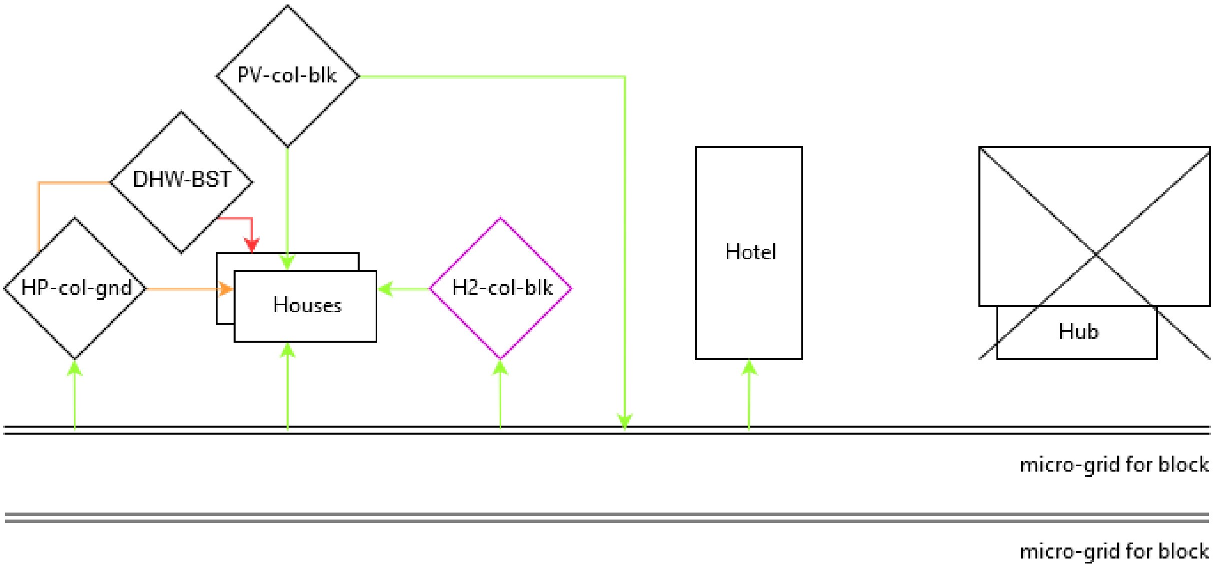


Figure 33: Schematic of system 3: block level collective with hydrogen

System 3	Block level collective with hydrogen
Amount of installations per building	-
Sense of community	++
Display of hydrogen	0
Subterranean infrastructure	0
Off-grid operation (Electric) building level	+
Off-grid operation (Electric) neighborhood level	N/A

Table 9: Rating of system 3 according to multi criteria analysis

Similar to variant 2, but in this variant the energy is stored in the form of gaseous hydrogen. All surplus energy that is produced during sunny days can be used to produce hydrogen by means of electrolysis. The surplus energy will be elaborated on in chapter 7. Hydrogen, as opposed to a battery, can store energy for a long period. In this context, it can be used as seasonal storage. Rather than charging and discharging every day, surplus energy is stored for the winter when the heating and thus electricity demand is higher.

This storage method is more sustainable than battery storage, but requires a large installation for the whole building block. Also every block has its own installation which is expensive and requires a more work for maintenance per block. Instead of one installation, all installations need to be maintained per block. The efficiency of this system is relatively low, so in this case it can be argued that storing the energy in a battery may be a better choice.

In Thailand this system has been built and it has been proven to work (Phi Suea House, 2015). The energy production is higher there because the solar radiation is higher, so naturally a larger surplus exists. This combined with a large storage capacity gives the building compound a high level of self-sufficiency.

Figure 34: Phi Suea House in Thailand. image retrieved from https://newatlas.com/phi-suea-house/41033/

4.2.4 System 4: Block level collective with hydrogen, DHW and mobility integrated

Heating/cooling	Collective heat pump ground/water or individual air
DHW	Booster heat pump individual + fuel cell cogeneration hotel
Electricity	Electricity grid + micro-grid
Photovoltaics	Collective PV installation for the block
Storage	Collective storage in hydrogen
Mobility	Hydrogen

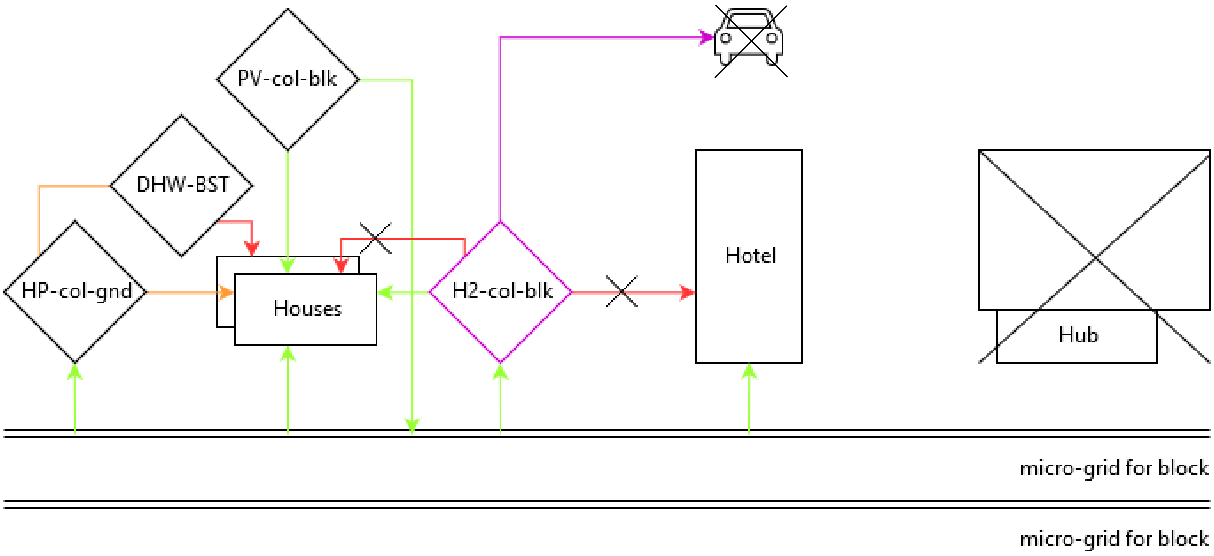


Figure 35: Schematic of system 4: block level collective with hydrogen & DHW integrated

System 4	Block level collective with hydrogen & DHW
Amount of installations per building	--
Sense of community	++
Display of hydrogen	++
Subterranean infrastructure	0
Off-grid operation (Electric) building level	+
Off-grid operation (Electric) neighborhood level	N/A

Table 10: Rating of system 4 according to multi criteria analysis

Variant 3 is supplemented with cogeneration of heat. The fuel cell is the equipment that transforms hydrogen to electricity. This process has an efficiency of 50%, meaning 50% of the energy contained in hydrogen is transformed into electricity. The other 50% is converted into heat. The equipment can reach temperatures of up to 80 °C, which is enough to produce domestic hot water or to supply buildings with heat. The heat demand for space heating of dwellings is low because of they are well-insulated. In previously mentioned variants, it was already established that DHW for dwellings should be produced on a building scale, and thus an alternative use is sought for the high temperature heating. It is found in the hotel that will be built in the neighborhood, which can use the heat to produce DHW for its guests. However, to recover the heat from all blocks and send it to the hotel requires a pipeline which is expensive an many installations. Integration is Additional to variant 3, the produced hydrogen can be used to fuel hydrogen cars owned by the residents of the block. The mobility aspect can also be integrated in variant 3, but require extra installations. Because of this, the mobility is more suitable to include in a neighborhood system, because it makes no sense to build a hydrogen fueling station for every building block.

4.2.5 System 5: Neighborhood level collective

Heating/cooling	Individual heat pump air
DHW	Booster heat pump individual + fuel cell cogeneration hotel
Electricity	Smart grid
Photovoltaics	Collective PV installation for the neighborhood
Storage	Collective storage in hydrogen
Mobility	Hydrogen

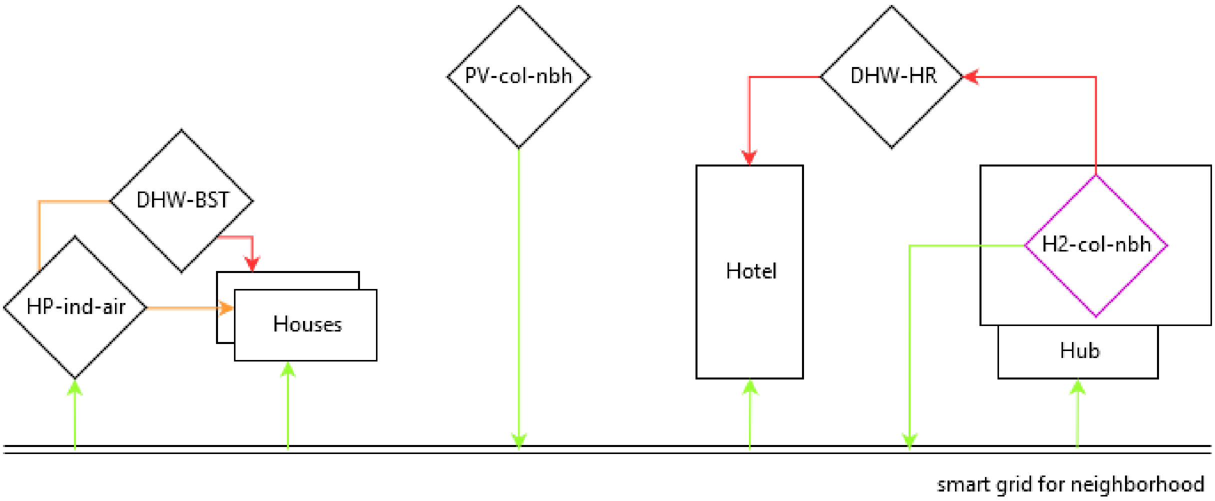


Figure 36: Schematic of system 5: neighborhood level collective

This variant focusses on a neighborhood collective with an optimal use of energy while reducing the amount of installations in each building. All electricity is generated collectively on the roofs of the buildings and the surplus energy is stored in one central location near the hotel. At this location, the surplus energy is used to power an electrolyser that splits water in hydrogen and oxygen. Hydrogen is stored under pressure until the production season has passed. When the energy demand exceeds the energy production during the consumption season, a fuel cell transforms hydrogen into electricity for consumption by the residents and heat that is used to prepare DHW for the hotel.

System 5	Neighborhood level collective
Amount of installations per building	++
Sense of community	+
Display of hydrogen	+
Subterranean infrastructure	++
Off-grid operation (Electric) building level	--
Off-grid operation (Electric) neighborhood level	+

Table 11: Rating of system 5 according to multi criteria analysis

4.2.6 System 6: Hydrogen pipeline network

Heating	Hydrogen boiler or micro CHP
Cooling	PCM
DHW	Hydrogen boiler or micro CHP combined with booster
Electricity	National grid or smart grid
Photovoltaics	Collective or individual PV installation
Storage	Collective or individual storage of electricity in a battery
Mobility	Hydrogen

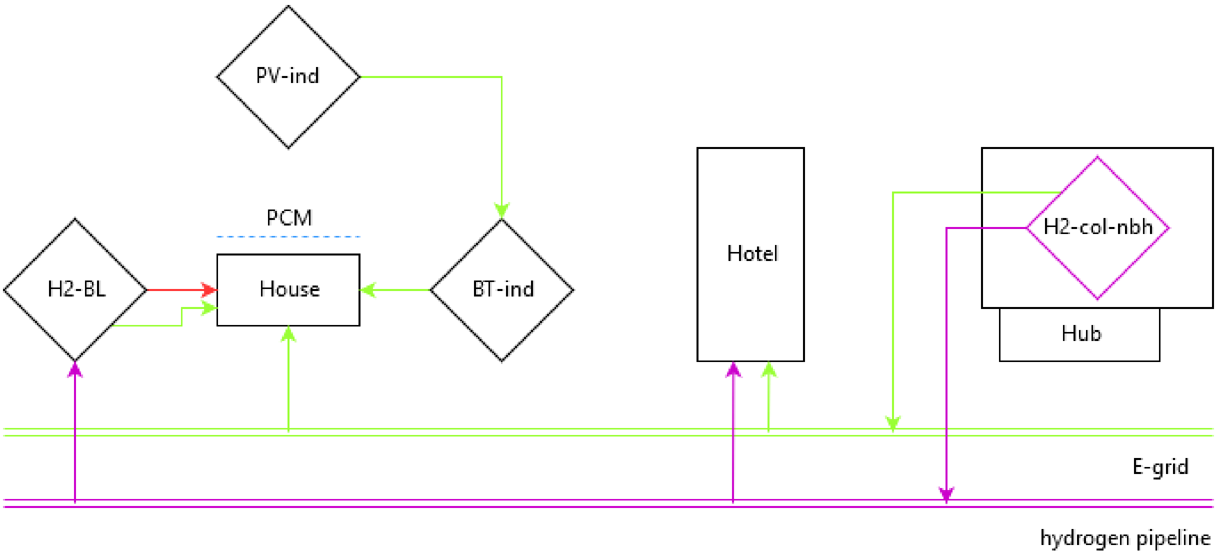


Figure 37: Schematic of system 6a: hydrogen pipeline network variant hydrogen boiler

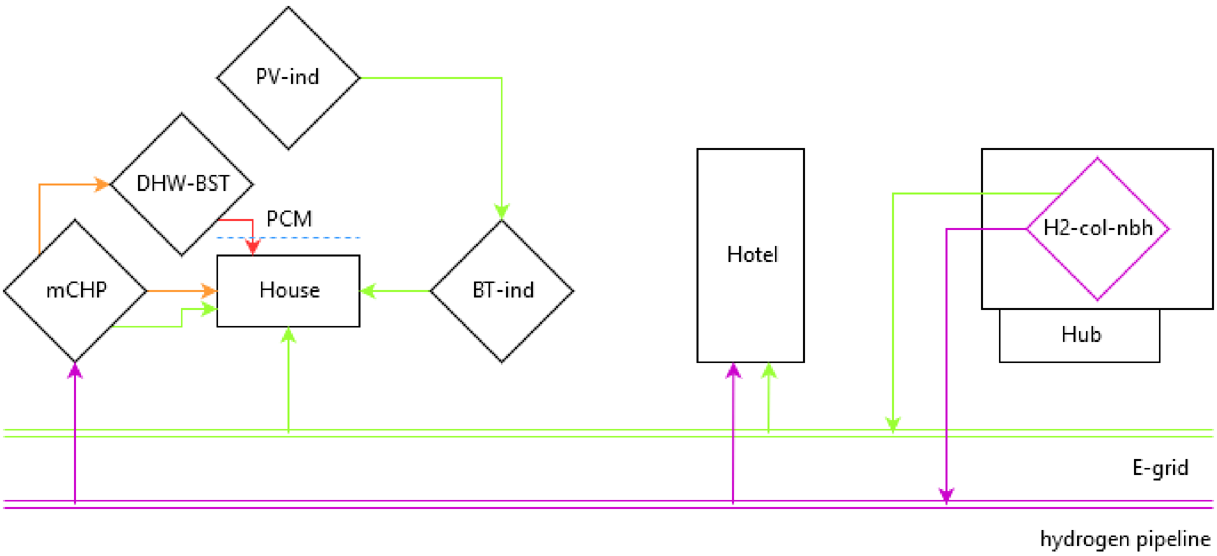


Figure 38: Schematic of system 6b: hydrogen pipeline network variant combined heat and power

System 6	Hydrogen pipeline network (H2 boiler)	Hydrogen pipeline network (mCHP)
Amount of installations per building	-	
Sense of community	-	-
Display of hydrogen	++	++
Subterranean infrastructure	--	--
Off-grid operation (Electric) building level	+	++
Off-grid operation (Electric) neighborhood level	0	+

Table 12: Rating of systems 6a and 6b according to multi criteria analysis

The before discussed variants assume an all-electric approach for the energy system. Alternatively, it is possible to distribute hydrogen through the neighborhood for direct consumption. Hydrogen can be burnt in a hydrogen boiler that produces high temperature heating, like a conventional boiler. The high temperature water can be used for heating and DHW. Additionally, hydrogen can be used for cooking. Instead of burning hydrogen, it can also be used as feedstock for a micro combined heat-and-power system. This system cogenerates heat and electricity.

Electricity can be produced on the roof and stored individually or as a collective as described in the previous variants. Since hydrogen is available throughout the entire neighborhood, mobility can easily be integrated. Hydrogen storage on building scale is not necessary, as it will be available just like natural gas is available in traditional houses.

Since the installations in the house only produce heat, another method of cooling the building is necessary. Although the buildings are very well insulated, cooling may be desirable for summer comfort. A solution can be found in PCMs: phase change materials. These materials have the ability to store energy in the same manner building mass does. By this effect, the indoor temperature of the building is less fluctuant and thus will the building not heat up as much.

Surplus energy can still be used to produce hydrogen by means of electrolysis. The green hydrogen can be fed directly into the hydrogen pipeline network in the neighborhood. Hydrogen has a very dominant role in this energy system because it can even be used to generate electricity for the houses. This makes the houses highly independent on the national electricity grid in case of a power outage. However, this should only be considered as a backup option because the hydrogen consumption will be very high, more than can be produced in the neighborhood.

The most important disadvantage of this system is de necessity of a hydrogen pipeline in the neighborhood. This makes no sense, because in the future, the Dutch building stock will be taken of the national gas grid. In paragraph 4.1 it is already described that there is not a lot of room in the street profile to add an extra pipeline. Finally, safety aspects should be taken into account if hydrogen is distributed through the neighborhood into the houses. The houses need sensors to detect hydrogen leakages and constant ventilation of the houses is necessary. This can have an undesirable effect of the energy consumption of the building.

4.2.7 System 7: Heat grid

Heating	Heat grid
Cooling	PCM or Weerwater
DHW	Heat grid or booster
Electricity	National grid or smart grid
Photovoltaics	Collective or individual PV installation
Storage	Individual or collective storage of electricity in a battery
Mobility	Hydrogen

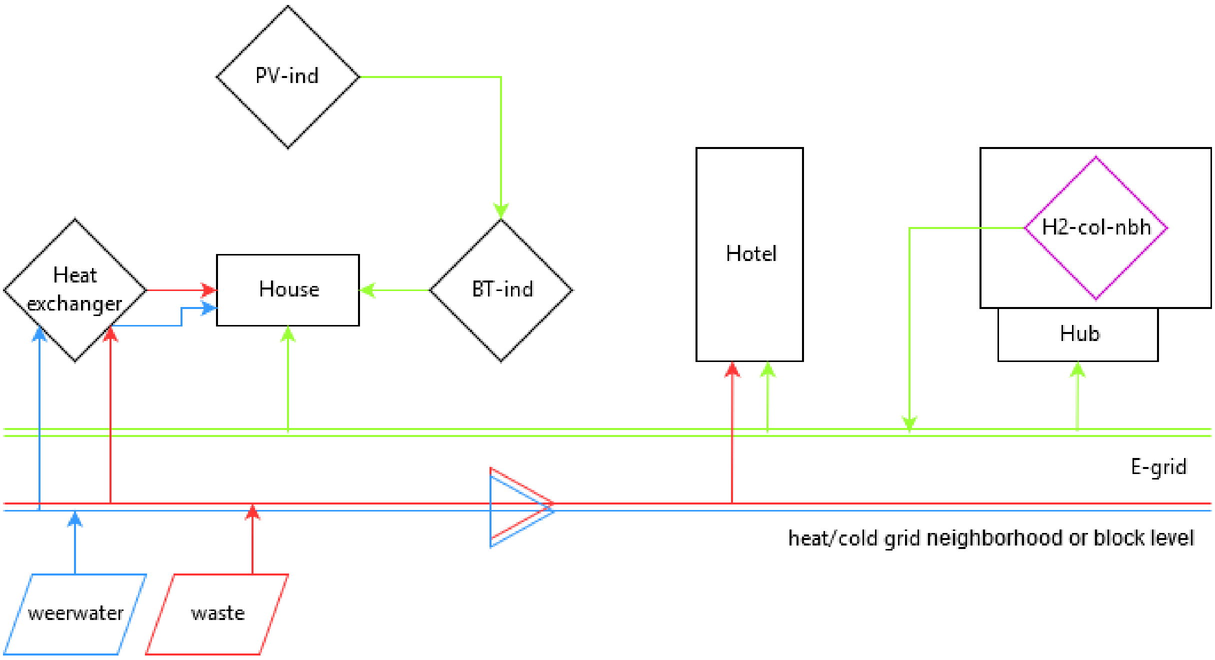


Figure 39: Schematic of system 7: heat grid

Another energy system that assumes a different source for heating and cooling is a heat grid. A subterranean pipeline network transports heat recovered from e.g. a nearby factory or waste incineration throughout the neighborhood. The buildings can use this heat for space heating or even domestic hot water. Cooling demand can either be fulfilled by PCMs as described in the previous variant, or by using the water from lake Weerwater. The water can be pumped through the heat grid instead of hot water from a waste incineration, for example to use as floor cooling.

System 7	Heat grid
Amount of installations per building	-
Sense of community	-
Display of hydrogen	0
Subterranean infrastructure	-
Off-grid operation (Electric) building level	+
Off-grid operation (Electric) neighborhood level	0

Table 13: Rating of system 7 according to multi criteria analysis

Since waste heat is used, the system has a high efficiency. Normally this heat would go to waste, but in this case it is used to heat the buildings. An extensive subterraneal infrastructure is required to transport the heat from the source to the neighborhood. The source of the heat is as gas stoked power plant operated by Dutch electricity supplier Nuon. A heat grid is already in place in Almere, because the power plant in Diemen already supplied heat to 11.000 houses in the in neighborhood Almere Poort.

In the future, hopefully these power plants will be closed to achieve the goals of reducing the CO_2 emissions in the Netherlands to 50% relative to 1990 by 2030. An alternative source of heat could be a waste incineration plant, but hopefully the amount of waste will also be reduced in the future. The feasibility of this system is based on predictions for the future, so a feasibility check should be performed.

4.2.8 System 8: Geothermal storage

Heating/cooling	Geothermal storage with collective or individual heat pump
DHW	Booster heat pump
Electricity	National grid or smart grid
Photovoltaics	Collective or individual PV installation
Storage	Collective or individual storage of electricity in a battery

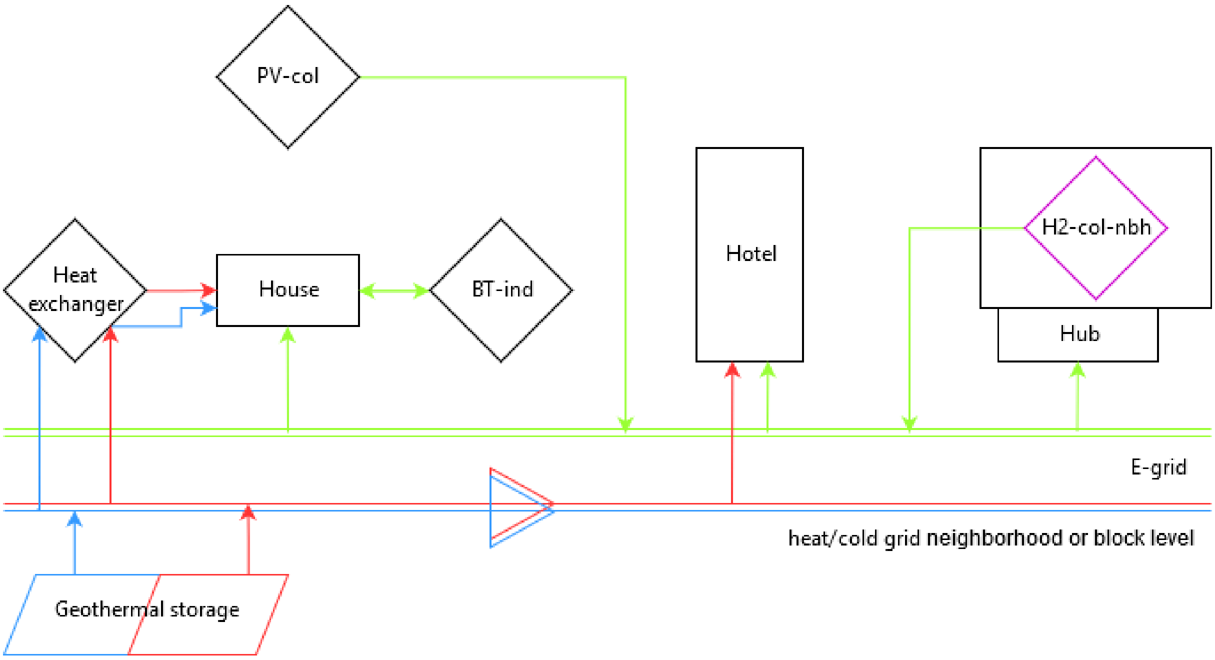


Figure 40: Schematic of system 8: geothermal storage

Name	Geothermal storage
Amount of installations per building	-
Sense of community	0
Display of hydrogen	0
Subterranean infrastructure	-
Off-grid operation (Electric) building level	+
Off-grid operation (Electric) neighborhood level	0

Table 14: Rating of system 8 according to multi criteria analysis

This system is a season storage for either heat or cold. During the winter, cold water is pumped into the source, while hot water is being extracted. This process is reverses itself during the summer, when the cold water that is pumped into the source during the winter is pumped back up to fulfill the cooling demand of the building.

4.3 Energy system selection

	Name	Amount of installations per building	Sense of community	Display of hydrogen	Subterranean infrastructure	Off-grid operation (Electric) building level	Off-grid operation (Electric) neighborhood level
1	Stand alone	-	--	--	++	++	N/A
2	Block level collective	0	++	--	+	+	N/A
3	Block level collective with hydrogen	-	++	0	0	+	N/A
4	3+ DHW and mobility integrated	--	++	++	0	+	N/A
5	Neighborhood level collective	++	+	+	++	--	+
6a	Hydrogen pipeline (H2 boiler)	-	-	++	--	+	0
6b	Hydrogen pipeline (mCHP)		-	++	--	++	+
7	Heat grid	-	-	0	-	+	0
8	Geothermal storage	-	0	0	-	+	0

Table 15: Multicriteria analysis for the energy system selection

The leading boundary for the system selection is the subterranean infrastructure. Besides the fact that there is little space in the street profile, it also requires high investments to install extra pipelines in the neighborhood.

The display of hydrogen in the neighborhood is determined by what happens above ground level and the experience of people with hydrogen. Decentralized energy hubs with the installations on block levels spread the display of hydrogen through the neighborhood, but require a lot of maintenance as every system on block level needs maintenance. One central hub where people can come to learn about hydrogen technology and see the system in one building can also generate exposure of hydrogen.

The sense of community can be achieved by collectively producing energy on the roof surfaces. This is the case for all systems except for system 1. The sense of community is important because people can talk to each other about energy consumption reductions. If they produce the energy together, they have a reason to talk to each other about it.

Finally, the amount of installations will be much higher if energy production and storage is organized on building or block level. If the system components are collected in one building, the costs of maintenance and investments will be lower.

4.4 Energy system components

4.4.1 Introduction

System 5 is selected for the neighborhood energy system. This chapter describes the system components that are part of the energy system on both a building scale and an neighborhood scale. First an overvien is given the of the components, later it is described how they fit in either the dwellings, hotel and the energy hub.

4.4.2 Electrolyser

The electrolyser is produced by NEL hydrogen and is built into three shipping containers. This system is selected because its functionality is proven, and the containerized electrolyser is small in size and easy to transport (NEL Hydrogen, 2018). It delivers hydrogen at a pressure of 200 bar, this can directly be fed to the hydrogen storage system. It is suitable for placement outside, because it often applied to produce hydrogen for hydrogen cars.

Specification	Value	Unit
Capacity range	300	Nm^3H_2/hour
Production capacity dynamic range	15-100	%
Power consumption	3.8-4.4	kWh/ Nm^3H_2
Outlet pressure	30-200	bar
Operating temperature	80	^{0}C
Feed water consumption	0.9	liter/ Nm^3H_2
Dimensions	1 x 12,0 x 2,9 x 3,6 2 x 9,0 x 2,9 x 3,2	m x m x m

Table 16: Specifications of the electrolyser

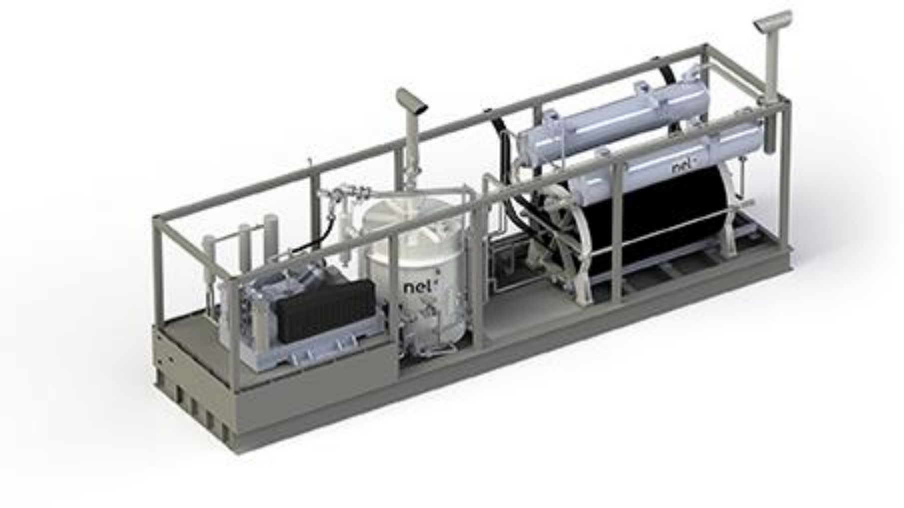


Figure 41: One of the containers of the NEL hydrogen electrolyser

4.4.3 Hydrogen storage

The hydrogen storage tanks are also designed and produced by Nel hydrogen (NEL Hydrogen, 2017). This modular system consists of tanks that can deliver up to 500 kg storage per rack. The racks can be connected to increase the size of the storage. The hydrogen that comes out of the electrolyser at 200 bar, can directly be stored in the tanks.

Specification	Value	Unit
Operating pressure	200	Bar
Storage capacity	500 (long rack) 264 (short rack)	kg
Storage vessel type	Steel vessels type 1	
Operating temperature	-20 to 40	^0C
Weather suitability	Suitable for outdoor installation	liter/ Nm^3H_2
Dimensions	6,5 x 2,4 x 0,6-3,0 12,3 x 2,4 x 0,6-3,0	m x m x m

Table 17: Specifications of the electrolyser

Figure 42: Nel hydrogen storage rack 6,5 meters

4.4.4 Fuel cell

A fuel cell system will be installed to convert hydrogen to electricity and heat. As a reference a large scale fuel cell system designed by MTSA technopower that contains fuel cells manufactured by Nedstack. This system is too big for the 226 dwellings because it would consume too much hydrogen and the power output would be too high. A smaller stack of fuel cells of the type FCS 10-XXL of 50 PEM cells is used (Nedstack, 2014). Fuel cells are modular, so they can be stacked to increase the capacity of the fuel cell system. Fuel cells are designed for constant operation, which is an important for the energy system design. It is not supposed to be turned on and off regularly. This aligns with the principle of seasonal storage, where at consumption season, long periods of demand exist. Fuel cells have a theoretical output of 50% electric, 50% heat as can be read about the example fuel cell. (Fuel Cells Bulletin, 2011).

Specification	Value	Unit
Power output electrical	25 x 9,5 = 237	kW
Power output heat	25 x 9,5 = 237	kW
Hydrogen consumption	3000	liter/minute
Dimensions	25 x 0,3 x 0,2 x 0,55 = 1,5 x 2,0 x 0,55	m x m x m

Table 18: Specifications of the fuel cells

Figure 43: Specifications of fuel cells type FCS 10-XXL

4.4.5 Battery

The battery system operates as a buffer of energy in the energy system. It delivers a constant output to the electrolyser and delivers a constant output to the smart grid of the neighborhood. Each battery has a usable capacity of 521 kWh and is as well fitted inside a small sea container. The type that will be applied in the energy system is a TB-548-1C and is manufactured by Alfen (Alfen, 2018).

Specification	Value	Unit
Capacity	548	kWh
Usable capacity	521	kWh
Power @ 25 ^{0}C	636	kVA
Power @ 40 ^{0}C	498	kVA
Weight	10.200	kg
Dimensions	2,5 x 6,1 x 2,6	m x m x m

Figure 44: Specifications of the batteries

Figure 45: Alfen TheBattery

4.4.6 Heat recovery

A heat recovery system has to be installed to produce DHW for the hotel. The heat is recovered by heating up water that is pumped along the fuel cell stack, so the fuel cell is water cooled. The heated up water passes a nickel brazed plate heat exchanger that exchanges the heat again with water that can be directly used. The proposed system is specifically designed by Tempco to increase the efficiency of fuel cell systems (Tempco, 2017).

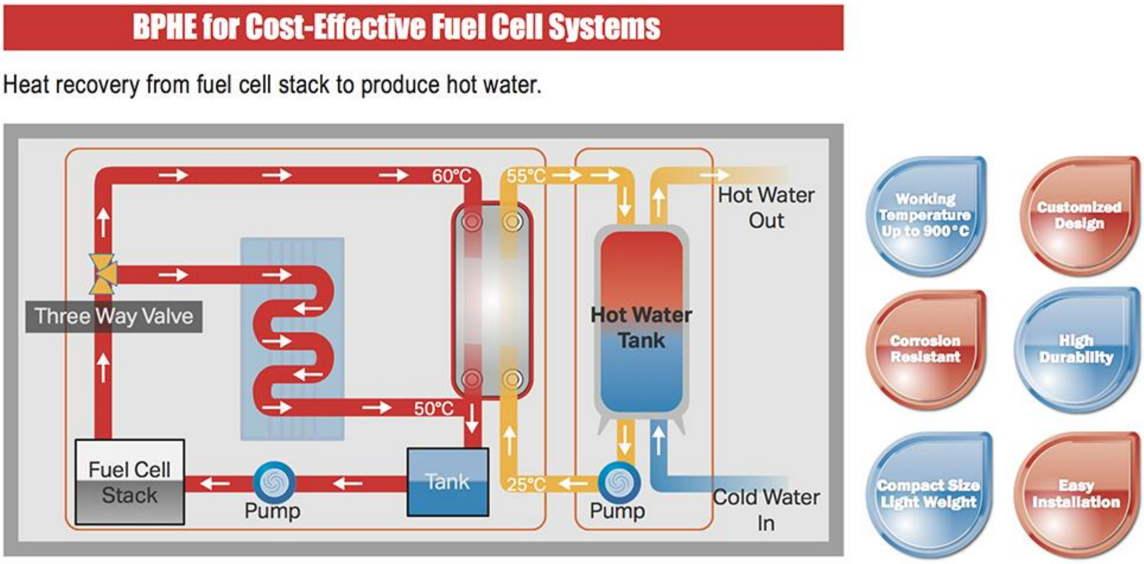


Figure 46: System schematic of the heat recovery system. retrieved from https://www.tempco.it/blog/en/6066/heat-echangers-fuell-cells-clean-energy/

Figure 47: Heat recovery elements designed by Tempco. retrieved from https://www.tempco.it/blog/en/6066/heat-echangers-fuell-cells-clean-energy/

4.4.7 DHW tank

The heat that is recovered from the fuel cell stack is used to prepare domestic hot water. This water is stored because it will be consumed at different points in time. The suggested tank for this energy system is manufactured by ECOTHERM (ECOTHERM, 2018). The stainless steel tank is compatible with external heat exchangers, which makes it suitable for integration with the proposed plate heat exchangers.

Specification	Value	Unit
Storage capacity	8000	liters
Operating pressure max.	6	bar
Hydrogen consumption	6000	liter/minute
Dimensions	2,2 x 2,2 x 4,2	m x m x m

Table 19: Specifications of DHW tank

Figure 48: Section view of DHW storage tank. retrieved from http://www.ecotherm.com/en/Products/Water-Heaters/Hot-Water-and-Combination-Tanks/88-ESWG-Large-scale-recuperation-tanks-with-extra-large-heat-exchanger-surfaces

4.4.8 Photovoltaics installation

All energy will be produced by the photovoltaics array on the roofs of all buildings in the neighborhood. To produce as much energy is possible, state of the art PV panels will be installed. The type that is used for all the calculations is produced by LG Electronics (LG, 2018). It has a maximum power output of 365 W per panel.

Specification PV panels	Value	Unit
Maximum power output panel	365	W
Panel surface	1.7	m2
Maximum power output/m2	214.7	W/m2
Panel efficiency	21.5	%
Total power of PV array	3,236	kW

Table 20: Specification of the selected PV panels

Specification inverter	Value	Unit
Maximum capacity	5	MW
Peak efficiency	98.9	m2

Table 21: Specification of the selected inverter

Figure 49: LG NeON R PV panel. image retrieved from https://www.groene-energiewinkel.nl/47112030--lg-zonnepaneel-lg-370q1c-a5-mono-neon-r.html

A photovoltaics installation with this capacity requires a large scale inverter to invert the direct current (DC) output into alternating current (AC). The selected inverter is Conext CL125, which is a string inverter suitable for decentralized PV arrays of up to 5 MW. The inverters can be distributed across the PV array (Schneider Electric, 2018). In figure 50 an overview of the PV array installation is given. For the rest of the report, this will be referred to as the PV array.

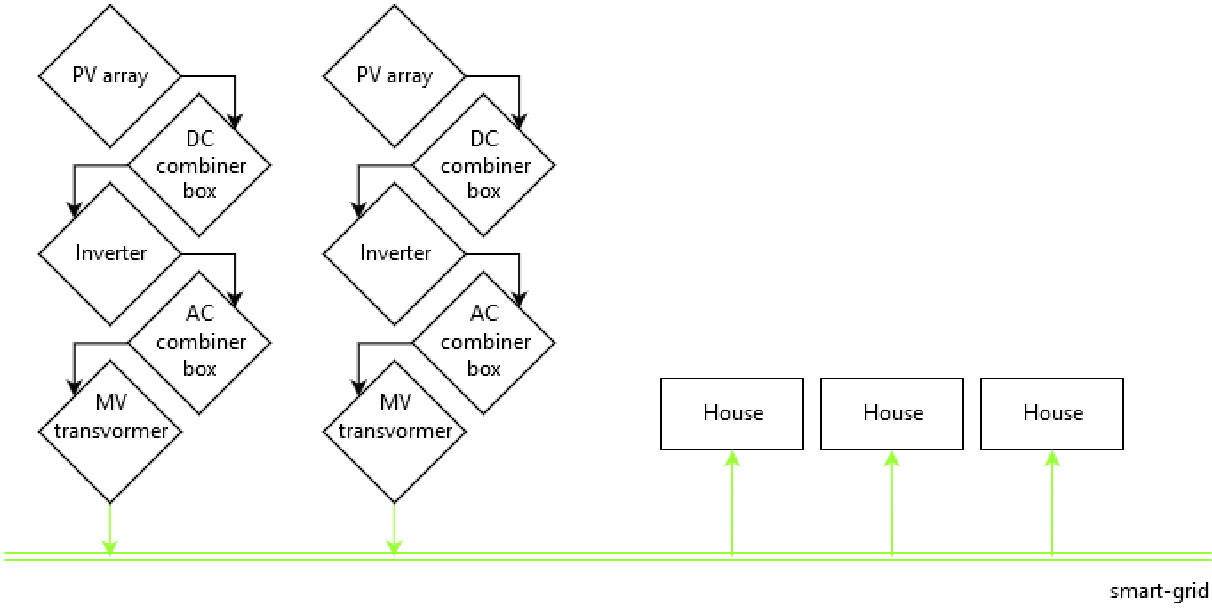
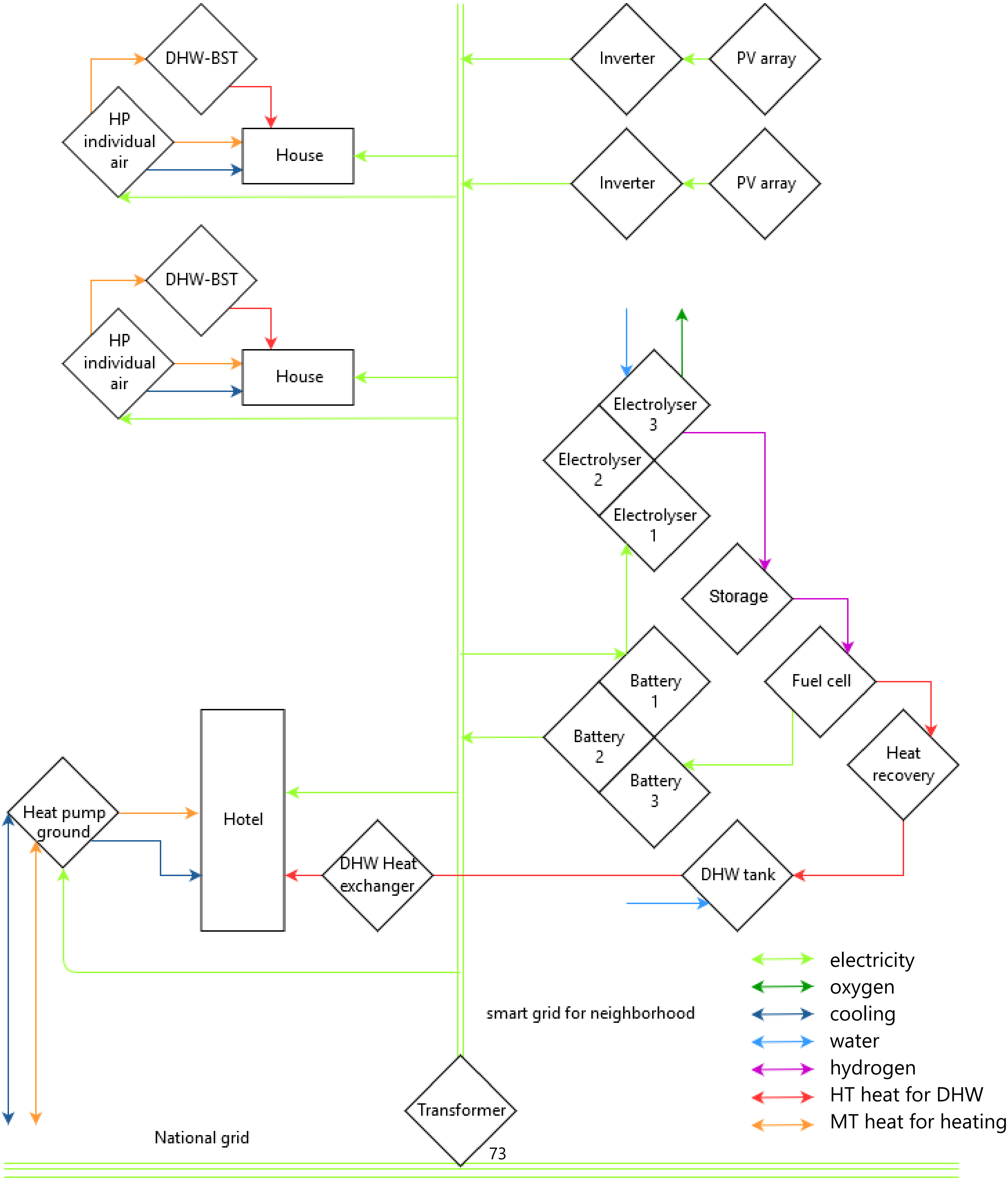


Figure 50: System layout of a PV array

The energy produced by the PV array is connected to the smart grid via a DC combiner box, which combines all cables. These cables are connected to a inverter, that changes DC power to AC power. The AC combiner box combines all cables that transfer the energy from the inverter to the grid. The MV transformer turns High Voltage into medium voltage. This is necessary before it can be connected to the smart grid.

4.5 Energy system layout



On the previous page, an overview is given of the energy system of the Floriade. All components are displayed, with the arrows showing their relation to one another and the stream of energy.

4.6 Impact

The energy system design has an impact on different levels of the neighborhood and consequently on the national grid.

Building level

Because of the way the energy system is designed, the impact on a building scale is minimal. It saves space in the house because only a heat pump and a booster for DHW have to be installed to supply the building with heating, cooling, DHW and electricity. A ventilation system should also be installed but this is not considered in the research. The cables of the PV array on the roof of the building are collected outside of the houses, so no installations inside the building are required for the PV system.

Neighborhood

The energy system is not visible in the neighborhood, with an exception for the energy hub. All installations, besides the inverters of the PV array, are placed inside the hub. The impact on the neighborhood is low, but the energy hub is the center of the energy system of the neighborhood. The neighborhood can be 12.5 days self-sufficient on a winter day. This is further elaborated on in chapter 7.3. The maintenance of the system is efficient because all the system components are placed in one building.

Residents

The residents live in a sustainable neighborhood where energy is shared and effort is made to set an example for others. The residents live in very well insulated buildings with state-of-the art installations. These installations require some cooperation from the residents to be able to optimally perform. If the residents can adjust the installations too much, the energy consumption will change. This can be explained by an example of underfloor heating: The system works best if the indoor temperature does not fluctuate too much. So, the building should, more or less, be kept at a constant temperature. If this is not the case, high peak loads will occur because the temperature difference between the desired indoor temperature and the actual temperature is high.

It can be concluded that the building performs best when the installations can perform according to the pre-installed setting.

National grid

Because renewable energy is buffered locally, the load on the national grid is reduced. The intermittent characteristic of renewable energy demands buffer capacity on the national grid. Currently, this buffer is created by adjusting the production capacity of power plants. The switch from fossil fuels to renewable energy sources demands a change in this system. The share of renewable sources in the energy mix is growing, this is associated with a growing demand for buffering of renewable energy. This can be done on a national scale, but also on a local scale. The energy hub sets an example of how energy can be stored locally. Next to reducing the load on the national grid, less transmission losses occur. However, it should be mentioned that the efficiency of the Floriade energy system is low so energy loss still occurs.

4.7 Conclusion energy system design

The neighborhood-level collective, so the energy system as proposed, can work in theory. The alternatives that are considered in section 4.2 can also offer solutions for the Floriade. However, the selected system has many benefits, as described in section 4.2 of this report. The system components are not yet completely optimized, as described in section 4.4. Therefore, a dynamic simulation is necessary to get more insight in the optimal configuration of the components of the system.

The energy system design and its efficiency strongly depends on the other parts of this research. This elaborated on in the next chapters. A change in consumption and production numbers can strongly influence the capacity of the components in the energy system. This, again, should be researched in a dynamic model.

5 Energy model

5 Energy model

5.1 Approach

The basis of the energy modelling is formed by the unbalance in energy production and consumption. This can lead to waste of renewable energy and disruption of the energy system. To gain insights of the magnitude of the unbalance, a model of (part of) the neighborhood is created. The output of the model should contain at least hourly information on energy consumption and production potential so a balance can be made. This can be applied to Floriade to gain insight in the energy unbalance for the neighborhood.

Different systems, models and software packages are used to come to a final design for the energy system and energy hub. To finalize the design, a model for the energy consumption of the buildings and a model for the energy production by the PV array is required.

5.2 Software selection

Multiple software packages are used for the energy modelling of this research. The selection of these tools is based on previous knowledge, obtained during the Building Technology master track. The features and limitations of each software package are considered during the selection process.

5.2.1 HOMER Pro

HOMER Pro is micro-grid software for optimizing micro-grid design (Homer Energy, 2018). The software offers the possibility of entering different criteria in order to come to an optimized system design. It simulated different combinations of system components in time steps from one minute to an hour.

Insight into energy system design was gained by taking an example energy system that includes hydrogen. The example file is adjusted to match an estimation of energy consumption of 600 dwellings, which was the assumed amount of houses at this stage of the research. A very rough estimation of an electric load of 8.000 kWh is entered to do an example calculation. A schematic of the HOMER Pro model is shown in figure 51 and an overview of the system components is displayed in table 22.

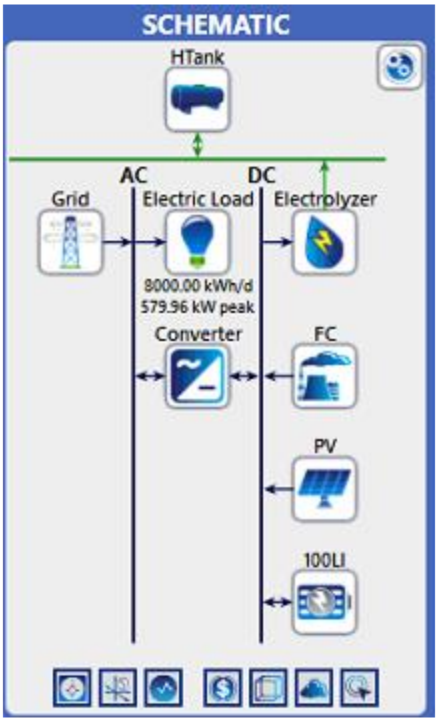


Figure 51: Schematic of HOMER Pro input

System component	Capacity	Unit
PV installation	4.000	kW
Fuel cell	400	kW
Battery	100	kWh
Electrolyser	450	kg/year
Hydrogen tank	500	kg
System converter	1000	kW

Table 22: HOMER Pro output of system component capacity

HOMER Pro was only used during the initial stages of the energy system design process due to its limitations. It soon became clear that the software has extensive modelling features and in-depth analyses are possible. The interpretation of the results requires specialist knowledge of energy system design and detailed information is necessary to get representative output. Although this may be relevant for this research, it is decided to not look further into HOMER Pro. Also, optimization of the energy system mainly focusses on economizations, which, for this research, is not as relevant as the optimization of the capacity of the system components.

5.2.2 Honeybee

The combination of Rhinoceros, Grasshopper, Ladybug & Honeybee and OpenStudio are selected for the first calculations of energy consumption of a reference building. After gaining insight in the system design, a more in-depth analysis of the energy consumption of the buildings in performed using a combination of different design tools. 3D modelling software Rhinoceros 6 (McNeel, 2018) is used to create a 3D model of the Floriade terrain and the buildings that are considered in this research. Grasshopper is an algorithmic modelling tool integrated with Rhinoceros 6's modelling tools. It is a visual programming tool that add parametric design options to Rhinoceros 6.

The Grasshopper parametric functions are supplemented with two plug-ins: Ladybug and Honeybee (Ladybug Tools LLC, 2018). It is a collection of components for weather data visualization, solar radiation studies and sunlight hour analysis. The weather, climate and solar radiation data can be used to model a photovoltaics installation.

The tools integrate energy simulation software OpenStudio (Alliance for Sustainable Energy, 2018), which is a collection of software tools to support whole building energy modelling using EnergyPlus. This tool combines all the building information with the location, weather and climate data to simulate energy consumption profiles.

Varying geometry of the different building types and extensive input parameters are required to make the building geometry of each typology. Because of this, the energy modelling of each building typology require loads of work. Therefore another software packaged is selected: Design Builder

5.2.3 Design Builder

Design Builder is a software package that helps designers develop comfortable and energy efficient buildings (DesignBuilder Software Ltd, 2018). It simulates, among other things, energy consumption and building installations based on user input and climate data. The simulation engine is the same as the one used in the Honeybee model: EnergyPlus. Because of this, the calculation method of the DesignBuilder model is similar to the calculation of the Honeybee model, but the input method differs. It is decided to use this software for the energy consumption simulation of all building typologies.

The reference house is modelled in both Honeybee and DesignBuilder to compare the output of the simulation. This validates the simulation results and will be elaborated on in paragraph 5.5.4.

5.3 Model set-up

5.3.1 Honeybee model

Energy consumption simulation

The modelling started with the reference house that is described in the previous paragraph. The energy balance gave a first impression of the energy balance of one house, which is important to get a sense of magnitude of energy consumption and production in the neighborhood. First, the consumption of the reference house is modeled.

The reference house is modelled in Rhinoceros based on dimensions provided by the architect. This empty volume is the input for the Honeybee (Grasshopper plug-in) model. In Honeybee the building related properties are applied to the building volume. As a result, the building is no longer an empty volume, but a building with properties. Relevant properties at this stage are building method, materials, floor areas, surface areas and window-to-wall ratio.

Next, the building-related installations and properties, as described in the complete energy system design, are applied to the model. The all-electric energy system of Floriade reduces the amount of installations per house required for a heat pump for heating and cooling, booster heat pump for domestic hot water and a converter for PV installations on the roof. Ventilation requirements, airtightness and building method are also modelled.

Finally, user-related properties are modelled. This comes down to occupancy and the equipment in the building. This is highly dependent on the occupants, so an assumption had to be made. In this model, a family consisting of four is assumed, which coheres with the layout of the building.

The building, with all its properties, is loaded into Open Studio, an energy simulation plugin for Grasshopper. It takes into account all building and user related properties and combines it with location data, climate data and reference weather data to perform an annual simulation of the building. For this research, hourly data is required to be able to draw up an annual balance.

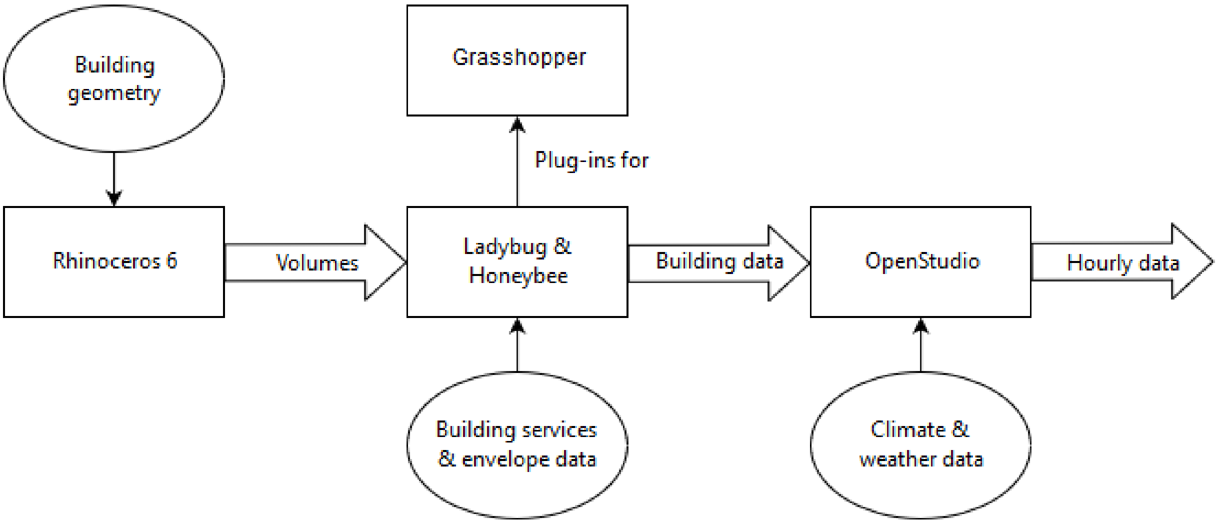


Figure 52: Workflow of Honeybee model

Energy production simulation

A second model is created with Ladybug and Honeybee. This model calculates the total energy production of the photovoltaics array on all the roofs of the buildings in the neighborhood. This model combines climate data with roof geometry and product data of the selected PV panel type to calculate hourly data for energy production by the photovoltaics.

5.3.2 Design Builder model

The set-up of the Grasshopper & Honeybee model takes a long time. Although it is designed for parametric calculations, it is limited in the adaptability of building specific properties, i.e. it is a complex process to get all the windows in the right orientation at the right position. For the hourly calculations of the other building typologies an alternative method was used.

Design Builder as well gives hourly data on energy consumption of buildings. Although each building type has to be drawn separately, the workflow of Design Builder is much faster because surfaces can easily be drawn and connected in the 3D working environment. To each surface and zone, building related and user related data is applied. The installation and occupational data can easily be copied from one building to another, so every building uses the same input data.

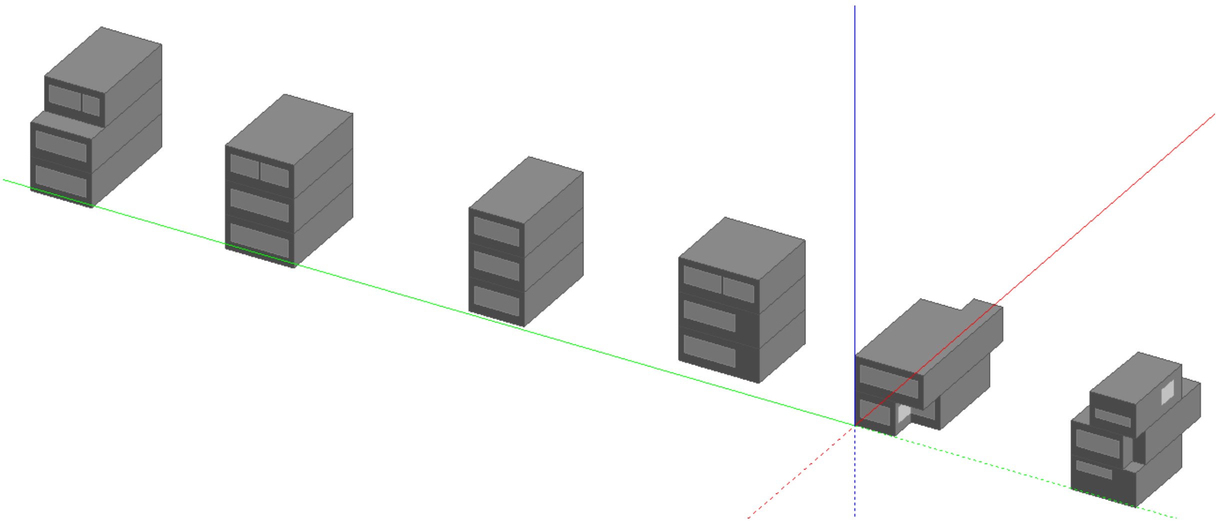


Figure 53: The volumes of the various building typologies drawn in Design Builder. From left to right: 6/plot, 8/plot, 10/plot, 12/plot, 14/plot and 16/plot

The reference house (14/plot) is the first building that is modeled in Design Builder. This way, the output data of the Honeybee model can be validated. The input of Design Builder should be similar to the input of the Honeybee model to be able to compare the two models. Although most input values are similar, it is not possible to enter identical data in both models. This may also explain possible divergent output.

5.3.3 UMGO

Another easy validation of data can be performed by comparing the results of the model with the data of an UMGO building. UMGO (Uniforme Maatlat Gebouwde Omgeving) is a standard measuring tool for the built environment published by the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, 2018). It describes reference data on the energy consumption of buildings with three different energy concepts: gas, all-electric and external heat delivery. It is assumed to be representative for newly built buildings in the Netherlands. As of 2020, newly built buildings have to comply with regulations on energy performance which are described in NTA 8800 (NEN, 2018).

In the energy model, no distinction is made between corner rowhouses and between rowhouses. For this reason, an average is taken of for the consumption of rowhouses. Table 23 shows the annual load per square meter per year according to the UMGO calculation standard.

Load	Semi detached	Row-corner	Row-between	Row-average
Heating	20.9	15.5	9.2	12.4
Cooling	2.1	4	3	3.5
DHW	13.5	14.7	15.9	15.3
Lighting	5	5	5	5
Equipment	14.8	14.8	14.8	14.8

Table 23: Annual load in kWh/m2/year according to UMGO calculation method

5.4 Model input

5.4.1 Building input

To get started with the energy model, the 14/plot reference house as proposed by the architect, was selected. This building type will be built 56 times according to the masterplan, it fits 14 times on one plot of Floriade. The different building typologies are defined by the amount of houses that fit on one plot, as can be seen in table 24. All houses will be fitted with state-of-the-art installations and building services, PV panels and high quality building materials to achieve high insulation values and low energy consumption. Table 25 gives an overview of the relevant properties of the building envelope and the building installations and services.

Name	Amount	GFA [m^2]	Roof area [m^2]	No. of floors
6/plot	24	133	37	3
8/plot	50	162	54	3
10/plot	4	130	43	3
12/plot	28	147	49	3
14/plot	56	119	65	2
16/plot	64	110	28	3

Table 24: Overview of building types

Building envelope	Value	Unit
Rc value roof, walls, floor	8.0	m^2K/W
U-value windows	1.0	W/m^2K
g-Value glazing	0.46	-
Infiltration rate	20	dm^3/sm^2
Window-to-wall ratio	50	%

Table 25: Building enveloppe properties

This building type is used as a reference for both calculation methods (Honeybee and Design Builder). The other buildings are only modeled in Design Builder because setting up the model in Honeybee takes longer. In paragraph 5.5.2 it will be explained that it is not necessary to model all building types in both Honeybee and Design Builder. After comparing the result, it turns out that the output of both models is nearly the same for the reference house.

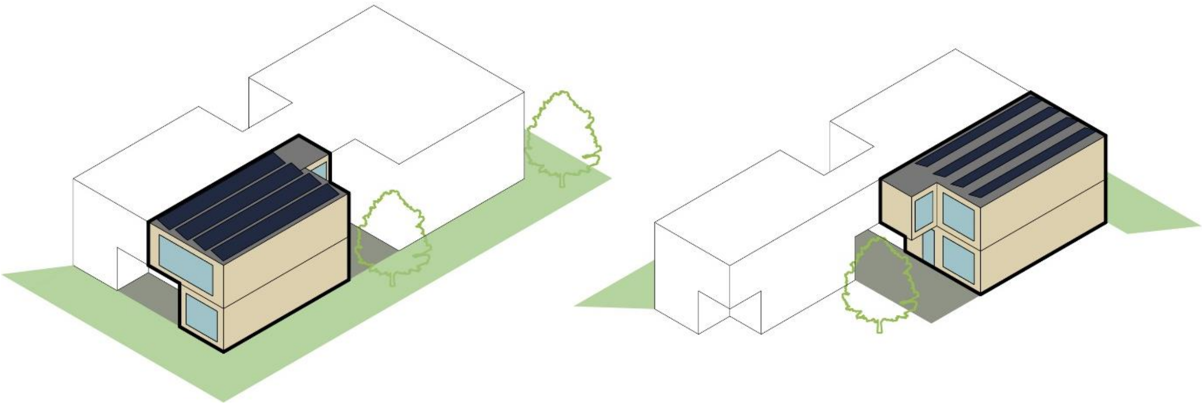


Figure 54: Isometric view of the reference house

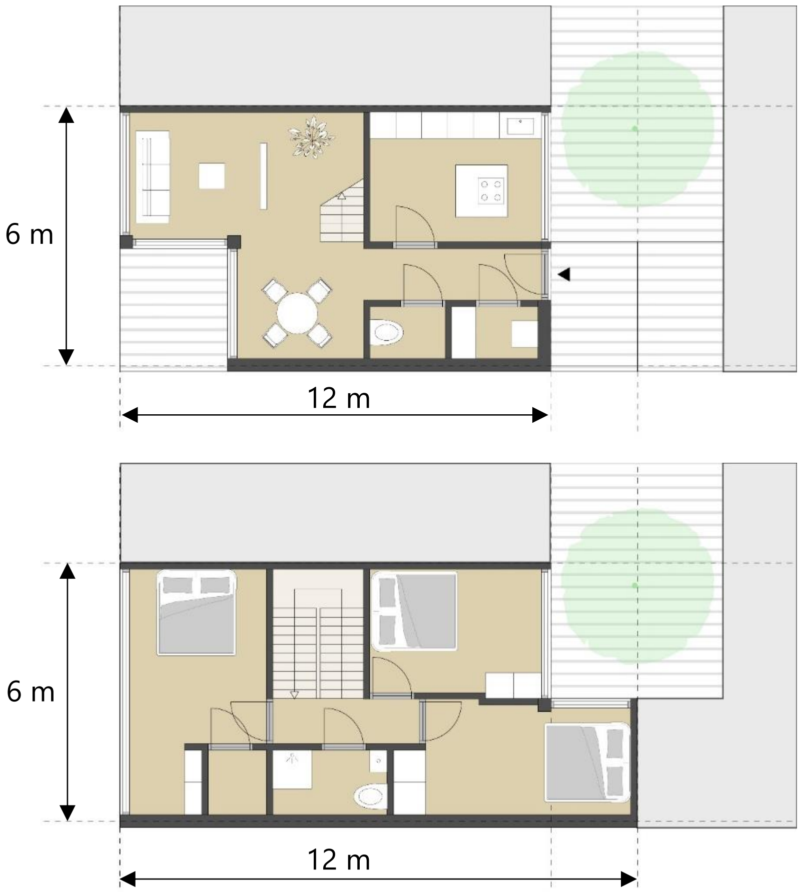


Figure 55: Floorplans of the reference house (above ground floor, below first floor)

5.4.1 Consumption input

Each model requires an extensive amount of information about the building. In the previous paragraph it is shortly mentioned that it is not possible to enter exactly the same data in each model. It is to be expected that when using two software packages, it is not possible to enter the exact same data. In the Honeybee model, it is possible to enter custom values for properties of building materials, while in Design Builder, a construction from a database has to be selected. A selection of input data is shown in table 26, diverging input and output and the possible effects it has on the results is described later. In appendix I, detailed information about the Design Builder input is shown. In figure 56, the complete model input of the Honeybee model is given. The separate elements of the model are shown in appendix II.

Input parameter	Honeybee	Design Builder	Unit
Building envelope			
R-value wall	8.00	7.92	m2K/W
R-value roof	8.00	7.90	m2K/W
R-value floor	8.00	7.90	m2K/W
U-value window	1.00	1.00	W/m2K
g-value window	0.46	0.47	-
Glazing ratio	50	50	%
Building services			
HVAC system	PTHP	PTHP	-
COP heating	4	4	-
COP cooling	4.5	4.5	-
Heating setpoint	20	20	C
Cooling setpoint	26	26	C
Heat recovery	not modelled	85	%
Lighting	2.5	2.5	W/m2
Domestic hot water COP	not modelled	0.85	-
Domestic hot water type	not modelled	heat pump	-
Occupancy	4	4	persons

Table 26: Input parameters for both energy consumption models

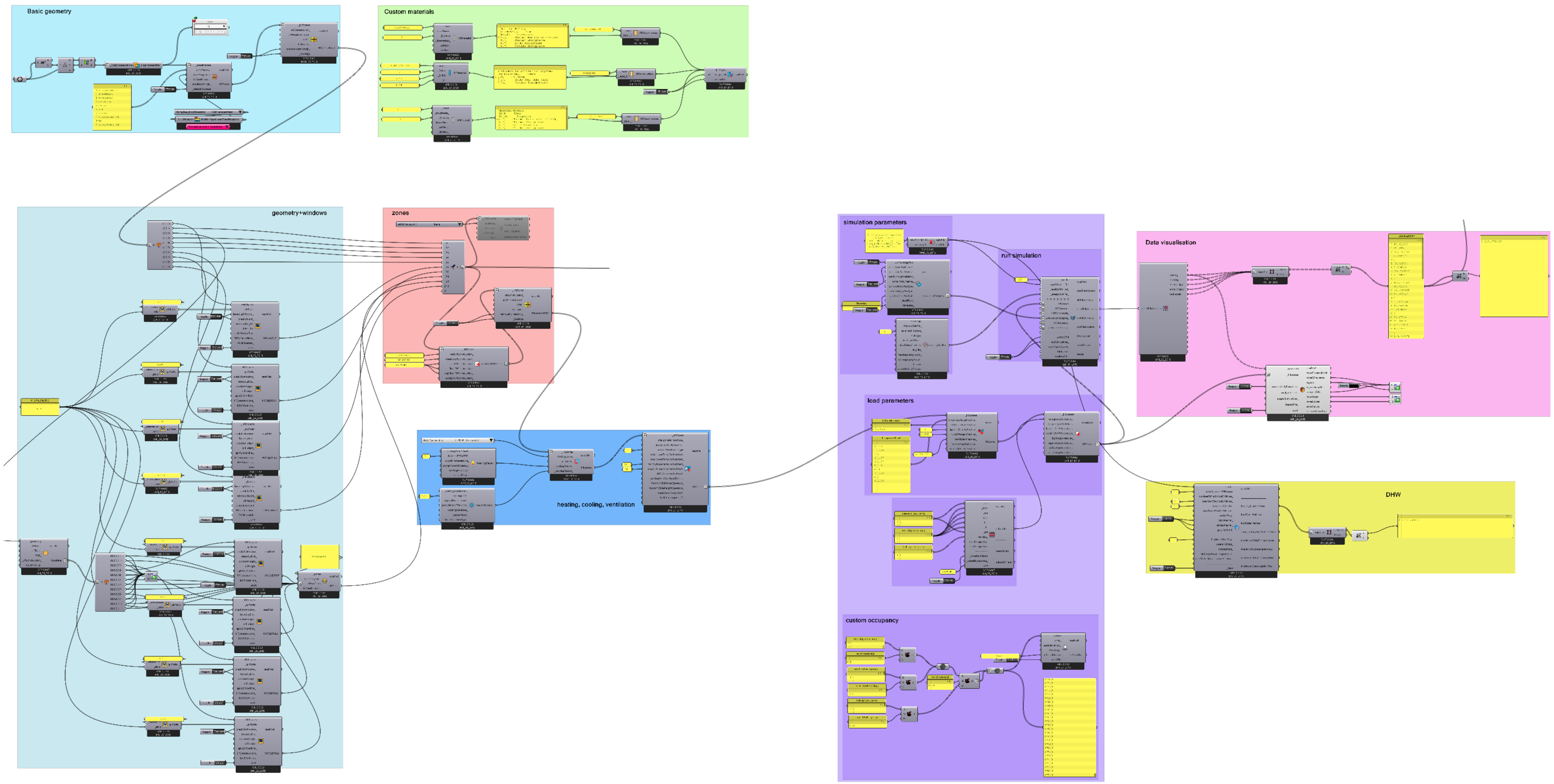


Figure 56: Honeybee consumption model overview

5.4.2 Production input

Input parameter	Ladybug	Hand calculation	unit
Roof surface	20506	20506	m2
Roof % covered	80	80	%
PV surface	16404.8	16404.8	m2
Placement angle	15	15	° rel. to horizontal
System size	3236	3236	kW
Maximum power output panel	365	365	W
Panel surface	1.7	1.7	m2
Maximum power output/m2	214.7	214.7	W/m2
Panel efficiency	21.5	21.5	%
Annual solar irradiation	model data	1024.8	kWh/m2
Efficiency	model data	0.877	kW/kWp
Conversion losses	10	10	%

Table 27: Input parameters for the energy production calculations

Annual solar radiation and the efficiency are calculated with hourly climate data in the Ladybug model, while the data used for the hand calculation is based on average solar irradiation and average solar array efficiency numbers published by the Netherlands Enterprise Agency (van Sark, 2014). Figure 57 shows a map made by KNMI (Dutch Meteorological Institute) with the annual global irradiation in the Netherlands in 2017. The map is take from the annual report on the weather in the Netherlands (KNMI, 2017). Values are given in kJ/cm^2. to convert to kWh/m2, the number should be multiplied by 2.778.

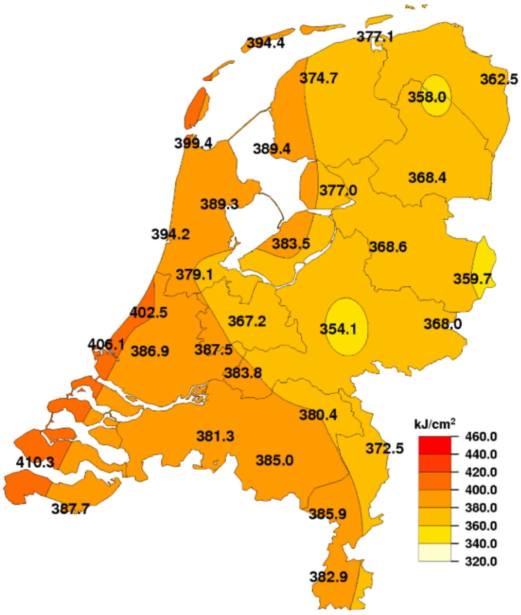


Figure 57: Global irradiation in the Netherlands in 2017

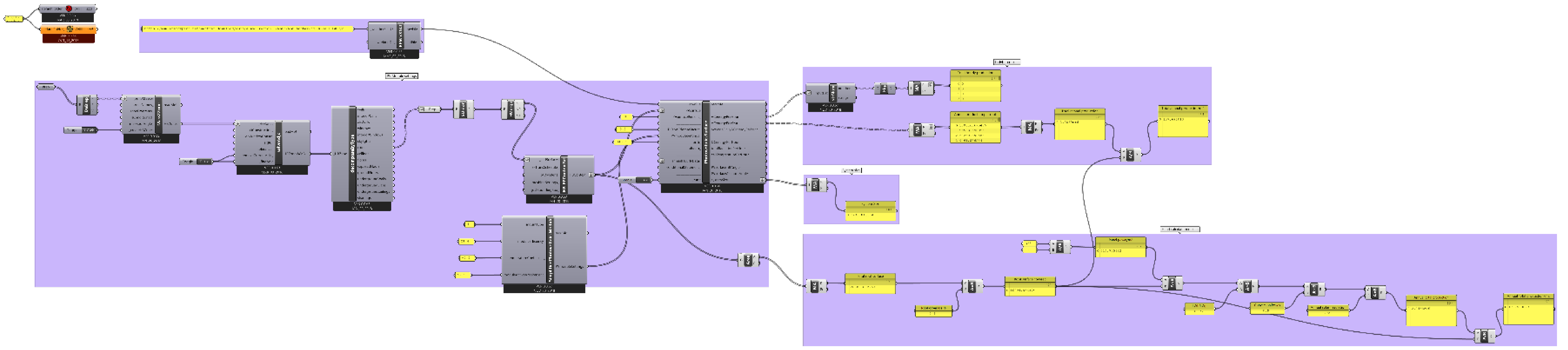


Figure 58: Honeybee production model overview

5.5 Results of energy consumption simulation

5.5.1 Introduction

For each building typology, the results are displayed in tables and graphs. Notable simulations are reviewed per building typology. In section 5.6.3 the results of the reference building are discussed. Here, a comparison is made between the output of the Honeybee, the DesignBuilder model and the UMGO calculation method. For the other types, a comparison is made between the DesignBuilder model and UMGO calculation method.

Variation between the energy consumption of different typologies can be observed. These variations are discussed in appendix III. Diverging results specific to that building typology are also discussed per building type.

5.5.2 Results overview

Table 28 and figure 59 show the annual energy consumption for all building typologies.

	Annual consumption					
	Heating	Cooling	DHW	Equip	Light	Total
type	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*
6/plot DB	2218	823	2537	1244	819	7641
6/plot UMGO	1649	399	2115	1968	665	6796
8/plot DB	1851	1294	2843	1961	1075	9024
8/plot UMGO	2009	486	2576	2398	810	8278
10/plot DB	1771	822	2188	1348	813	6942
10/plot UMGO	1612	390	2067	1924	650	6643
12/plot DB	1915	1205	2411	1338	908	7776
12/plot UMGO	1823	441	2337	2176	735	7512
14/plot DB	2130	360	1705	1243	611	6049
14/plot UMGO	1476	357	1892	1761	595	6081
14/plot HB	2059	616	4301	1795	710	9481
16/plot DB	1478	613	1458	1092	568	5209
16/plot UMGO	1364	330	1749	1628	550	5621

Table 28: Energy consumption of all building types

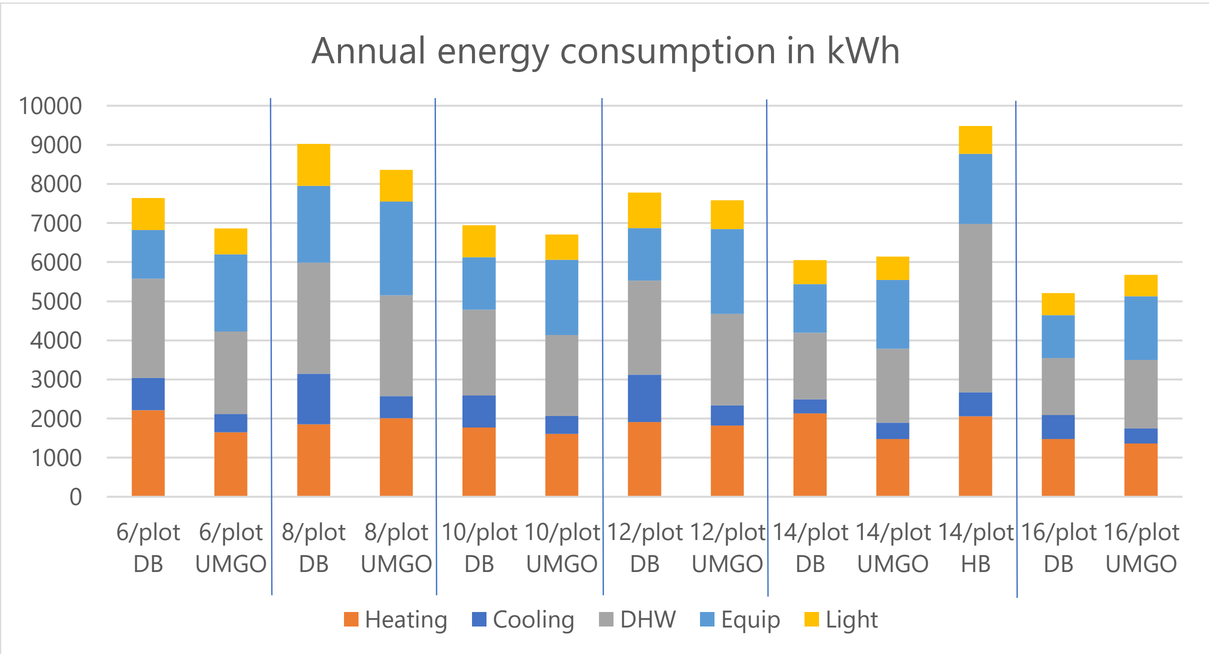


Figure 59: Graph of annual energy consumption of all building types

5.5.3 Results 14/plot buildings

Building type 14/plot is the building that is used as the reference house and for comparison and validation of model output. The table and graph below show calculation results of the DesignBuilder model, Honeybee model and UMGO calculation method. First, the results of the simulation are compared, then the consumption profile of this building type is given.

	Annual consumption					
	Heating	Cooling	DHW	Equip	Light	Total
type	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*
14/plot DB	2130	360	1705	1243	611	6049
14/plot UMGO	1476	357	1892	1761	595	6081
14/plot HB	2059	616	4301	1795	710	9481

Table 29: Annual energy consumption of building type 14/plot

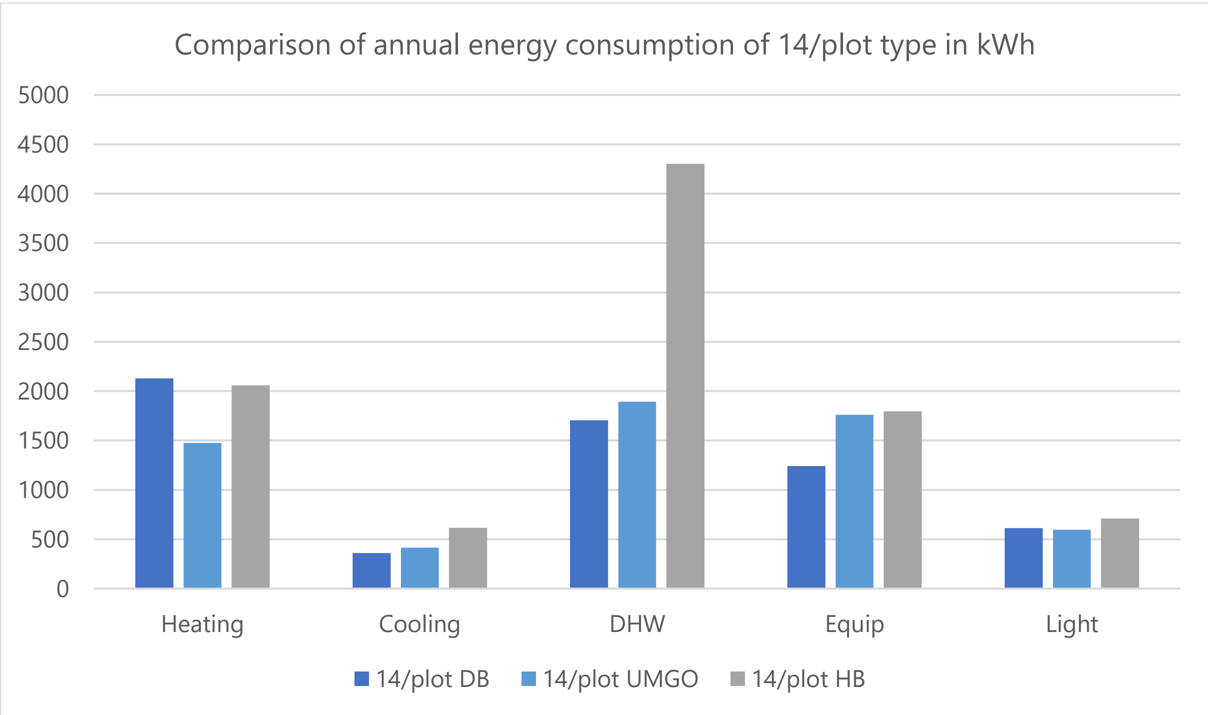


Figure 60: Graph of annual energy consumption of building type 14/plot in kWh

Heating

The heating demand is rather similar according to the DB and HB calculations. The UMGO calculations prescribe a lower energy demand for space heating. This can be explained by the fact that this building has a lot of windows, which leads to energy losses during the winter.

Cooling

The cooling load is approximately two times higher in the HB model. In the HB model, no heat recovery system is modelled, this is further elaborated on in the validation section. If heat recovery is not applied, high losses of energy can exist, leading to a high cooling load during the summer

Domestic hot water

The consumption for domestic hot water production is approximately twice as high in the HB model. This has to do with the calculation method in HB, which does not take into account a COP for DHW production by means of a heat pump. It is only based on the amount of people that live in the house. This is further elaborated on in the validation and interpretation section.

Equipment

The equipment load according to the DB model is lower than it should be according to UMGO and HB. This is discussed more in the validation and interpretation section.

Lighting

The results are rather similar in each model so this is not further debated.

Energy profiles

Figure 61 shows the annual daily consumption of the 14/plot building type. It can be expected that the energy consumption is higher during the cold months. The temperature outside is much lower than the temperature inside, so a lot of energy is needed to achieve a comfortable indoor climate. During the summer, this temperature difference in much lower, so the amount of energy needed for cooling is much lower. Three obvious peaks can be observed during the summer season. This is explained by the fact that the measured outdoor temperature of the reference year rose above 30 °C on these days, so it took a lot of energy to cool the building.

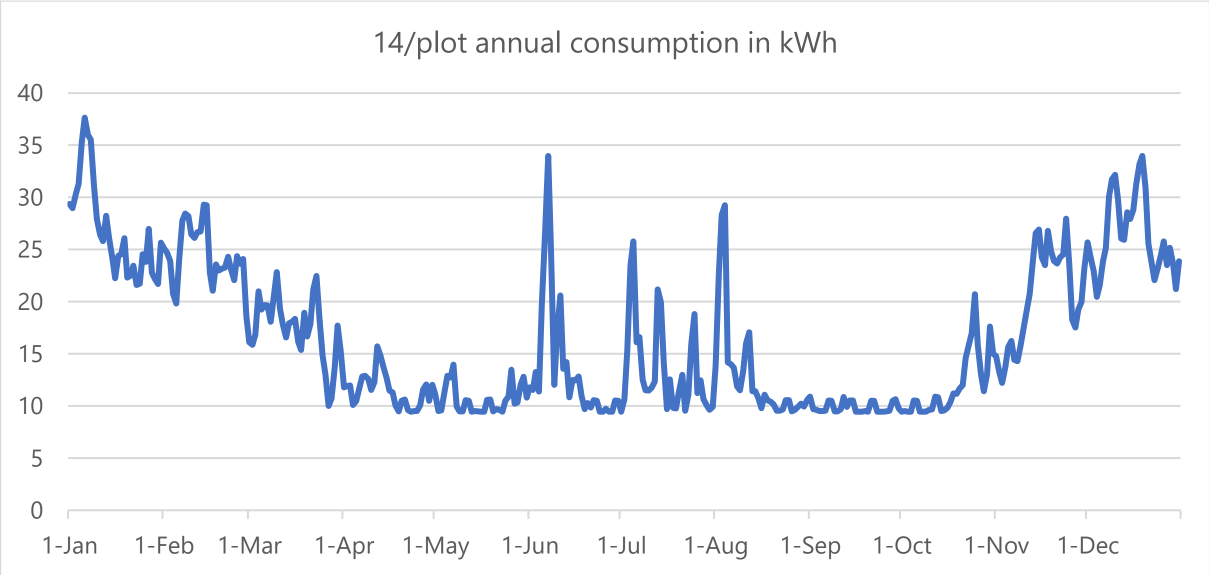


Figure 61: Annual energy consumption profile of building type 14/plot

Figures 62 and 63 display the energy consumption for the 14/plot building type on a summer day and on a winter day. These days are selected because they show the energy consumption profile of a typical day of the reference year. The hourly energy consumption consists of five elements: heating, cooling, domestic hot water, equipment and light.

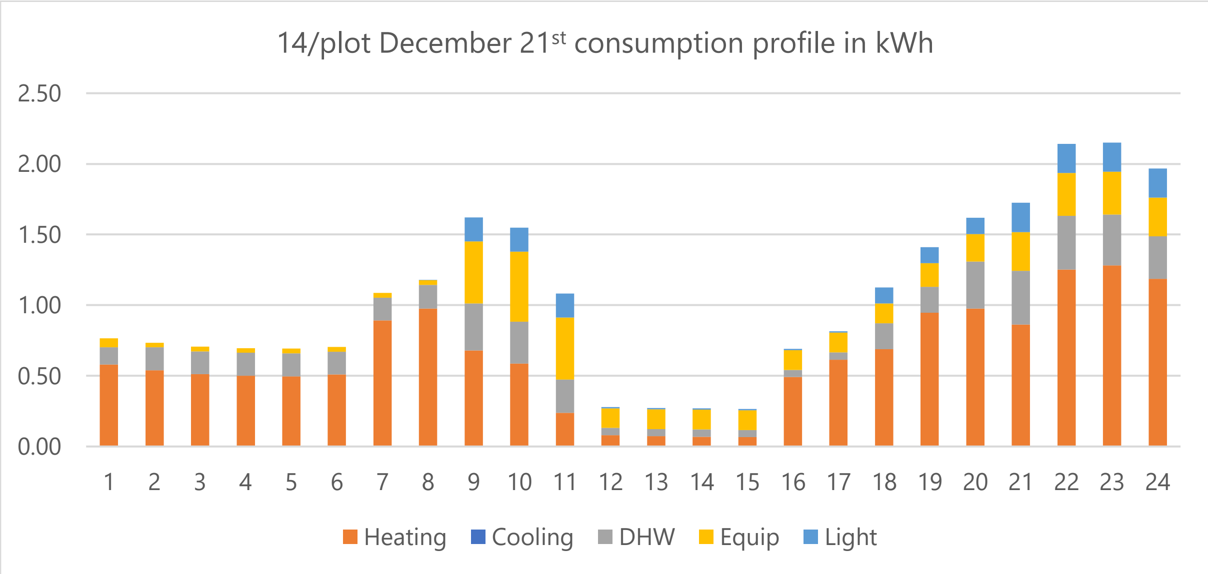


Figure 62: Breakdown of the energy consumption of 14/plot building type on December 21st of the reference year

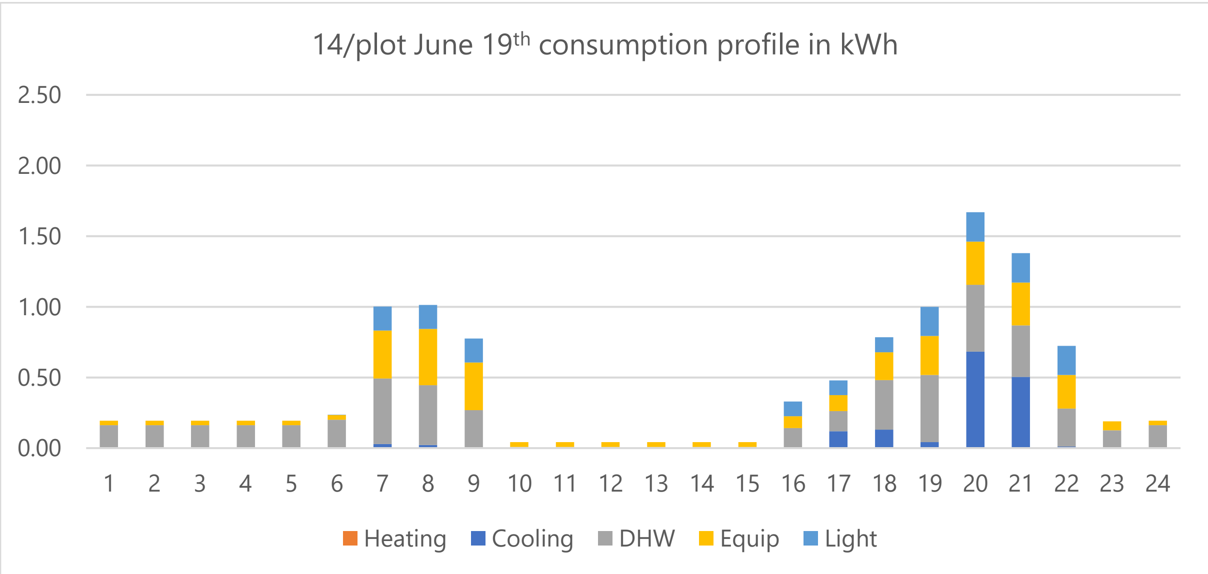


Figure 63: Breakdown of the energy consumption of 14/plot building type on June 19th of the reference year

5.5.4 Validation & interpretation

This chapter discusses the results of the models and how it should be interpreted. After discussing and interpreting it, a conclusion is given in the next chapter. This chapter contains an overview of all the data that is used during the rest of the research.

Domestic Hot Water

The annual energy consumption for the preparation of DHW as calculated by Honeybee is about three times greater than calculated by Design Builder and estimated by UMGO. This can be explained by the fact that the input parameters in Honeybee are very different from the input parameters of Design Builder. Design Builder bases the total energy consumption for DHW on occupation and the COP of the DHW system. Honeybee calculates the energy consumption based on the amount of adults and school children and the equipment in the house. A closer look at the output learns that every hour of the year, the DHW system consumes energy, which is highly unlikely. Since a DHW storage system was not taken into account in neither the Design Builder nor the Honeybee model and because Honeybee does not take the COP of DHW into account, it is safe to assume that the output result of Honeybee are not representative for this case study.

Heat pump

In both the Design Builder and Honeybee model, the heating and cooling system is a heat pump, specifically a Packaged Terminal Heat Pump (PTHP). This type of heat pump is ductless and sometimes described as a through the wall heat pump. This type is used because it allows in both software packages for a COP for heating and cooling parameter. This type of heat pump may not be the exact type of heat pump that is described in the energy system design, but it is only used for the heating and cooling demand based on a COP. So, the type of heat pump that is used in the simulation is less relevant, more relevant is the heating demand of the building, which is independent of the heat pump type.

Heat recovery

The Honeybee model does not allow for a combination of a certain type of heating and cooling system and a heat recovery system. This is a substantial deficiency in the model and adds uncertainty to the results of the Honeybee model. On the other hand, the lack of a heat recovery system in the model has a negative effect on the energy consumption of the building, which, in turn, has a positive effect on the energy surplus of the building and thus on the amount of energy that can be used by the electrolyser. In the DB model, a heat recovery system with an efficiency of 85% is simulated.

Equipment loads

The equipment load according to the DB model is lower than it should be according to UMGO and HB. In the DB model, the equipment load is entered very precisely, specific to each zone in the house, while the UMGO calculation uses an average for equipment loads. This generalization can cause high loads on buildings with a relatively large GFA, even if the equipment that is applied in the house is very energy efficient. A low equipment load aligns with the green and sustainable ambitions for Floriade. It requires some cooperation from the residents, but that can be expected from people who choose to live in a "green city of the future"

5.5.5 Conclusion energy consumption simulation

The uncertainties and deviations that are discussed in the previous paragraph can be explained. The consumption calculations are performed for this research are used to make an annual balance for energy production and consumption. The calculations are based on the climate data of 2002, but are representative for the current climate, so the results are also representative for the current climate.

The output is, among other things, based on occupation of the building. This is purely theoretical, but actual consumption profile could be very different and is dependent on the people that live in the houses. So, in conclusion, the results can be representative for the actual building, but can also deviate due to preferences and use of the residents of the building.

5.6 Results of energy production simulation

5.6.1 Methodology

The energy production is calculated with a Ladybug model. All buildings masses are drawn in Rhinoceros in order to get a 3D model of the neighborhood. In this model only the buildings that are considered for this project are included. The volumes are the input for the Ladybug model. This model takes all volumes and extract all roofs of the buildings. 80% of the extracted roof surfaces is covered with PV panels facing south placed under an angle of 15°.

Based on annual climate data and solar radiation data, the model can calculate the amount of energy that is produced by the PV installation. The output of the model is hourly data of energy production in kWh.

5.6.2 Results hand calculation

This energy production data is validated with a hand calculation and climate data. The report "Opbrengst van zonnestroomsystemen in Nederland" (Yield of photovoltaic arrays in the Netherlands), published by the Netherlands Enterprise Agency describes and average yield of 877 kWh/kW$_p$ (van Sark, 2014). This average is based on Dutch climate data and 634 researched PV arrays. Not every array has an optimal layout or tilt. However, for the purpose of validating the data, it is a reliable source of information.

The total installed capacity is 3236 kW, so based on the report of the Netherlands Enterprise Agency, the annual yield should be 3236 x 0.877 = 2.837.972 kWh. A more extensive calculation is given in the table below.

Hand calculation	Value	unit
Roof surface	20,506	m2
Roof % covered	80	%
PV surface	16,404.8	m2
Placement angle	15	° rel to horizontal
System size	3,236	kW
Maximum power output panel	365	W
Panel surface	1.7	m2
Maximum power output/m2	214.7	W/m2
Panel efficiency	21.5	%
Annual solar irradiation	1,024.8	kWh/m2
Efficiency	0.877*	kW/kWp
Conversion losses	10**	%
Annual production per m2	174	kWh/m2
Annual total production	2,849,024	kWh/m2

Table 30: Input of the hand calculation

Calculation						
20,506	x	0.8	=	16,404.8	Total roof surface x % covered = covered area
365	÷	1.7	=	214.7	Panel output power ÷ panel area = power per m^2
21.5%	x	1,024.8	=	220	Power x irradiation = STC max annual output in kWh
220	x	0.877	=	193	Output x efficiency kWh/kWp
192	x	0.9	=	174	Output - conversion losses = annual production/m^2
174	x	16,404.8	=	2,849,024	Power/m^2 x total PV area = total annual production

Table 31: hand calculation

5.6.3 Results PVGIS tool

Hourly hand calculations require too much time, so the hand calculations are only used to validate the annual production data. A quick check is performed with a simple online tool called Photovoltaic Geographical Information System, published by the European Commission (European Commission, 2012). The output of this tool is given in table 32. Details on the input and output of the calculation are given in appendix IV.

Fixed system: inclination=15°, orientation=-16°

Month	E_d	E_m	H_d	H_m
Jan	2,270	70,500	0.95	29.6
Feb	3,840	108,000	1.6	44.9
Mar	7,490	232,000	3.18	98.7
Apr	11,300	339,000	4.96	149
May	12,000	371,000	5.37	166
Jun	12,400	372,000	5.65	169
Jul	11,800	366,000	5.42	168
Aug	10,400	322,000	4.7	146
Sep	8,080	242,000	3.59	108
Oct	5,140	159,000	2.23	69.2
Nov	2,560	76,700	1.09	32.8
Dec	1,780	55,300	0.76	23.6
Yearly average	7,430	226,000	3.3	100
Total for year		2,710,000		1210

Table 32: results of the PVGis tool

E_d: Average daily electricity production from the given system (kWh)
E_m: Average monthly electricity production from the given system (kWh)
H_d: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)

H_m: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)

The output of the hand calculations is discussed in paragraph 5.6.4 together with the output of the energy production simulation.

5.6.3 Results energy production simulation

The output of the Ladybug simulation is a list of 8760 values that represent the hourly energy production in kWh of the complete photovoltaics array on the roofs of all houses.

Property	value	unit
Roof area covered	80	%
Total PV surface	16,408	m2
Placement angle	15	°
Placement direction	south	-
Panel efficiency	21.4	%
annual electricity generation	2,586,934	kWh

Table 33: results of the energy production simulation

The total amount of energy generated by the PV in the reference year is 2,586,934 kWh.

5.6.4 Validation & interpretation

Table 34 gives an overview of the results of the production calculations and simulations.

Overview of results	Ladybug	Hand calculation	PVGIS	unit
Roof surface	20,506	20,506	-	m2
Roof % covered	80	80	-	%
PV surface	16,404.8	16,404.8	-	m2
Placement angle	15	15	15	° rel. to hor.
Placement direction	-16	-16	-16	° rel. to S
System size	3,236	3,236	3236	kW
Maximum power output panel	365	365	-	W
Panel surface	1.7	1.7	-	m2
Maximum power output/m2	214.7	214.7	-	W/m2
Panel efficiency	21.5	21.5	-	%
Annual solar irradiation	model data	1,024.8	-	kWh/m2
Efficiency	model data	0.877	-	kW/kWp
Conversion losses	10	10	-	%
Annual production per m2	158	174	-	kWh/m2
Annual total production	2,586,900	2,849,024	2,710,000	kWh/m2

Table 34: Overview of the results of the production calculation

The results of the three calculations methods are not exactly the same. The Honeybee simulation is the only calculation that takes into account hourly data and the context of the building. The hand calculation is based on an number that is described in a publication of the Netherlands Enterprise Agency. In this document, it is described that this is an average number for photovoltaics arrays in the Netherlands. It is also described that the annual production strongly depends on circumstances specific to the project. Many projects have a higher annual yield per m^2, but some systems also perform worse. The number 877 kWh/kW_p has a standard deviation of 137 kWh/kW_p, which can already explain the difference between the Honeybee and hand calculation. If the efficiency is lowered to 0.800 instead of 0.877, the result of the hand calculation is 2,598,882 kWh per year. With the afore mentioned standard deviation, an efficiency of 0.800 is realistic.

Another explanation for the deviating results is the climate data that is used for the Honeybee model. It is based on the solar radiation as measured in the year 2002. The average number from Netherlands Enterprise Agency is based on data from 2011, 2012 and 2013.

The PVGIS output is produced by a tool that informs people in general about possible production potentials of PV arrays. The tool notifies the user as follows:

There are a number of reasons why the results we show could contain errors. Among these are: Uncertainties in the estimation of PV performance depending on PV technology and local conditions. Because of these uncertainties, the 5% is considered acceptable.

5.6.5 Conclusion energy production simulation

The system size of the PV array is determined by the roof surface covered. The generated energy is much higher than the consumption of the buildings in the neighborhood, so the system size is too large. Normally, the system size would be reduced, but since other buildings that are not considered in this research are being built in the neighborhood, the array can be shared with the other buildings. This way, the surplus will not be as high. The implications of the surplus are discussed later in the report.

The climate data that is used in the Honeybee model, is taken from a dataset that is used all over the world for simulations. This hourly data is selected and made publicly available because it is representative for the Dutch climate. The Honeybee model takes into account the location of the PV array and reliable hourly climate data, while the other calculations are based on averages. For this reason, the output of the Honeybee model is used for the energy balance, as described in the next chapter.

6 Energy balance

6 Energy balance

6.1 Introduction

In order to make the energy balance of the neighborhood, the energy consumption and production at any point in time must be known. The neighborhood has a collective PV system, so the residents do not own the PV installation on their roof. All energy produced is fed to the micro-grid and can be used by all houses. Surplus energy will be used to produce hydrogen by means of electrolysis. This chapter describes the calculations performed to find this balance and elaborates on the efficiency of the energy system. This balance is relevant for the amount of energy that needs to be stored in the energy hub, which will be elaborated on in the next chapter.

The energy balance can be found by obtaining data on energy consumption and production. For this reason the following questions must be answered:

- How much energy is consumed by the houses at any given moment of a year?
- How much energy is produced by the collective photovoltaics installation of the neighborhood?

The balance is found by deducting the hourly energy consumption from the hourly energy production. It can be expected that during sunny summer days the production is higher than the consumption, resulting in an energy surplus. On the other hand, during winter days with little or no sun, the energy consumption will be higher than the energy production, which will result in an energy deficit. Since all surplus energy is used to produce hydrogen, all the hydrogen that is stored functions as a buffer of renewable energy.

6.2 Energy consumption

6.2.1 Methodology

The methodology of obtaining consumption results is extensively described in the previous chapter, so only a summary is given in this chapter.

The energy consumption is built up out of five elements: heating, cooling, DHW, lighting and equipment. The consumption data is initially obtained by performing a building simulation in Honeybee and Ladybug, plug-ins of Grasshopper, which is in turn a plug-in of Rhinoceros. Rhinoceros is a 3D modelling software, Grasshopper is a parametric design tool, Ladybug and Honeybee are environmental design tools. All model input is based on energy system that is being proposed for all the houses. In a nutshell, the buildings are very well insulated, have a high air tightness and are heated and cooled with an air source heat pump.

Due to the complexness of the Honeybee and Ladybug model, a different method is used to calculate the energy consumption of the other build typologies. The results from the building type of the first model are compared with the results of the second model and validated.

In the previous chapter the energy consumption is discussed on building level, in this chapter the energy consumption and consumption profiles will be discussed on neighborhood level.

6.2.2 Consumption data

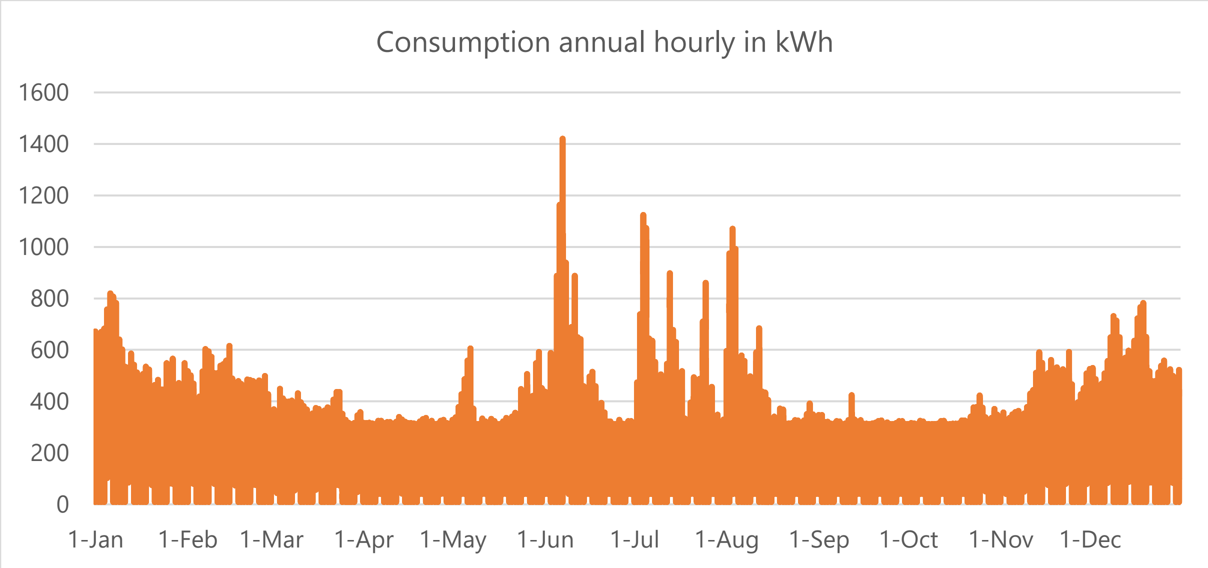


Figure 64: Total annual hourly consumption

Each point in this graph represents the total energy consumption of the 226 houses during one hour of the reference year. The peaks in consumption during the summer are explained by very high outside temperatures. On June 6^{th} of the reference year the measured outside temperature was above thirty °C between 12:00 and 19:00. The buildings heated up all day, which resulted in high cooling loads as output of the model. This is displayed in the graphs on the next page.

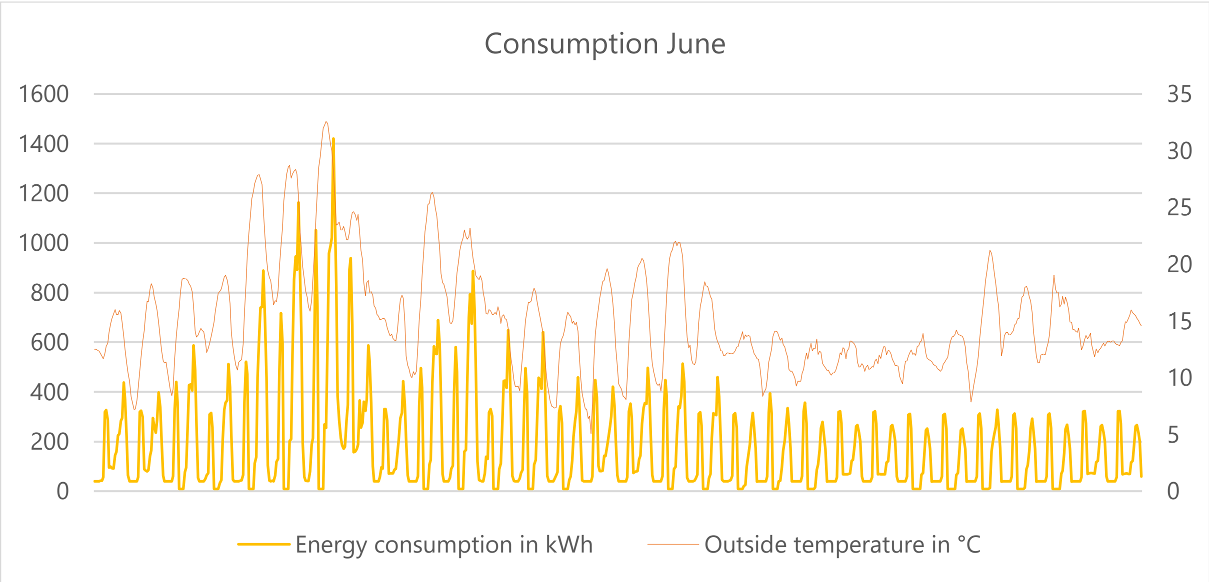


Figure 65: Consumption and outside temperature in June

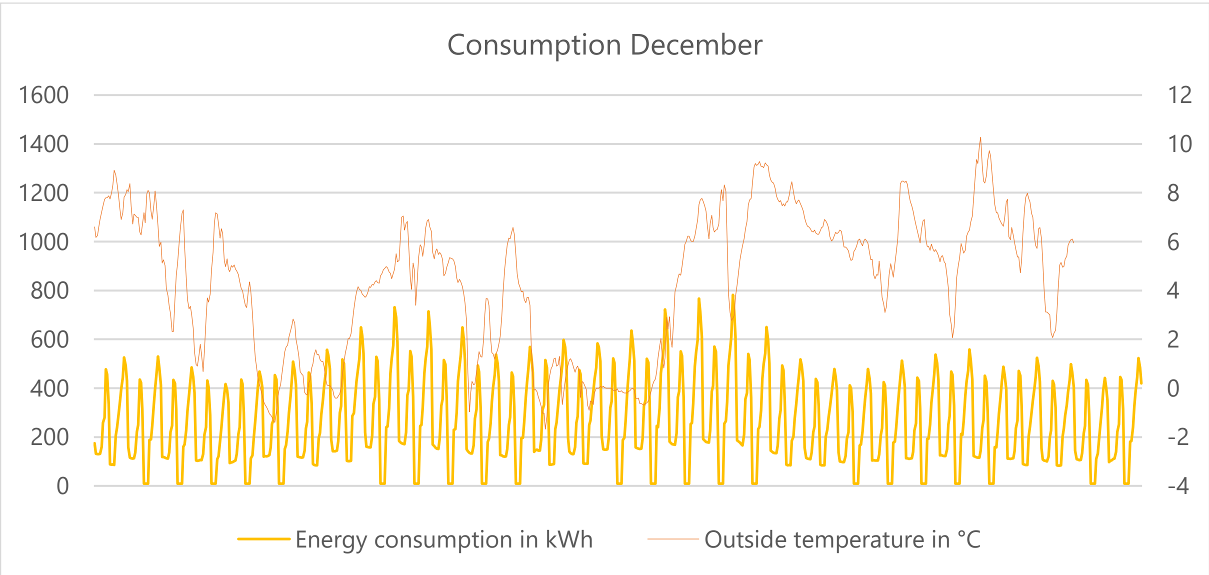


Figure 66: Consumption and outside temperature in December

In December high peaks like in June are not observed. This is explained by the high insulation value of the building envelope. The combination of temperature fluctuations and the high glazing ratio makes it difficult to keep the building at a comfortable temperature in the summer. The large window surfaces allow solar heat to enter the building so it heats up quickly.

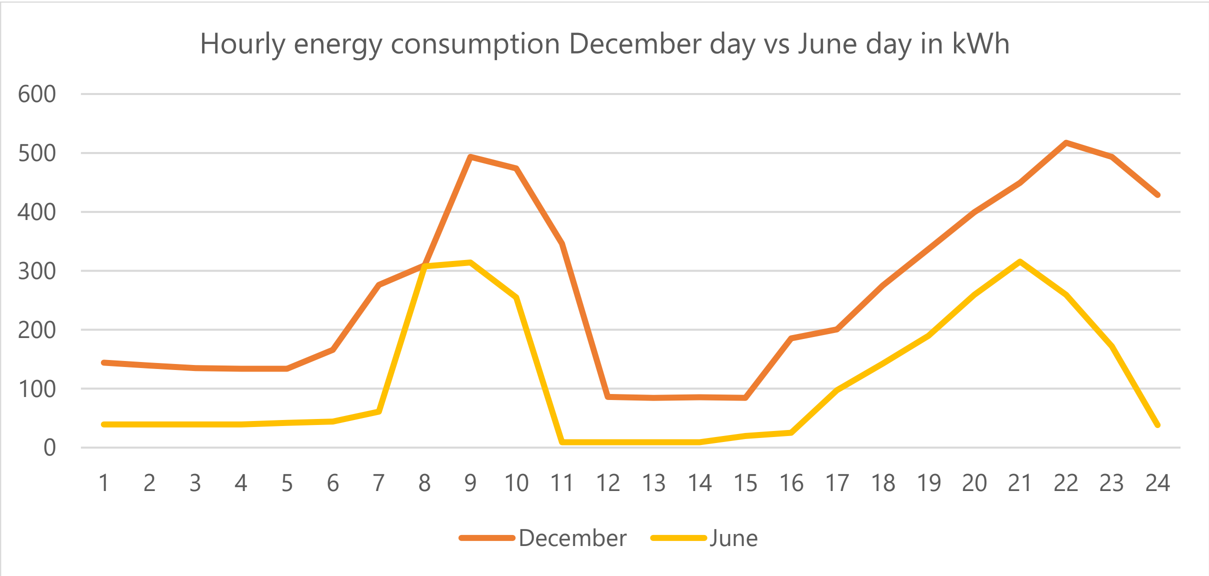


Figure 67: Energy consumption of a summer day and a winter day

From this graph it becomes very clear that building occupancy is taken into account in the simulation model. The occupants are not home during daytime so the energy consumption is relatively low. In the morning and evening, when people usually take a shower a peak in the demand is visible. The heating setpoint keeps the building at a base temperature, so the base load in the winter is higher.

6.3 Energy production

6.3.1 Methodology

The methodology for energy production is already described in the previous chapter. The production on building scale is the same as the production on neighborhood scale because it is produced by the same system.

6.3.2 Production data

Each point in figure 68 represents the total energy generated by the PV installation of the neighborhood during one hour of the reference year. During the summer months, the sun shines more hours per day with higher radiation, so it expected that the production is highest during the summer months. This is confirmed by figure 69 and 70, where the energy production on a monthly and daily scale is displayed.

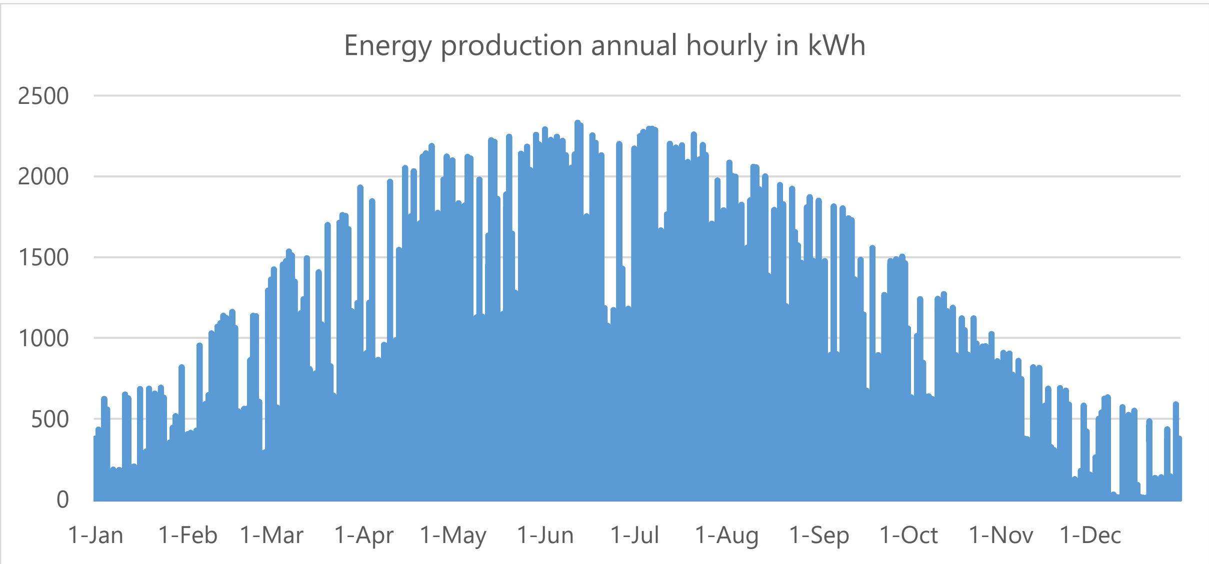


Figure 68: Total annual hourly production

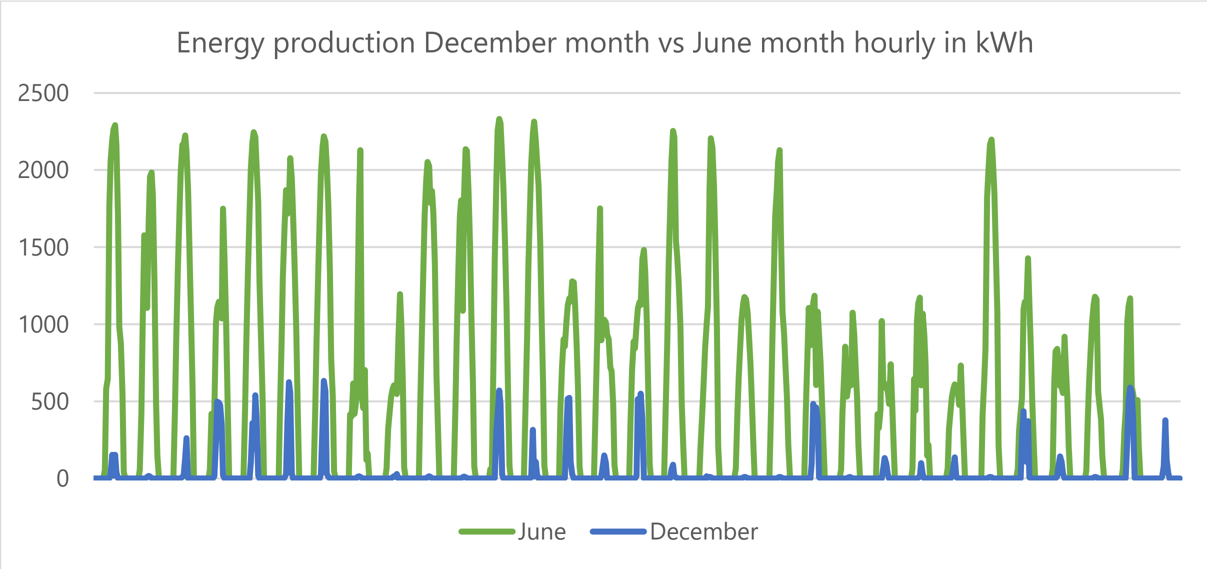


Figure 69: Hourly data of energy generated by the neighborhood PV array in June and December

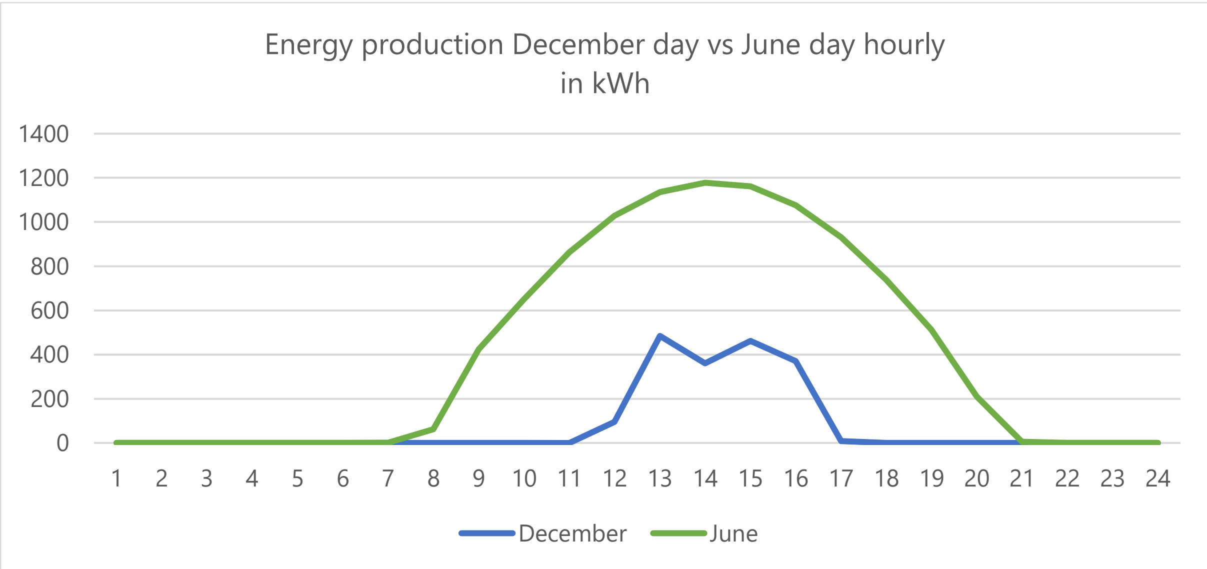


Figure 70: Hourly data of energy generated by the neighborhood PV array of a day in December and June of the referendce year

6.4 Energy balance

With the hourly energy consumption and energy generation known, a balance can be made by subtracting the consumption with the production. If the hourly generation is greater than the hourly consumption, a surplus of energy exists. This is used to power the electrolyser that produces hydrogen from electricity. During production season (summer), the seasonal buffer is charged and during consumption season (winter) the season buffer is discharged.

Since it is not the intention to make the neighborhood energy neutral, the buffer will not discharge during the production season in the initial system design. The fuel cell needs a constant feed of hydrogen, because it is designed for continuous operation.

Subtracting the annual production and consumption does not suffice to calculate the amount of surplus energy. If this method was applied, no insight would be gained in what happens each hour of the day. The daily balance can be negative, even if a surplus exists during the day. In this case, the surplus would not be accounted for in the total surplus calculation.

Taken this into account the following annual energy balance is composed:

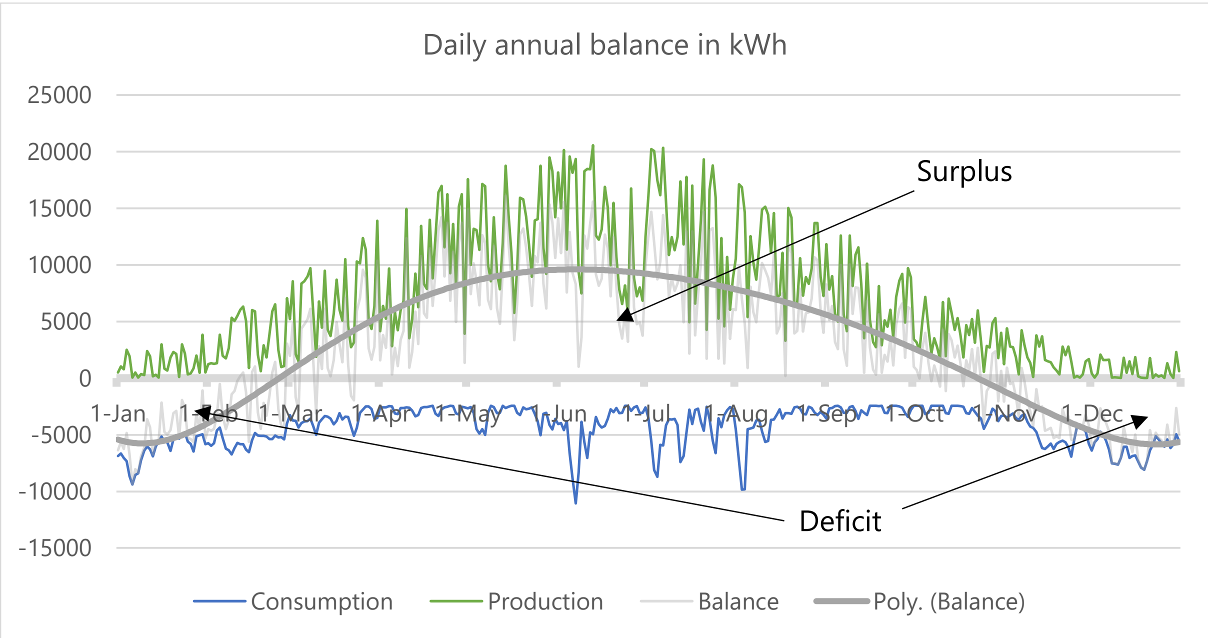


Figure 71: Graph of the annual energy balance of the neighborhood

Annual balance		
Production	2,586,934	kWh
Consumption	1,552,109	kWh
Surplus	1,034,825	kWh

Table 35: Annual balance

This balance, as displayed in figure 71 and table 35, is a sum of deficits and surpluses that exist during the year. Every time a surplus exists, a battery is charged, that can feed energy to the electrolyser, which, in turn, produces hydrogen that is stored as seasonal buffer.

Figures 72 until 75 give more detailed information on the monthly and daily consumption, production and balance of the reference year. In table 36, an example of a daily balance for a winter and a summer day is given.

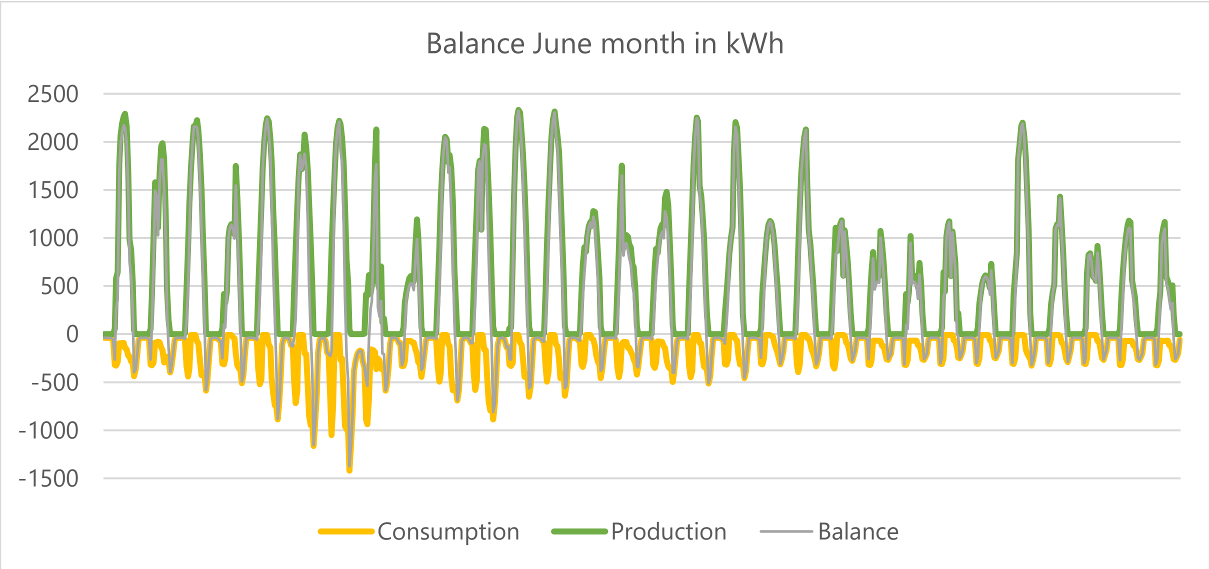


Figure 72: Energy balance in June of the reference year

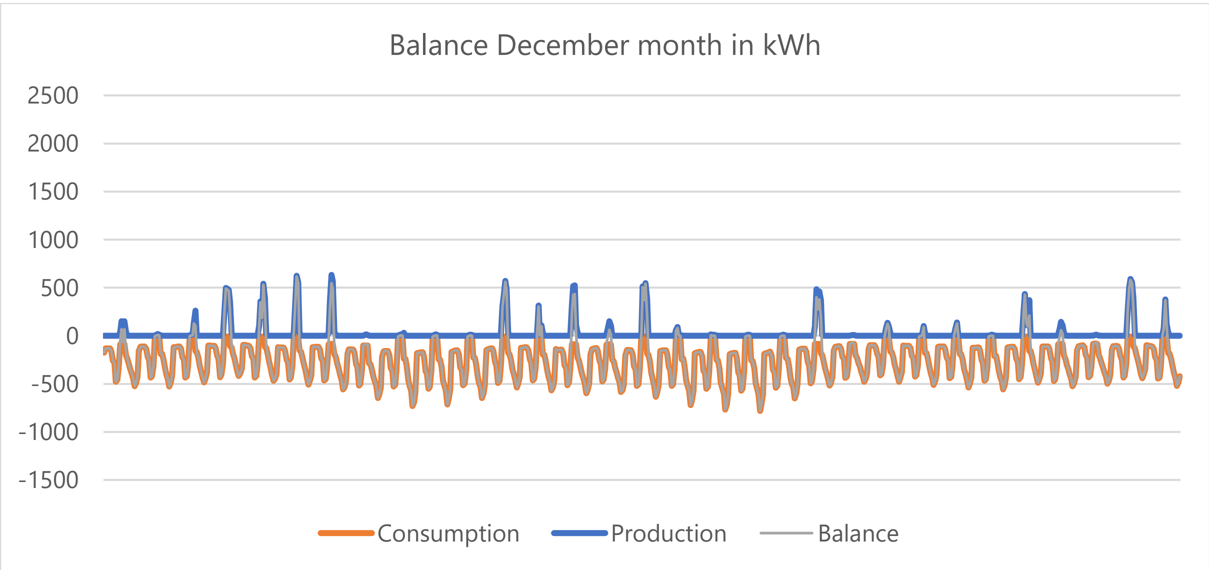


Figure 73: Energy balance in December of the reference year

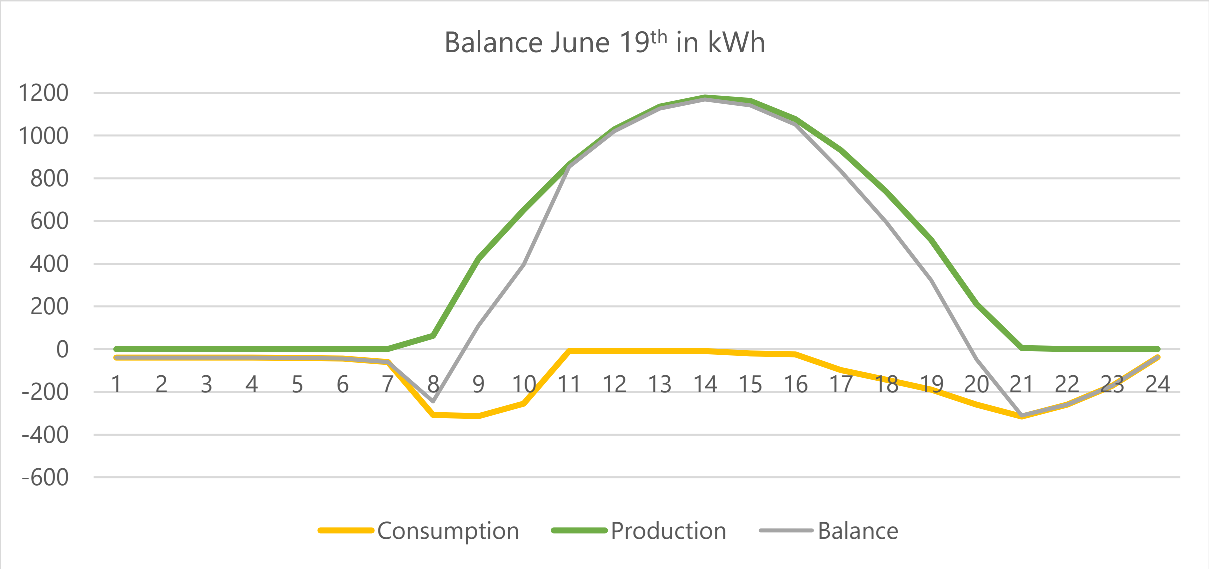


Figure 74 Energy balance for June 19th of the reference year

Balance June 19th			Balance December 21st		
Production	9,975	kWh	*Production*	1,780	kWh
Consumption	2,737	kWh	*Consumption*	6,375	kWh
Surplus	7,238	kWh	*Deficit*	4,595	kWh

Table 36: Overview of the energy balance of two reference days

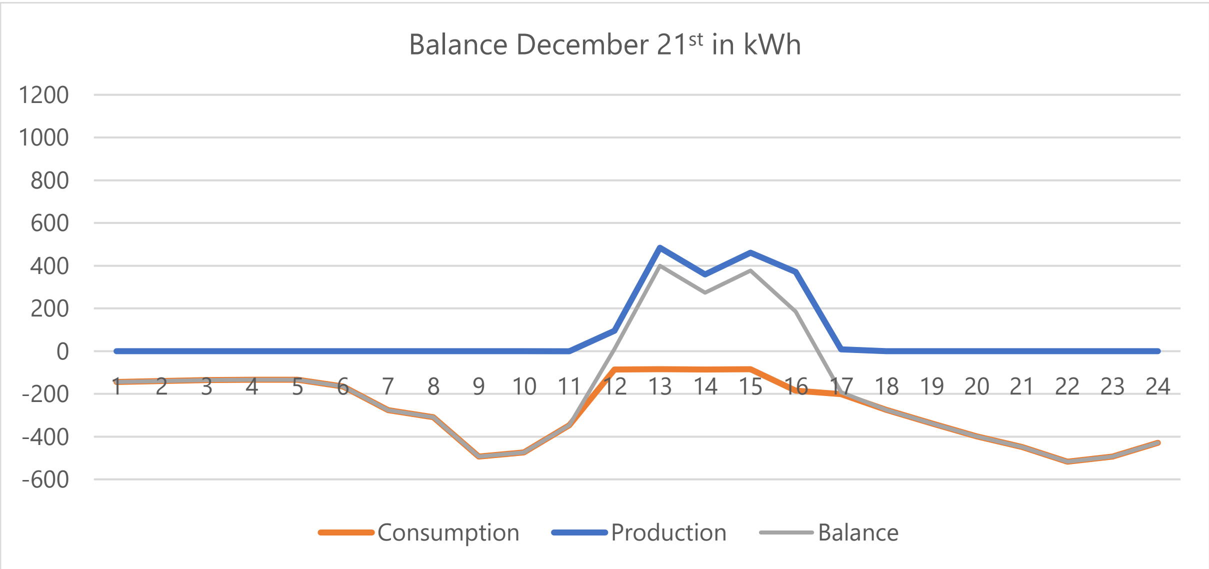


Figure 75: Energy balance for December 21st of the reference year

6.5 Conclusion energy balance

The calculated surplus is the result of a static balance. Every hour the consumption is subtracted with the production, so the balance is the result of hourly surpluses and deficits. The proposed system takes the surpluses to charge the seasonal storage, at short periods of deficits e.g. summer night, the consumer uses energy from the national grid. So the surplus described in this chapter is not the sum of all the surpluses that exist during the year, but the surpluses minus the deficits.

The sum of all the surpluses that exist during the year is 2,217,714 kWh, this is enough to charge the seasonal storage seven times. The implications of these results are discussed in the next chapter.

7 Energy surplus & efficiency

7 Energy surplus & efficiency

7.1 Electrolyser consumption

The surplus charges a battery that, in turn, powers the electrolyser. The electrolyser is not directly connected to the grid because the battery can deliver a constant power to the electrolyser. It takes up to 5.2 kWh to produce 1 m^3 of hydrogen (NEL Hydrogen, 2018) compressed to 200 bar.

The compressed hydrogen is stored in storage racks that can be placed inside or outside. The energy hub contains 12 storage racks, 6 racks can contain 264 kg (6.5 meters long) and 6 racks can contain 500 kg (12.3 meters long), which adds up to a total capacity of 4.590 kg of hydrogen compressed at 200 bar. One kilogram of hydrogen contains 120 MJ or 33.33 kWh.

Electrolyser consumption	Value	Unit
Electricity consumption incl. compression	81.1	kWh/kg
Energy capacity of hydrogen	33.33	kWh/kg
Storage capacity	4,590	kg
Energy storage capacity	152,984	kWh

Table 37: Electrolyser consumption data

One kilogram of compressed hydrogen at 200 bar at room temperature has a volume of 15.6 m3, according to Hydrogen Europe (Hydrogen Europe, 2018). Since 1 m3 of hydrogen requires 5.2 kWh electricity input for the electrolyser, 81.1 kWh is needed to produce 1 kg of hydrogen. So in order to completely fill the buffer 372,341 kWh of electrical energy is needed. This is much less than the surplus of electricity generated by the PV installation (2,217,714 kWh). This has consequences for the total energy system design and the design of the energy hub.

7.2 Fuel cell consumption

During the consumption season, the stored hydrogen is transformed back into electricity and heat with a fuel cell. The fuel cell has an efficiency of 50% electricity. Theoretically, the rest of the energy is liberated in the form of heat. This can recovered with a heat recovery system that is described in chapter 4.4.5.

Fuel cell consumption	Value	Unit
Hydrogen consumption	3,000	liter/minute
Stored hydrogen	4,590	kg
Hydrogen density	0.089	g/l
Stored liters	51,573,033	l
Hours operational	286	hours
Days operational	~12	days
Power output electric	67,904	kWh
Power output heat	67,904	kWh

Table 38: Fuel cell consumption data

7.3 Efficiency

372.341 kWh goes into the electrolyser, 67.904 kWh electric and 67.904 kWh of heat energy is produced by the fuel cell. The efficiency of the hydrogen system is 34%. This number is a theoretical maximum, the electric output efficiency should at least be reduced by 5% because of losses of the battery. The electric input should at least be enlarged by 5% because of the battery that connects the grid with the electrolyser.

Electric efficiency			
Input E from grid to battery	390,958	kWh	-5 % battery losses
Input E to electrolyser	372,341	kWh	
Output E from fuel cell	67,904	kWh	-5% battery losses
Output E to grid from battery	64.509	kWh	
Total efficiency electric	16.5	%	

Table 39: Electric efficiency of the electrolyser and fuel cell

The total efficiency for electricity and heating of the system comes down to

Total efficiency		
Input electric	390,958	kWh
Output electric	64,509	kWh
Output heating	67,904	kWh
Total efficiency	34	%

Table 40: Total efficiency of the electrolyser and fuel cell

As a reference, the average daily consumption between October and February is calculated: 5.150 kWh per day for all 226 houses. This means that the energy hub can supply the neighborhood energy for 12.5 days, so theoretically the neighborhood could be off-grid for almost two weeks during the winter.

7.3.1 Domestic hot water for the hotel

The heat from the fuel cell is used to produce domestic hot water for the guests of the hotel. According to AgentschapNL, the heating demand for domestic hot water for hotels in the Netherlands is 45 MJ/m^2 per year (AgentschapNL, 2012). To convert MJ to kWh, the number should be divided by 3.6 (because 1 kWh = 3.6 MJ). The annual energy consumption is 12.5 kWh/m^2 per year. The hotel is not designed yet so the floor area of the hotel is unknow.

DHW production for the hotel	Value	unit
Heating output from fuel cell	67,904	kWh
Consumption per m^2	12.5	kWh/m^2
Floor area	10800	m^2
Total consumption	135,000	kWh
Consumption covered by fuel cell heat	50	%

Table 41: maximum DHW production for the hotel

Based on the footprint of the hotel in the masterplan and, assuming two equal buildings on each side of the energy hub and 6 building levels, the hotel will have a surface of 10.800 m^2. So theoretically, the hotels energy consumption for the production of DHW can be reduced by 50%. However, transportation losses are not yet taken into account and the fuel cell is only operational for 12.5 days per year according to the energy system that is suggested in chapter 4. So 50% of the annual heating demand for DHW is produced during 12.5 days. To store this energy, another seasonal buffer would be required, but this is not part of the system.

This calculation is another incentive for a dynamic calculation. This way, the time of heat delivery and demand can be taken into account, rather than having the heat delivered only when the fuel cell in producing electricity.

7.4 Surplus versus balance

Chapter 6 is concluded with a suggestion of a dynamic balance calculation. Due to the high surplus and the low demand, several scenarios are imaginable to find a better balance in the energy system. A list of interventions and the possible effect on the energy balance of the system is given in this chapter.

7.4.1 Increase storage size

If the storage capacity of the energy hub is increased, more renewable energy that is produced in the neighborhood can be stored. The neighborhood can be self-sufficient for a longer period of time. Since the total surplus is 2,217,714 kWh and 390,958 kWh is needed to fill the buffer, the buffer should be 5.6 times larger to store all the surplus energy produced by the PV array. The storage containers that are proposed in the original system design are modular, so the storage size can be easily increased. In the design for the energy hub, more storage space is not taken into account, so a location near the energy hub should be found if the storage size is increased. A possible location could be inside the natural sound wall, which is situated to the south of the energy hub. This way, it would not only have the function of a sound wall, but also as a storage facility for renewable energy.

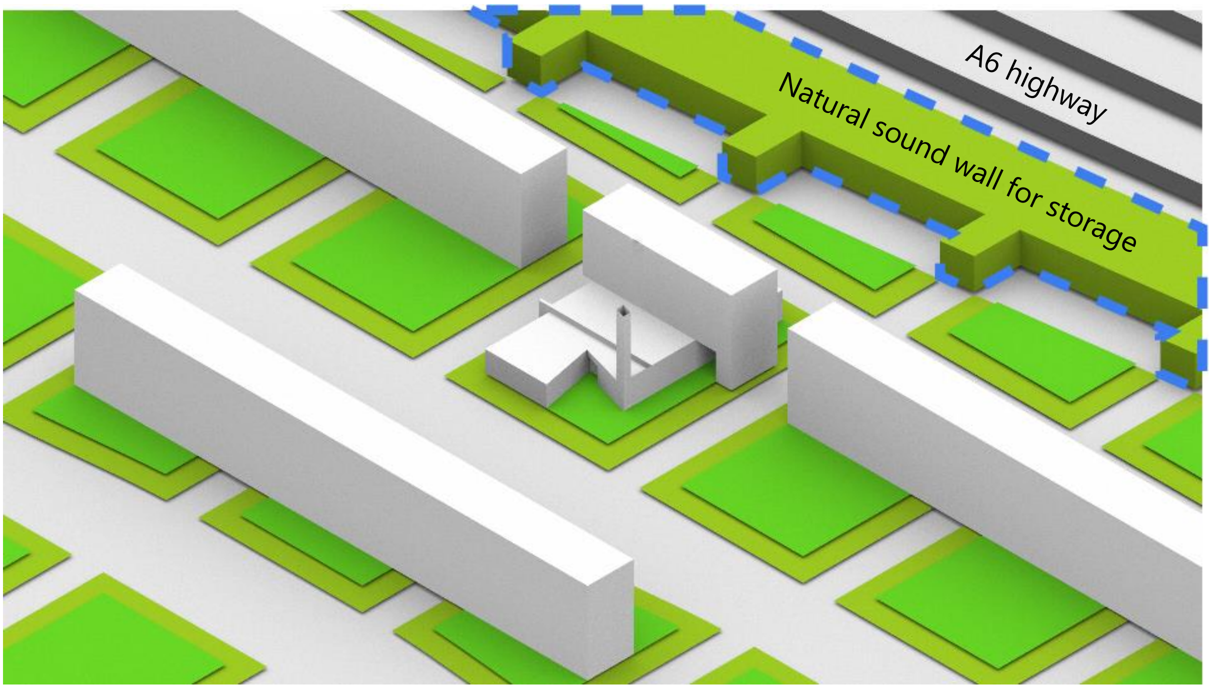


Figure 76: The natural sound wall as a possible location for additional hydrogen storage

7.4.2 Increase storage pressure

If the pressure of the storage system is enlarged, more hydrogen gas will fit in the same volume. The compression on hydrogen also costs energy, so doubling the pressure does not mean that the storage capacity is doubled. This can be explained by using the following method and formula to calculate the energy consumption of adiabatic compression:

$$W = \frac{n}{n-1} \times P0 \times V0 \times \left(\frac{P1}{P0}^{\frac{n-1}{n}} - 1 \right)$$

Symbol	*Meaning*	*Value*	*Unit*
W	Specific compression work	1.67913×10^5	J/kg
n	Adiabatic coefficient	1.41	-
P_0	Initial pressure	200 bar = 200×10^5	Pa
P_1	Final pressure	700 bar = 700×10^5	Pa
V_0	Initial specific volume	0.05555*	m^3/kg

Table 42: Values for adiabatic compression formula

*The initial specific volume is calculated with the ideal gas law:

$$PV = nRT$$

Symbol	*Meaning*	*Value*	*Unit*
P	Pressure	200	bar
V	Volume	0.05555	m^3
n	Amount of substance of gas	11.11	m^3/kg
R	Gas constant	Constant	
T	Absolute temperature	Constant	

Table 43: Values for ideal gas law equation

The electrolyser consumes 5.2 kWh/m^3 to produce compressed hydrogen at 200 bar. To further compress the hydrogen, an additional energy of 1.67913×10^5 Joule is required. Since 1 kWh equals 3,600,000 Joule, and a compressor has an efficiency of approximately 56%, it takes 0.83 kWh additional electricity to compressed hydrogen to 700 bar. So the total energy needed to produce hydrogen compressed to 700 bar, is approximately 6.0 kWh/m^3.

The density of hydrogen is 40 kg/m^3 (Makridis, 2016) when stored at 700 bar and the volume is about 2.5 times smaller. So 2.5 times more energy can be stored in the same volume, while costing only 15% more energy compared to storage at 200 bar.

7.4.3 Intermediate discharge of buffer

If the buffer discharges intermediately, e.g. to supply electricity to the smart grid at night or to refuel hydrogen vehicles, the buffer can be used more efficiently. It has been described before that a dynamic calculation is necessary to fully optimize the system components and to estimate the storage capacity and off grid operation duration.

Instead of applying hydrogen as seasonal storage, it could also be used as storage for a shorter term. If the buffer discharges when it is full, it can be recharged again so it becomes for example a bi-weekly storage. It can be argued that if short term storage is applied, other short term storage options should also be evaluated. It has become clear that the process of converting electricity to hydrogen and back to electricity has a low efficiency. So in that case short term storage in batteries might be more attractive.

Another possibility of intermediate discharge is mobility. Hydrogen can be used as fuel for fuel cell electric vehicles (FCEV). FCEV fit within the sustainability principles of Floriade, so in this case it could be interesting to use hydrogen to power hydrogen busses or even private cars. This is elaborated on in section 7.4.8.

7.4.5 Reduce amount of PV panels in the neighborhood

The balance can be adjusted by reducing the amount of PV panels on the roofs of the buildings. A quick calculation in the Honeybee model has shown that if the covered % of the roof would be lowered from 80% to 60 %, energy produced on the roofs would decrease by 25%. Less energy produced means a smaller surplus, but also results in more days where the daily balance is negative instead of positive.

7.4.6 Connect more users to the PV array

This intervention is a realistic option to flatten out the energy balance. For this research, 226 dwellings are considered. Because of the shortage of housing, the Municipality of Almere has decided that more houses should be built. If more houses are included in the system, the daytime surplus will be lower. It’s also possible to connect a hotel and a supermarket to a grid, but this will heavily disrupt the balance. Especially the supermarket has a very high energy consumption because of the high cooling demand for food.

7.4.7 Feed surplus energy to the national grid

Feeding the electricity is a possibility, but goes beyond the boundaries that are set for this research. If the energy cannot be buffered locally, it will be buffered on a national scale, making it the “problem” of the national grid operator.

7.4.8 Integration of mobility

With the increasing popularity of electric cars, the technology of electric mobility is advancing rapidly. Different types of electric vehicles can be distinguished: Conventional Hybrid Vehicles, Plug-in Hybrid Electric Vehicles (PHEV), Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV). (Union of concerned scientists, 2014)

Conventional hybrid vehicles

Hybrid vehicles combine a gasoline engine with an electric engine and contain a battery that is charged by capturing energy when braking. Gasoline consumption can be reduced because the electric engine works together with the gasoline engine. In some hybrid vehicles, the gasoline engine can be completely turned off to further reduce the gasoline consumption. The battery in this type of vehicle can only be charged by the energy captured when braking.

Plug-in hybrid electric vehicles

This type of vehicle is similar to the conventional hybrid vehicle, except they can be charged by plugging into an outlet. Like the conventional hybrid vehicle, the PHEV contains both a gasoline and a electric engine. Unlike the conventional type, it can use electric energy from the grid to power the engine. If renewable energy is used to charge the vehicle, it lowers the environmental impact. Most PHEV have an electric range of between approximately 20 kilometers and 80 kilometers. Vehicles with a higher electrical range up to 156 kilometers are also available (Autotrader, 2018).

Battery electric vehicles

BEVs run exclusively on electricity via on-board batteries. These can be charged by plugging into an outlet or charging station. The vehicles do not contain gasoline engines, so more space is available for batteries to increase the driving range. If the batteries are charged with renewable energy, BEVs do not produce tail pipe emissions. The range of this vehicle type ranges from approx. 200 kilometers to approx. 500 kilometers. Depending on the battery capacity (and thus the driving range) it can take up to 13.5 hours to completely charge the vehicle. This is the case for Tesla Model S, which has a driving range of 539 kilometers.

Fuel cell electric vehicles

This type of vehicles as well contains an electric engine, but the energy is stored differently. FCEV contain a hydrogen tank and a fuel cell that provide electricity for the electric engine. The hydrogen tank is filled like in a conventional car, at a hydrogen fueling station and takes approximately five minutes to refill. If the vehicle is filled with hydrogen obtained from electrolysis with renewable energy, the vehicle runs carbon neutral. Currently, the Netherlands counts only four hydrogen fueling stations, which should be mentioned as a disadvantage for FCEVs. However, eleven additional fueling stations are currently being planned. The first commercially available FCEV, the Toyota Mirai has a driving range of approximately 500 kilometers on a full tank of 5 kilograms of hydrogen. An important advantage of FCEV is that they can be refueled in minutes, similar to traditional vehicles.

If the stored hydrogen is used for mobility as well, the buffer is discharged intermediately. Private vehicles use on-board stored hydrogen at 700 bar, so the hydrogen from the buffer needs to be compressed before it can be used for vehicles. Since the density of hydrogen is 40 m^3/kg at 700 bar, an additional energy of 40 × 0.83 (see section 7.4.2) × 5 = 166 kWh is needed to compress 5 kg hydrogen to 700 bar for one car.

In case the buffer is used only for refueling hydrogen cars, 918 cars with a driving range of 500 kilometer can be filled, so it can provide enough hydrogen for a driving range of 918 × 500 = 459,000 kilometers. To compress all hydrogen to 700 bar, 40 × 0.83 × 4,590 = 152,388 kWh is needed. Since it takes 390,958 kWh to fill the buffer, the total energy needed for 918 refuels of cars is approximately 544,000 kWh.

A Tesla model S contains battery of 100 kWh and has a driving range of 539 kilometers. So per kilometer, 0.18 kWh is needed. Table 44 shows a comparison of battery electric vehicles and fuel cell electric vehicles.

	FCEV	*BEV*	*unit*
Energy needed	544,000	100	kWh
Driving range	459,000	539	km
Energy/kilometer needed	1.19	0.19	kWh/km

Table 44: comparison of hydrogen vehicles and electric vehicles

Instead of private vehicles, hydrogen can also be used for public transport. Belgian bus manufacturer has manufactured busses that run solely on hydrogen. They are equipped with a 38.6 kg on board hydrogen tank, that supplies enough energy for the bus to run on a full day schedule (Van Hool, 2018). The driving range is approximately 350 kilometers. So if the hydrogen storage is used for public transportation, it can deliver energy for (4,590/38.6) × 350= 41,619 kilometers of pollutant free public transport.

7.5 Conclusion energy surplus & efficiency

A solution must be found for the energy surplus, because wasting the surplus energy is not an option. An optimized solution for the amount of PV panels, amount of houses connected to the grid and adjustments to the storage components has not yet been found. This requires a dynamic model that takes into account all consumers and system components at the same time. For this research, only the consumption and production is considered. No optimal solution can be found by only looking at the production and the consumption, so a dynamic model that takes into account all components should be made. This model can be simulated and optimized to find a good balance for this neighborhood. A good way to start with this optimization would be to make a new model in HomerPro with the current knowledge of the building programme and energy consumption and production profiles.

8 Energy hub design

8 Energy hub design

8.1 Design goals & boundaries

The final part of the research consists of the design of a building that can house the central equipment that are part of the energy system design: the energy hub. The design of this building is defined by a set of boundaries that can be divided in three categories: dimensions of components, safety and visibility.

8.1.1 Dimensions of components

The design of the energy system includes various components that will be placed in the energy hub. The components that are selected for the energy system have been proven to work as discussed in the section where system components are described. The components that will be housed in the energy hub are described in the programme of requirements as can be seen in table 45.

Component		Dimensions [l x w x h] [m]	Room area [m^2]
Electrolyser	1x 2x	12.0 x 2.9 x 3.6 9.0 x 2.9 x 3.2	210
Fuel cell	1x	25 x 0.3 x 0.2 x 0.55 = 1.5 x 2.0 x 0.55	70
Battery	4x	6.1 x 2.4 x 2.6	125
DHW & heat recovery	1x	6 x 3 x 3	102
Hydrogen storage	6x 6x	6.5 x 2.4 x 3.0 12.3 x 2.4 x 3.0	189
Presentation room	1x		77
Entrance	1x		9
Staircase	1x		14

Table 45: Component dimensions & programme of requirements

8.1.2 Safety

In the literature research section, the hydrogen safety features are discussed. Hydrogen is a highly explosive gas at the right temperature and right mixture with air. Because of the high pressure storage of hydrogen, explosive mixtures can be formed quickly in case of a leakage. Therefore, measures should be taken to rule out risks of leakages. Leakages can exist if the hydrogen containing equipment is damaged, e.g. by impact. It is recommended to place a barrier between hydrogen equipment and the outside world to avoid damage by impact.

Barriers can exist in the shape of walls and poles, but natural barriers such as tranches or trees are also applicable. The barriers protect the equipment from impact from outside, but should also protect the outside from explosions inside the building. If an explosion takes place, the heat radiation should not be directed towards the public, but towards the sky.

In the unlikely case that a leakage does exist, accumulation of hydrogen should be prevented. This can be achieved by installing installations that dissipate the hydrogen, e.g. by increasing the pressure in the room and opening vents so the gas can egress the room and building.

A more low tech approach is proposed for the energy hub design. Because of the low volumetric weight of hydrogen and the resulting buoyant effect, hydrogen will disperse to the outside of the building though slits and cracks. This has been observed in a study performed by Kiwa Gastec (Crowther et al., 2015). Rooms that contain hydrogen equipment are naturally ventilated and an open connection between the inside of the room and the outdoor exists. Accumulation at ceiling level is prevented by placing the vents up to ceiling level and the ceilings are sloped towards the vents where the hydrogen can exit the building. To detect hydrogen leakages, air sensors should be installed, that give a notification if the hydrogen level increases.

8.1.3 Visibility

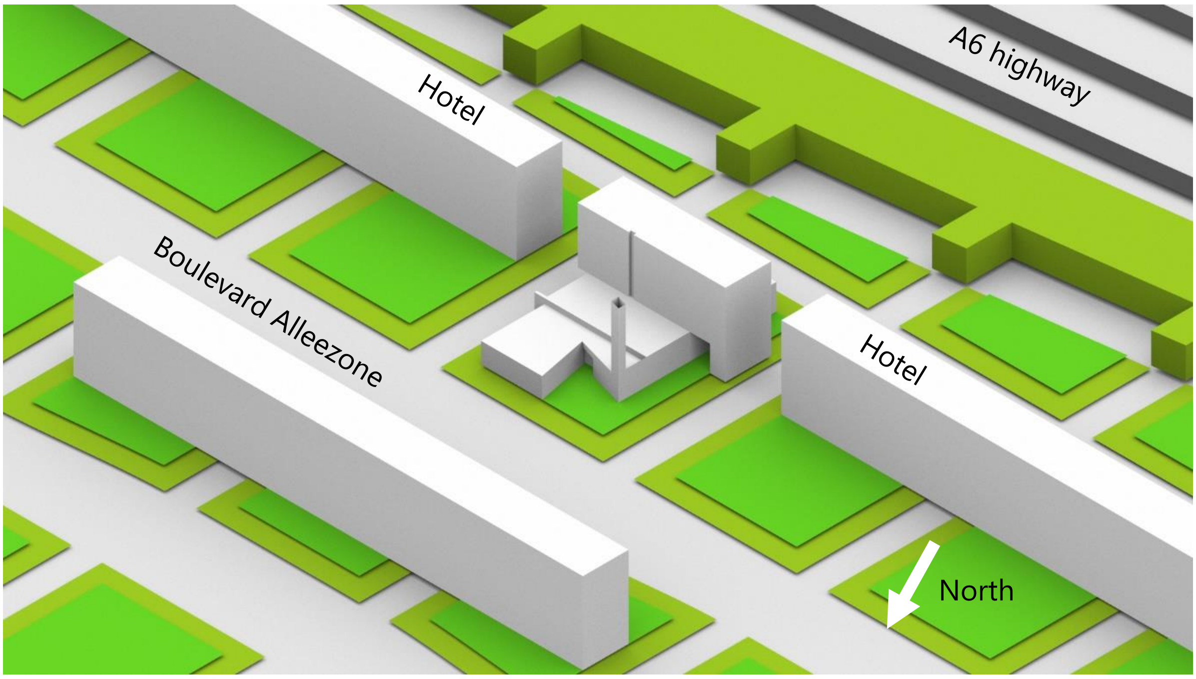
At the beginning of this research, it is described that hydrogen should have an example role and it should be a display of technology. The energy system is placed under the ground and the photovoltaics are placed on the roofs of the buildings, making it nearly invisible to visitors and residents. The element of the research that is visible to the public, is the energy hub.

Architectural design is not within the scope of this research, but a display of technology is. A balance should be found between technocracy (including safety and component size) and esthetics and experience. This poses a challenge because from a point of technocracy, it would be best to simply build a concrete bunker to keep outsiders out and explosions in. If an example should be set and a sensation of safety should be created, transparency is the way to go.

8.2 Context

The building is situated at the border of the neighborhood and surrounded by hotels and a highway. This location is chosen because from here, the heat recovered from the fuel cell can be fed directly to the hotel. The façade that faces the highway is also facing south, making it very suitable for a photovoltaics installation. The energy hub is isolated from houses, because it is situated on a boulevard, called "Alleezone" in the masterplan. In this area, the public functions of the neighborhood such as a cinema and a supermarket are housed. The building fits in this area of the neighborhood because of its large dimensions. The large volume would not fit in the residential area.

The height of the storage part of the building is aligned with the height of the surrounding hotel buildings.


A6 highway
Hotel
Boulevard Alleezone
Hotel
North

8.3 Design

The components and the way they have to be connected form the basis of the building layout.

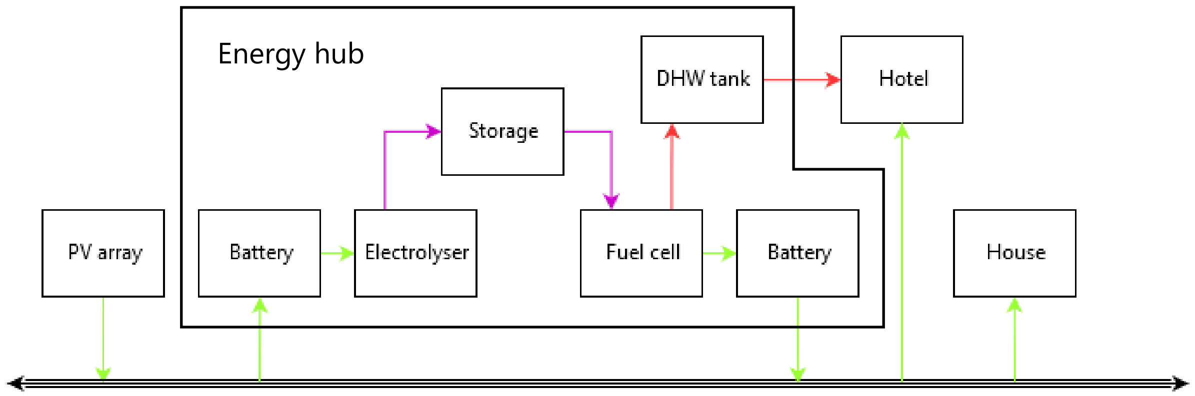


Figure 77: Energy flow in the energy hub

The components are arranged in a logical sequence, starting with energy coming in and energy going out. The delineated parts of figure 77 are the parts of the energy system that are placed in the energy hub. Electricity comes in through a battery and exits the building through a battery. Heat exits the building as hot water that can be used as DHW for the hotel.

Figure 78: Day and night view of the entrance of the energy hub

To rule out risks of impact from outside of the building, the storage volume is lifted above floor level. The impact of accidents as a result of leakage of the storage components are the highest. This has to do with depressurization of the high pressure storage vessels. If the hydrogen tanks quickly decompress, hydrogen will rapidly flow out. If the hydrogen is ignited e.g. by a spark caused by metal hitting metal, a flash flame will exist.

The risk of flash flames is lower for the other components as they do no handle compressed hydrogen, except the output of the electrolyser. The pipe that transport the compressed hydrogen from the electrolyser to the storage vessels should be protected against impact.

300 millimeter concrete walls protect the components on the ground floor of the building and protect the outside in case of an explosion. In case of an explosion the energy will be directed towards the sky restricting the damage to the energy hub and its equipment. The roof of the building is made of light weight metal, so this will be the easiest direction for heating radiation in case of an explosion. Openings in the building are necessary to naturally ventilate the rooms and to avoid accumulation at ceiling level. The rooms where hydrogen is produced or consumed are naturally ventilated by vents in the wall, ceiling or floor.

The storage room is ventilated by a large vent in the floor of the cantilevering part of the second floor. At the top of the room, vents are placed at ceiling level so the hydrogen naturally escapes the building. The electrolyser room and fuel cell room are ventilated with vents in de wall and vents on ceiling level. The wall that supports the cantilevering part of the storage volume also counts as a fire barrier. Heat that exits the building through the opening in the wall of the electrolyser room is partially stopped by this wall. Heat that exits the building through the opening in the fuel cell room is redirected towards the side of the building.

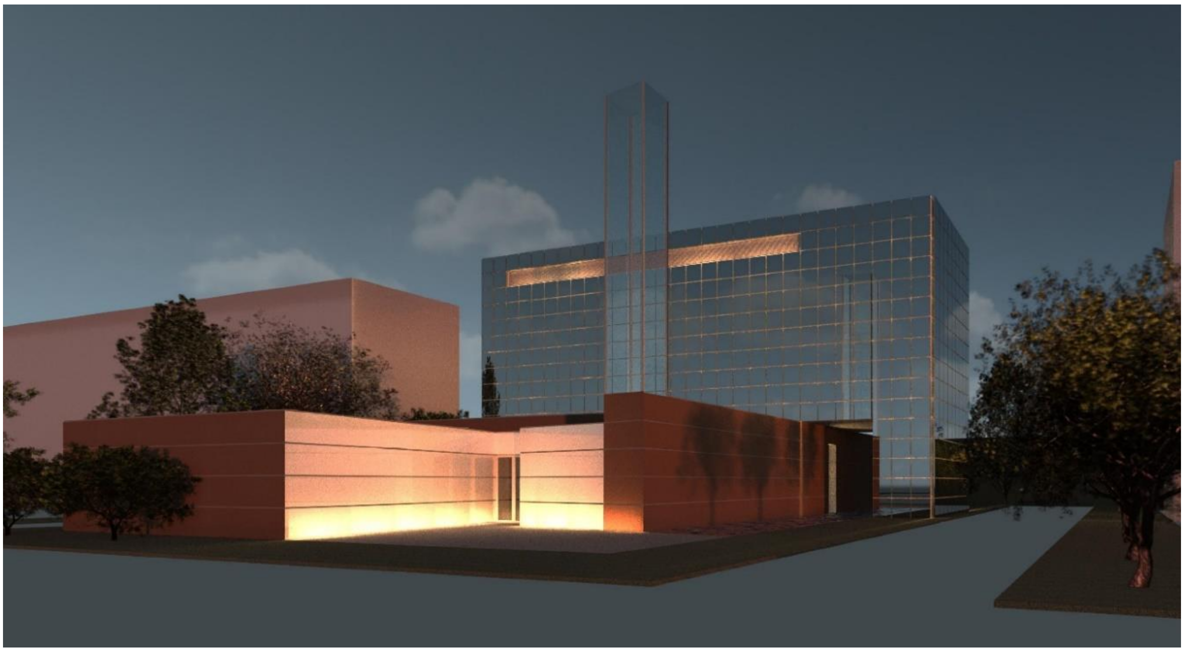


Figure 79: Night view impression of the energy hub

The thick walls give the feeling of a bunker. However, at the center of the building, a presentation room is situated. In this room presentations can be given and visitors can be received. This room is the only insulated room in the building, because the other rooms are connected directly to the outside of the building for ventilation purposes. The insulation is placed on the interior side of the presentation room, so the room becomes an insulated box. Visitors are attracted towards the entrance of the building because of the contrasting light metal façade on the north-west part of the building. The building can be entered through tall glass doors and the first thing that is noticeable when entering the building are the skylights. The large skylights offer a view on the mirror façade of the storage volume and allow light to enter the room. From this room, all "hydrogen" rooms can been seen through tall interior windows and they can be entered from this room.

Figure 80: Day and night view of the presentation room

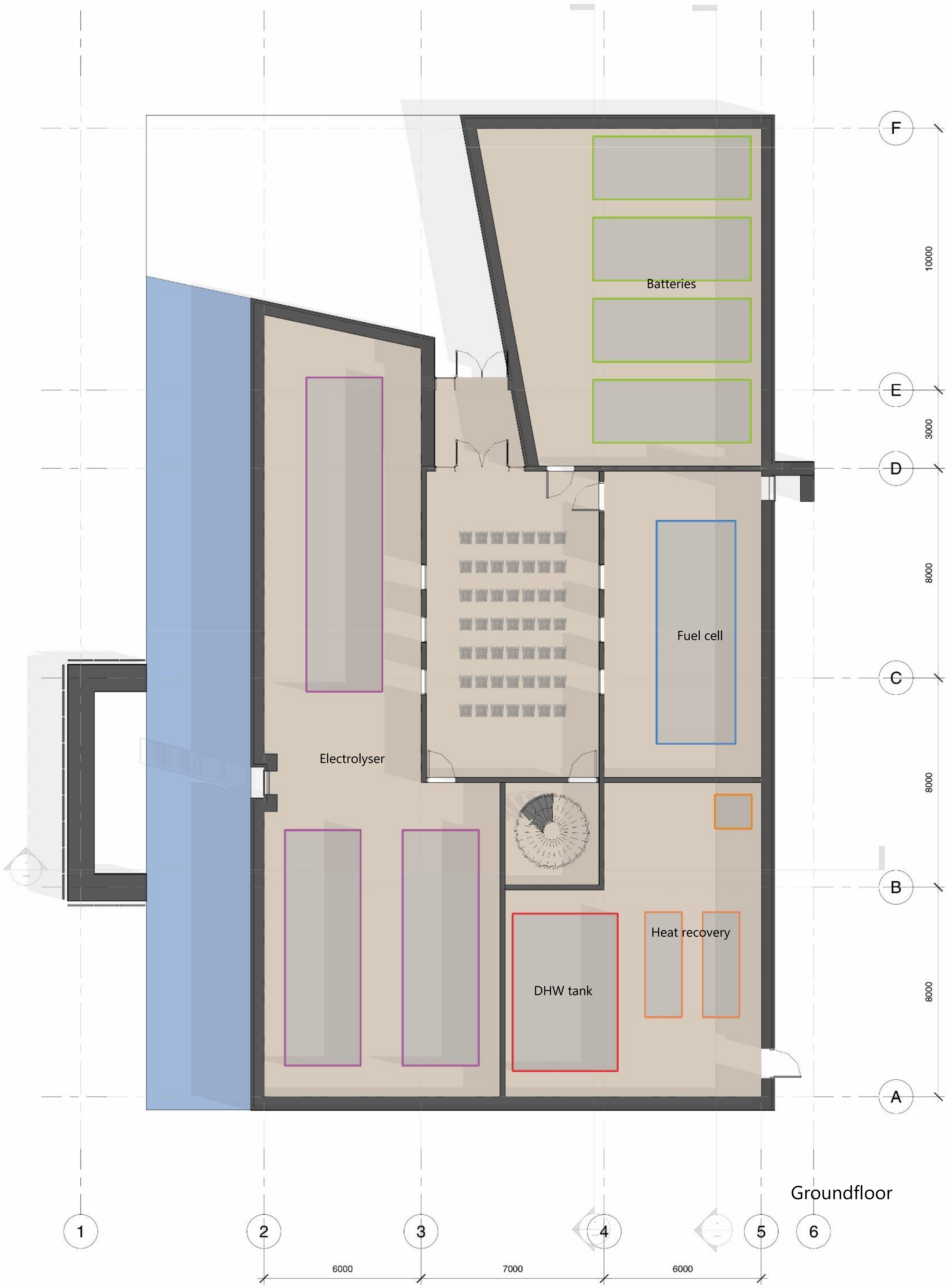
One door leads towards the staircase that lead visitors towards the storage volume. The spiral staircase takes the visitors 12 meter high storage room where 4590 kg of hydrogen is stored in 6 large and 6 small sea containers. From here , the visitor has a view of the Floriade terrain because this part of the façade is partially semitransparent.

Because of the safety measures, it is assumed that no explosion will take place. For this reason, the interior walls are not explosion resistant. The applied system components are proven to work and are all suitable for placement outside. For this reason, thermal insulation is also not taken into account.

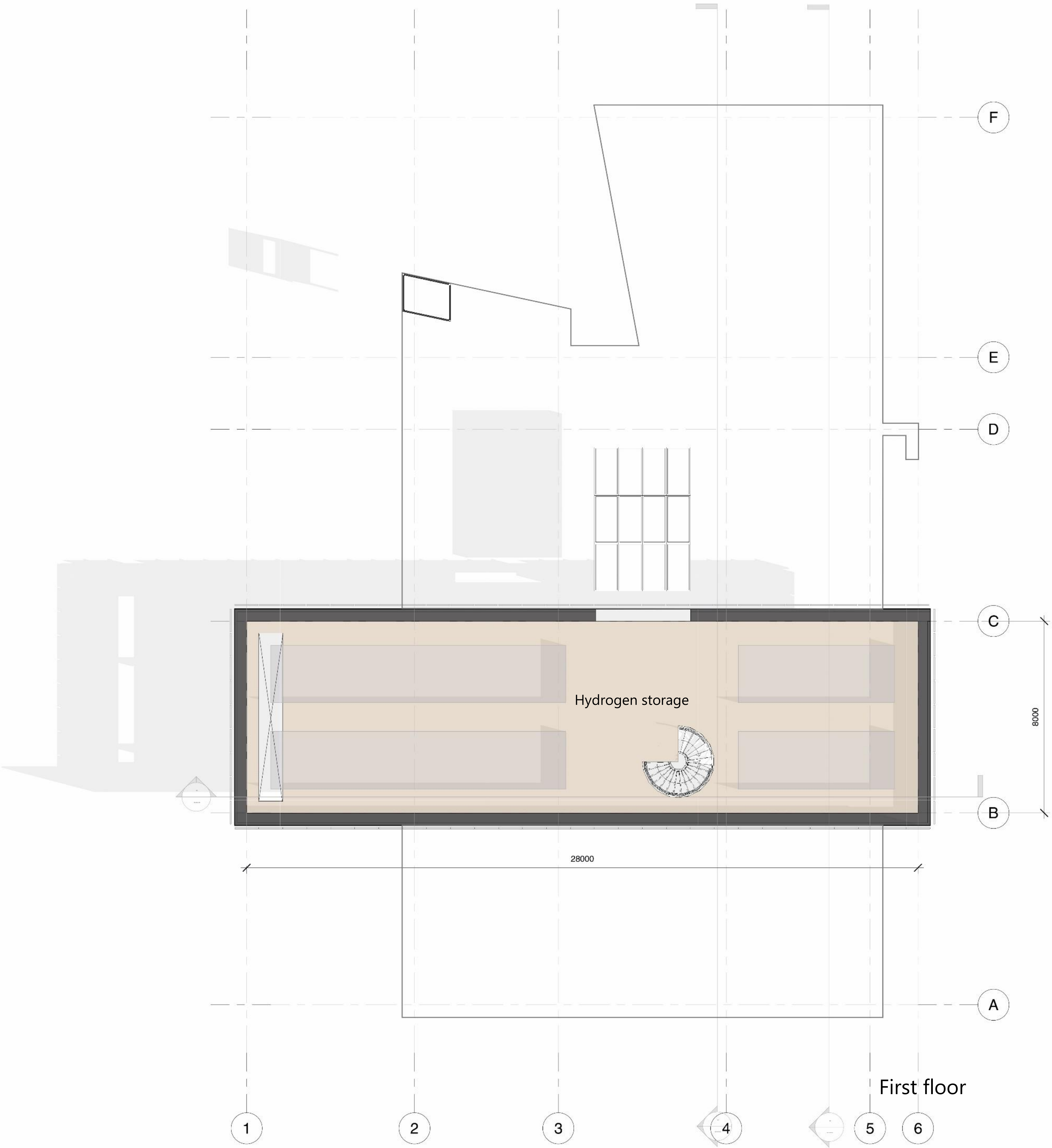
To get a sense of openness, the façade of the storage part of the building is cladded with semitransparent mirrors. These mirrors will reflect the Floriade terrain by day, so the storage part more or less disappears in the building landscape of the Alleezone. By night, these mirrors will no longer reflect views from the outside, but give a hint of what is happening inside the building. The part where the visitors can walk around in the storage part will be illuminated so the interior of the building becomes visible. The other part of the façade will display the current stored capacity of the seasonal buffer. This is achieved by placing LED light strips. If the storage is empty, the façade will not be illuminated, but the more the buffer is charged, more LEDs will be illuminated. With a relatively simple system, the façade can be display how much the buffer is charged. It can even be programmed with moving effects, so it actually looks like the building is charging, similar to the battery charging icon on a telephone. Under the cantilevering part of the building, a pond is built. This way, the public has no access to the vents that lets in air to avoid hydrogen accumulation. But it also reflects the reflective façade, so that even when people don't look up, the mirroring façade can still be seen.

Iconic for a power plant is the chimney, that usually lets pollutants or waste heat exit the building. In the design of the energy hub a chimney is also included. Instead of polluting the environment, it vents pure oxygen into the atmosphere. The oxygen is a " waste" product of the electrolysis process. Representative for the clean air it exhausts, the chimney is made of glass. If it would exhaust pollutants, soot would be form on the surface of the glass, but this is not the case for pure oxygen.

Figure 81: Day and night view of the north facade



Groundfloor



First floor


1
2
3
4
5
6
Level 6
15500
Level 5
12000
Level 4
8500
Level 3
5000
Level 2
4000
Level 1
Hydrogen storage
Electrolyser
DHW &
Heat recovery


A
B
C
D
E
F
Level 7
Level 6
15500
Level 5
12000
Hydrogen storage
Level 4
8500
Level 3
5000
Level 2
4000
DHW
Heat recovery
Fuel cell
Batteries

8.4 Building technology

8.4.1. Piping

The system components are placed in the building in a logical sequence. Each component is placed in its own room, but is connected to the other components through wall openings.

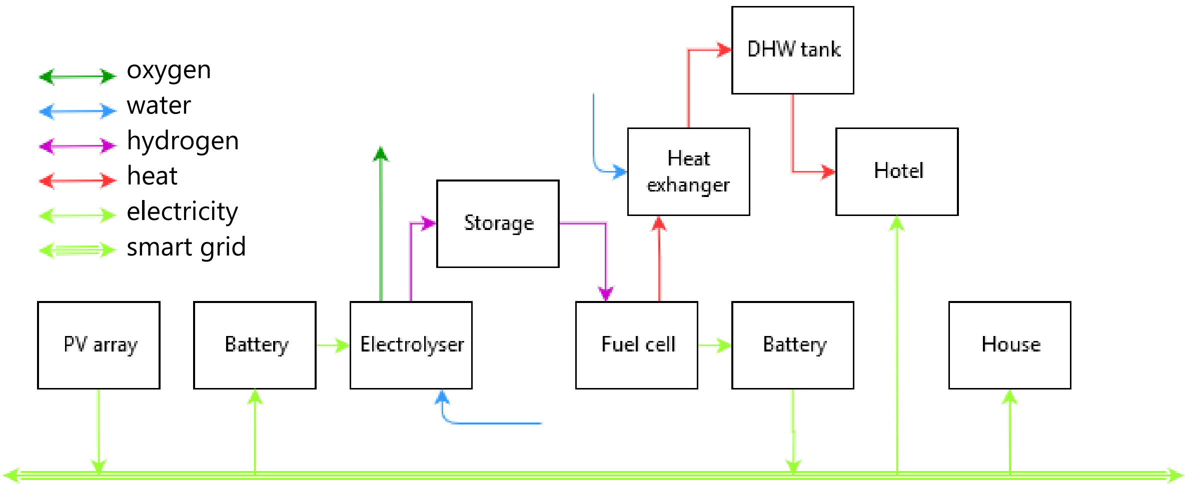


Figure 82: flow diagram of material streams in the energy hub

The energy in the energy hub follows the following sequence:

1. The collective PV array converts solar energy to electrical energy and feeds the electricity to the smart grid.
2. In case of a surplus of energy, a battery is charged
3. The battery powers the electrolyser
4. The electrolyser uses the electricity to split water in hydrogen and oxygen
5. The hydrogen is stored in hydrogen vessels at 200 bar
6. Hydrogen is the feedstock for the fuel cell, which converts it to heat and electricity
7. The electricity is used to charge a battery, this feeds it back to the smart-grid at times of deficits
8. The fuel cell is water-cooled, so the heated water is fed to a heat exchanger, that exchanges heat with cold water.
9. The heated water is stored in a tank, until it is ready for consumption by hotel guests

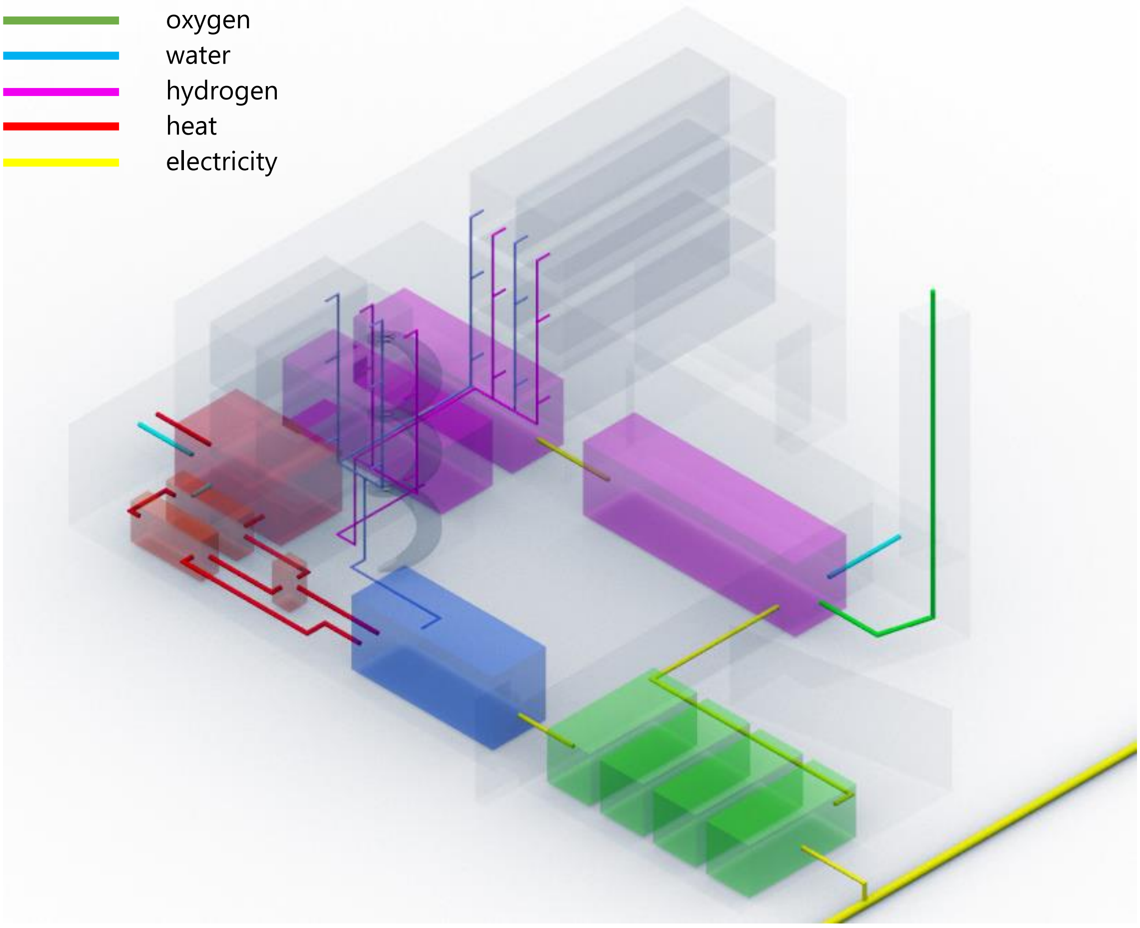


Figure 83: Overview of the piping in the energy hub, view from north east

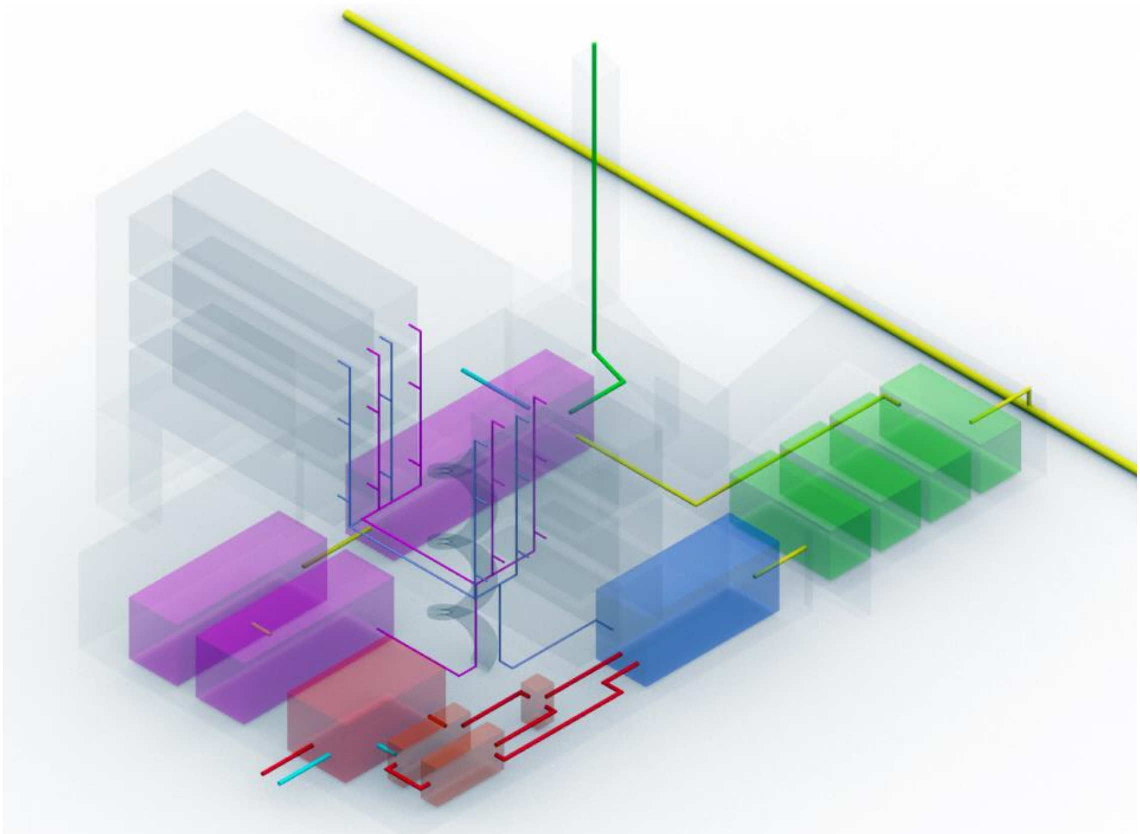


Figure 84: Overview of the piping in the energy hub, view from south east

8.4.2 Construction

The building is mostly constructed of concrete for safety reasons. The ground floor level is basically a concrete box with ventilation openings and an entrance. The equipment on the ground floor is very heavy, e.g. a completely filled DHW tank weighs over 8.000 kgs and one battery bank weighs over 10.000 kgs. This should be taken into account when designing the foundation of the building.

The construction design of upper volume of the building is more interesting due to the weight of the hydrogen storage tanks. The weight of these tanks is not given by the manufacturer, Nel Hydrogen, so an assumption is made. The only know properties are the vessel type and material: type II and steel. According to Züttel, the wall thickness of a high pressure cylinder capped with two hemispheres is given by the following equation (Züttel, 2003):

$$\frac{d_w}{d_o} = \frac{\Delta \mathrm{p}}{2 \times \sigma_\mathrm{v} + \Delta \mathrm{p}}$$

Symbol	*Property*	*Value*	*Unit*
d_w	Wall thickness	0.0066	m
d_o	Outer diameter	0.75	m
Δ_p	Overpressure	200 bar (20 MPa) – 1 bar (0.1 MPa)= 19.9	MPa
σ_v	Tensile strength of HQ steel	1100	MPa

The amount of steel needed for the tubular part of one vessel is estimated by multiplying the area of the section of the vessel with the length and density of steel:

$$(\pi \times d_o^2 - \pi \times (d_o - d_w)^2) \times l \times \rho$$

Symbol	*Property*	*Value*	*Unit*
d_w	Wall thickness	0.0066	m
d_o	Outer diameter	0.75	m
l	Length of vessel	12.3 (long rack) 6.5 (short rack)	m
ρ	Volumetric density of steel	7900	kg/m^3

The amount of steel needed for the hemispherical part of one vessel is estimated by deducting the volume of the outer hemisphere with the volume of the inner hemisphere according to:

$$V = \frac{1}{2} \times \frac{4}{3} \times \pi \times r^3$$

Tubular part:

Long: $\pi \times 0.375^2$ - $\pi \times (0.375\text{-}0.0066)^2 \times 10.3 \times 7900$ = 1315 kg

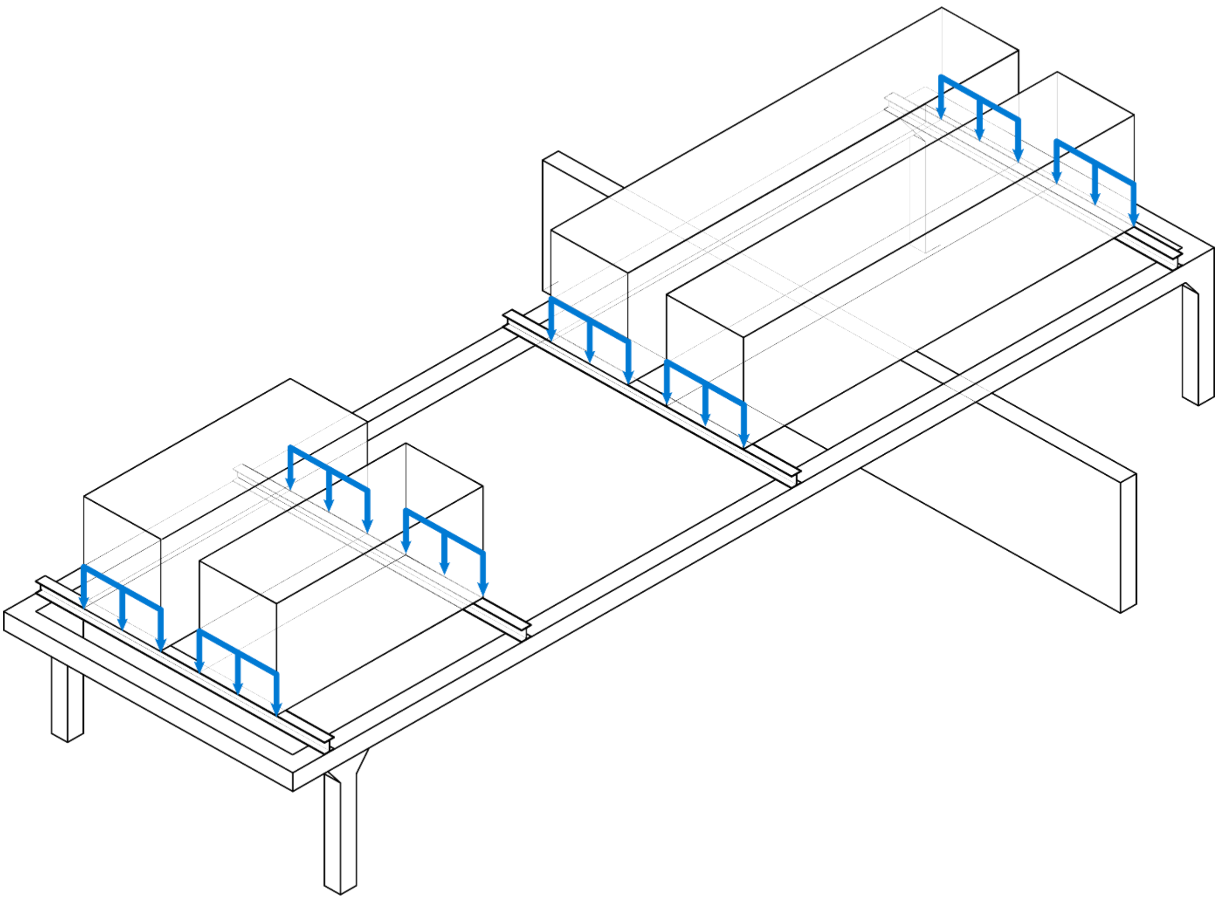
Short: : $\pi \times 0.375^2$ - $\pi \times (0.375\text{-}0.0066)^2 \times 5.0 \times 7900$ = 608 kg

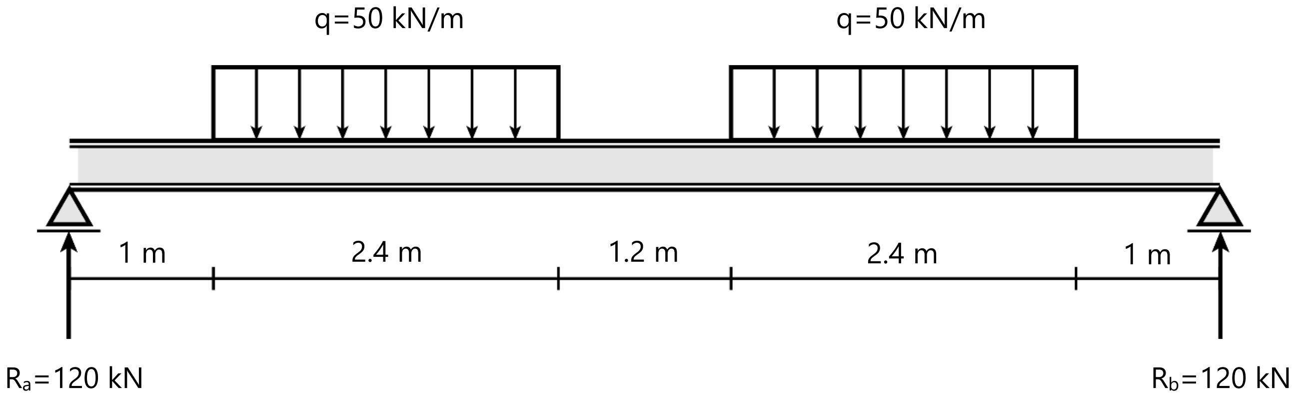
2 x Hemispherical part:

$2 \times \frac{1}{2} \times \frac{4}{3} \times \pi \times 0.375^3 - \frac{1}{2} \times \frac{4}{3} \times \pi \times (0.375 - 0.0066)^3$ = 90 kg

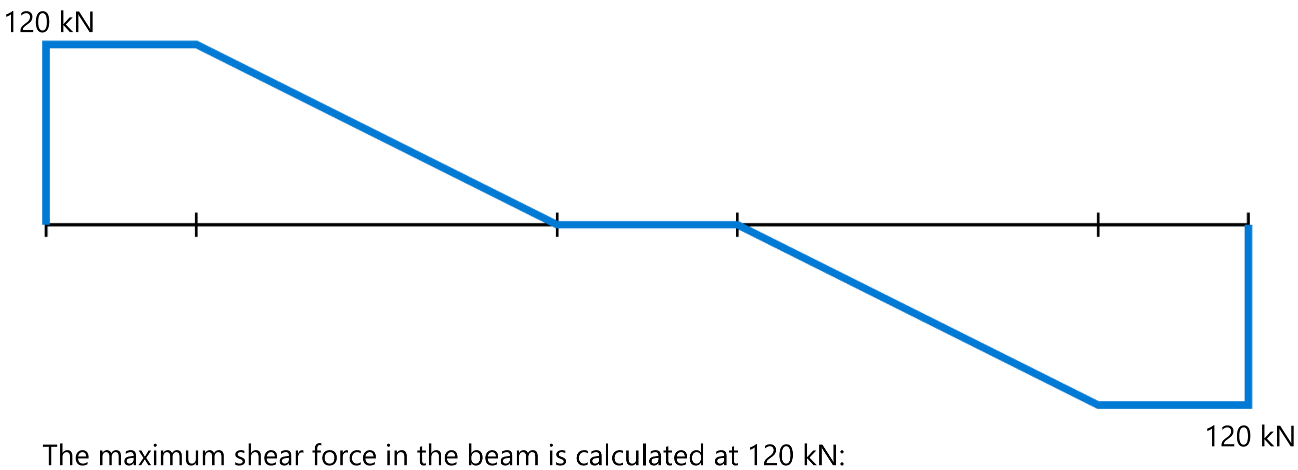
	Weight per vessel	*Amount of vessels*	*Storage capacity*	*Total weight*	*Unit*
Long rack	1315 + 90	15	500	21575	kg
Short rack	608 + 90	15	264	10734	kg

Now that the weight of the storage containers is know, the dimensions of the structure can be determined. This is an estimation based on the volume of the steel vessels, the weight of the carrying structure is not included. For the calculations, the numbers are simplified to 24.000 kg for the long rack and 12.000 for the short rack. This is leads to the following statically determined scheme:





The weight of the long storage rack is assumed to be 24.000 kg. It is supported by two beams, so each beam should support 12.000 kg per storage rack. Each beam supports two storage racks, so two q loads are placed on the beam. The calculation is only performed for the long storage rack, because these beams have to support the most weight.



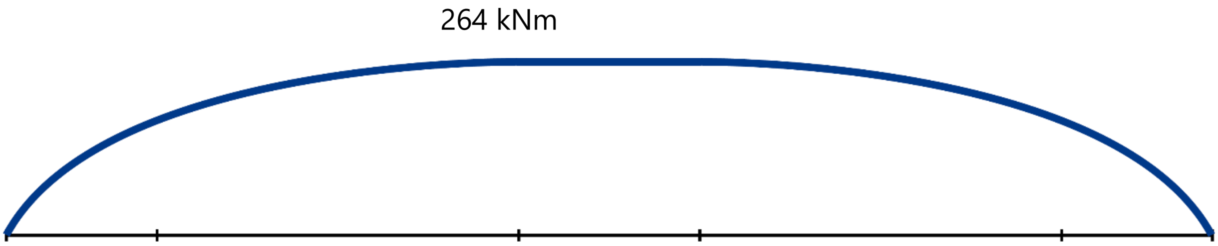
The maximum shear force in the beam is calculated at 120 kN:

∑vertical forces: $R_a+R_b-q_1-q_2= 0$

Symmetry so $R_a=R_b$ and $q_1=q_2$ so

$R_a=120$ kN

$R_b=120$ kN



The maximum bending moment in the beam is calculated at:

2.2 × 120 kN = 264 kNm

With the shear forces and bending moment known, a beam that supports the storage racks can be selected. According to NEN-EN 1993-1-2+C2:2011 nl, a HEA340 profile is suitable when a safety factor γ_{M0}=1.4 is applied. The relevant properties of this steel profile are given in table 46.

HEA 340	*Value*	*Unit*	*check*
Steel type	S235	-	
Second moment of area	276.9	$\times 10^6$ mm^4	
Design elastic bending moment resistance	281.7	kNm	>264 kNm
Design elastic shear force resistance	435.6	kN	>120 kN

Table 46: Properties of HEA340 steel profile

The website ("Constructieberekeningen.info," 2019) calculates the maximum deflection of the beam, which is in this case 31.57 mm. This is taken into account for the design of the concrete "Vierendeel" construction.

The storage racks are supported by a rigid concrete frame, sometimes described as a Vierendeel structure. The frame consists of reinforced concrete columns and beams that form a rigid construction. Because of the height of the building, it has to deal with wind loads and shear forces. To offer resistance against these forces, the voids in the frame consist of standard infill walls. Two walls of the ground and the thick wall that supports the cantilever part on the west side of the building transport all forces to the foundation. This foundation consists of concrete beams and round foundation piles.

There is one exception in the structural system where concrete walls are replaced with windows. Visitors of the energy hub can go up to the storage part of the building to have an overview of the Floriade through windows. At places where windows are placed in the concrete frame, a steel cross is placed instead of a concrete wall. An overview of the structural system is given in figure 85.

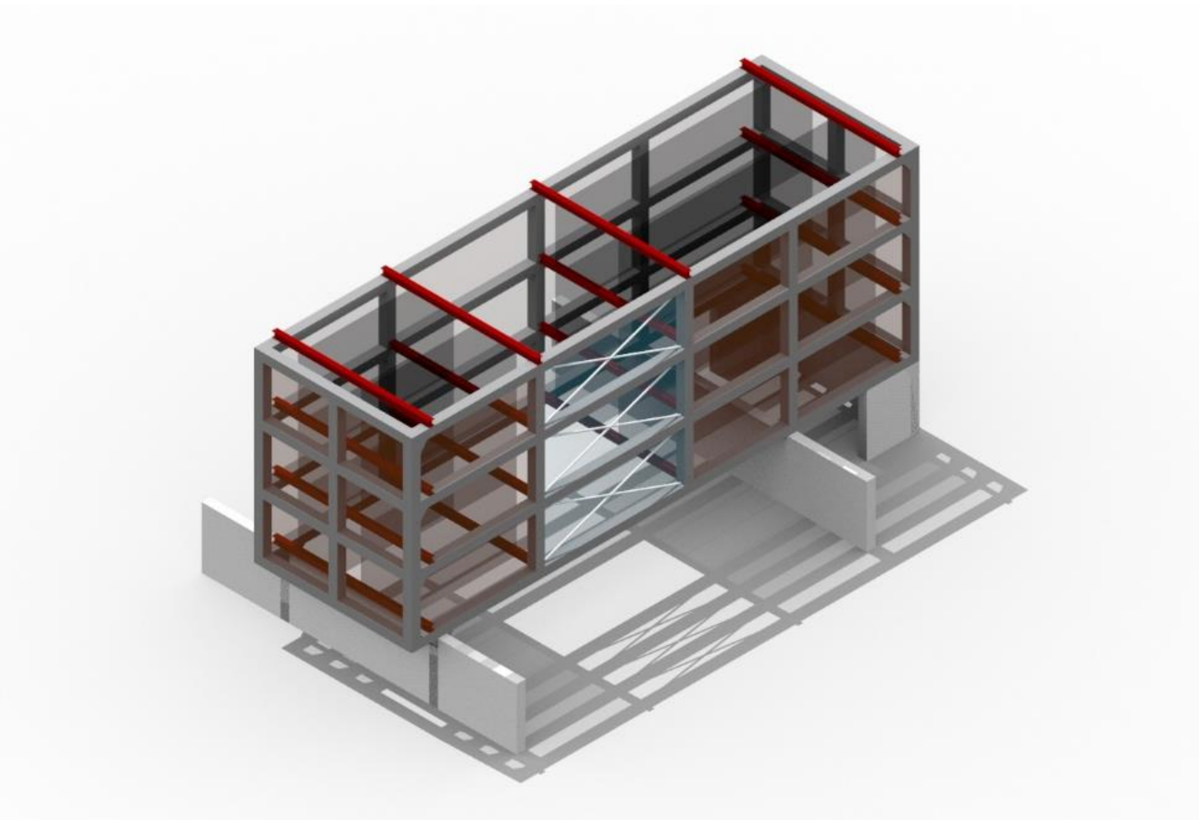


Figure 85: Visualization of the construction elements of the energy hub

8.4.3 Façade design

The building has three types of facades, the façade of the ground floor is mostly cladded with weathering steel panels, with an exception on the part where visitors enter the building. This inner part of the ground floor façade is cladded with white metal panels. The panels are mounted on brackets so the mounting system is not visible. The weathering steel façade looks heavy and the white panels look light. This light material is chosen to offer some contrast with the closed façade. The weathering panels are selected because its appearance match with the function of the façade: protecting the equipment inside the building.

For the part of the façade that directs visitors towards the entrance of the building, a material with a lighter appearance is selected. It stands out from the rest of the façade and looks friendlier than the weathering steel. The entrance of the building is at the intersection of the two white façades.

Figure 86: A weathering steel facade. image retrieved from https://www.ssab.com/products/brands/ssab-weathering-steel

Figure 87: A white metal plate facade. image retrieved from https://www.universefacadesolutions.com/about/materials/alpolic-metal-composite

The upper part of the building is made out of a concrete frame that supports HEA 340 profiles which support the hydrogen storage containers. The north, east and west part of the storage volume is cladded with semitransparent mirrors that are mounted to a construction. This construction is secured to the concrete walls. LED strips are placed between the mirrors and the concrete walls, so the building is illuminated in the dark. The LEDs are placed inside a steel profile that offers room to both the LED strips and the cables to connect all LED strips. The part of the profile that is directed towards the exterior, contains an perspex translucent plate that diffuses the light emitted by the LEDs. This way, the light is visible as a clear line in the façade, as can be seen in figure 88. Figure 89 shows the detail of the façade system. This detail with more information is included in appendix V on 1:1 scale.

Figure 88: example of facade with LED lightstrips combined with a diffuser. retrieved from https://www.osram.com/ls/projects/gwh-tower-block/index.jsp on 21-01-2019

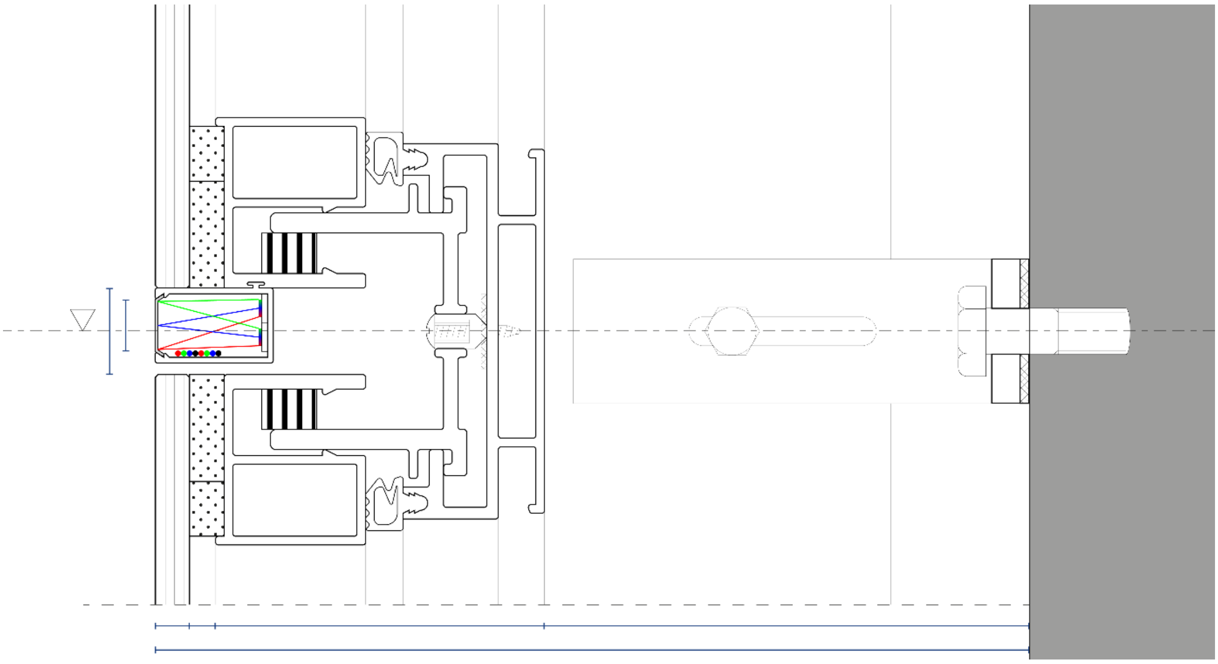


Figure 89: detail of the facade system with integrated LED strips

The concrete walls stop at the staircase, here the façade only exists of mirrors placed on the steel frame, so visitors of the energy hub have a view of Floriade.

Figure 90: Mirror facade of Sears headquarters in Alhambra, Califormia USA by Albert C. Martin & Associates. image retrieved from https://pinupmagazine.org/articles/panorama-a-short-history-of-the-mirrored-glass-facade-buildings-ouida-biddle

The second row of panels from the top of the building is removed to make room for a vent. This vent makes sure hydrogen cannot accumulate at ceiling level. The vent is also illuminated so it becomes part of the architecture instead of being hidden, similar to Delftse Poort tower in Rotterdam.

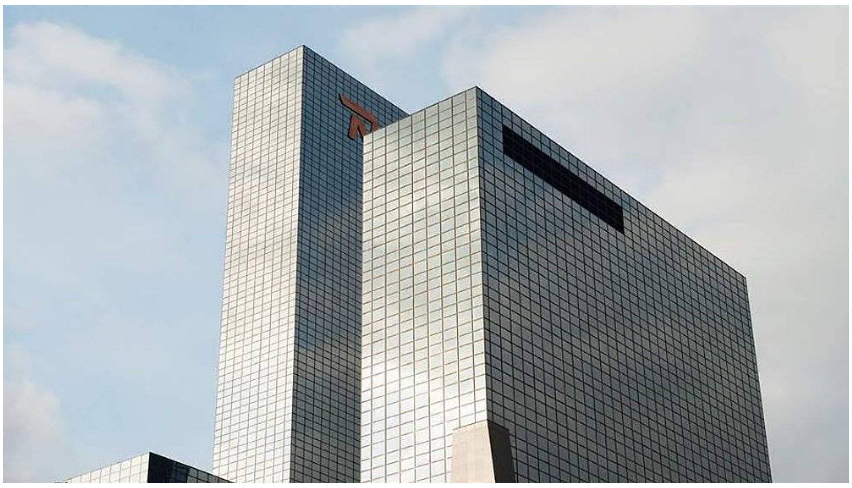


Figure 91: Delftse Poort in Rotterdam by Abe Bonnema. image retrieved from https://www.cityguiderotterdam.com/nl/er-op-uit/architectuur/delftse-poort-rotterdam/

The south façade is covered with 174 PV panels that generates 8636 kWh additional electricity per year. The production is 37.2 kWh/m2 which is much lower than the roof mounted PV panels. This is explained by the efficiency reduction due to the placement angle. They are mounted on a steel frame that is attached to the concrete wall of the storage volume. This façade faces the A6, but because of the natural sound wall that separates the Floriade terrain from the highway, the façade is barely visible from the point of view of a driver. The natural sound wall is low enough and the building is far enough away from the dyke to not cast a shade on the PV panels, so they can perform optimally.

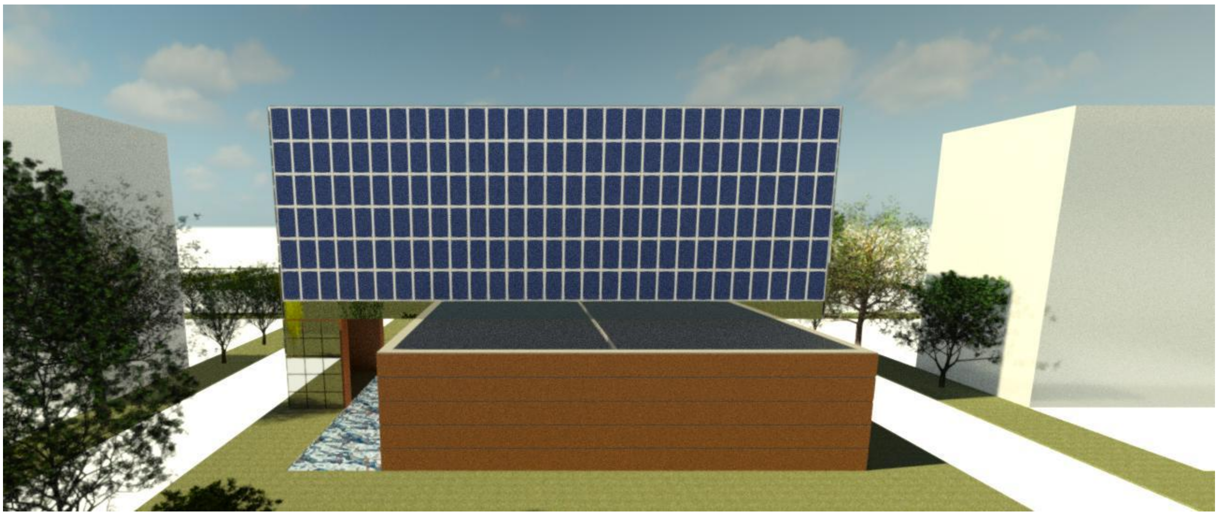


Figure 92: View on the south facade standing on top of the natural sound wall

8.4.4 Ventilation

The building is naturally ventilated to avoid accumulation of hydrogen in case of a leakage. Figures 93 and 94 show the vents and the natural flow of air through the building. The ceilings of the rooms are placed under a slight angle so the in unlikely event of a leakage, the hydrogen automatically egresses the building through the vents near the roof. In figure 95 on the next page, a detail of the cantilevering part of the building is given. Figure 96 shows a detail of the lightweight metal roof where also a vent is placed. These details with more information are included in appendix V on 1:10 scale and 1:5 scale.

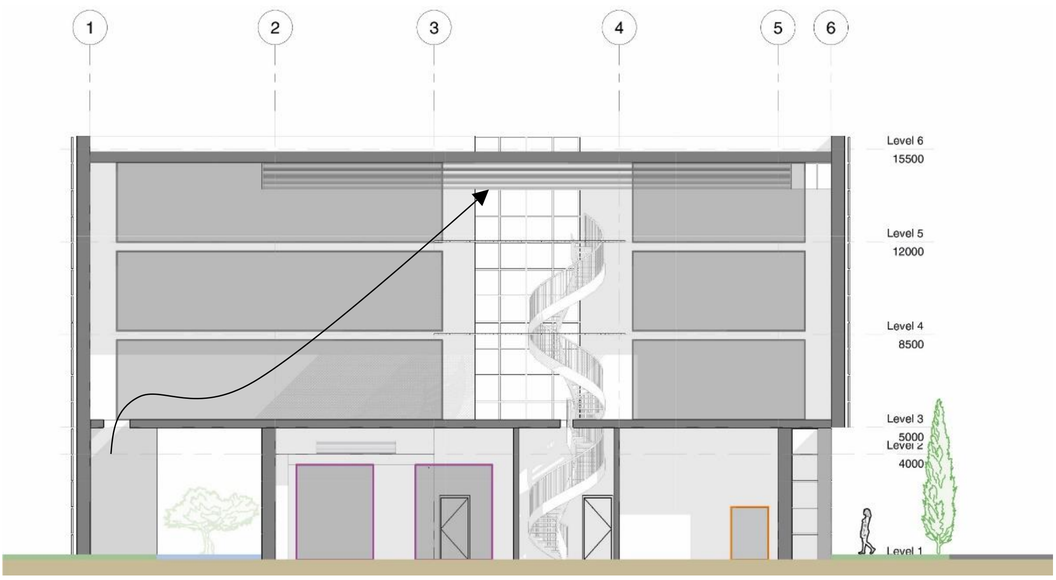


Figure 93: Natural ventilation principle of the energy hub storage volume

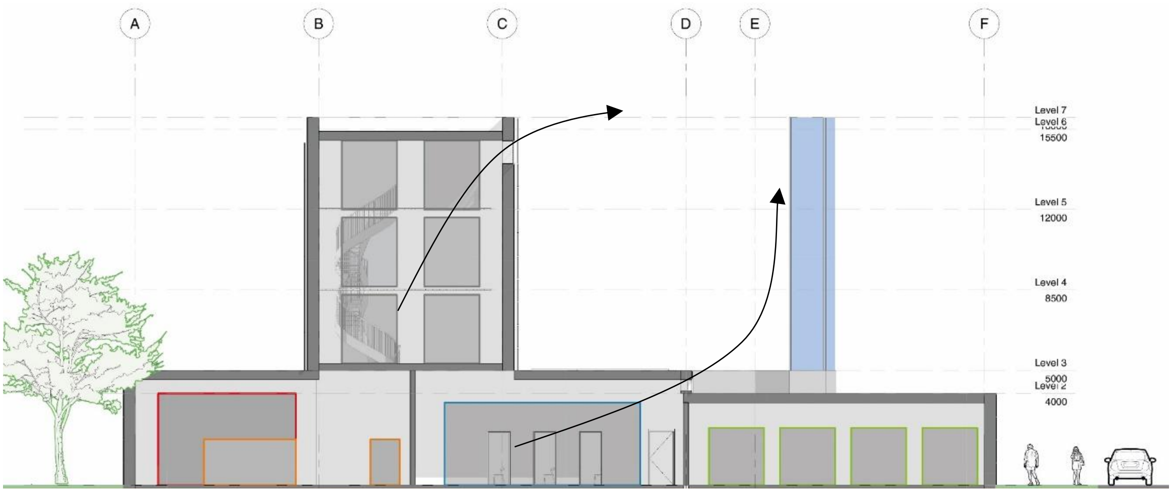


Figure 94: Natural ventilation principle

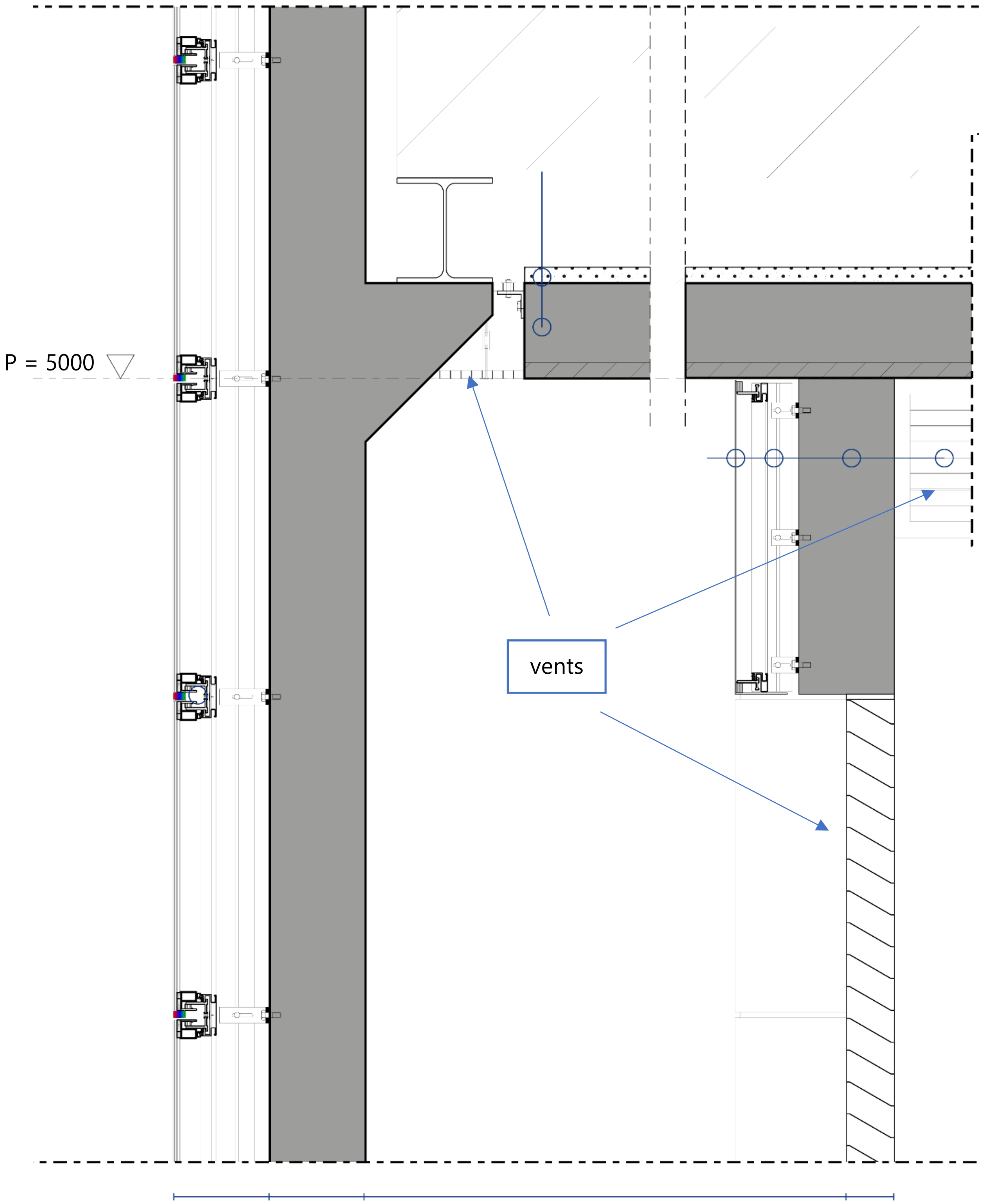


Figure 95: Detail of cantilvering part on the west side of the building

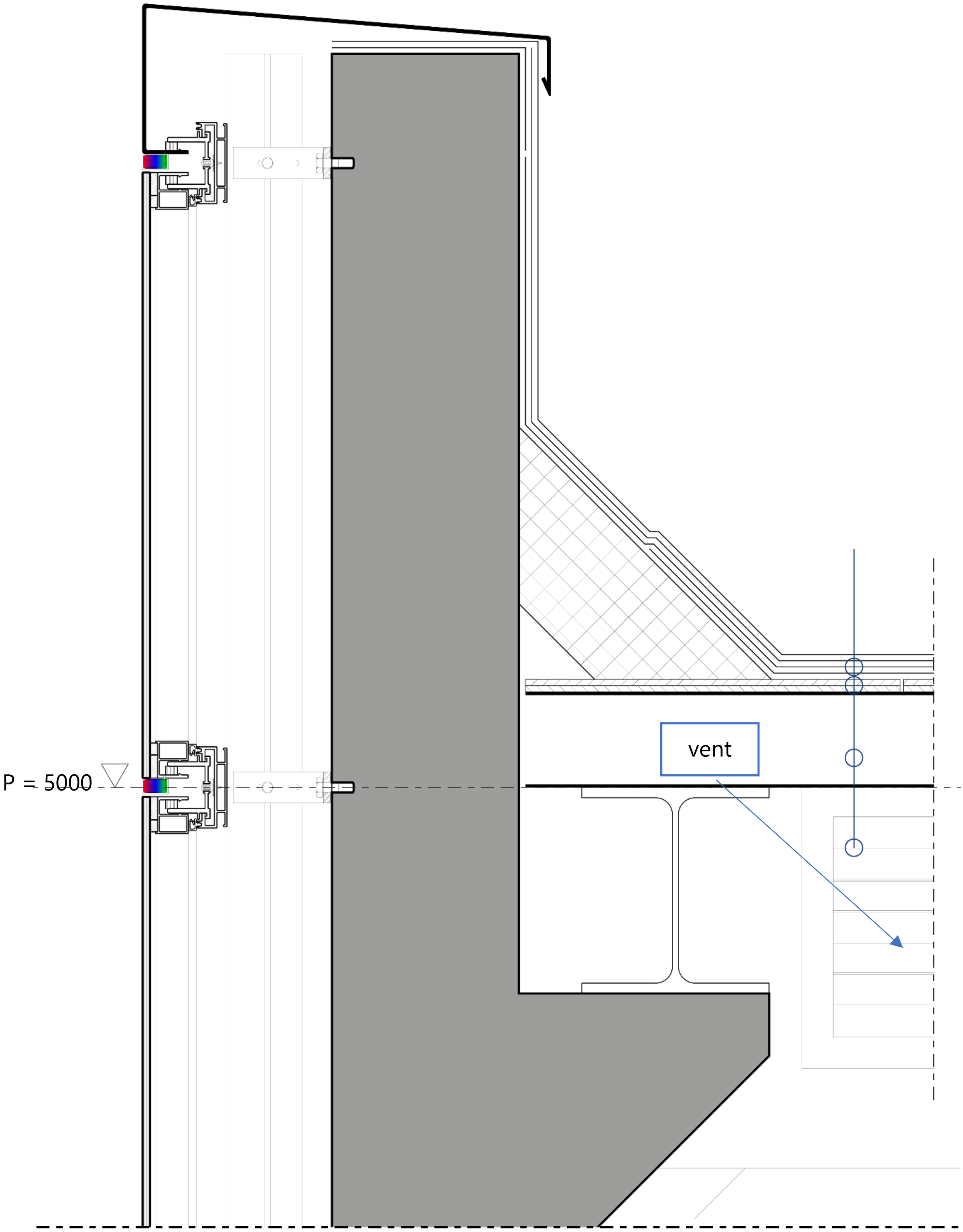


Figure 96: Roof detail

8.5 Conclusion of the energy hub design

The energy hub is designed from a technical perspective. The system components fit in the building and the build protects the components from impact. On the other hand, the building protects the surroundings of the energy hub from explosion by directing heat radiation in a direction where people are not immediately hurt. The explosion scenario is an extreme scenario and prescribes a lot of boundaries for the building design. The components that are placed in the building are suitable for placement outside, where they are even more perceptible for outside forces. The building is naturally ventilated so the hydrogen cannot form explosive mixtures because the hydrogen is dispersed in the air.

9 Conclusions & recommendations

9 Conclusions & recommendations

The research started with a literature to get up to speed with the state of the art of hydrogen. The literature gave an idea of the possibilities of hydrogen as energy storage vector but it also became clear that many challenges need to be overcome. The energy transition has to happen and no all-inclusive solution exists. The literature has described that hydrogen will play a role in the energy transition, so hydrogen technology should advance quickly to make optimal use of the positive properties of hydrogen.

The research has a wide focus because multiple aspects of the inclusion of hydrogen in the energy system are researched. The relation between the different aspects of the energy system design requires an approach that takes into account the results of intermediate calculations, decisions and simulations for all the design elements. One of the goals of the research is to display hydrogen technology by setting an example. The research is not conclusive of the perfect configuration of components of the energy system, so hydrogen technology cannot yet be optimally displayed in this research. To get the optimal configuration of system components in the energy hub, but also to find the optimal system size of the photovoltaics array, a dynamic model should be developed. In the current model, the annual balance is described as the subtraction of the sum of the hourly production (2.586.934 kWh) and the sum of the annual hourly consumption (1.552.109 kWh). This gives insight in the energy profiles for consumption of the buildings and the energy generation by the PV array, but does not take into account intermediate charging and discharging of system components. The positive balance of roughly 1,000,000 kWh that now exists is not the actual surplus. This number is even higher, roughly 2,200,000 kWh of electricity. Every time a surplus occurs, the electrolyser takes this energy from the local smart grid to produce hydrogen, but during short periods of deficits the users consume energy from the national grid. Intermediate discharge of the seasonal buffer is a good solution, but again, a dynamic model is required to gain insight in capacity of the storage component.

In the current proposal, the hydrogen storage component in the system design has a capacity of 4,590 kg of hydrogen compressed to 200 bar, it can provide the neighborhood with energy for 12.5 days during the winter. The houses can be completely disconnected from the grid and still be fully operational. This is possible because the energy system is completely based on electricity. Buildings are heated by an air heat pump, domestic hot water is produced with a heat pump booster and electricity is supplied by batteries that are charged by the fuel cell. The calculated efficiency of electricity to hydrogen to electricity and heat including conversion losses is 34%. The electrical output of roughly 64,500 kWh of the system is fed to the local smart grid and the heating output of 64,500 kWh is used to produce domestic hot water for the hotel.

Part of the research involves the design of an energy hub. This hub is the only part of the research that can be seen when walking the streets of Floriade. Basically, the building is a power plant and reference of power plants of this type are not available. So a balance should be found for what is right for the functional reasons and what is right for esthetic reasons. The system components are the basis of the design and the building envelope is folded around the components. The envelope protects the equipment from impacts from the outside, while also protecting the outside from heat radiation in the unlikely event of an explosion. This risk is further reduced by naturally ventilating the building, so no explosive mixtures of air and hydrogen can exist.

It is recommended to make a dynamic model that takes intermediate charging and discharging of energy system components into account. This way, a more representative balance can be made and the capacity of the system components can be optimized.

10 Reflection

10 Reflection

Topic

The research is focused on hydrogen as a carrier of renewable energy. Hydrogen and energy storage are in basis not a part of the Building Technology track, but are based on chemical processes. However, the application of hydrogen as seasonal buffer in the built environment very much aligns with the topic of the studio: sustainable design, specifically the department of climate design.

Graduation process

The approach of basing the design on research has lead to several models and calculation methods. The outcome of these calculations are validated, but did not always turn out as expected. Especially in the end, it has become clear that the used model did not have the output necessary to come to an optimized design. A lot of research is done into system components and alternatives. Reflection on the research period, it has now become clear that the definition of the model should have been done at an earlier stage. This way, the lack of output information would have been come to attention sooner.

During the calculation phase it sometimes seemed like the system would have such a low efficiency that the research seemed less relevant. Solutions to enhance the efficiency of the system were sought for and partially found. This improved the prospects and so the research was again aimed at doing research for a good design instead of trying to force the topic of the graduation.

Societal impact

The applied technology has been proven to work, but it has not yet been applied on this scale. The system components can be configured in such a way that the system will work. However, because of the low efficiency of the system it can be argued that, with the technological state of the art of hydrogen, alternatives should be applied.

On the other hand, the case study is very suitable for displaying technologies, so it is a great opportunity to aid in the advancement of hydrogen as carrier of renewable energy in the built environment. The newly developed neighborhood that is part of the case study offers a stage for innovation, so the research perfectly fits in with the sustainability principles of the case study. Hydrogen is an essential part of the energy transition, so the quicker the technology advances, the sooner it becomes feasible. And by becoming feasible sooner, it can speed up the energy transition. It has not yet been applied in the built environment, so this project can set an example by placing an energy producing power plant that emits nothing but water and oxygen in a residential area.

11 Nomenclature

AC	Alternating Current
BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
COP	Coefficient of Performance
DB	DesignBuilder (used to reference to DesignBuilder software)
DC	Direct Current
DHW	Domestic Hot Water
FCEV	Fuel cell electric vehicle
GFA	Gross floor area
GHG	Green House Gasses
HB	Honeybee (used to reference to the Honeybee model)
HHV	High Heating Value
HT	High Temperature (heating)
LHV	Low Heating Value
LT	Low Temperature (heating)
PHEV	Plug-in Hybrid Electric Vehicle
PTHP	Packaged Terminal Heat Pump
PV	Photovoltaic
SMR	Steam Methane Reforming
TRL	Technology Readiness Level
UMGO	Uniforme Maatlat Gebouwde Omgeving (standard measuring tool for the built environment)

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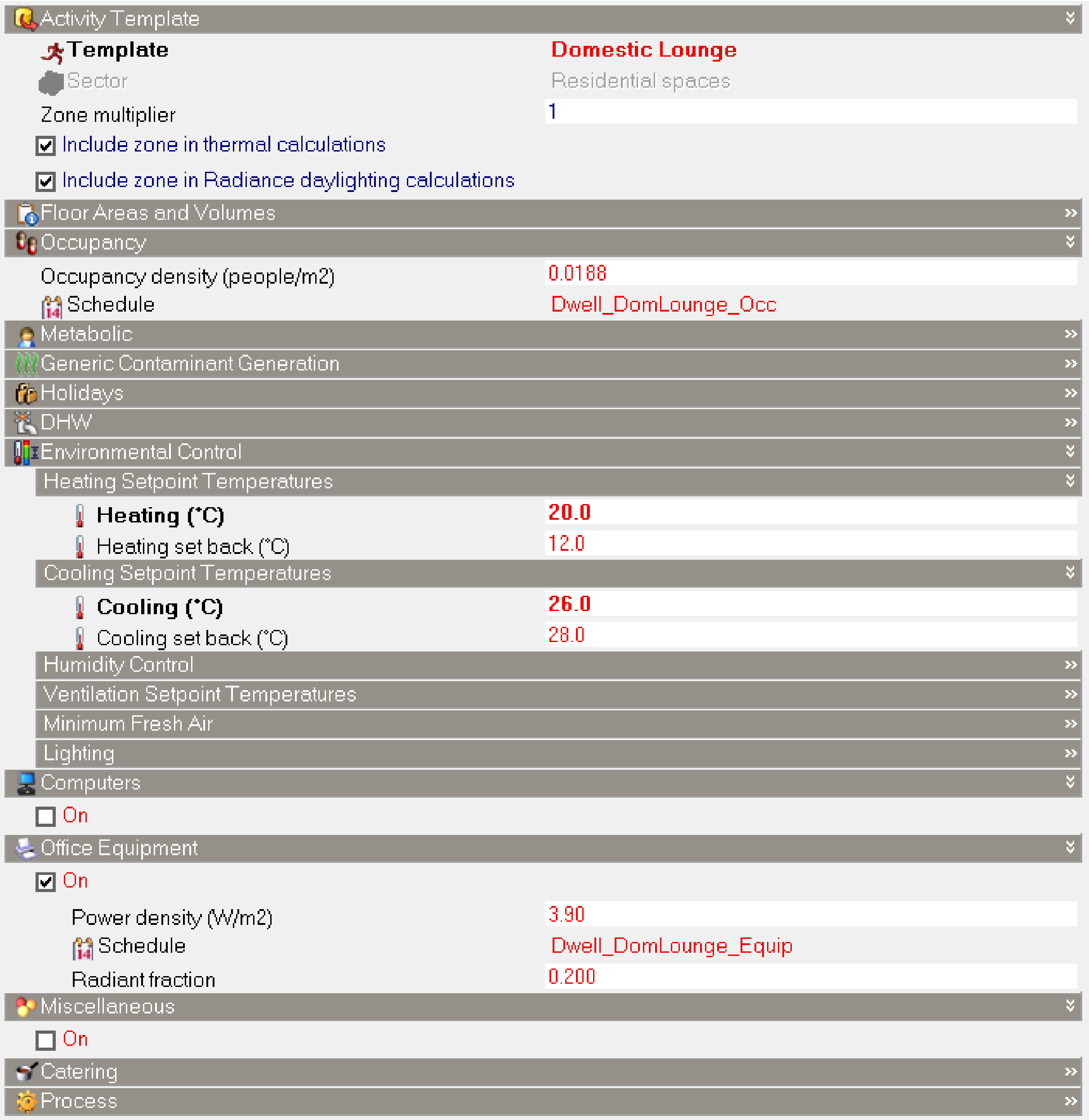
Images & illustrations

Appendices

Appendix I: DesignBuilder input



Construction Template	
Template	**RC8 Floriade**
Construction	
External walls	Wall, Mass, R-45.0 (7.92), U-0.022 (0.12)
Below grade walls	Wall, Mass, R-45.0 (7.92), U-0.022 (0.12)
Flat roof	Roof, Attic & Other, Steel Joists, R-45 (7.9), U-0.031 (0.17)
Pitched roof (occupied)	Pitched roof - Energy code standard - Lightweight (data m
Pitched roof (unoccupied)	Pitched roof - Uninsulated - Lightweight (data modified wh
Internal partitions	Lightweight 2 x 25mm gypsum plasterboard with 100mm c
Semi-Exposed	
Semi-exposed walls	Semi-exposed wall Energy code standard - Lightweight (d
Semi-exposed ceiling	Combined semi-exposed roof - Energy code standard - Li
Semi-exposed floor	Combined semi-exposed floor Energy code standard - Li
Floors	
Ground floor	Slab-On-Grade, Heated, Fully Insulated, R-45.0 (7.9), F-0.2
External floor	Combined external floor - Energy code standard - Lightwe
Internal floor	100mm concrete slab
Sub-Surfaces	
Internal Thermal Mass	
Component Block	
Geometry, Areas and Volumes	
Surface Convection	
Linear Thermal Bridging at Junctions	
Airtightness	
☑ Model infiltration	
Constant rate (ac/h)	**0.200**
Schedule	On 24/7
Delta T and Wind Speed Coefficients	
Cost	

Glazing Template	
Template	**Triple glazing, clear, LoE, argon-filled**
External Windows	
Glazing type	Trp LoE (e2=e5=.1) Clr 3mm/13mm Arg
Layout	**Horizontal strip, 50% glazed**
Dimensions	
Type	1-Continuous horizontal
Window to wall %	50.00
Window spacing (m)	5.00
Sill height (m)	0.80
Reveal	
Frame and Dividers	
Shading	
Airflow Control Windows	
Free Aperture	
Internal Windows	
Sloped Roof Windows/Skylights	
Doors	
Vents	

Lighting Template	
Template	**LED**
General Lighting	
☑ On	
Normalised power density (W/m2-100 lux)	2.5000
Schedule	Dwell_DomLounge_Light
Luminaire type	1-Suspended
Return air fraction	0.000
Radiant fraction	0.420
Visible fraction	0.180
Convective fraction	0.400
Lighting Control	
☐ On	
Task and Display Lighting	
☐ On	
Exterior Lighting	
☐ On	
Cost	

HVAC Template	
Template	**PTHP**
Mechanical Ventilation	
☑ **On**	
Outside air definition method	2-Min fresh air (Per person)
Operation	
Schedule	Dwell_DomLounge_Occ
Economiser (Free Cooling)	
Heat Recovery	
Auxiliary Energy	
Pump etc energy (W/m2)	0.0000
Schedule	Dwell_DomLounge_Occ
Heating	
☑ Heated	
Fuel	1-Electricity from grid
Heating system seasonal CoP	**4.000**
Sizing Zone Equipment	
Type	
Operation	
Schedule	Dwell_DomLounge_Heat
Cooling	
☑ Cooled	
Cooling system	Default
Fuel	1-Electricity from grid
Cooling system seasonal CoP	**4.500**
Supply Air Condition	
Operation	
Schedule	Dwell_DomLounge_Cool
Humidity Control	
DHW	
☑ On	
DHW Template	**Netherlands**
Type	7-Heat pump
DHW CoP	0.8500
Fuel	1-Electricity from grid
Water Temperatures	
Delivery temperature (°C)	65.00
Mains supply temperature (°C)	10.00
Operation	
Schedule	Dwell_DomLounge_Occ
Natural Ventilation	
☑ **On**	
Outside air definition method	1-By zone
Outside air (ac/h)	5.000
Operation	
Schedule	Dwell_DomLounge_Occ
Outdoor Temperature Limits	
Delta T Limits	
Delta T and Wind Speed Coefficients	
Mixed Mode Zone Equipment	
☐ Mixed mode on	
Earth Tube	
Air Temperature Distribution	
Cost	

Appendix II: Detailed overview of the Honeybee model

This appendix gives an overview of the elements of the Honeybee model. Figure 97 below gives an overview of the model, on the next pages the elements are enlarged so the input can be read. Each element can be recognized by the background color of the element.

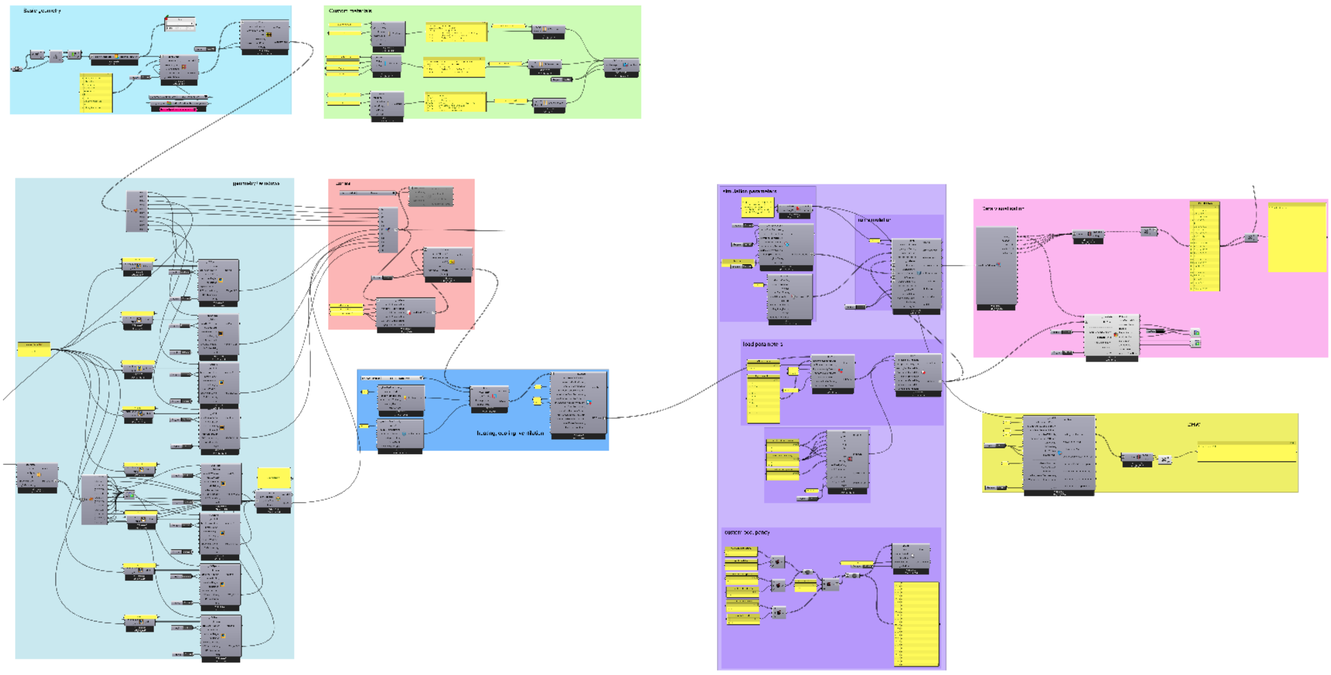


Figure 97: Overview of the Honeybee model

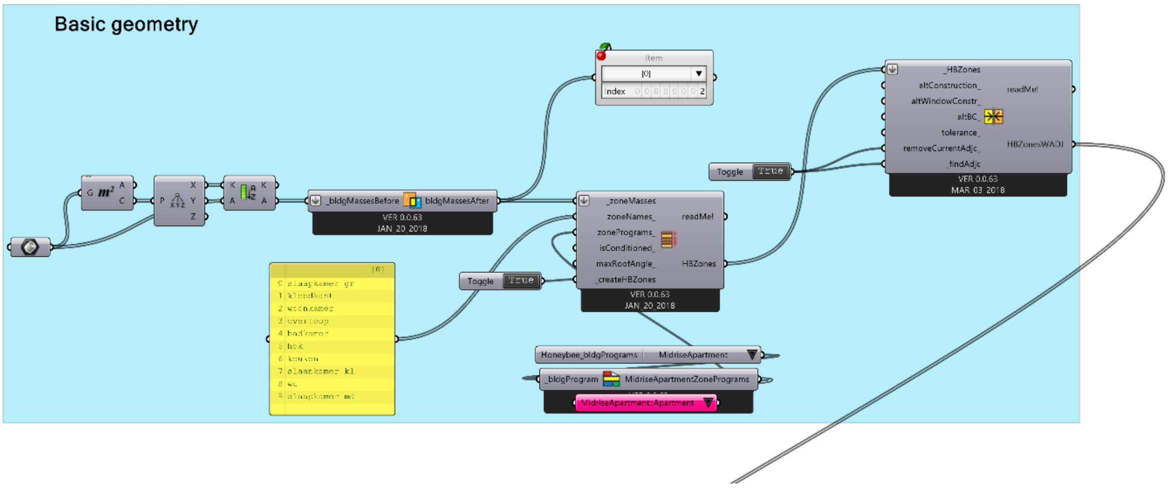


Figure 98: Geometry input of the Honeybee model

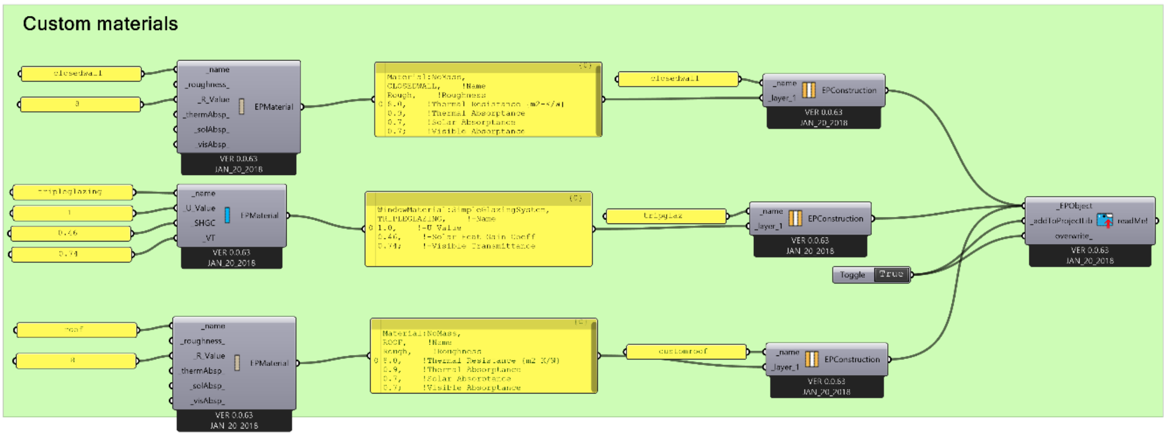


Figure 99: custom materials in the Honeybee model

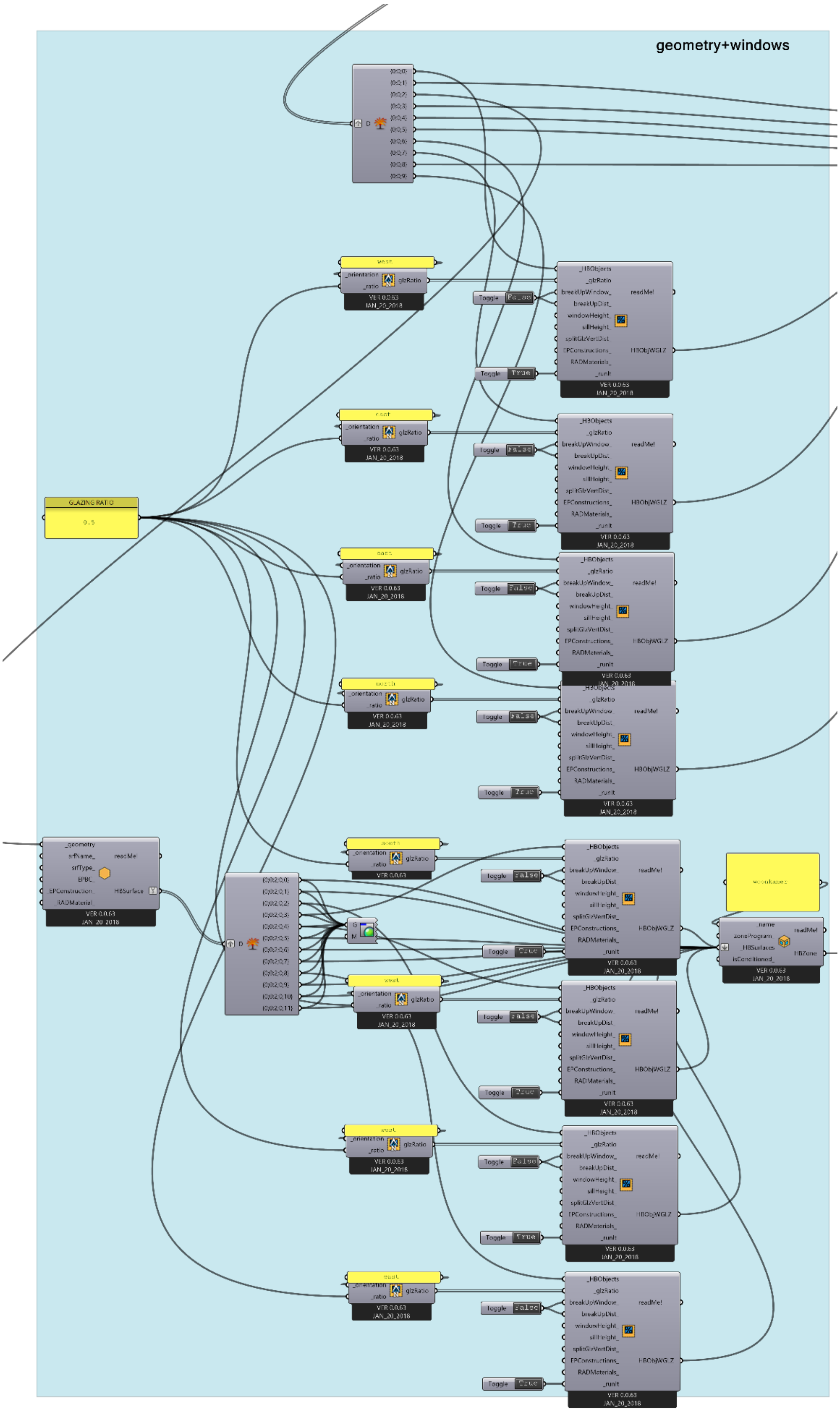


Figure 100: Window geometry of the Honeybee model

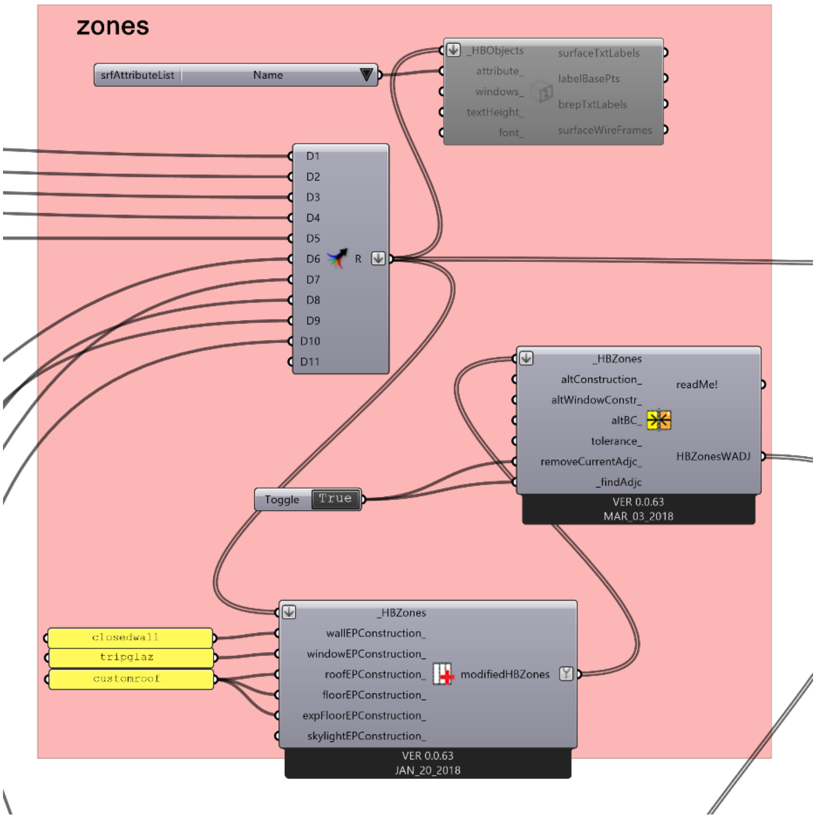


Figure 101: Zone component of the Honeybee model

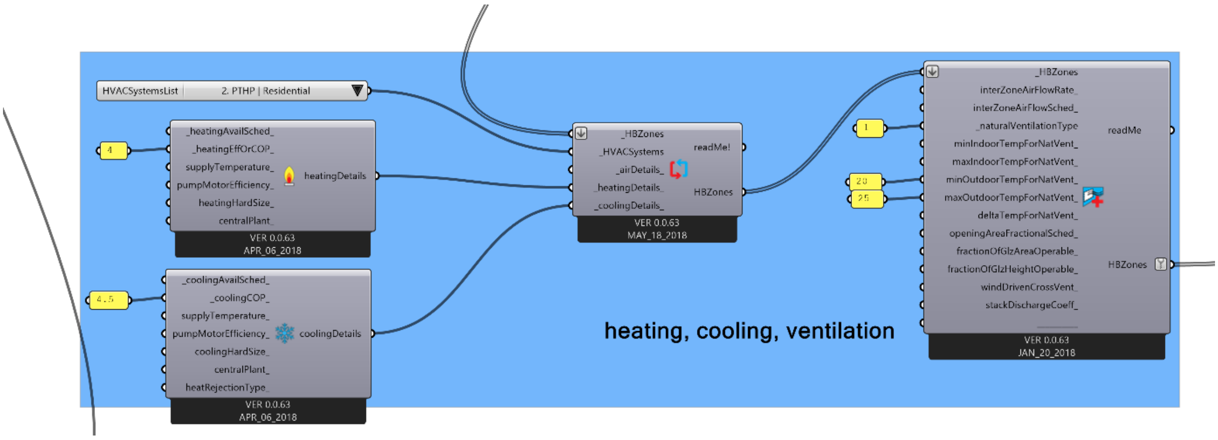


Figure 102: Heating, cooling and ventilation input of the Honeybee model

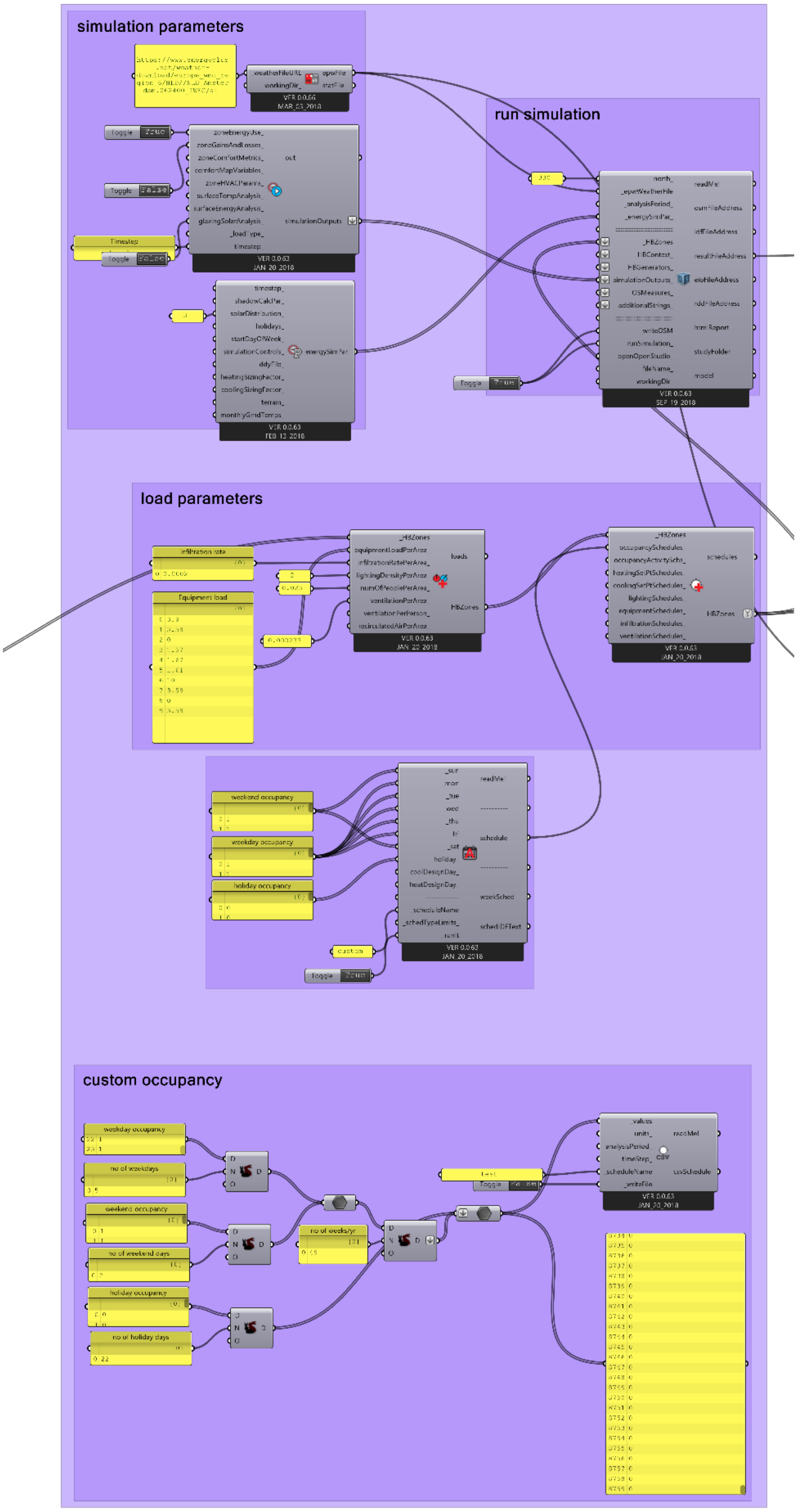


Figure 103: Simulation parameters of the Honeybee model

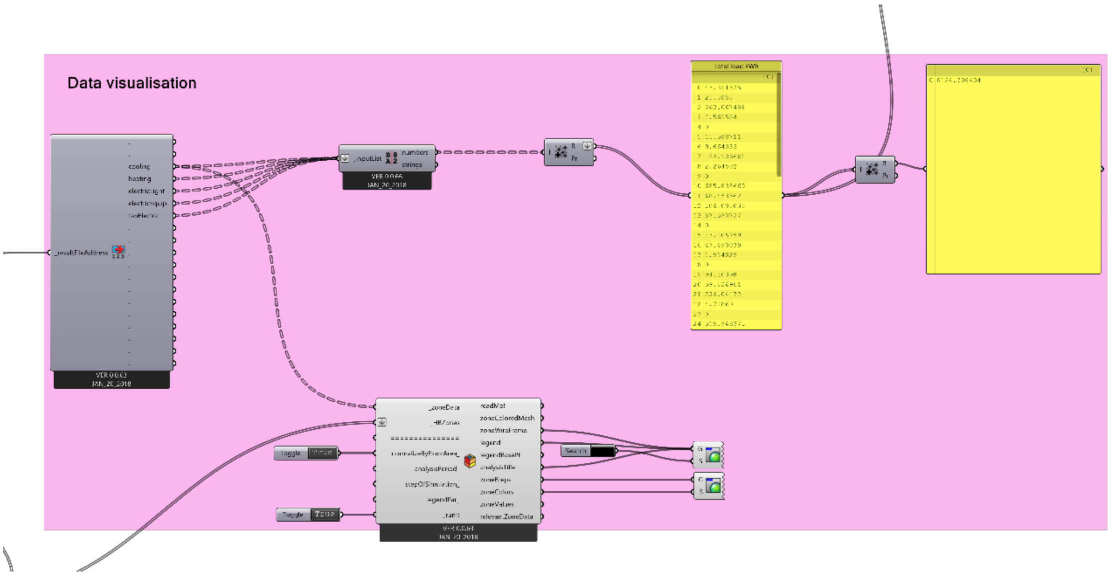


Figure 104: Data visualization component and output of all loads of the Honeybee model

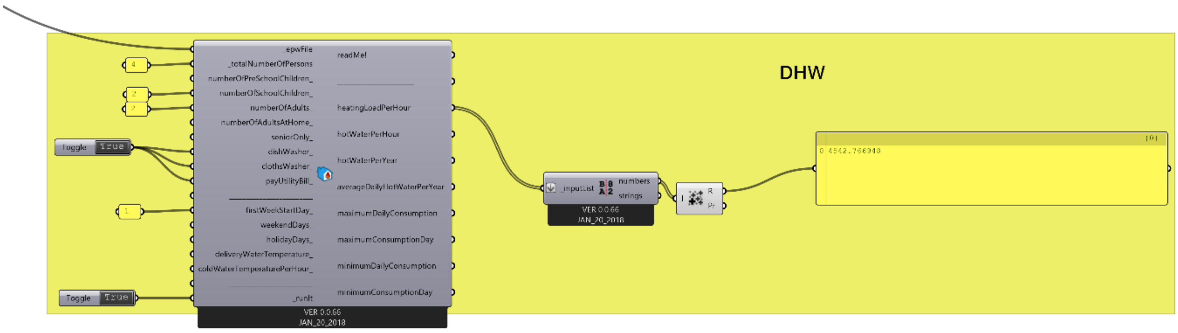


Figure 105: DHW calculation in the Honeybee model

Appendix III: results of consumption simulations for building types

Results 6/plot buildings

Comparison of the models

The table and graph below show calculation results of the DesignBuilder model, and UMGO calculation method.

	Annual consumption					
	Heating	Cooling	DHW	Equip	Light	Total
type	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*
6/plot DB	2218	823	2537	1244	819	7641
6/plot UMGO	1649	399	2115	1968	665	6796

Table 47: Annual energy consumption of building type 6/plot

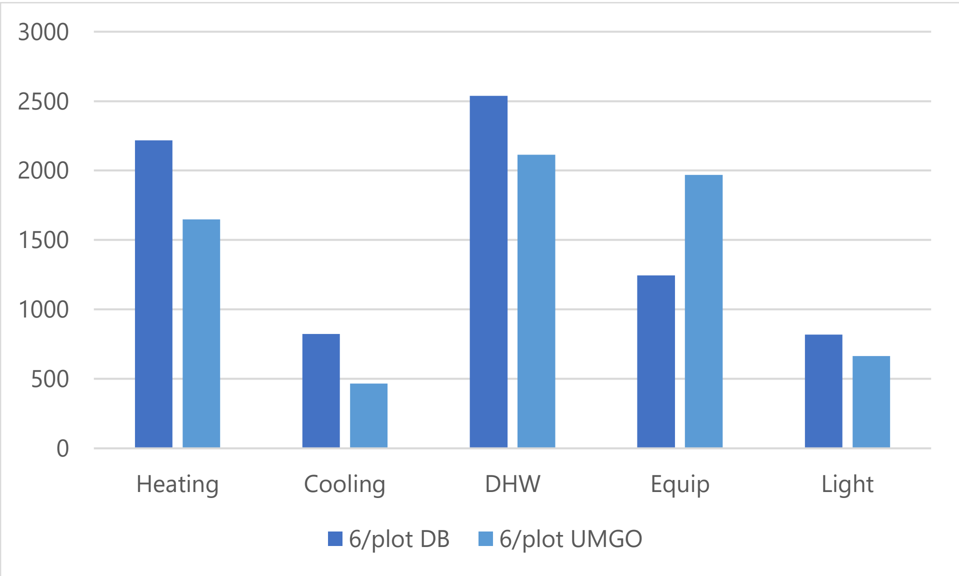


Figure 106: Graph of annual energy consumption of building type 6/plot in kWh

Heating

The heating demand is similar according to the DB and HB calculations. The UMGO calculations prescribe a lower energy demand for space heating. This can be explained by the fact that this building has a lot of windows, which leads to energy losses during the winter.

Cooling

The cooling load is two times higher in the HB model. In the HB model, no heat recovery system is modelled, this is further elaborated on in the validation section. If heat recovery is not applied, high losses of energy can exist, leading to a high cooling load during the summer

Domestic hot water

The consumption for domestic hot water production is twice as high in the HB model. This has to do with the calculation method in HB, which does not take into account a COP for DHW production by means of a heat pump. It is only based on the amount of people that live in the house. This if further elaborated on in the validation section.

Equipment

The equipment load according to the DB model is lower than it should be according to UMGO and HB. This is more in-depth discussed in the validation section.

Lighting

The results are similar in each model so this is not further debated.

Energy profiles

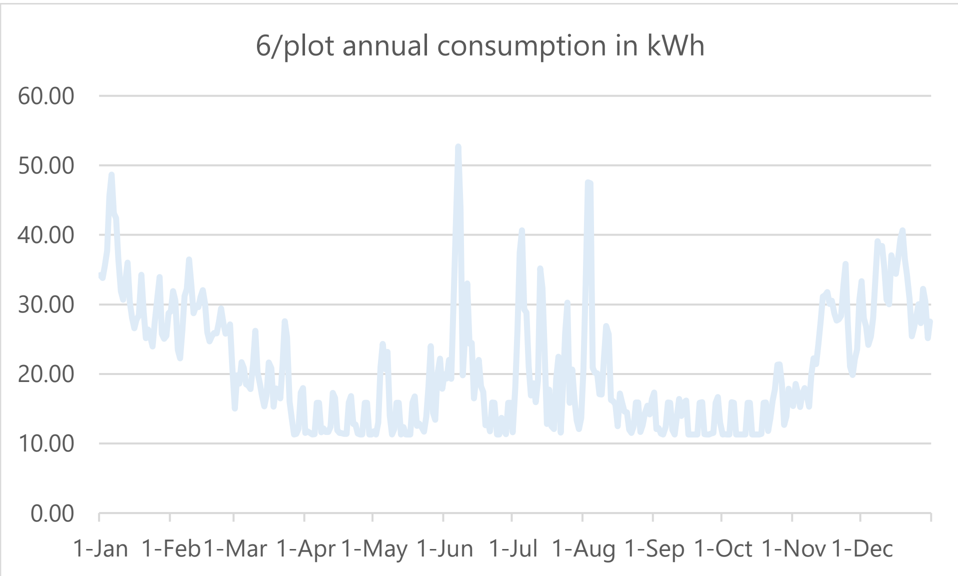


Figure 107: 6/plot annual consumption

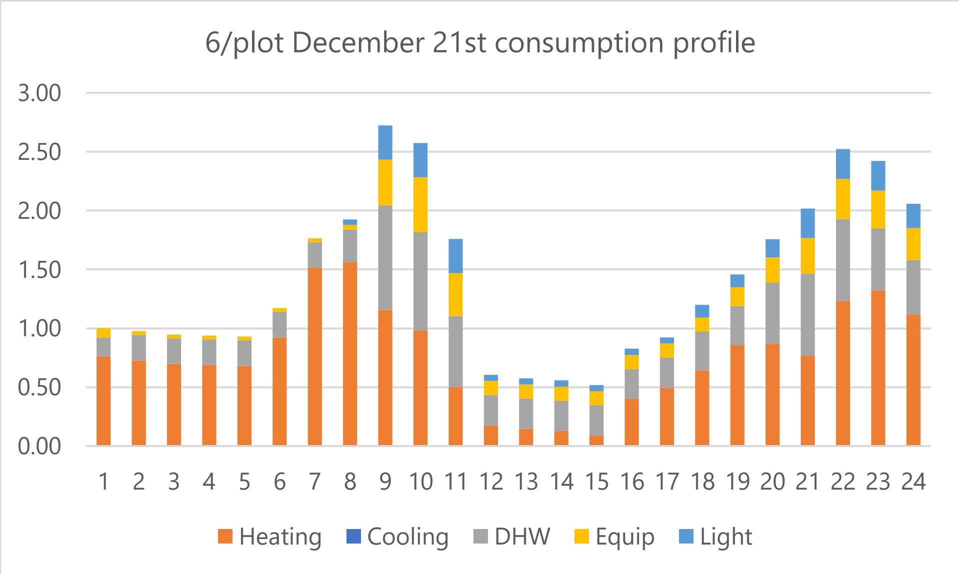


Figure 108: 6/plot December 21st consumption profile

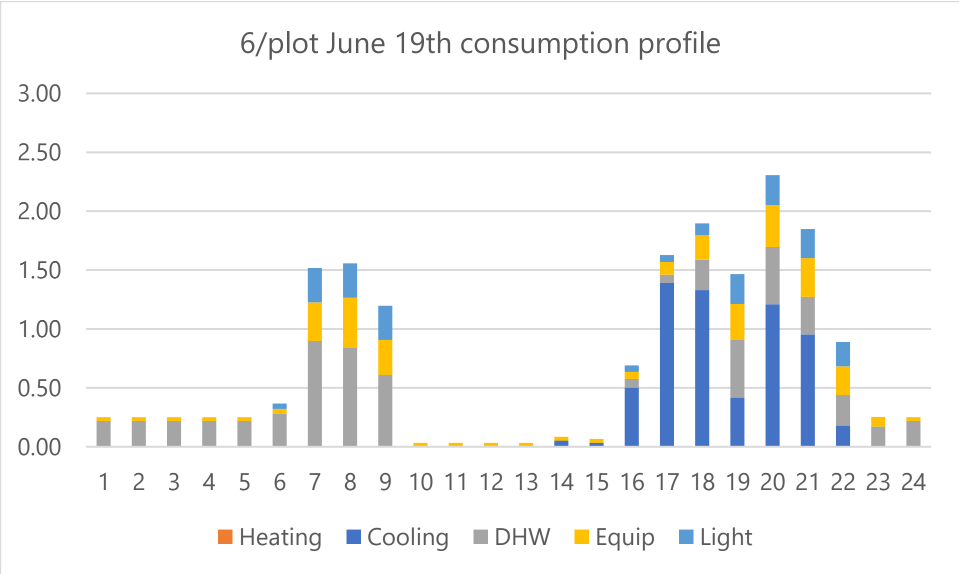


Figure 109: June 19th consumption profile

Results 8/plot buildings

Comparison of the models

The table and graph below show calculation results of the DesignBuilder model, and UMGO calculation method.

	Annual consumption					
	Heating	Cooling	DHW	Equip	Light	Total
type	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*
8/plot DB	1851	1294	2843	1961	1075	9024
8/plot UMGO	2009	486	2576	2398	810	8278

Table 48: Annual energy consumption of building type 8/plot

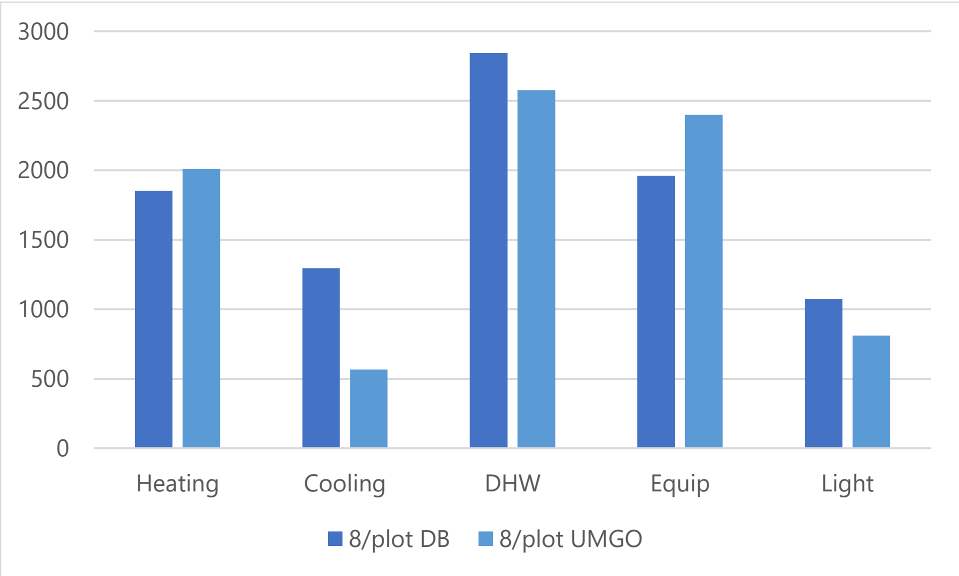


Figure 110: Graph of annual energy consumption of building type 8/plot in kWh

Cooling

The cooling load is two times higher in the HB model. In the HB model, no heat recovery system is modelled, this is further elaborated on in the validation section. If heat recovery is not applied, high losses of energy can exist, leading to a high cooling load during the summer

Equipment

The equipment load according to the DB model is lower than it should be according to UMGO. This is more in-depth discussed in the validation section.

Energy profiles

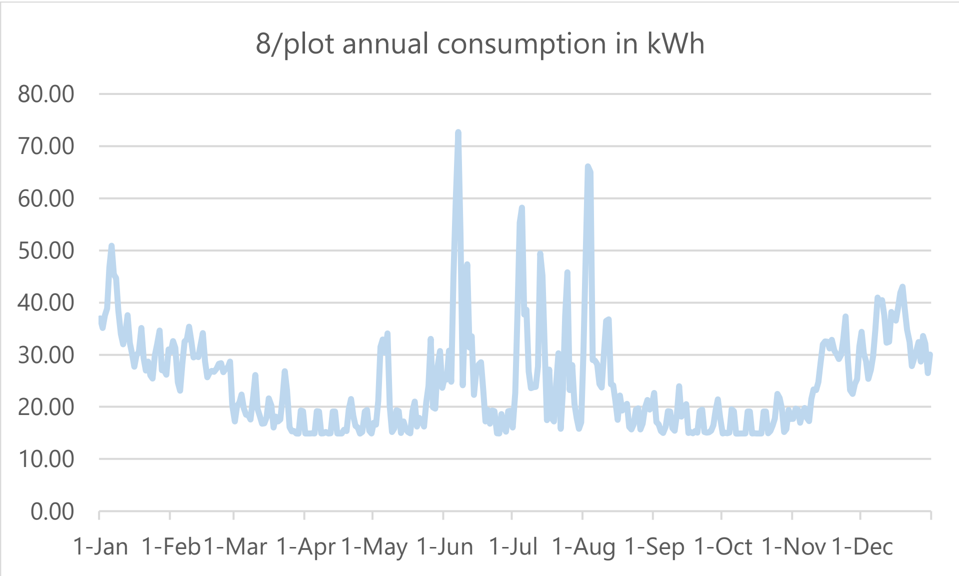


Figure 111: 8/plot annual consumption in kWh

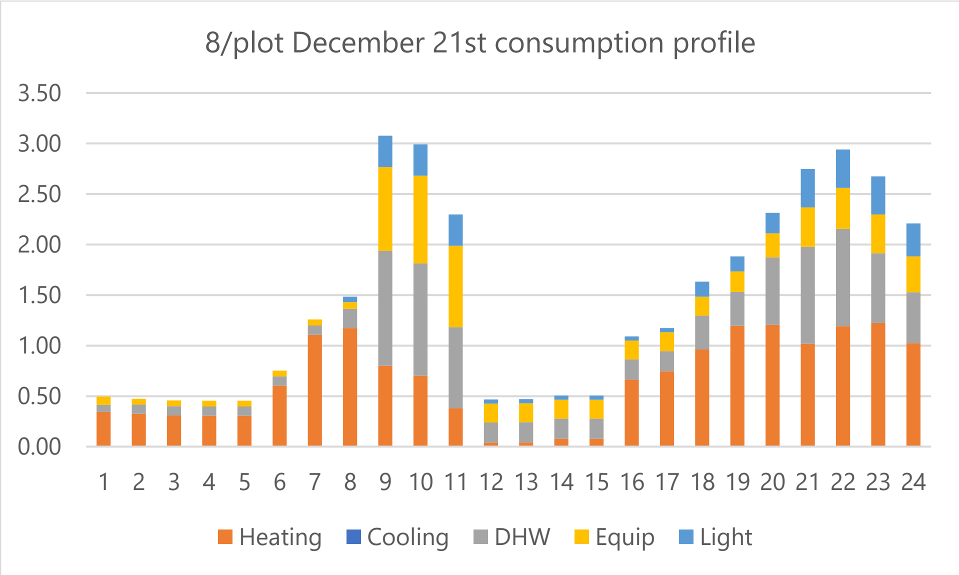


Figure 112: 8/plot December 21st consumption profile

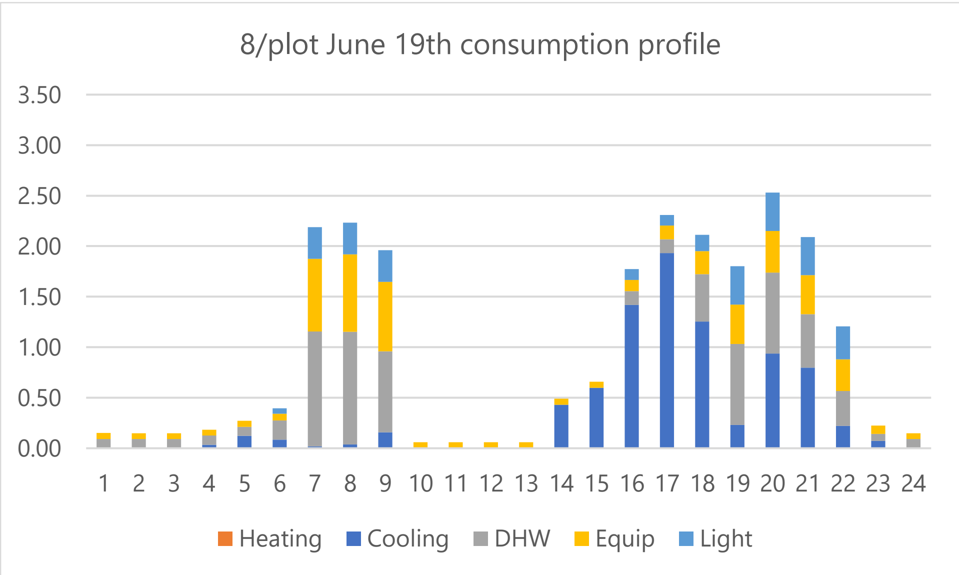


Figure 113: 8/plot June 19th consumption profile

Results 10/plot buildings

Comparison of the models

The table and graph below show calculation results of the DesignBuilder model, and UMGO calculation method.

	Annual consumption					
	Heating	Cooling	DHW	Equip	Light	Total
type	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*
10/plot DB	1771	822	2188	1348	813	6942
10/plot UMGO	1612	390	2067	1924	650	6643

Table 49: Annual energy consumption of building type 10/plot

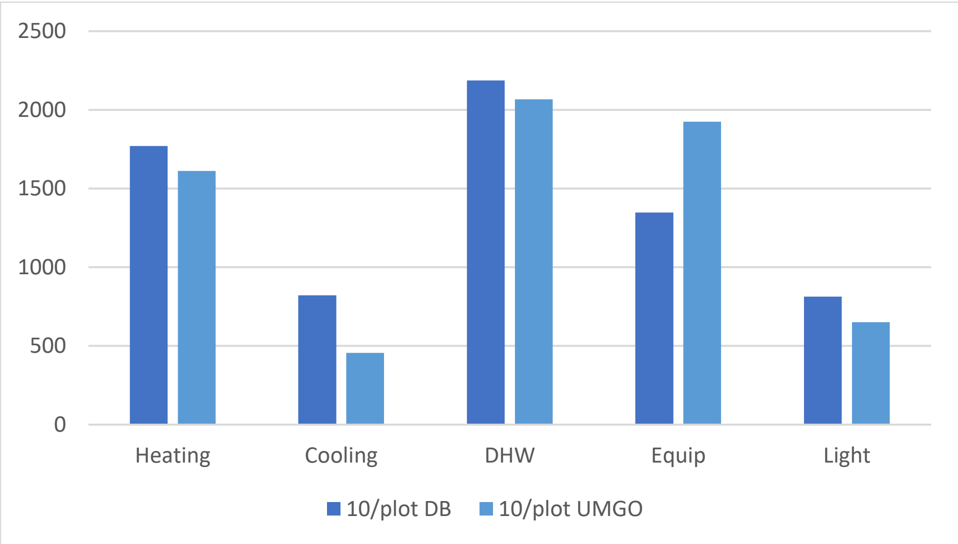


Figure 114: Graph of annual energy consumption of building type 10/plot in kWh

Cooling

The cooling load is two times higher in the HB model. In the HB model, no heat recovery system is modelled, this is further elaborated on in the validation section. If heat recovery is not applied, high losses of energy can exist, leading to a high cooling load during the summer

Equipment

The equipment load according to the DB model is lower than it should be according to UMGO and HB.

Energy profiles

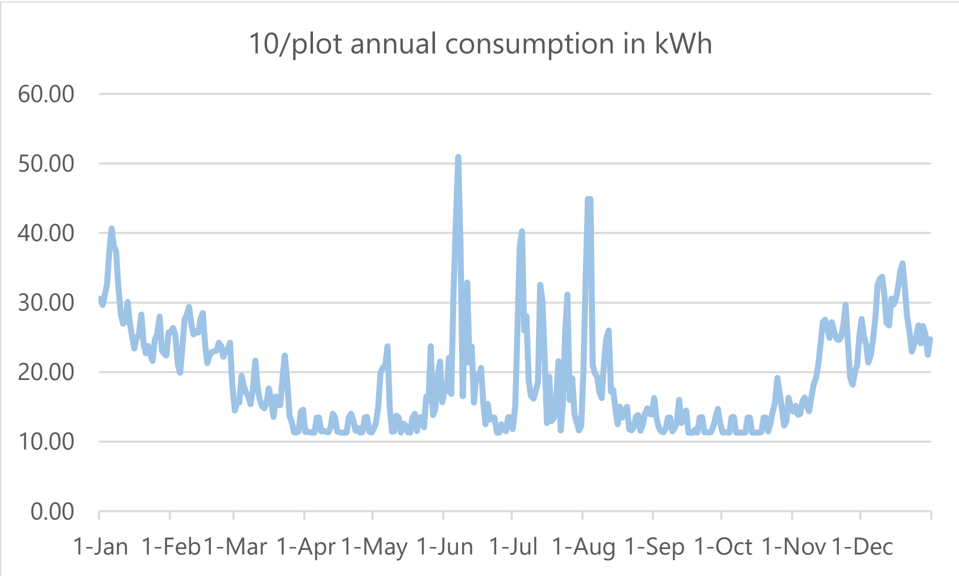


Figure 115: 10/plot annual consumption in kWh

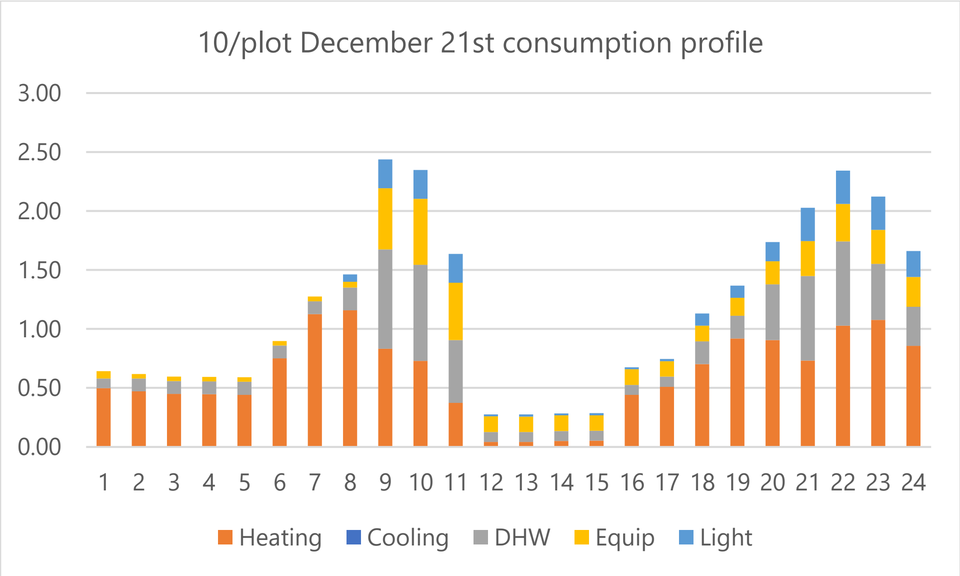


Figure 116: 10/plot December 21st consumption profile

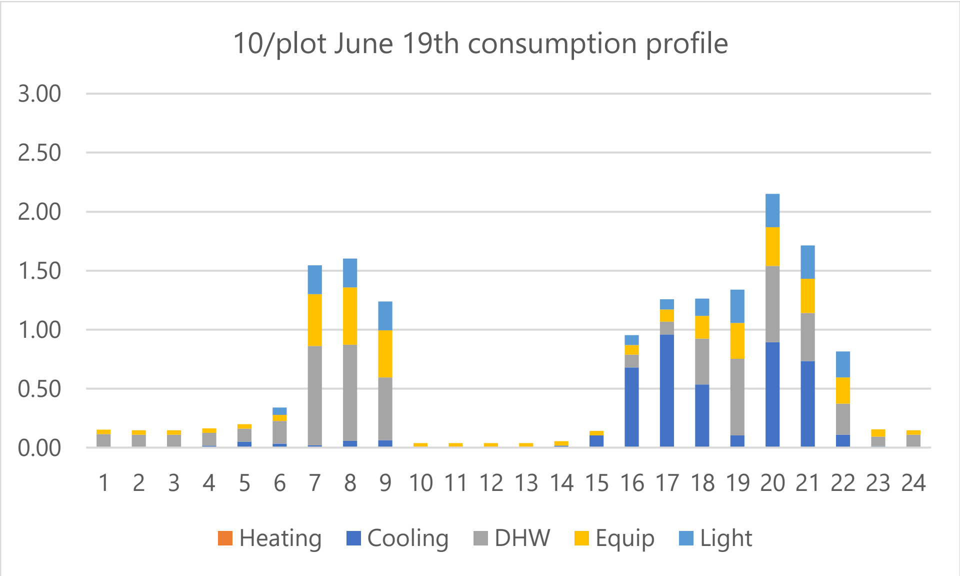


Figure 117: 10/plot June 19th consumption profile

Results 12/plot buildings

Comparison of the models

The table and graph below show calculation results of the DesignBuilder model, and UMGO calculation method

	Annual consumption					
	Heating	Cooling	DHW	Equip	Light	Total
type	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*
12/plot DB	1915	1205	2411	1338	908	7776
12/plot UMGO	1823	441	2337	2176	735	7512

Table 50: Annual energy consumption of building type 12/plot

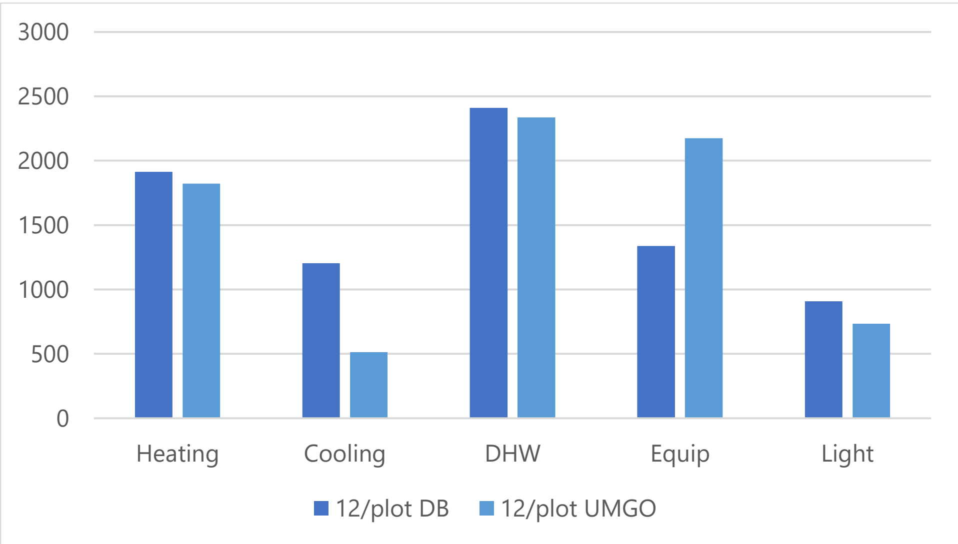


Figure 118: Graph of annual energy consumption of building type 12/plot

Cooling

The cooling load is two times higher in the HB model. In the HB model, no heat recovery system is modelled, this is further elaborated on in the validation section. If heat recovery is not applied, high losses of energy can exist, leading to a high cooling load during the summer

Equipment

The equipment load according to the DB model is lower than it should be according to UMGO and HB. This is more in-depth discussed in the validation section.

Energy profiles

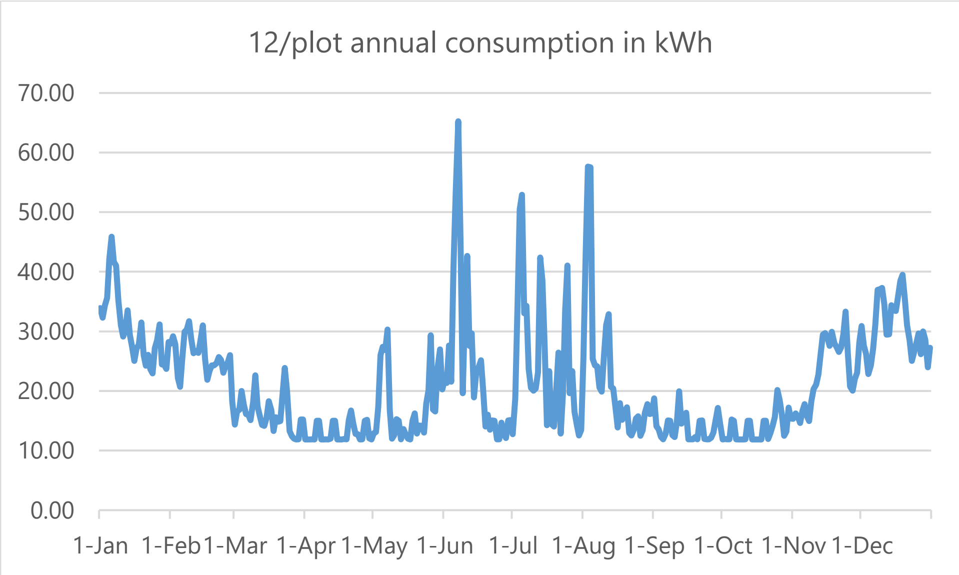


Figure 119: 12/plot annual consumption in kWh

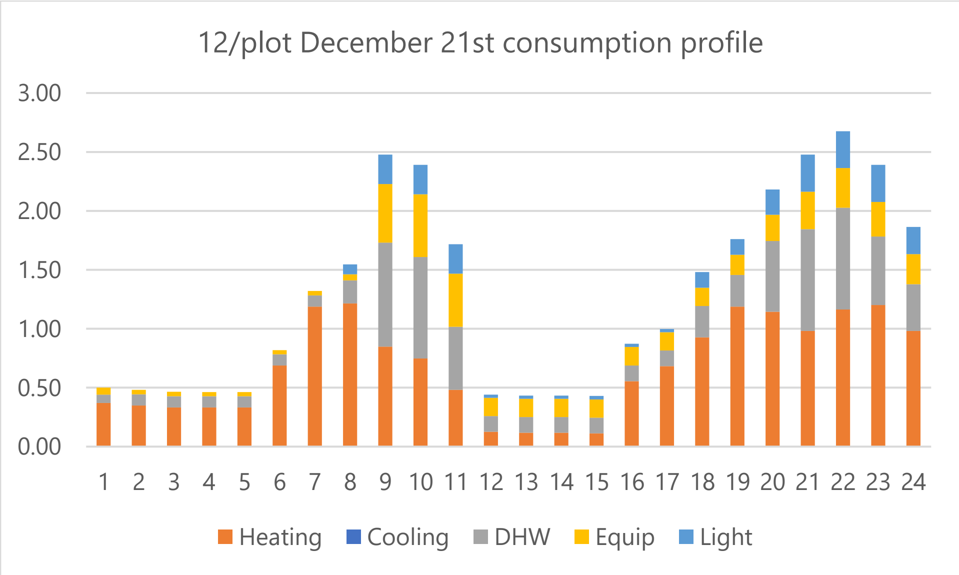


Figure 120: 12/plot December 21st consumption profile

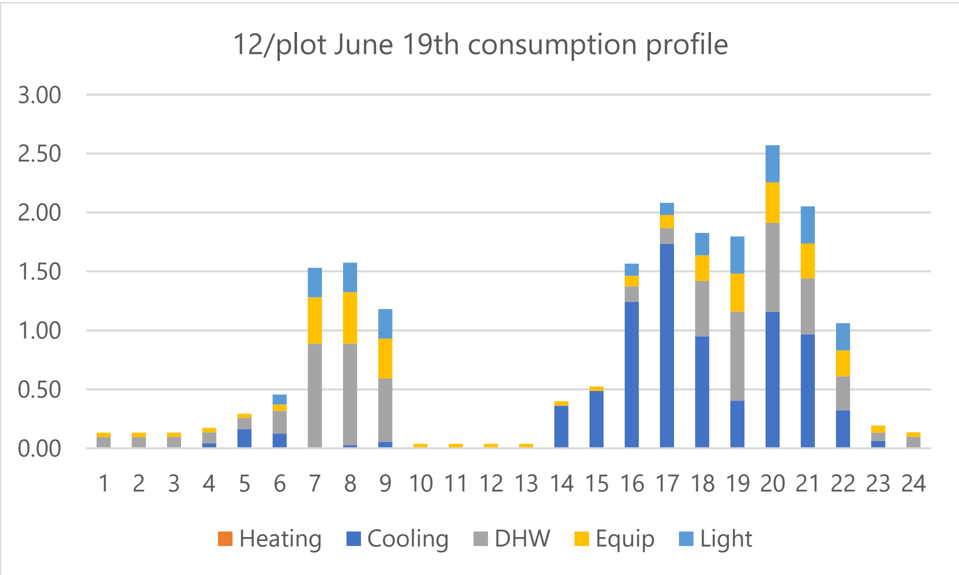


Figure 121: 12/plot June 19th consumption profile

Results 16/plot buildings

Comparison of the models

The table and graph below show calculation results of the DesignBuilder model, and UMGO calculation method

	Annual consumption					
	Heating	Cooling	DHW	Equip	Light	Total
type	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*
16/plot DB	1478	613	1458	1092	568	5209
16/plot UMGO	1364	330	1749	1628	550	5621

Table 511: Annual energy consumption of building type 16/plot

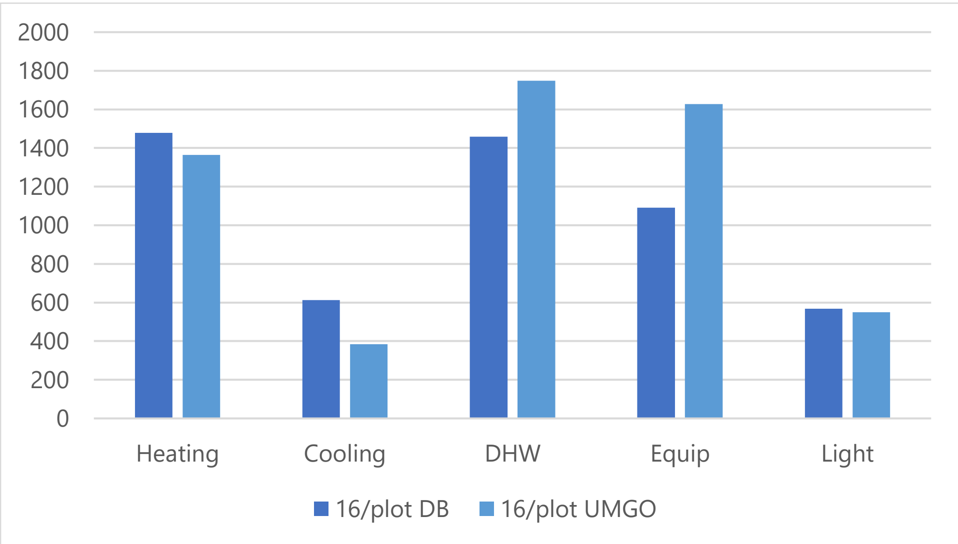


Figure 122: Graph of annual energy consumption of building type 16/plot in kWh

Cooling

The cooling load is two times higher in the HB model. In the HB model, no heat recovery system is modelled, this is further elaborated on in the validation section. If heat recovery is not applied, high losses of energy can exist, leading to a high cooling load during the summer

Equipment

The equipment load according to the DB model is lower than it should be according to UMGO and HB. This is more in-depth discussed in the validation section.

Energy profiles

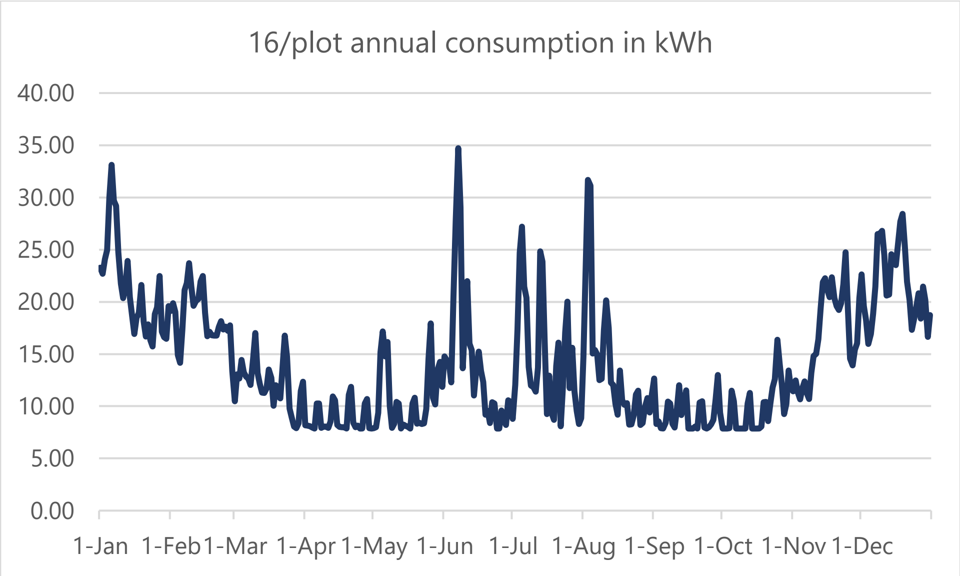


Figure 123: 16/plot annual consumption in kWh

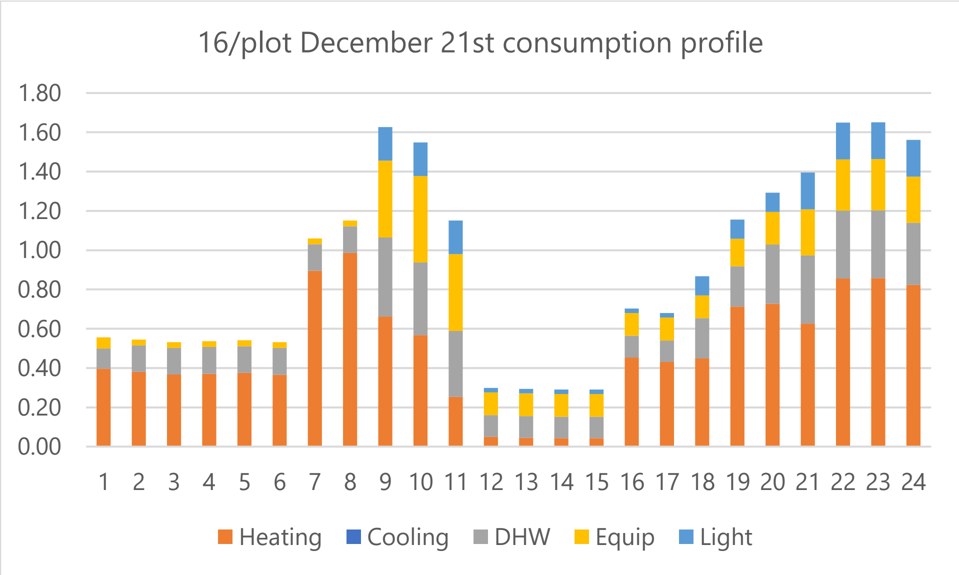


Figure 124: 16/plot December 21st consumption profile

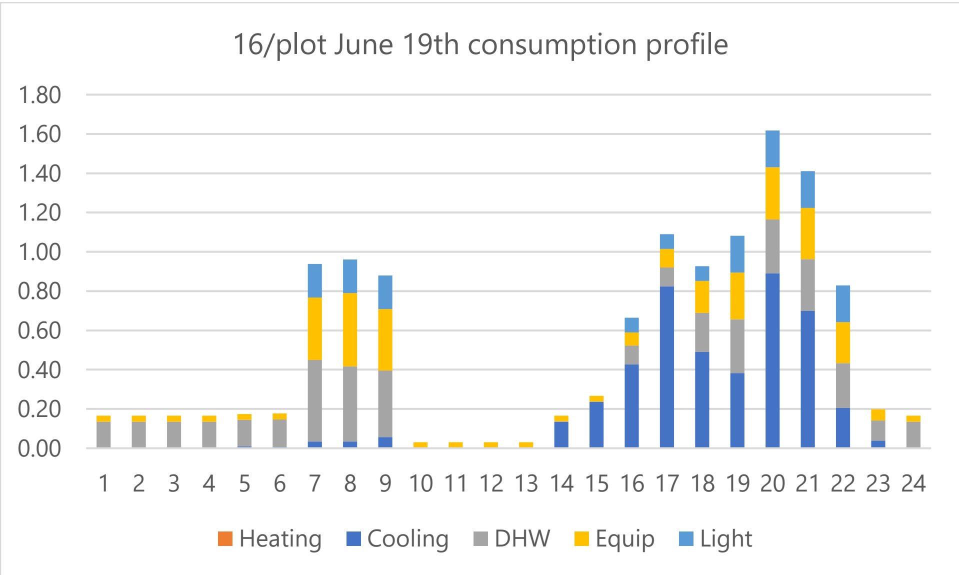


Figure 125: 16/plot June 19th consumption profile

Appendix IV: Output PVGIS

JRC
EUROPEAN COMMISSION

Photovoltaic Geographical Information System

European Commission
Joint Research Centre
Ispra, Italy

Performance of Grid-connected PV

PVGIS estimates of solar electricity generation

Location: 52°21'29" North, 5°13'47" East, Elevation: -1 m a.s.l.,
Solar radiation database used: PVGIS-CMSAF

Nominal power of the PV system: 3236.0 kW (crystalline silicon)
Estimated losses due to temperature and low irradiance: 7.2% (using local ambient temperature)
Estimated loss due to angular reflectance effects: 3.6%
Other losses (cables, inverter etc.): 22.0%
Combined PV system losses: 30.2%

	Fixed system: inclination=15 deg., orientation=-16 deg.			
Month	**Ed**	**Em**	**Hd**	**Hm**
Jan	2270.00	70500	0.95	29.6
Feb	3840.00	108000	1.60	44.9
Mar	7490.00	232000	3.18	98.7
Apr	11300.00	339000	4.96	149
May	12000.00	371000	5.37	166
Jun	12400.00	372000	5.65	169
Jul	11800.00	366000	5.42	168
Aug	10400.00	322000	4.70	146
Sep	8080.00	242000	3.59	108
Oct	5140.00	159000	2.23	69.2
Nov	2560.00	76700	1.09	32.8
Dec	1780.00	55300	0.76	23.6
Year	7430.00	226000	3.30	100
Total for year		2710000		1210

Ed: Average daily electricity production from the given system (kWh)
Em: Average monthly electricity production from the given system (kWh)
Hd: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m2)
Hm: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m2)

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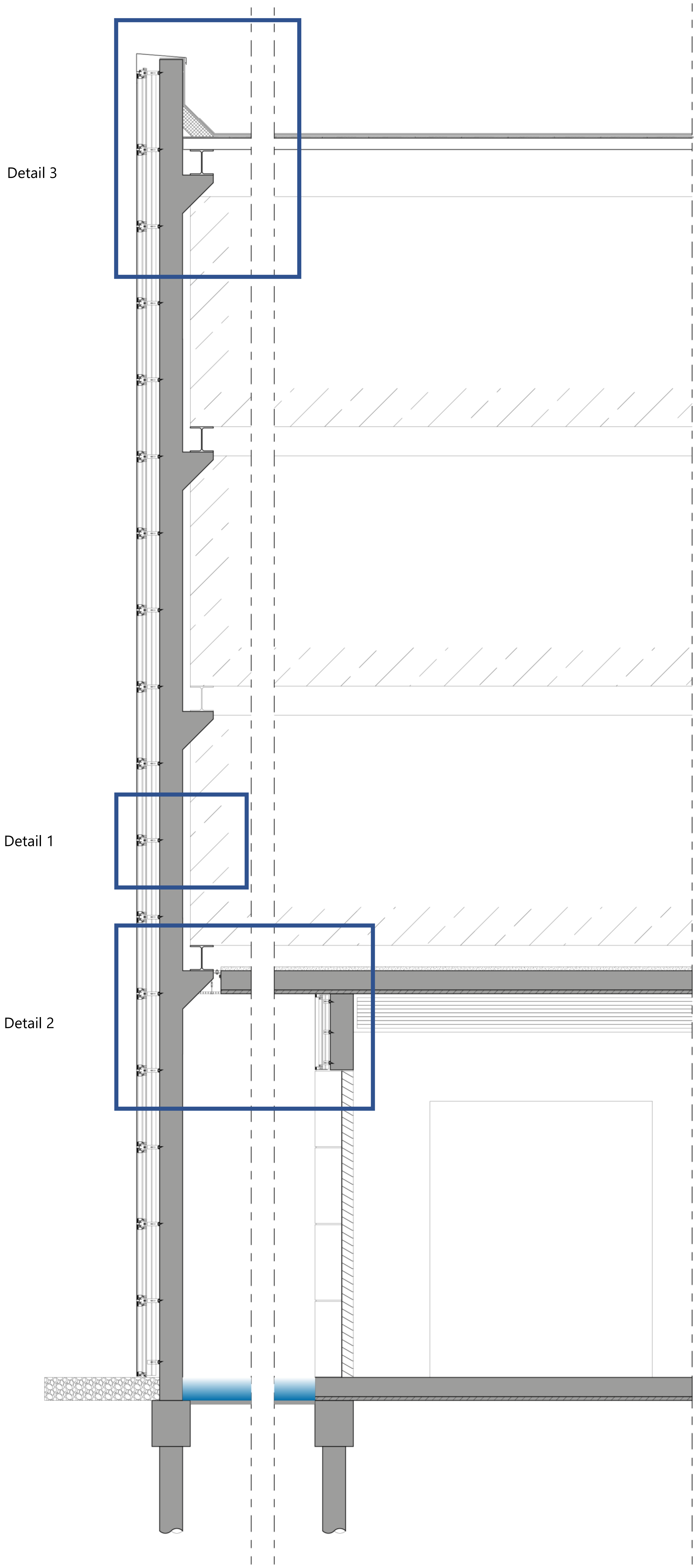
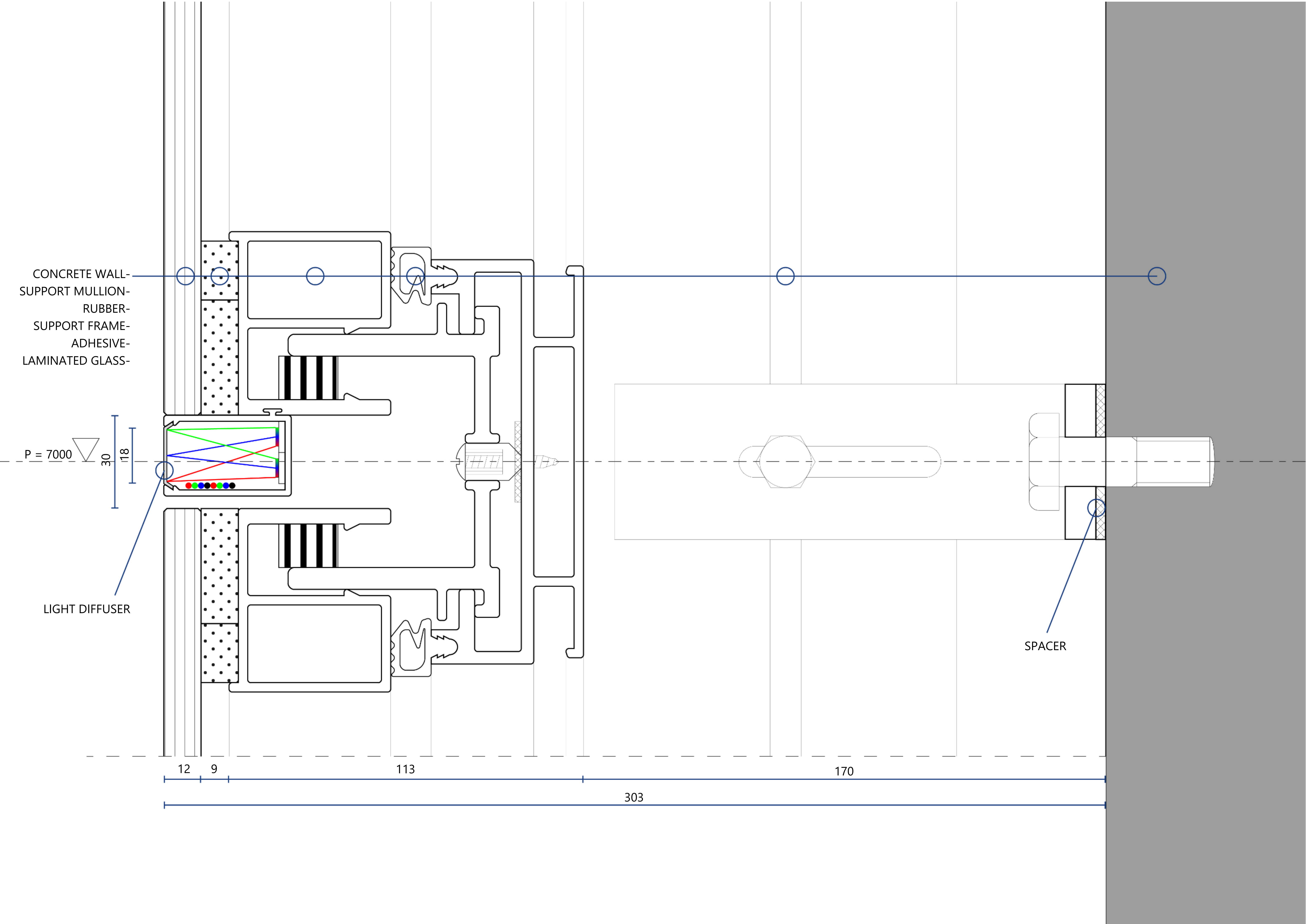
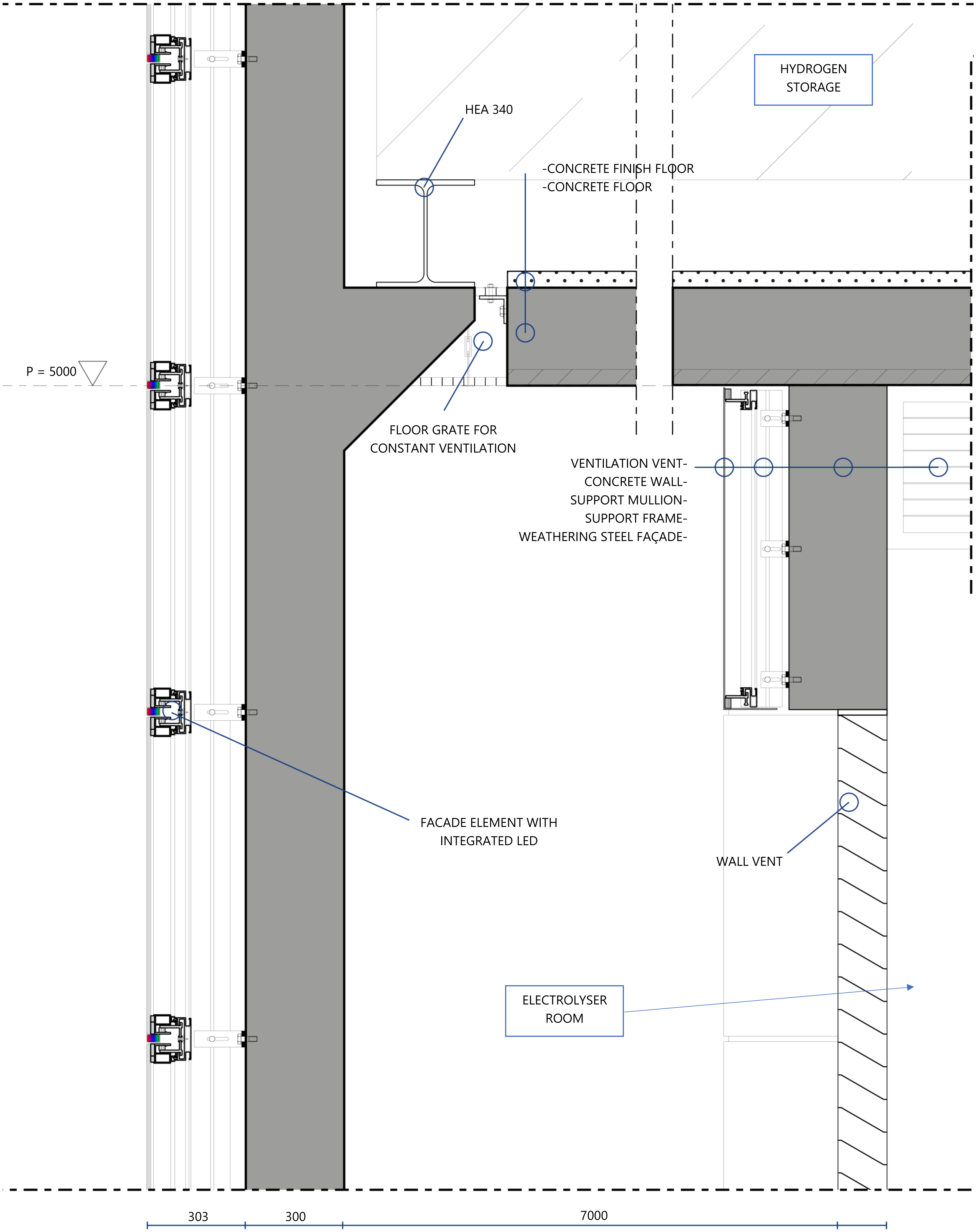
Appendix V: Façade details

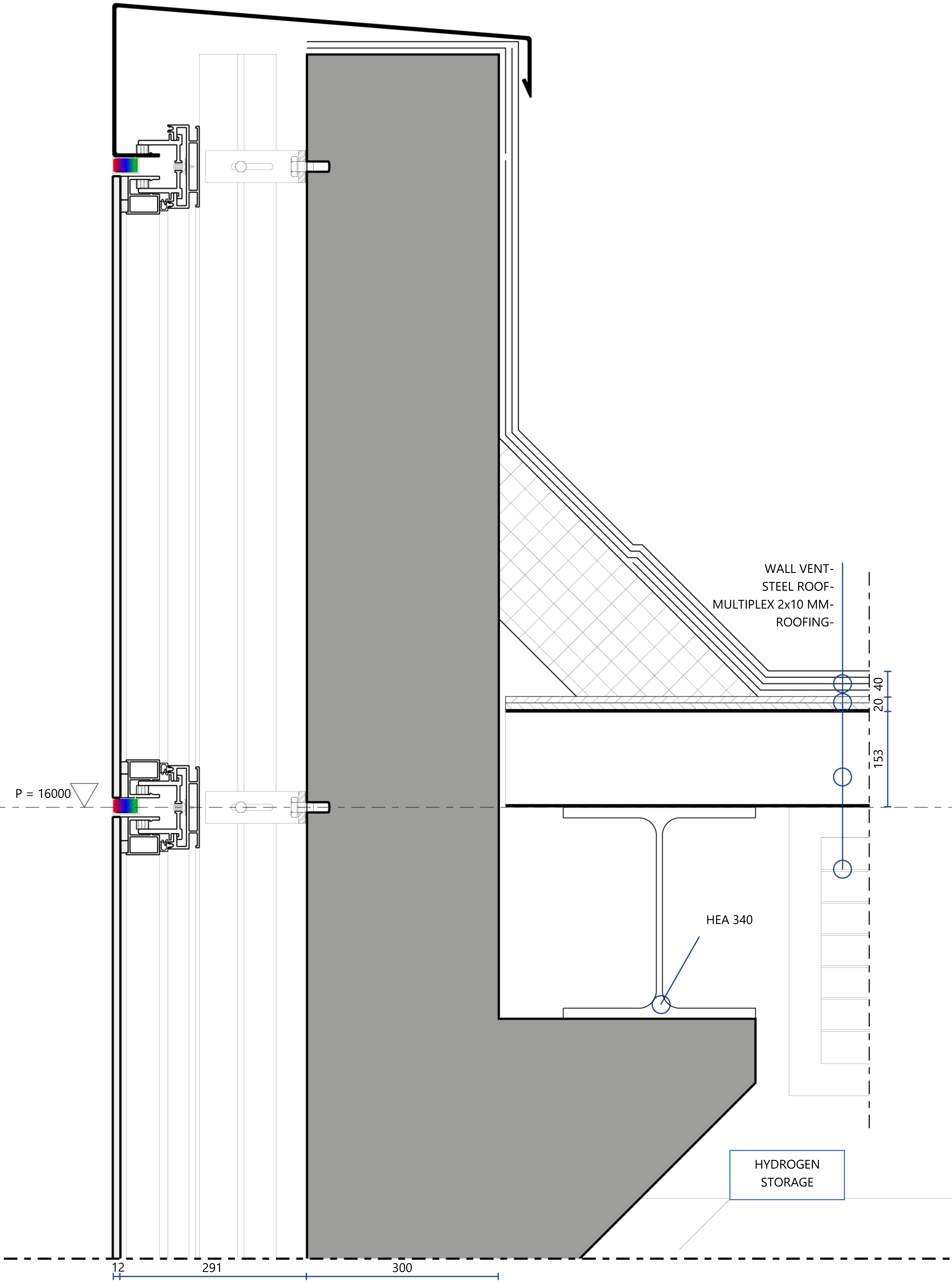
Section 1:	Overview of west façade	scale 1:50
Detail 1:	Façade system with integrated LEDs	scale 1:1
Detail 2:	Detail of cantilevering part	scale 1:10
Detail 3:	Detail of roof connection	scale 1:5



Detail 3
Detail 1
Detail 2


CONCRETE WALL-
SUPPORT MULLION-
RUBBER-
SUPPORT FRAME-
ADHESIVE-
LAMINATED GLASS-
P = 7000
30
18
LIGHT DIFFUSER
SPACER
12
9
113
170
303


HYDROGEN
STORAGE
HEA 340
-CONCRETE FINISH FLOOR
-CONCRETE FLOOR
P = 5000
FLOOR GRATE FOR
CONSTANT VENTILATION
VENTILATION VENT-
CONCRETE WALL-
SUPPORT MULLION-
SUPPORT FRAME-
WEATHERING STEEL FAÇADE-
FACADE ELEMENT WITH
INTEGRATED LED
WALL VENT
ELECTROLYSER
ROOM
303
300
7000


WALL VENT-
STEEL ROOF-
MULTIPLEX 2x10 MM-
ROOFING-
40
20
153
P = 16000
HEA 340
HYDROGEN STORAGE
12
291
300