The integration of smart heating and energy management within a neighborhood

An advice report for the Brainport Smart District

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Table of content

Tables and Figures index

1 Introduction

1.1 Context

Currently the ambition to create a sustainable environment is increasing. Buildings need to be built more and more sustainable in terms of energy usage, generation and storage. Associated with this are the problems with energy losses for those buildings and changing regulations for construction of buildings and supplying energy.

Brainport Smart District is a new project as a part of the neighborhood Brandevoort, situated between Helmond and Eindhoven. This new district aims to create a smart and sustainable living and working district for people by integrating state-of-art technologies. The Brainport Smart District formulated seven important program lines (Brainport Smart District, 2019):

- Circular neighborhood: self-sufficiency, organic developments and co-creation are some key aspects.
- Participation and co-creation.
- Social and safe neighborhood: the developers are striving for a mix of inhabitants and would like to experiment on the social-economic aspects.
- Healthy neighborhood: the focus of this program line is to prevent issues by using (new) technologies, the environment and a strong social basis.
- Digital neighborhood: privacy in the data used is an important feature in the current times, the inhabitants of the neighborhood will have their own control over the data to be used, but the data is needed to innovate.
- Mobile neighborhood: for personal mobility and the deliveries of goods in the neighborhood a mobility plan will be developed together with the future inhabitants.
- Neighborhood with energy: the neighborhood should have a user-friendly energy system.

Within the neighborhood several houses, office spaces and common areas will be developed. Around the development area, 80 hectares of ground will be available for food production, water storage, nature and energy generation (Brainport smart district, 2019).

1.2 Problem statement

Currently the world is facing an energy transition from fossil fuel to renewable energy, which challenges the future buildings that need to be designed more environmentally friendly. This implies that the function of energy grids must be smart, flexible and adaptive. For the future design, as well as development of energy management systems (EMS), buildings should be designed to integrate not only energy loads, but also distributed generation and storage (Zeiler & Labeodan, 2019).

A smart EMS at the neighborhood level, should be capable of: 1) optimizing local energy demand, generation and storage; 2) achieving energy efficiency by making optimal decisions, for example automatically increase energy consumption when prices are low; 3) delivering thermal comfort to users. However, standard EMS control strategies in neighborhoods still rely on fixed scheduled operations, without integrating local climate conditions, users' needs/demands and grid requirement (Wen & Mishra, 2018). For the creation of the EMS, the storage is of great importance. But this in one of the most complex and inefficient parts of the energy system (ESA, 2019). To solve the mismatch between the demand and supply of energy, storage seems to be the most challenging problem.

Not only the storage is a problem, but also buildings consume a large portion of overall energy (51% of total national energy use), especially in HVAC systems which consume about 60% of the total energy of an individual home (Roberts, 2019). However, most of the building energy control systems still use rule-based methods (Wen & Mishra, 2018) which requires users to fill in their temperature preferences, set points and schedules based on certain activities. These methods are less adaptive in terms of scalability and flexibility, as well as energy efficiency (Schein & Bushby 2006.) On the other hand, creating a comfortable indoor climate is one of the essential functions of both residential and commercial buildings. However, only 44% of buildings (Kim, 2018) succeed to accomplish this goal that delivers a standard thermal climate that is perceived comfortable.

Associated with heating is the thermal comfort, it is a subjective phenomenon based on mainly two categories: environmental factors and personal factors (Katić et al, 2018). Environmental factors include indoor-outdoor temperature, humidity and building insulation etc. Personal factors consist of body weight, age, gender, metabolism rate and physical condition (sick or not). Theoretically, combining both categories of factors would potentially deliver a thermal climate that satisfies most of the building occupants, however, everyone has their own individual preference, therefore, to create a thermal climate that is able to adopt different individual's thermal preference is yet a challenging practical problem that needs to be solved.

1.3 Research questions

The main research question associated in the research will be:

What could be an integrated solution for a smart HVAC system coupled with an energy management system for buildings within the Brainport Smart District?

To answer the main research question, the following sub-questions are developed:

- Which smart HVAC systems are already available for different scale buildings?
- Which storage and generation facilities are available for operating in the BSD?
- Which criteria are important for the selection of the integrated system?

1.4 Methodology

In this research the method visible in Figure 1 will be used. The first step is the investigation of the possible smart heating and energy management systems which have the possibility to be integrated within the neighborhood. This stage will be conducted according to a literature review of possible systems. Sub-question 1 and 2 can be answered after this stage.

In the second step, case studies will be conducted to evaluate how the combination between a smart heating system and a storage system are working. This evaluation of practice will be used to formulate an advice.

The third step is the definition of the criteria for the different aspects, this gives answer to the third sub-question. The selection of the best combined solution(s) will be determined in the fourth step of the analysis. Morphological charts will be the main tool of assessment of the different possible solutions for both EMS and heating systems. Through a visual way, a wide range of alternatives can be explored and eventually the best solution, according to the characteristics defined in stage 3, will be selected. More specifically, after identifying the criteria of assessment, a matrix will be created with these criteria in columns. Then the rows will be filled with the different solutions (alternatives for different systems). By scoring the different solutions, the best one(s) of them will be finally determined. Together with the final advice the research question could be answered.

The results of the morphological chart will be used to formulate the advice for the Brainport Smart District. The advice will be based on the previous stages and the outcomes for an integrated system.

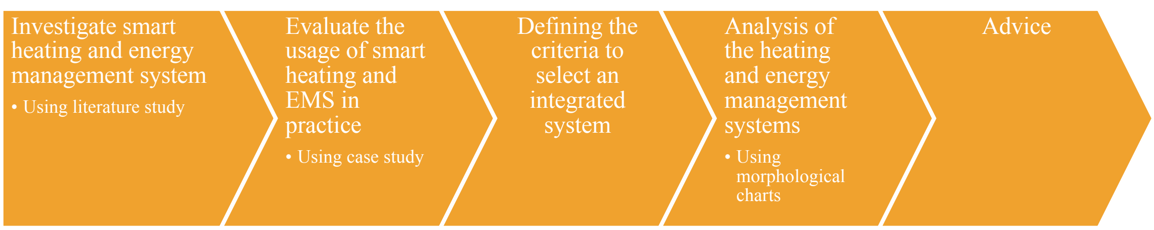


Figure 1 Methodology

2 Literature review

The first part of the research consists of a literature review into the associated sections in the heating system and the energy management system. This literature review is used to answer the first sub-question: "Which smart HVAC systems are already available for different scale buildings?" This is done in the first part of the literature review where literature is collected to describe the function of HVAC systems and which systems are already available for operation, heating and cooling. The second part of the literature review is about answering the second sub-question: "Which storage and generation facilities are available for operating in BSD?" Where a literature review into storage facilities and generation options are used to answer this question.

2.1 HVAC Systems

The built environment plays a very important role in reducing energy consumption and greenhouse gas emissions. In fact, it is estimated that approximately 20-40% of the total energy consumption in the world comes from building systems (Ilhan, I., Karakose, M., & Yavas, M., 2019), so it is crucial to take immediate action both in individual building level and neighborhood level. Smart buildings use a variety of technologies and systems in order to operate in a more efficient way, in terms of energy usage, sustainability and the smart electrical grid. These systems include building automation, life safety, telecommunications, user systems, and facility management systems as shown in figure 2. Among others, the building automation systems, such as HVAC control, lighting control, power management and metering, play an important role in determining the operational energy efficiency in the building.

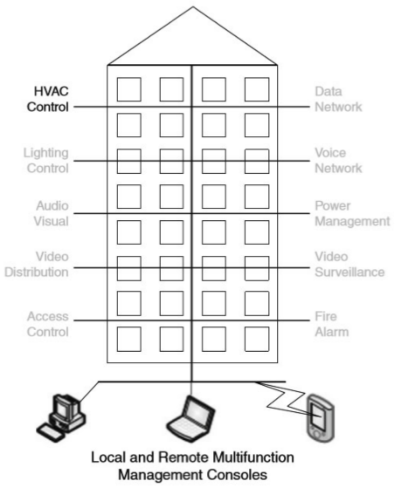


Figure 2 Integrated building systems
Source:(Sinopoli, 2010)

HVAC stands for Heating, Ventilating, and Air Conditioning. The main purpose of an HVAC system is to provide thermal comfort and good indoor air quality for the occupied buildings. The technology of HVAC systems is designed using the principles of thermodynamics, fluid mechanics and heat transfer. They are installed in residential buildings such as family homes and apartments, as well as in industrial, commercial and institutional buildings. For each building type there is an HVAC system available that can provide the necessary comfortability to the occupants of the building. Designing an HVAC system for a specific building is based on climate, type of building, specific user preferences, budget of the client and designer of the project. HVAC systems can be classified according to basic processes and the process that handles the distribution. The basic requirements of such a system are the heating process, the cooling process and ventilation process. In addition to these processes, there is also the possibility to add new processes if it is a user request such as humidification and dehumidification process or an air purifier process. The distribution system is essential for providing the required quality air to the different spaces in the building. The configuration of the distribution depends strongly on the type of HVAC system operation. The distribution method is achievable with air ducts, air handling equipment, water pipes, air handling equipment and water pipes. Building automation devices help determine the amount of heating or cooling the rooms need based on user preferences. User input activates the HVAC system and it pulls the right amount of air into the building. The system either heats or cools the coils inside depending on the temperature set by the user. The air is pushed through these coils and distributed to the rooms. During this process, air in the room is displaced from the rooms back into the system where it is used to help with heating up the fresh air from outside (Seyam, 2018).

In terms of components, HVAC systems are complex, as they consist of many components. The major components include boilers, chillers, air-handling units (AHUs), air terminal units (ATUs), and variable air volume equipment (VAV) (Sinopoli, 2010). More specifically, the basic components of a HVAC system are:

- Mixed-air plenum and outdoor air control
- Air filter
- Supply fan
- Exhaust or relief fans and an air outlet
- Outdoor air intake
- Air Ducts
- Terminal devices
- Air recovery system
- Heating and cooling coils
- Self-contained heating or cooling unit
- Cooling tower
- Boiler
- Control
- Water chiller
- Humidification and dehumidification equipment

2.1.1 Classification and selection of HVAC systems

HVAC systems can be classified into two categories: central system and local system. Central HVAC systems provide heating, ventilating, and air conditioning to the whole interior of a building from one point to multiple rooms. Primary equipment is centralized and from there water and air is distributed to the different zones in the building. Local systems, however, focus on a specific zone of the building and have their main equipment installed in these zones. The air and water distribution system should be designed based on system classification.

System selection depends on three main factors including the building configuration, the climate conditions, and the requirements of the user. Various systems are available to meet the requirements and satisfy the user of the building. Some criteria can be considered when selecting an HVAC system such as climate, building capacity, spatial requirements, cost such as capital cost, operating cost, and maintenance cost, life cycle analysis, and reliability and flexibility (Seyam, 2018). The criteria for central system and local system is shown in Table 1.

Table 1 Comparison of central and local systems according to the selection criteria

Criteria	**Central system**	**Local system**
Temperature, humidity and space pressure requirements	• Fulfilling any or all the design parameters	• Fulfilling any or all the design parameters
Capacity requirements	• Considering HVAC diversity factors to reduce the installed equipment capacity • Significant first cost and operating cost	• Maximum capacity is required for each equipment • Equipment sizing diversity is limited
Redundancy	• Standby equipment is accommodated for troubleshooting and maintenance	• No backup or standby equipment

Special requirements	• An equipment room is located outside the conditioned area, or adjacent to or remote from the building • Installing secondary equipment for the air and water distribution which requires additional cost	• Possible of no equipment room is needed • Equipment may be located on the roof and the ground adjacent to the building
First cost	• High capital cost • Considering longer equipment services life to compensate the high capital cost	• Affordable capital cost
Operating cost	• More significant energy efficient • A proposed operating system which saves operating cost	• Less energy efficient primary equipment • Various energy peaks due to occupants' preference • Higher operating cost
Maintenance cost	• Accessible to the equipment room for maintenance and saving equipment in excellent condition, which saves maintenance cost	• Accessible to equipment to be in the basement or the living space. However, it is difficult for roof location due to bad weather
Reliability	• Central system equipment can be an attractive benefit when considering its long service life	• Reliable equipment, although the estimated equipment service life may be less
Flexibility	• Selecting standby equipment to provide an alternative source of HVAC or backup	• Placed in numerous locations to be more flexible

Source: (Seyam, 2018)

2.1.2 Types of HVAC Operations

Operating the HVAC system is one of the parts analyzed. There are several operation systems that can be applied in different scale buildings. The six operation systems selected are as follows; rooftop units, heat pumps, water source or geothermal heat pump and geothermal heating and cooling.

2.1.2.1 Rooftop Units

Rooftop units are also often known as air handlers. They are large HVAC systems that are installed on a rooftop in order to moderate the temperature of a large scale in the building. Inside the big boxes that you see on top of office or apartment buildings are a blower, heating and cooling elements, filter racks, and chambers and dampers. These boxes typically connect with a ductwork ventilation system, that will distribute the air through the building before returning it to the box to either discharge or return air back into the system like an air recovery system (Krishna, 2017).

2.1.2.2 Heat Pumps

Heat pumps are an efficient system that extracts heat from a cold space (such as the outdoors during winter), and then warms up and releases it into a room to control the temperature inside. When used for heating, heat pumps use the same refrigeration-type cycle that is used in an air conditioner, but rather than release the air outside as a cooling system would do, it pushes air in the opposite direction back into the room to be heated. Heat pumps can also be used for cooling a room, reversing the flow of air to again expel the heated air that is brought into the system. The real benefits are achieved when the system is used for heating, as heat pumps can be up to four times as efficient in their use of power than more traditional heater systems (Krishna, 2017).

2.1.2.3 Water Source/geothermal heat pump

Water source heat pumps offer a sustainable heating and cooling solution. Water source heat pumps are relatively uncommon as they require proximity to a body of water. However, the adoption of geothermal heat pumps is growing fast. This heat pump is not entirely depending on water. Regardless of whether there is water in the ground, the system can heat or cool the building in both cases. The system offers both heating and cooling by transferring heat in or out of the ground and using the moderate changing temperatures of the earth to boost the efficiency of the system. The system can be optimized by drilling down in the ground to create a bore near the building. Cooled water underneath the earth can be extracted out of the ground to provide drink water and feed an open-loop heat pump. This would take the heat from the water and use it to raise the temperature in a home's water system, providing heating and hot water. Excesses of grey water can then be used for irrigation for the garden for example (Krishna, 2017).

2.1.2.4 Geothermal Heating and Cooling

Geothermal heating and cooling system or geothermal HVAC system is a central heating system that takes advantage of stable earth temperatures to provide heating or cooling for buildings. The system uses the earth as a heat source during the winter and a heat sink in the summer. Outdoor temperatures fluctuate a lot during the seasons, but beneath the surface the temperature remains relatively constant. The earth offers a stable temperature between 16-29 degree Celsius at around 6 meters deep all year-round thanks to its insulating properties. A geothermal HVAC system consists of an indoor handling unit and a network of underground pipes, called earth loop. These ground loops function as a geothermal earth connection system that will help exchange the heat with the earth. The pipes are usually made of high-density polyethylene (HDPE) or the more expansive option copper due to its high thermal conductivity. The diameter of pipe ranges from 29 to 38 mm depending on the heating and cooling demand (Krishna, 2017). The length of the loop is important for the overall efficiency of the system. The efficiency of the system can be improved by increasing the length of the loop. The required length of the ground loop depends on the geographical and building characteristics.

There are two different options for the ground loop. The first option is an open loop system. This configuration has two wells drilled into the underground water. One is for pumping up the water from the source to run it past a heat exchanger and the second is for returning the water. For utilizing this system, the availability of water needs to be 5.67-7.57 Liters per minute (Lpm) per ton (Krishna, 2017). The main disadvantage of this system is the quality of water that the system will be using. It may affect the longevity of components and will eventually result in high maintenance costs.

The second option is a closed loop system in which water is re-circulating through a coil in the handling unit. This system provides more control over the water quality that will result in a greater lifespan. The water contains antifreeze mixture to avoid freezing. The closed loop system has two configurations: horizontal loop and vertical loop.
Horizontal closed loop field are pipes running horizontally in the ground. A horizontal loop field is about half the cost of vertical loop configuration. The size of the field depends on the heating

requirement of the building. For example, a detached house with a heating capacity of 10 kW (3 ton) requires approximately three loops of 120 to 180 meters of polyethylene pipes (DN 32) at a depth of 1 to 2 meter (Chiasson, 1999). They also require approximately 232 m2/t of area but are easy to be installed and are less costly. The depth of the loops influences the energy consumption of the handling unit in two different ways. Shallow loops absorb more heat from the sun when the ground is still cold after the winter period. However, shallow loops cool down much easier by weather changes. This is especially a problem during cold winters when heating demand peaks. This problem can be reduced by increasing the depth and the length of the ground loops. As a result, this will increase installation costs. By weighting the pros and cons, a clear picture can be made of whether the installation expenses are feasible or not. Recent studies show that by using non-homogeneous soil profile with a layer of low conductive material above the ground loops can help mitigate the adverse effects of shallow pipe burial depth. This soil profile has a significant lower conductivity than the surrounding soil profile and increases the energy extraction rates from the ground to as high as 17 percent for cold climate and about 5 to 6 percent for a relatively moderate climate (Rezaei, 2012a).

Vertical closed loop field utilizes pipes that run vertically in the ground. The loops are installed in the ground with a varying depth of 15 to 122 meters. Foundation piles can carry the vertical loops to reduce the amount of drilling, therefore decrease the installation cost. A pair of pipes in the borehole are connected by a U-shaped cross connector at the bottom of the hole. The empty space in the borehole, after the ground loops are installed, are filled up with a bentonite grout to provide thermal connection to the surrounding soil. The space between boreholes is at least 5 to 6 meters. For example, a detached house with a heating capacity of 10 kW (3 ton) requires approximately three boreholes of 80 to 110 meter deep. This type of system requires 23 to 27 m2/t of area. The installation cost is higher than the horizontal loop configuration. The advantages of vertical loop are less space requirement, less variations due of temperature and thermal properties of soil and greater efficiency.

The geothermal heat pump system consists of a compressor, condenser, expansion valve and evaporator and is governed by the second law of thermodynamics. The system raises the temperature of vapor by isentropic compression. The cooling effect is created by expanding the compressed vapor in the expansion valve and lowering its temperature. The system acts as a refrigerator in the summer. The heat pump transfers heat from lower temperature to higher temperature. It does not generate heat by itself. Heat pump converts 1 KW of electricity into 3 KW of useful work. The lifespan of a heat pump is more than 20 years. The distribution system of a geothermal heat pump consists of an air handling unit. The air handling unit distribute the required temperature air to the desired room. Energy savings by using a geothermal heating and cooling systems are as follows; 51 percent of the energy is free, hot water is decreased with 6 percent compared to a home energy system without geothermal heat pump and heating and cooling saw a huge decrease from 64 percent to just 19 percent (Krishna, 2017). Thus, the heat pump has high energy efficiency. Traditional HVAC systems are depending on outside temperature. With a geothermal heating system, all these factors are eliminated. It has a lower maintenance and operating cost compared to traditional systems. Geothermal heating and cooling are an eco-friendly solution that will save a huge amount of CO_2 (Krishna, 2017). The advantages and disadvantages are evaluated in table 2.

In the winter periods heating is the main objective. The ground loop absorbs the heat of the earth and therefore increases the heat of the water in the pipes. The expanded vapor refrigerant is circulated within the heat conductive copper pipes. The refrigerant absorbs the heat from the water in the ground loop. This vapor refrigerant is transferred to the compressor where it is compressed to high pressure and high temperature. The hot refrigerant vapor is passed from the copper coil in air handling unit. The cold air from the room is blown over the hot refrigerant in the coil using a fan where it will heat the incoming air by absorbing the heat from the hot vapor refrigerant.
When the system is in cooling mode, it will reverse its operation from heating to cooling. The water in the loop release the heat to the earth. The temperature of the water in the ground loop will decrease. The hot refrigerant from the compressor release its heat to ground water in the loop. The same will happen to the hot refrigerant, its temperature will decrease. After this process, the refrigerant vapor is expanded in the expansion valve where it will reduce its temperature even more. The cold refrigerant then

circulates in copper coil of the air handling unit. In this case the hot air in the room will blow over the cold copper coil. The air will cool down and returns to the room. The refrigerant will become hot and returns to the compressor, where it is compressed to high temperature and high pressure. After this the whole cycle will repeat (Krishna, 2017).

Table 2 (Dis-) advantages of geothermal heat pump.

Advantages	**Disadvantages**
Extremely efficient	High installation cost
Harnesses renewable energy	Surface needed underneath building
Low heating costs	
Modular system	
Almost no maintenance	
Long lifespan	

Source: (Krishna, 2017)

2.1.3 Types of HVAC systems

Heating and cooling will account for as much as half of the energy use in the building. It is important to select an HVAC system that will provide optimal comfort, is efficient with energy usage and ensures a return on investment. Buildings that are in hot or cold climates might be interested for a single stage system, which means that it is just designed for heating and cooling. This system is inexpensive but is inefficient to operate and will work at a maximum capacity even when it is not required. More advanced systems will offer more flexibility due to a variable fan speed. However, this type of setup will remain inefficient compared to multi-stage systems and will cost more to operate in the long run. Zoned systems are designed to heat or cool individual parts of the building. These have a zone valve and damper inside the vent that can control the airflow inside the rooms. This system allows to turn of heating and cooling in individual parts of the building, therefore reducing the energy consumption. HVAC systems can also contain a dedicated humidity control for both humidifiers and dehumidifiers. For people living in very dry environments this can be essential. For every requirement there is a wide range of heating, cooling and air conditioning systems available (Seyam, 2018).

2.1.3.1 Heating Systems

Heating systems come in different forms with each a set of unique functionalities. There is a wide variety of heating systems on the market that can provide comfort in public and private buildings. Heating systems have three basic components: the fuel source, the energy source and the distribution system. They are either central or local based as discussed in table 1. Most common is the central system, such as furnaces. Furnaces burn material to provide heated air through the ductwork. Other popular systems are boilers that heat water for steam radiators, forced-water systems with baseboard radiators, electric heat and heat pumps. A furnace uses natural gas or propane to heat the rooms, while a boiler operates on gas or oil to heat the water. Another option is radiant floor that uses the floor to heat the room. Two types of radiant floor heating are available, electric and water-bases systems. Both provide consistent heating in a room by heating the entire floor. This system is highly efficient and requires almost no maintenance (Kubba, 2016). Some other systems that regulate temperature in buildings are discussed in the following paragraphs.

2.1.3.1.1 Electric heating

Electric heating converts electricity to heat by using resistors that emit radiant energy. Resistors are mostly made of metal-allow wire, nonmetallic carbon compounds or printed circuits. Common applications are space heating, water heating and industrial processes. Electric heating is a popular option for both residential and public buildings. The cost to operate electric heating is in general higher than conventional systems such as combustion or fuel-based heating systems due to the higher price of electricity. However, electric heating is more convenient, stylish and uses less space. The rooms can be heated by using electric coils or strips in floors, walls and ceilings (Kubba, 2016). The summarized pros and cons of electric heating system are evaluated in table 3.

Table 3 (Dis-)advantages of electric heating

Advantages	Disadvantages
Provide more safety and comfort	Expensive to operate
Simplicity and convenience	Limited to small spaces
Higher efficiency and durability	
Lower standby loss	
Lower maintenance	

Source: (Kubba, 2016)

2.1.3.1.2 Electric baseboard Heaters

Baseboard heating is a common heat source and essentially a zoned heating system. Baseboard heating is simple quiet and installation cost are low. However, they can be expensive to operate due to high cost of electricity. Rooms are heated by the process of electric resistance. The baseboard heaters are provided with electric cables that warm up the circulating air. Most of the time these heaters are installed on the wall close to the floor to provide perimeter heating. Air in the room rises when its heated by the device. The warm air will be replaced by cooler air which will cause a continuous convective flow of warm air during operation of the system. Baseboard heaters do not have any moving parts and therefore it will have a higher durability (Kubba, 2016). Summarized in table 4 are the (dis)advantages of the electric baseboard heating system.

Table 4 (Dis-)advantages of electric baseboard heating

Advantages	Disadvantages
Zoned system for comfort	High level of electricity needed for operation
Set specific temperature for each unit	Specific placement is necessary
No ductwork	Cannot place furniture in front of the system
Long-term option	Needs maintenance
Durable due to no moving parts	

Source: (Kubba, 2016)

2.1.3.1.3 Furnace heating

Furnace heating is designed to heat air for distribution to various rooms. Small capacity furnaces that uses natural convection for heat distribution can be classified as a local system. They are more effective for a single room only. The system can be upgraded with fans to serve more rooms. This system is used in residential and small commercial buildings. Furnaces typically use natural gas, fuel oil propane or electricity to operate. Solar energy and heat pumps are also used as source. Natural gas furnaces can also be equipped with a condensing unit to add a cooling functionality. Today's furnaces have an efficiency between 78% and 96% according to the measurement of annual fuel utilization efficiency (AFUE) for seasonal performance (see table 5). Traditional furnaces have an efficiency of 80-82% (Kubba, 2016).

Table 5 (Dis-)advantages of furnaces

Advantages	Disadvantages
Electric furnaces are inexpensive to install and have long lifespan	Gas furnaces can pose risks to your wellbeing such as fires and carbon monoxide poisoning
Furnaces provide reliable heating	Gas furnaces don't have a long lifespan compared to electric furnaces
High comfort	Expensive to operate
Long-term option	Requires higher maintenance
Efficiency between 78 and 96%	

Source: (Kubba, 2016)

2.1.3.1.4 Radiant heating

Radiant heating system is clean, quiet, efficient, dependable and invisible when appropriately integrated into the building. There are two types of radiant heating, hydronic (water) radiant heater or electric radiant heater. Hydronic radiant heating system uses continuous loops of tubing that are integrated into floors, walls or ceilings. Warm water circulates through the loops to heat the room. The water is heated by a boiler that is connected to the loops. The tubing system transfers the heat into the floor and upward into virtually any surface that's in the room such as carpeting, ceramic tile, concrete and vinyl flooring. If electricity is used for radiant heating, panels are mounted on the wall, baseboard or ceiling of the room. The advantages of radiant heating are that it provides uniform heat and is both efficient and inexpensive to operate (Kubba, 2016). The efficiency is high due to radiant heat that raises the inside surface temperature of the room. This provides comfort at a lower room air temperature (Kubba, 2016).

Table 6 (Dis)advantages of radiant heating

Advantages	Disadvantages
High efficiency	Substantial upfront cost
Inexpensive to operate	Risk of leaks in hydronic systems
Long-term option	Risk of fire in electric systems
Space efficient	Difficult to repair
Uniform heat distribution	

Source: (Kubba, 2016)

2.1.3.1.5 Warm air heating system

Gravity and forced air systems are two basic types of warm air heating systems that are available on the market. The gravity system operates by the process of air convection. When air is heated, it expands and becomes lighter. The lighter air will rise and makes place for cooler air. The difference in air temperature creates the convection to move the air in the room. The gravity system cannot be restricted by a filter otherwise a positive convection won't be possible. The furnace has a burner compartment and a heat exchanger. The heat exchanger is used to transfer heat from the flame to the air. The warm air is distributed through ductwork to various rooms. The heat exchanger helps keeping the fuels separate for the air. Humidification can be added as an option. Forced air systems typically have a fan or blower placed in the package, which blows air through an evaporator coil to cool the air. The cooled air is forced through air ducts. The advantage is that the same equipment is able to provide air condition throughout the year. This drives adoption of forced air warm air systems in residential buildings (Kubba, 2016).

Table 7 (Dis-)advantages of warm air heating system

Advantages	Disadvantages
Quick response time	Substantial higher upfront cost
Long life span	System doesn't work well when doors or windows are open
More control	
Air is free of allergens	
Option for both summer and winter months	

Source: (Kubba, 2016)

2.1.3.1.6 Hot water heating systems

Hot water heating systems typically have a central boiler in which water is heated. The warm water is distributed by pipes to the coil unit such as the radiators in the various rooms. Circulation is initiated by pressure and gravity in the system. Forced circulation can be achieved by using a pump. It adds flexibility and control over the system. In the rooms there are emitters installed that produce heat from their surfaces by convection and radiation. The cooled water returns to the boiler where it gets heated again. Additional systems can be added such as an air handling unit (AHU). Hot water will warm up the air before it enters the room. Hot water systems provide more convenience and save water. However, the system is not cost-effective because it uses a lot of energy (see table 8 for an overview)(Kubba, 2016).

Table 8 (Dis-)advantages of hot water heating system

Advantages	**Disadvantages**
Longer lasting heat	Costly to install
Quieter operation	Difficult to add central air conditioning
Better air quality	Radiators take up space in the room
More convenience	Risk for leakage in the system
Water saving	Uses a lot of energy

Source: (Kubba, 2016)

2.1.3.1.7 Steam heating systems

Steam systems take advantage of high latent heat, which is generated when steam condenses into liquid water. This system works like hot water systems except that steam circulates though pipes to the radiator. The steam is used to carry heat from the boilers to the rooms. Three common steam systems used are air vent systems, vapor systems and vacuum or mechanical pump systems. Steam heating systems are rarely installed in new single-family houses (Kubba, 2016). The advantages are compared with the disadvantages in table 9.

Table 9 (Dis-)advantages of steam heating systems

Advantages	**Disadvantages**
Quiet system	Expensive to install
Good efficiency	Heating is slower to initiate
Lower energy cost	

Source: (Kubba, 2016)

2.1.3.1.8 Reverse cycle chiller

Reverse cycle chiller (RCC) is a heat pump variant that's one of the latest technological advancements in the heating industry. This type of heating system uses hot water as a heat source. When the cycle is reversed, the reverse cycle chillers will kick in to cool the room. The advantage is that this system can provide both heating and cooling, more advantages are visible in table 10. The reverse cycle chiller heat or cool an insulated tank of water and then distributes the heating or cooling either through fans and ducts or radiant floor systems. This system is more suitable for cold climates compared to traditional heat pumps due to the elimination of auxiliary electric heating coils and defrosting cycles. Some benefits of using reverse chillers is the energy efficiency of the system. They use about 25 to 50 percent of the electricity used in a single-family house with a complete air conditioning system. The RCC system is modular and is easy to scale up for larger buildings. Newer models provide solar-powered water heating for the unit. These models require an exterior condenser unit like traditional HVAC systems (Kubba, 2016).

Table 10 (Dis-)advantages of warm air heating system

Advantages	**Disadvantages**
Extremely efficiency	High upfront cost
Inexpensive to operate	
They cool in summer and heat in winter	
Help purify the air	
Modular system, adaptable and flexible	
Long-term option	

Source: (Kubba, 2016)

2.1.3.1.9 Solar thermal collectors

Solar thermal collector is a device designed specifically to collect heat by absorbing sunlight. This system is used for heating water or air to heat the building. The operation of the system is based on the radiation from the sun that heat the water or air and it is then stored in a tank. The tank acts as a thermal storage system. The thermal storage heats the water or air that is running through pipes to heating system such as radiant floor heating. The thermal heat is transferred by using a heat exchanger, in figure 3 the system is presented. This system is also called a solar combi system. Water solar collectors can replace or supplement a boiler in water-based heating system. Air heating collectors may replace or supplement a furnace. Solar collects are renewable energy technologies that provide huge economic benefits. They have an estimated lifespan of 25 to 30 years or more and require almost no maintenance. When used in combination with an absorption refrigeration system, the water solar system can provide heated water that can be used for space cooling (Kubba, 2016).

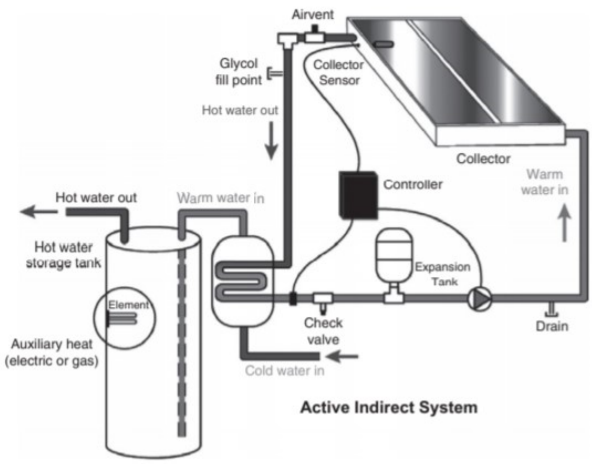


Figure 3 Diagram of an active solar system
Source: (Southface Energy Institute; Kubba, 2016)

To summarize the functioning of the solar thermal collector system, the table 11 lists the advantages and disadvantages.

Table 11 (Dis-)advantages of solar thermal collector (solar combi system)

Advantages	Disadvantages
High efficiency	High upfront cost
Renewable energy source	
Easy storage of thermal energy	
Modular system	
No maintenance	
Long-term option	

Source: (Kubba, 2016)

2.1.3.2 Ventilation and Cooling Systems

Air conditioners come in many forms, from the massive boxes designed to cool an entire house to a portable window-mounted box that can be pulled out and used in cooler climates to handle short summers. Many air conditioners can even be installed by the owner, with ductless mini split systems a popular choice. Installation is still a major project, as the interior and exterior elements of the system need to be properly connected, but they are relatively inexpensive to buy and run.
For dryer climates, evaporative coolers are a popular choice. They draw outside air into the system, passing it through water-saturated pads, which cool and moisten the air before pushing it into the living space and displacing the hot air.

Smaller air conditioning systems collect the heat from within a room and distribute it to the same room to cool it down. This type of air conditioning system is used in a lot of automobiles. Figure 5 shows how this system works and table 12 combines the necessary components of an air conditioning system.

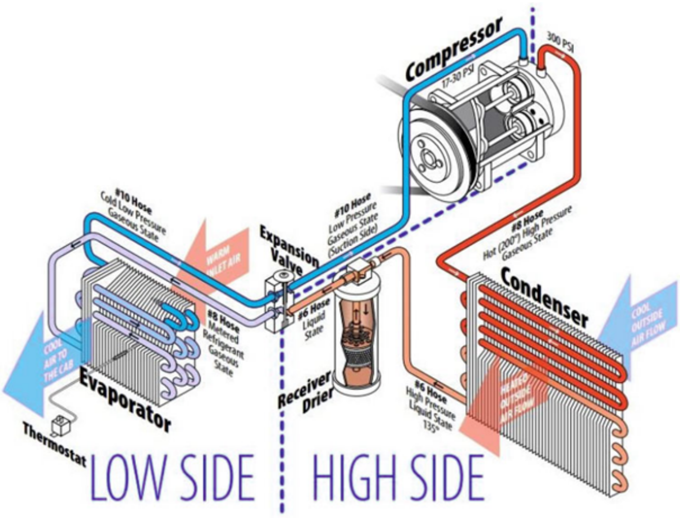


Figure 5 Working principle of air conditioning system
Source: (21Celsius, n.d.)

Table 12 Necessary components of air conditionig system

Component	**Function**
Expansion valve	Restricts the liquid in the system to create a pressure drop
Evaporator	Removes heat from the space by exchanging it for a boiling refrigerant
Compressor	Pushes the refrigerant through the system
Condenser	Pushes the buildup heat inside the refrigerant into the outside air
Receiver driver	Storage area for excess refrigerant that contains a drying agent and a filter that removes contaminants from the air

Source: (21Celsius, n.d.)

The ventilation of rooms within the building are of great importance for the level of comfort of the users, this is both for public and private buildings.

According to ASHRAE, there are several characteristics an air conditioning system should comply on;

- Air temperature control
- Air humidity control
- Air circulation control
- Air quality control

The cooling system is not just about providing cool air to the room it is also about the comfort of the above-mentioned aspects. These aspects play an important role in the eventual level of thermal comfort of the occupants.

A distinction can be made between different types of systems:

- All air
- Air/water or air/refrigerant
- Combination systems

2.1.3.2.1 Vapor compression refrigeration

This system is largely used for different scale buildings, from small private buildings to large public buildings. During periods of higher temperatures, the heat is removed from the building. The heat transfer fluid, which functions as refrigerant, can flow the heat from inside to outside.

The system consists of four major parts: A gas compressor, condenser, expansion valve and an evaporator. The compressor is used to take in low pressure air and compress this into a higher pressure at a certain temperature. Within the condenser a phase change occurs, and heat is rejected happening on a high pressure. After that, the refrigerant flows into the expansion valve where the mass changes to a low pressure and temperature. Finally, the evaporator is used to change the phase back to a gaseous stage (Aspen, 2017).

Table 13 (Dis-)advantages of vapor compression refrigeration

Advantages	**Disadvantages**
Flexible thermal management	High initial costs
Low operating cost system	Refrigerants can de toxic or hazardous
Usage of latent heat with phased change	

Source: (Mecholic, 2017)

2.1.3.2.2 Exterior wall or window air conditioning units

The general use of this system is for single-room applications where there is no central air conditioning system. The system consists of ductless units where the system is placed through the wall. With removing warm air from the room, the air flows through the system via the condenser where the air is cooled (Kubba, 2017).

The system consists of the following parts: compressor, expansion valve, a hot coil and a chilled coil, two fans and a control unit.

Table 14 (Dis-)advantages exterior wall unit

Advantages	**Disadvantages**
New systems with usability innovations (like timers, digital temperature read outs etc)	Noisy
Flexible	Only for cooling small areas
	Lower adjustability due to single system

Source: (Kubba, 2017)

2.1.3.2.3 Central air conditioning system

The name of the system already mentions the central system. The system is depending on the room structure where cooling is needed but also the situation towards the sun and climate play a role in this. Furthermore, the usage of the rooms/building is important as well for example the number of inhabitants or users or the activities performed in the room.
The central system consists of three major components; the outdoor units which consists of condenser and compressor, an indoor unit which consists of a blower coil or evaporator and the indoor thermostat.

The central system is mostly applied for offices, public buildings etc. And can supply heating, cooling and ventilation combined in the building.

2.1.3.3 Packaged air conditioners

Packaged air conditioners are comparable with the rooftop units but are designed for smaller domestic use. Where window and mini split air conditioners are good for small room cooling of up to five tons, central air conditioning systems are designed for loads in excess of 20 tons. For that reason, the packaged air conditioner has been designed to accommodate the needs of anyone who fits between those two frames (Kubba, 2017).

There are two types of packaged air conditioners:

- Packaged air conditioners with water cooled condensers are, as the name suggests, air conditioners in which the condenser is cooled by water. Water needs to be supplied constantly to keep these air conditioners in working order. These air conditioners are generally installed inside buildings.
- Packaged air conditioners with air cooled condensers, meanwhile, are cooled by the atmospheric air and are therefore outdoor units. These devices have a fan that sucks in air before blowing it onto the condenser coil, much like in the larger rooftop units. These are the more popular of the two types of packaged air conditioners, as they don't need constant maintenance to ensure a smooth flow of water.

2.1.3.4 Split HVAC system

The split system uses two central units that are separated and deployed in different places. The setup of the system has two options. The first one is a ductless system and is often called the mini split. The other option is a central system. Central systems are ducted systems that are designed specifically around cooling the space. They can offer multi-zone temperature control capability using air-louver-control boxes. This system is used for rooms that do not need constant cooling. The system is easy to operate by the user when using the room and can be switched off when nobody is using the room to save energy. Heat-exchanger is integrated inside the central AC unit of the central system. It is then used to distribute chilled air through the rooms (Kubba, 2017).

2.1.3.5 Ductless System

The smallest of all systems, the ductless or mini split air conditioner is designed for small deployments such as a single large room, or multiple small rooms. They require minimal wall space, and the compressor and heat exchanger unit can be located further away from the main building, allowing greater flexibility in use.
This is the main type of air conditioner you'll find on the market, as it's explicitly designed for home use and fits into the consumer mass-consumption model. These systems are easy to install, even as a home project, and the internal unit is aesthetically pleasing as it forms part of the furniture. The downside to ductless systems is that they can cost more to operate than central systems. However, as with other split systems, these are the only option for customers looking to retrofit existing buildings, as they don't require the installation of ducts (Kubba, 2017).

2.1.3.5.1 Heat recovery

According to Hundy, Trott & Welch (2016) the term heat recovery can be descripted as "describe the passive system that recovers heating or cooling which would otherwise be lost due to the need to maintain ventilation".

Opportunities for heat recovery (Hundy et al, 2016):

- Whenever cool or hot air is extracted from the building and usable air for pre-heat or pre-cool
- Cooled or warmed liquid leaving the process
- Hot gasses can be used to heat up water
- Heating from condenser can be used for heating in the winter.

Thermal wheel
One of the options for integrating heat recovery into the process, is a thermal wheel. As is visible in figure 4, the thermal wheel is placed in between two airstreams. Using an electric motor, the wheel is rotated. The fresh air is flowing through the thermal wheel and pre-heated with the extracted air from the rooms. The operation system, the room thermostat, drives the drive motor in terms of speed. After the air flowing through the thermal wheel, the fresh air is supplied in the room. Later on, the extraction

system extracts the air from the room and flows again through the thermal wheel and then it is used to heat up the fresh air (De Antonellis, Intini, Joppolo & Leone, 2014).

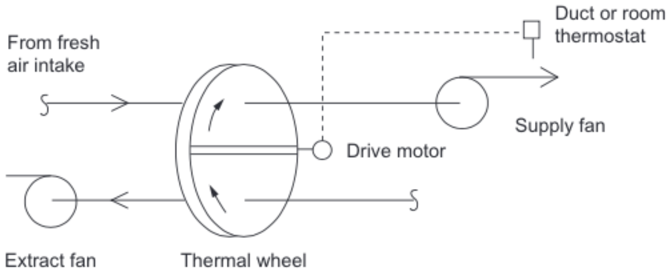


Figure 4 Thermal wheel system
Source: (Legg, 2017)

The advantages and disadvantages are discussed in table 14 below.

Table 15 (Dis-)advantages of thermal wheel

Advantages	**Disadvantages**
Efficiency remains high with every thermal load	Cross contamination, application of thermal wheel is not suitable for hospitals for example
No problems with bacterial growth	
No frost and ice build ups	
Sizes between o.5-4,5 meters	
Flow rate between 0.2-70m3/s	
Efficiency of heat transfer between 70-90%	
Reduction of ventilation and humidity costs	

Sources: (Enegir, 2010; Legg, 2017; O'Connor, Calautit & Hughes, 2016)

2.2 Smart HVAC systems

Smart HVAC systems must respond to a variety of conditions inside and outside the building, such as weather, time of day, different types of spaces within a building and building occupancy, while simultaneously optimizing its operations and related energy usage. They aim to control the levels of temperature, humidity, air flow, and the overall air quality in the house and offer a healthy and indoor environment for the building occupants (Sinopoli, 2010). To achieve this, they use many sensors that can monitor temperature, humidity, presence of occupants, air velocities, air and water flow rates, pressures, electricity or gas consumption, etc. and most of them must be chosen and installed by professionals (Durier, 2017). However, the way smart HVAC systems work varies according to the different scale and type of buildings they are integrated to. In this paper, smart HVAC systems are presented in the context of private-use buildings, such as smart homes, and public-use buildings, such as office buildings.

2.2.1 Smart homes

The term "smart home" has gained momentum during the last three decades and represents a potential research area, as its significance is growing rapidly because of the increasing industrial demand. The main objectives of smart homes are related to providing comfort, healthcare, and security services to their inhabitants (Alam, M.R., Reaz, M.B.I., Ali, M.A.M., 2012). In the first objective, user comfort is closely related to the operation of the integrated smart HVAC system, which is a crucial component in the performance of smart homes (Pallotta, V., Bruegger, P., & Hirsbrunner, B., 2008). The smart HVAC system aims to optimize the energy usage and efficiency of the house. This can be achieved either through human activity identification or through remote home management from distant locations.

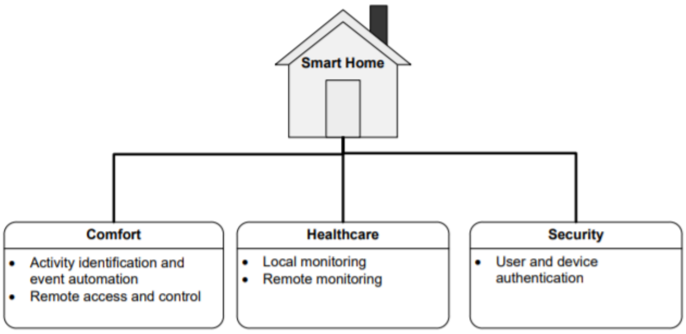


Figure 5 Categorization of smart home projects according to the intended services
Source: (Alam, Reaz & Ali, 2012)

More specifically, smart thermostats allow the building occupants to know and manage their heating and cooling loads, especially from their personal devices, such as smartphones (Durier, 2017). In this way, they can control the heating remotely, by adjusting their heating schedule, and cut down on heating their home unnecessarily at the same time. In addition to this, there is the possibility of installing an intelligent zoned HVAC system which allows the occupants to control the temperature of each room individually and automatically, depending on how they use the rooms in their home throughout the day. In this case, the smart thermostat adjusts the room temperature considering different parameters such as temperature, humidity and occupancy of the room (Ilhan, Karakose & Yavas, 2019). It is also interesting to point out that intelligent zoned heating systems are self-learning as they can adjust the temperature accordingly (Wood, 2015).

Several research and state-of-the-art-projects have been conducted which aim to develop a "smart" home that essentially programs itself by monitoring the environment and sensing actions performed by the inhabitants (e.g., turning lights on and off, adjusting the thermostat), observing the occupancy and behavior patterns of the inhabitants, and learning to predict future states of the house. Among others, “The Adaptive Home” (University of Colorado), the “House_n” (Massachusetts Institute of Technology), “The Aware Home” (Georgia Institute of Technology), the “MavHome” (The University of Texas at Arlington) and “The smart home project” (Duke University) involve interesting approaches in smart house design. The last one will be described in detail since it is selected as one of the case studies presented in the paper.

2.2.2 Smart HVAC strategies

As already discussed, many operation systems are available for heating, cooling and ventilating the building. For Smart HVAC systems there are several systems applicable which can be used for operation and usability within the building.

Strategy 1: Rule-Based Methods.
Rule-based methods are popular because their implementation is relatively easy and intuitive, to apply rule-based methods in buildings allow HVAC experts to apply their best practices and experiences into a set of rules, which can be translated to schedules and conditional setpoints (Wen & Mishra, 2018). For instance, preheating the room around a certain time before the occupants entering the building in the morning; activating ventilation systems when the CO2 sensor detects the CO2 level reaches to certain degree etc.

However, in practice, this approach has several limitations (Wen & Mishra, 2018):

1. This method is less adaptive due to all the setpoints are programmed on a fixed schedule, which requires engineers and HVAC installers provide customized configuration based on the type of the building. This also requires companies to invest more expertise and time on one project and eventually increase the costs of installation and energy performance.
2. It is also difficult to ensure the quality of installation and keep consistency within all different rules, which could impact the efficiency of energy consumption and overall performance.

Strategy 2: Model-Predictive Control
It is no longer a novel feature that a smart building is fully equipped with smarts sensors and monitors platform within its HVAC systems (Lazarova-Molnar & Mohamed, 2019). More and more commercial and residential buildings incorporate state-of-the-art technologies nowadays, and usually with the goals of improving energy performance and occupant comfort.

To better operate buildings and improve building performance, engineers and designers start to take advance of these obtained data and try to generate useful insights. The most popular strategy for the HVAC system is the model predictive control strategy. It is being implemented and seen as an innovative solution to obtain a trade-off between energy efficiency and thermal comfort (Katić et al, 2018; Kim et al, 2018). This approach could overcome the limitations of rule-based methods as it can dynamically adjust all the setpoints based on current conditions.

Integrating these sensor technologies and monitoring platform within HVAC control systems usually generates a huge amount of data, which can be classified into mainly 3 categories:
1. **Environmental data** including indoor temperature, humidity etc.
2. **Energy performance data**: energy consumption, energy generation and storage
3. **User data**: thermal comfort, individual energy profile regarding user's individual consumption patterns

However, to implement the MPC strategy in the HVAC system requires a large amount of data, but in real practice, the collected data from every individual building are mostly insufficient both in quantity and quality. Besides, the implementation of this strategy needs good internet connectivity because all the data will be transferred into the cloud network, this needs also require a higher security mechanism to ensure building energy data security and privacy.

Strategy 3: Collaborative Data Analytics
This strategy is based on MPC but can be implemented at a neighborhood level. The implementation of MPC in a smart building is more feasible, but it is hard to apply this solution to the entire neighborhood or community. This is because of the implementation of MPC in a neighborhood faces more challenges: different types of buildings coupled with different functionality and energy profiles, lock of data collection etc.

Collaborative Data Analytics (Lazarova-Molnar & Mohamed, 2019) seems to be a good solution to implement MPC into neighborhood. Clustering is the most essential element in this solution. In a neighborhood, for example Brainport smart district, buildings with the same characteristics can be assigned to a cluster, the collected data from one cluster can be united in order to achieve a reliable model. By applying this approach in the BSD different clusters could be formed, representing different types of buildings: school, studio, apartment and shop etc.

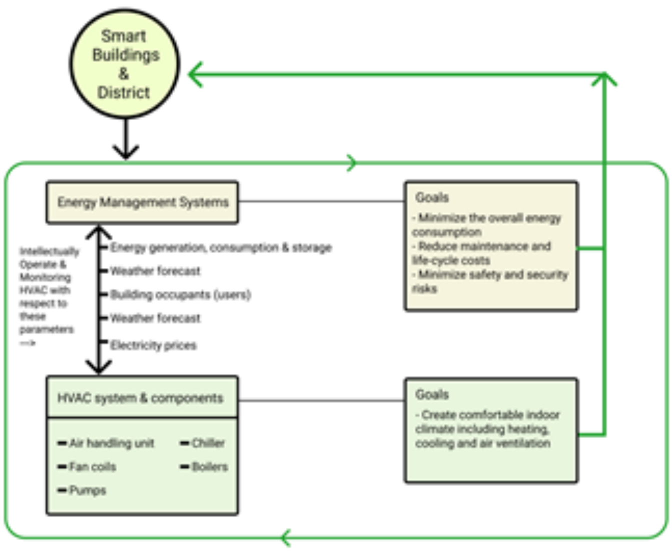
To sum up the above-mentioned strategies, table 15 presents some advantages and limitations of this method for comparison.

Table 16 Comparison of solutions for public buildings

	Features	Limitations	Advantages
Rule Based Methods	— Working both Online / Offline — Less predictive — Less complicated — Less Interactive data collection — Clueless for building users — Single owner	— Extra expertise are required — Less adaptive because it is type-based solutions — Intensive workloads from engineers and companies — High operating costs	— Implementation is relatively easy and intuitive for Engineers — Less security and privacy requirements
Model Predictive Control	— Internet connectivity is required — More predictive — More complicated — Interactive data collection — Smart monitoring and operation	— Data collection sometimes can be difficult — Collecting personal data is ethically difficult. — More security and privacy requirements — Extra expertise are required, for example: data engineers / scientists	— The indoor climate prediction is more accurate. — Improve energy performance and building performance
Collaborative Data Analytics	— Internet connectivity is required — More complicated — Applicable into a bigger scale (community)	— High cost — Multi stakeholder involvement — More buildings need to adapt to MPC in the same neighborhood	— Allow data collection from multiple places. — Accelerate the speed of model prediction.

2.3 The relation between Energy management system and Smart HVAC systems

In a smart building or neighborhood, energy management systems and HVAC systems are always intertwined, the eventual energy consumption solution would benefit from the integration of the systems, while creating a comfortable indoor climate to its occupants, bringing sustainability into their life.



Relations between energy management system & HVAC system and its goals

Figure 6 Relations between energy management systems & HVAC systems

The relation of energy management system and HVAC system can be displayed as in figure 6. Smart EMS should aim to minimize the overall energy consumption in smart buildings though intellectually operating and monitoring of HVAC systems with respect to the number of building occupants, weather forecast, energy consumption, generation & storage and electricity price. Smart HVAC systems in both private and public buildings are designed to fulfil the following functions:

- Providing as well as controlling a comfortable indoor climate through an automated control system in conjunction with its individual components (air handling unit, heat pump, chiller, boiler and fan).

The energy management systems consist out of many different parts and the distribution between them is of importance. In this report the generation of renewable energy and the associated storage facilities are discussed as part of the energy management systems. These two parts give the answer to the availability of storage and generation in sub-question 2.

2.4 Energy Generation

Energy generation can be done at multiple levels in society:

- Individual building level where the house or public building supports for its own energy
- Neighborhood level where energy is generated at a bigger scale for the whole community, for both private and public buildings
- Energy from the national grid where the type of (renewable) energy is depending on the energy producer.

For the Brainport Smart District it will be useful to investigate the first and second levels for energy generation.

There are a lot of sustainable energy solutions available to reduce the use of fossil fuels. These solutions generate energy by harnessing a natural process, like sunlight or wind. Some are best for powering homes and others might be better for industries. It depends on cost, efficiency, scalability, flexibility and deployment. The following types are optional for energy generation: solar energy, wind energy, geothermal energy and biomass energy. Furthermore, systems like hydroelectric and ocean thermal energy will not be discussed due to the geographical characteristics and scale of these systems.

2.4.1 Solar energy

The sun provides light and heat and is important to sustain in a livable environment. Solar energy is the technology used to harness the sun's energy. A variety of solar energy technologies are used to convert the sun's energy and light into heat: illumination, hot water and electricity (Evans, 2011).
Photovoltaic (PV) systems use solar cells to convert sunlight into direct current (DC) electricity. Most home appliances use alternating current (AC). An inverter is needed to change the DC to AC. Depending on how many PV panels are installed, it can cut on your electric bill or even cancel your dependency on energy providers. The initial cost can be high but will pay back later.

Solar hot water systems can be used to heat buildings by circulating water through flat-plate solar collectors. Mirrored dishes that are focused to boil water in a conventional steam generator can produce electricity by concentrating the sun's heat (Evans, 2011). Individual homes can leverage the sun's energy for larger scale needs for heating, cooling and ventilation. There is also the opportunity to design buildings that can passively take advantage of the sun's orientation for passive heating. A known initiative is bioclimatic design. These are some design principles that are heavily influenced by its environment. It is an attempt at designing buildings that connect with nature while maintaining a preferable comfort based on the local climate. This design strategy focuses entirely on climate, wind direction, soil characteristics, topography, solar exposure, façade area and finally, heat loss. It starts with grouping rooms together. This will save energy that is used for heating and lighting. A building that is designed with the bioclimatic principles usually has opaque northern facades. Service and access rooms are closely connected to the northern façade. The building has large glazed areas on the southern side, which allows for solar gain. Well insulated walls and roofs ensure minimal heat loss. For optimal efficiency orientation is key. The building's construction uses concrete mass that acts like thermal reservoirs. These reservoirs absorb heat during the warm period of the day and release heat when necessary, like at nighttime. The thermal mass can also prevent overheating of spaces. Using this solar gain reduces the need for heating systems. A simple rule for optimal solar gain can be applied. This rule is based in its entirety on the orientation of the building, the surface area of the glazing in the façade, well-insulated walls and roofs and thermal reservoir (Gauzin-Müller, 2002).

Solar heating, in the form of solar collector panels, is often used in combination with bioclimatic designs. These panels can be used for heating water by converting solar radiation into heat. This technology generates warm water during the entire year, even when it is cloudy outside. When these collectors are positioned and measured correctly, they can provide almost all warm water requirements from the months April to September and more than half percent of the total needs. Solar collector panels are quite cheap and therefore a cost-efficient way of using renewable energy (Gauzin-Müller, 2002).

Table 17 (Dis-)advantages solar energy

Advantages	**Disadvantages**
Low maintenance costs	Depending on weather
No noise pollution	Expensive
Does not cause air pollution	Space intensive
Little maintenance	
Scalable	
Placement on available roofs	

Source: (Sendy, 2020)

Solar energy is solution which can be applied easily applied in different scales. Due to the placement on roofs every building can be used to apply panels for both residential buildings as commercial/office buildings. Table 16 gives an overview of the disadvantages and advantages of solar energy generation.

2.4.2 Wind energy

Wind energy is available naturally and has the potential to produce vast amounts of power. To generate energy by utilizing the characteristics of wind, it is possible to convert the kinetic energy of wind to mechanical energy. This can then again be converted to electricity. Wind is an inconsistent energy source. They also are a lot more expensive than the other alternatives and therefore in most cases unsuitable for households. There are also more affordable wind turbines solely developed for commercial usage, but they are a lot less profitable. Still, wind energy has the potential to power individuals' homes. For Instance, smart neighborhoods have their own wind turbine parks to produce sufficient energy to power the various houses with electricity. The houses in this neighborhood are connected by a smart grid. Each household can pay subscription fees to get access to this form of sustainable energy. This will lead to more affordable wind energy solutions and might increase its adoption. Wind energy is an intermittent energy source. This means that it is a renewable energy source that is non-dispatchable due to its fluctuating nature. It cannot generate electricity on demand and provides variable power output. A reliable energy system uses more than just wind energy to produce energy for a neighborhood. Weather forecasting can help predict future energy production and can switch to other energy solutions when necessary (see table 17 for an overview).

Table 18 (Dis-)advantages wind energy

Advantages	**Disadvantages**
Natural power source	Reliability on wind
No waste	Noise pollution
Emission free	Visual damage
	Maintenance

Sources: (Conserve Energy Future, 2016; Amadeo, 2019)

Wind energy is mostly known by the high spinning wheels with multiple of these systems near each other. This visual damage and noise pollution are not preferable next to houses and recreational areas. The big wind park scales are in the case of the Brainport Smart District not preferable due to the comfort level of the inhabitants and visitors of the neighborhood.
Smaller scale wind energy systems can be useful but do not overcome the disadvantages of the visual and noise problems.

2.4.3 Geothermal energy

The earth produces heat in its core. Geothermal energy allows us to fetch the heat from deep beneath the earth. Smaller scale systems like a geothermal heat system allow individual homes to harness energy from earth. A Geothermal heat pump system uses a pump to push the water through pipes which are installed in the ground. The water is heated by the earth and can be used to heat the individual homes. This technology has a high thermal efficiency since there is no energy conversion needed. Even when the ground feels cold, there is enough heat in the deeper part of earth to generate warm water. The initial cost is high but due to their lower energy consumption for heating provides a solid source of renewable energy besides conventional solutions (Gauzin-Müller, 2002). Table 18 given an overview of the advantages and disadvantages of geothermal energy.

Table 19 (Dis-)advantages geothermal energy

Advantages	Disadvantages
No significant source of pollution	High upfront cost
Inexhaustible resource	Electricity is needed for operating system
Scalable	Large scale can be dangerous for earth surface
Savings on heating/cooling costs	Damage underground costly/difficult
Minimal space needed above ground	
Lifespan of 25+ years	
Small carbon footprint	

Sources: (Comfort pro, 2016; Friedman, 2018)

Geothermal energy can be applied at both the individual building level but also at district level. Where the individual building has the options between vertical energy as well as horizontal energy, the initial costs of the systems are quite high. The district heating by using geothermal energy consist of the production of energy/heat, a distribution system to customers and a building distribution system (GeoDH, n.d.).

2.4.4 Biomass energy

Biomass energy is derived from biomass to create heat and electricity. It is produced by burning of timber, landfills and municipal and agricultural waste. It is a completely renewable energy solution. Although it still produces the same amount of carbon dioxide as fossil fuels, it is cancelled out by replacement plants that are grown to remove an equal amount of CO_2 from the atmosphere. Biomass energy can be generated by burning biomass to capturing and using methane gas produced by the natural decomposition of organic material (Evans, 2011).

Table 20 (Dis-)advantages of biomass energy generation

Advantages	Disadvantages
Carbon-neutral	Environmental damages due to gasses
Waste reduction	Expensive
Plenty availability of sources	Much space needed
Wide variety of sources	

Source: (NS Energy staff, 2019)

As is visible in table 19, the biomass energy uses much space and the environment can experience pollution from the generation. Due to the scale of the system, for individual building level this is not a feasible generation method. For a neighborhood level, it could be appropriate in terms of space needed and scalability for the neighborhood size.

2.5 Energy Storage

Along the energy generation and distribution, the energy storage is one of the most important challenges nowadays. The struggle between matching the demand for energy during the day and seasons with the supply of renewable energy seems to be difficult part in the shift towards sustainability.

Most of the times, renewable energy is generated during daytime, but especially for housing the energy demand is mostly during nighttime. According to Diwan (2019) there is a night peak of maximum 4 hours that is needing energy storage to supply the households with energy.

There is not only a problem with daily energy demand but also cross seasons. During the summer there is a higher availability of solar energy combined with a lower demand for heating but cooling of buildings should be incorporated as well. It seems that 35-40% of the energy generated in the summer should be stored to provide the less sunny months with energy during the whole year (Lohnrott, Johansson & Steen, 1980). In figure 7 a graph is visible of the seasonal changes in energy consumption compared with the PV generation.

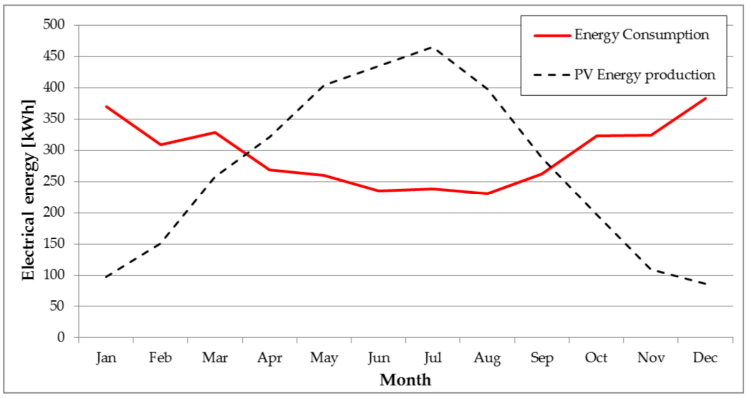


Figure 7. Monthly building electricity consumption with PV energy
Source:(Janelli, Minutillo, Lubrano & Falcucci, 2014)

With most of the storage facilities short charging times and lower capacity can be achieved, but the seasonal storage facilities can overcome the mismatch between the seasons (Zoethout, 2020). There are various types of energy storage facilities and they can be categorized into the following:
- Mechanical storage
- Thermal storage
- Chemical storage

2.5.1 Mechanical storage

The first storage category is the mechanical storage, this category uses kinetic energy to store the generated energy. A few systems could be derived within the mechanical storage. Nowadays the most used systems are hydro power, flywheels and compressed air.

2.5.1.1 Hydro power storage

The first system that is discussed is the hydro storage facility. This system works with a turbine where water is flowing through. During times where the energy should be stored the water is stored in a place at the back side of the dam. When energy is needed the water can be unleased and energy is generated immediately (ESA, 2019b). This system is quite big in general by using a dam and flowing water through it, but the system can be applied in smaller sizes (see table 20 for a summary of pros and cons).

An example of a system is PSP, this system works with two reservoirs where one is placed at a higher level than the other. At certain times when there is a higher supply than demand for energy the system pumps water into the higher laying reservoir. Just like the usage of the dam, the water is released whenever energy is needed and the turbine generates energy (GE renewable energy, n.d.).

Table 21 (Dis-)advantages of Hydro power storage

Advantages	Disadvantages

60-80 percent efficiency	Low energy density
Long discharge periods	Geographic restrictions
Water is a renewable energy source as well	High investment costs
No environmentally harmful restitutes	Long recharge periods
Long lifetime	

Sources: (Stettner, 2017; GE renewable energy, n.d.; ESA, 2019b)

The hydro energy storage is applicable in different scales but depending on the low energy density and the high demand for energy during the shifts in seasons, this method needs to be of big scale to support the seasonal energy storage.

While looking at the geographic situation of the Brainport Smart District it should tick the following points to create a sufficient location for a storage facility like hydro storage:

1. Conditions for an upper and lower reservoir
2. Availability of water in high quantities

Due to the geographic location we could conclude that the big scale hydro storage cannot be applied in the situation of Brainport Smart District.

2.5.1.2 Compressed air energy storage

The second system that is discussed is the CAES system where the water is released by air or gas. The air or gas is stored in a reservoir underground under pressure. During periods of demand the air is heated, due to the characteristics of air/gas the substance expands, and this generates energy by using a turbine (ESA, 2019c)

Table 22 (Dis-)advantages CAES

Advantages	**Disadvantages**
Fast start-up times	Efficiency of 40-55%
Modular system possible	Low energy density
	Large scale solution
	Dependency on geological structure

Sources: (Alami, 2020; Salameh, 2014)

Due to the low efficiency and low energy density the CAES system is depending on a large-scale solution, which can be concluded from table 21. The size of the CAES can be both large scale (+100 MW) and small scale depending on the amount of MW needed in the environment. Not every location is geographically suitable to be used for a reservoir, but to solve this problem modular systems are developed which function as reservoir (Alami, 2020).

While focusing only on the small or micro scale CAES systems, these have some more advantages compared to the battery systems that are already available. The unlimited amount of charge and discharge cycles is one of the great advantages and this makes the high investment costs a little better. But the problem of the low energy density and efficiency keeps arising, also for the small-scale systems. A large storage vessel is needed (De Decker, n.d.)

2.5.1.3 Flywheel

Another mechanical system is the flywheel. Energy is stored by spinning a device with a motor. At the times energy is needed the spinning system generated energy using a turbine which generates energy (ESA, 2019c)

Table 23 (Dis-)advantages flywheel

Advantages	**Disadvantages**
Low maintenance	Quick losses of energy

Long lifetime	Short discharge times
Efficiency of 70-85 percent	
Pollution free	
Quick response time	
Short recharge time	

Sources: (ESA, 2019c; Salameh, 2014)

Flywheel systems can be applied in different scales as well, both in low-energy applications as large-scale applications. As can be concluded from table 20, the system is suffering from quick losses and discharge

2.5.2 Chemical storage

Chemical storage could be seen at storing energy in batteries using different types of chemicals to storage. Batteries in general have a high efficiency between 60-95% depending on the material used and have a high response time (Diwan, 2019).

2.5.2.1 Sodium sulfur

Molten sulfur and molten sodium are used as the electrodes in a sodium sulfur battery. The two departments are separated by a ceramic where the positive sodium-ions can go through. Whenever the battery is discharges electrons are used for energy and then get back into the battery as positive electrode (ESA, 2019d).

Table 24 (Dis-)advantages sodium sulfur batteries

Advantages	Disadvantages
Efficiency of 89 percent	The systems need to stay hot, high temperatures
Long-lasting	High initial cost
High energy density	Requires sealing to prevent sodium from exposing
Fast response time	Easy to be damaged when high temperatures not reached

Source: (Ensia, n.d.; Pinnangudi et al, 2017)

2.5.2.2 Lithium ion

In this battery a graphite electrode and a lithium electrode are used. During usage of the battery the lithium ions flow from the graphite part towards the lithium electrode. During this flow the ions flow through a liquid, from this part the energy is generated. During the charging periods the process is reversed (Esnia, n.d.)

Table 25 (Dis-)advantages Lithium Ion

Advantages	Disadvantages
Low maintenance	Fire risks
High energy density	Decreasing stock of lithium
Longer lifespan	Fragile and the circuit needs protection
Decreasing prices	
Efficiency of 85-95%	
Scalable	

Source: (Pinnangudi et al, 2017)

2.5.2.3 Lead Acid battery

Lead acid batteries are widely used batteries which use lead dioxide and lead for the positive and negative materials. Just like other batteries, lead acid batteries use an electrode (sulfuric acid) to have electrode reactions. During discharge the positive ions migrate to the negative, during charge periods this cycle is reversed (Rand & Moseley, 2015).

Table 26 (Dis-)advanatages Lead Acid battery

Advantages	Disadvantages
Cheaper compared to other batteries	Shorter lifespan
Efficiency between 80-90 percent	Limited cycle life of 1500 cycles
	Lower energy density
	Self-discharge

Source: (Rand & Moseley, 2015)

2.5.2.4 Flow batteries

This battery uses two reservoirs filled with liquid which hold the electricity. This is the main difference with regular batteries where the electricity is hold within electrodes (Ensia, n.d.). The two liquids are separated by membrane which allows the two liquids to exchange ions, electrodes are used to extract the electricity from the circuit. When there is more energy generated the battery can be charges again by reversing the circuit (Rodriguez, 2015).

Table 27 (Dis-)advantages flow batteries

Advantages	Disadvantages
Stable solution compared to lithium ion	Costly liquids
Longer lifespan	Less efficient compared to Lithium ion
Less flammable liquids	
Easily up scalable with bigger reservoirs	
Efficiency of +- 66%	

Sources:(Ensia, n.d.; Rodriquez, 2015)

Uhrig, Koenig, Suriyah & Leibfried (2016) proved in their research the effectiveness of a flow battery compared to a lithium ion battery for the application in a household. The lithium ion batteries seem to work better in terms of the economic viability due to the higher efficiency. As mentioned before, the flow battery is easily scalable, this is confirmed by the research of Uhrig et al (2016). The overall conclusion of the research is that battery systems are too expensive for storage at household scale.

2.5.2.5 Hydrogen storage

During times of surplus of energy, hydrogen can be developed and stored. During times of demand the hydrogen is used as fuel to develop electrical energy. During these stages of energy storage carbon dioxide is developed as by-product and problems arise in all stages of the developments (Breeze, 2018).

There is another method where water is electrolyzed but this is a more expensive method. The cell contains two electrodes, a positive and negative. Whenever the electrodes are supplied with a high voltage, the positive hydrogen ions cluster to the negative electrode. At the positive electrode, the negative oxygen ions cluster (Breeze, 2018).
Hydrogen can be used for storage as well, in underground cavers hydrogen can be stored (ESA, 2019a). This is depending on the suitability of the underground.

After the hydrogen gas is stored and there is a demand for energy, the gas can be burned to generate the energy back.

Table 28 (Dis-)advantages hydrogen storage

Advantages	Disadvantages
60-70 percent efficiency	Carbon dioxide as by-product
Seasonal storage is possible	Must be compressed to store in high volume energy density

Non-toxic	

Sources: (Breeze, 2019; ESA, 2019a)

2.5.3 Thermal storage

In general, thermal storage is a methodology where thermal energy is stored combined with heating or cooling a storage facility. The thermal storage can be divided in the sensible heat storage and latent heat.

Sensible heat storage is a methodology where the thermal energy is used to heat of cool a liquid or solid material (water, salt or rocks). Latent heat storage uses the phase-change process to store energy. The main difference between latent heat and sensible heat is the higher capacity of latent-heat (Sarbu & Sebarchievici, 2018)

Thermal energy storage (TES) is the temporary storage of high or low temperature energy for later use when energy demand is higher. The storage cycle might be daily, weekly or seasonal depending on usage of the system. The input of the storage system is either thermal or electrical, while the output will always be thermal (Sarbu & Sebarchievici, 2018).

Table 29 (Dis-)advanatages thermal energy storage

Advantages	**Disadvantages**
Reduced running cost - load shifting provides reliable operation and lower annual electricity bills	Stored energy decreases over time
Reduced machinery - shifting peak load allows for smaller sized system	High upfront cost – the equipment and installing costs are high
Increased capacity – TES load increases the system output	
Green solution – lowers direct and indirect CO2 emissions	
Flexible system – capacity can be exactly matched to the system loads	

Source: (HTT, n.d.)

2.5.3.1 Phase change materials

Phase change materials (PCMs) can store and release large amounts of thermal energy during the processes of melting and freezing. Phase change materials, when freezing, release large amounts of energy in the form of latent heat but absorb equal amounts of energy from the immediate environment when melted. This allows storage of thermal energy. Heat or coolness is stored from a process and used or transferred to another location for later use. PCMs can also be used to provide thermal barriers or insulation (Ho, 2014)

Phase Changing Materials for Thermal Energy Storage
Phase changing materials can store more heat per unit volume than conventional storage such as water. Recent calculations by Heat Transfer Technologies (HTT, n.d.) resulted in PCM with 200kJ/kg could store two times more energy than water when both are at 50 degree Celsius. Another advantage is the energy delivery characteristics of PCM. It provides its energy capacity at constant temperature. This means that such a system utilizing PCM can maintain a constant temperature during usage. A system using only water cannot keep a constant temperature output. PCM's higher thermal capacity per mass promises to be more efficient than using a water tank as energy storage solution (Tyagi, 2005).

Table 30 (Dis-)advantages phase changes materials

Advantages	**Disadvantages**
No pressure vessel needed	High installation cost

Plastic storage tank – PCM storage tank made of plastic avoids corrosion	Larger storage tanks for seasonal storage – More surface area of PCM is needed
Constant temperature output – hot water is evenly distributed	
Long operational life – exceeds steel tank (water tank)	
Withstand higher system pressures	
Lower solar panel heat generation required	

Source: (PCM Products, 2013)

Passive cooling relies on naturally occurring temperature swings during night and daytime. The coldness of nighttime is stored within the PCM storage system. The stored energy is used to absorb the internal and solar heat gains during daytime for an energy free passive cooling system (Lizana, 2019).

2.5.3.2 Molten salt

This system uses liquid salt to be heated up through panels or heaters. The hot salt is storages in a tank or generator. The steam coming from the salt is used to generate energy by the use of a turbine (MAN, n.d.).

Table 31 (Dis-)advantages molten salt

Advantages	Disadvantages
No fire risks	High temperatures needed
High energy density	High cost materials needed for heat
Less polluting material	
Efficiency between 90-99 percent	

Source: (Salloom & Hala, 2018)

2.5.3.3 Pumped heat

The generated energy is used to drive a heat pump which is used to pump from cold to hot. In this way energy could be recovered but it could be reversed as well (ESA, 2019e). Heat pumps can be categorized into air source, water source or ground source (Patel, Bhadania & Chayal, n.d.).

Table 32 (Dis-)advantages pumped heat

Advantages	Disadvantages
Efficiency of 75-85 percent	Difficulties with installing
Low cost for investment and maintenance	
2-5 MW per unit	
Could be used for cooling in reversed system	
Long life-span	

Source:(Vekonu, n.d.)

Heat pumps can be applied both at the individual level and neighborhood level. For the large-scale solutions there needs to be a heat distribution system available (Averfalk, 2017).

2.5.3.4 Liquid Air Energy storage

This thermal system uses the generated energy to make air cooler until it becomes liquid. This liquid substance is stored in a tank. Whenever there is a demand for energy the gas is released and the turbine generates electricity (ESA, 2019e)

Table 33 (Dis-)advantages LAES

Advantages	Disadvantages
Long duration applications	Less efficient than battery and hydro

Lifetime of 30+ years	Big scale, less interesting for communities
Large scale possibilities	
Can use industrial waste to improve	
High density	

Sources: (Ramsdale, 2015; ESA, 2019[e])

Liquid air energy storage is comparable with the scales of CAES and pumped hydro storage, which are of big scale. As mentioned in table x the scale is less interesting for communities, combined with the geographical necessities and the lower efficiency this storage method is less interesting for BSD.

3 Case analysis

Within this chapter the case analysis will be described. These analyses are used to evaluate the working and integration of Energy management systems and HVAC systems within buildings. The choice is made to select one private building, a house in this case and a public building. In this case the Edge, Amsterdam is used. The case studies consist of a description of the building and their performance.

3.1 Private building: The Duke Smart Home, Durham, USA

Among others, an innovative approach about a smart home project is presented by the LEED Platinum certified Duke Smart Home in Durham, USA. It is a student organization at Duke University that consists of a residential program and a project-based student club and aims to explore sustainable living as well as environmentally friendly technology aspects. On the one hand, concerning the residential program, 10 undergraduate students from Duke University are selected through an application process to become Smart Home residents every year. On the other hand, the club is an organization open to all Duke students and aims at the investigation and exploration of smart home and sustainable technologies through projects (Duke Smart Home, 2019). For example, students are calculating formulas that will synch the building's heating, cooling and lighting with the outside environment's daily patterns. According to these, the thermostat will adjust the temperature inside to save energy (Jordan, K., 2008). In fact, with a total space of 6,000 square feet (almost 1830 square meters), the smart house incorporates a variety of smart design strategies and technologies. It is developed in three levels in total, including two floors and a basement. Each floor presents different features in terms of program, layout and integrated technology and all floors are connected through an atrium designed in the middle.

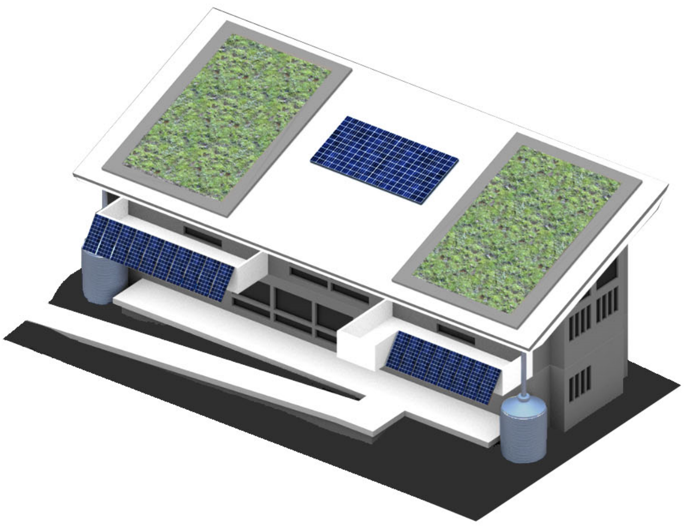


Figure 8 The Duke Smart home
Source: (Duke Smart Home, 2019)

<u>The roof</u>
The roof includes an array of solar panels which provide enough energy to heat up the water needed in the house. In addition, two green roof gardens are designed with native plants that aim to insulate the house and provide carbon sequestration. Finally, the inclination of the entire roof leads the direct water and other precipitation into the rainwater collection system. Then, two rainwater collection tanks collect rainwater, which is used for house and garden irrigation, laundry, and toilets (Duke Smart Home, 2019).

<u>The second floor</u>
There are four residence rooms on the second level of the house, housing eight students. Each bedroom is approximately 250 square feet (76.2 square meters) and is furnished with two each of: 3/4 loft, desk and chair, bookshelf, dresser, and wardrobe. Also, a two-person lab counter is provided in each room,

with a window view. Adjoining bedrooms share a bathroom except for the first floor, which has a guest bathroom. The ceiling begins at the standard height of 8 feet (2.5m) and rises to 18 feet (5.5m) in the back (Duke University, 2020).

The first floor

On the first floor there are various rooms and labs. More specifically, there is a single residence room that houses two students and there is also the media room which provides three wide-screen TVs and comfortable couches (Duke Smart Home, 2019). This room is designed to be a creative, user-friendly combination of television, gaming, and movie experience. There are no exterior windows so that the room lighting may be configured to any type of room display. Acoustic walls enhance sound effects. Concerning the labs, there is the clean lab on the southeast corner of the building and the dirty lab opposite to it. The labs were designed without doors to create a sense of openness—the lab space blends with the living space, allowing innovation to connect with all parts of the home, rather than being confined to a single room (Duke University, 2020). In the clean lab, there are computers, an e-Print station, and monitors that show the status of house systems. In the dirty lab, products are built and tested. It is equipped with tools, electronic parts, and basic lab equipment to help a student with an idea to work through a problem (Duke Smart Home, 2019).

The basement

The basement houses mechanical systems such as heat pumps, duct work and plumbing, and control panels. It also houses six 350-gallon (1325 liter) rainwater harvesting tanks, filtration, and solar hot water collection tanks (Duke University, 2020).

- Heat Pumps: HVAC systems consume a significant portion of the energy used in buildings. Electric heat pumps are used to both heat the home in the winter and cool the home in the summer. Central heat pumps are more efficient than conventional heating/air conditioning units. Not only do they combine multiple units into one, but they also simply move existing heat from outside to inside or vice versa instead of generating heat (i.e. through electrical resistance or burning fossil fuels). The units have a SEER (Seasonal Energy Efficiency Ratio) of up to 16 (Cooling Efficiency) and a HSPF (Heating Seasonal Performance Factor) of up to 9.85 (Heating Efficiency). For a comparison, the current national efficiency standard for new heat pumps requires a minimum SEER of 13 and a minimum HSPF of 7.7. The ENERGY STAR qualification is given at a SEER of 14, and a HSPF of 8.
- Refrigerant: The refrigerant used in the HVAC system is R-410a, which is an environmentally friendly refrigerant used in air-conditioning systems. It replaces R-22 (Freon) which has some potential for depleting the o-zone layer and will be phased out in the United States by 2020. The refrigerant does not contribute to o-zone depletion.
- Energy Recovery Ventilator: The Smart Home contains an energy recovery ventilation unit to pre-heat (or pre-cool) incoming air from outside the home with warm (or cool) exhaust air.
- Trane Clean Effects: The air in the Smart Home is purified by the Trane Clean Effects air purification system that filters air and creates up to 99.98% cleaner air via electrically charged fields making it easy to clean (simply wipe the filters). The system is 8 times more effective than the best HEPA filters and 100 times more effective than the standard 1 filter or ionic-type room appliance. The system removes 12% of 0.3-micron sized particles from the air in Smart Home every minute.

Overall, the Duke Smart Home proposes a sophisticated approach of house management, including daylighting, geothermal pump, fire-safety and media on demand, addressing the energy saving issue. It is an innovative initiative that presents a variety of state-of-the-art design strategies that could potentially consist useful advice for future sustainable and energy efficient building development.

3.2 Public building: The edge, Amsterdam

The edge is a building which is developed for the usage of Deloitte/AKD in the city of Amsterdam. OVG real estate is the developer of the building and is renting the building to Deloitte and AKD. The process of development started in 2006, but the initial building plans started in 2010. During this preliminary design the developers made the choice to use BREEAM as sustainability technique. To achieve the BREEAM excellent certificate many things had to be considered during design, construction and exploitation. The design of the building was so promising that the goal shifted from Excellent to Outstanding (OVG, 2014). Eventually the score of 98,4% was rewarded to the Edge, which was the highest score ever rewarded in terms of BREEAM (Randall, 2015). In table xx the main characteristics of the building are visible, focused on the performance in energy and size of the building.

Table 34 Characteristics of Edge building

Characteristics	
Available m2 of office space	39.673 m2
Available m2 of parking	11.558 m2
Building costs	74 million
Expected energy usage	2,27 kwh/m2
Expected usage of fossil fuels	0,00 kwh/m2
Expected generation renewable energy	3,10 kwh/m2
Expected water usage	4,1 m3/person/year
Expected usage of rainwater	22%

Source:(OVG, 2014)

Construction phase

In order to achieve the BREEAM certificate many aspects during construction needed to be considered. The following aspects were the main ones considered within the construction site (OVG, 2014):

- Energy efficient construction site and lighting
- Controlling of CO2 emissions of material
- Water efficient usage within construction site
- Ecological working protocol

Energy generation

The energy is generated by the solar panels that are installed in the southern façade of the building (500m2) and at the roof (1200 m2). Together with the placement of 4100 m2 of solar panels on the roofs of two school buildings in the neighborhood the building is completely energy neutral.

The building produces at the moment 2% more energy than their demand (Van Hooijdonk, 2018). During development there were no possibilities for giving energy back to the energy network. With the energy positivity of the building it would have been interesting to have a battery system to store the energy in times of higher demand. During the times this building was designed this was not an accurate solution according to Tiedema (2018).

Design of the building

In the design process of the building the sun was one of the starting points. The considerations of the natural light (at the southern part of the building) and the warmth that enters the building due to the sunlight. This resulted in a façade which is half transparent and the other half is used for solar energy as mentioned before. The other sides of the building, facing other directions, have more percentages of transparency in the facades (OVG, 2014).
With all this natural lighting in the building, an atrium is designed in the center of the building. This atrium is not only for the visual experience inside, but also from a technical perspective. Exhausted air from the offices around the atrium, is drained into the atrium and eventually drained at the top of atrium. This ‘warmed’ air is used to heat up the fresh air for the offices again (OVG, 2014).

Heating and cooling

Underneath the building, a 130-meter-deep storage facility is created for the hot-cold storage facility. This system uses thermal energy for heating and cooling the building for both air treatment as well via the pipes in the climate ceilings. During winter the hot storage is used and during summer the pumps use the cold storage (OVG, 2014).

The initial design did not contain the climate ceilings, but the preference of Deloitte and AKD was to integrate them. The comfort level of employees and visitors is supported better with this system, but also the BREEAM score improved with this adjustment.

Due to arrangement with the municipality of Amsterdam, the developers of the Edge were obligated to connect the Edge to the district heating system as well in case of peaks.

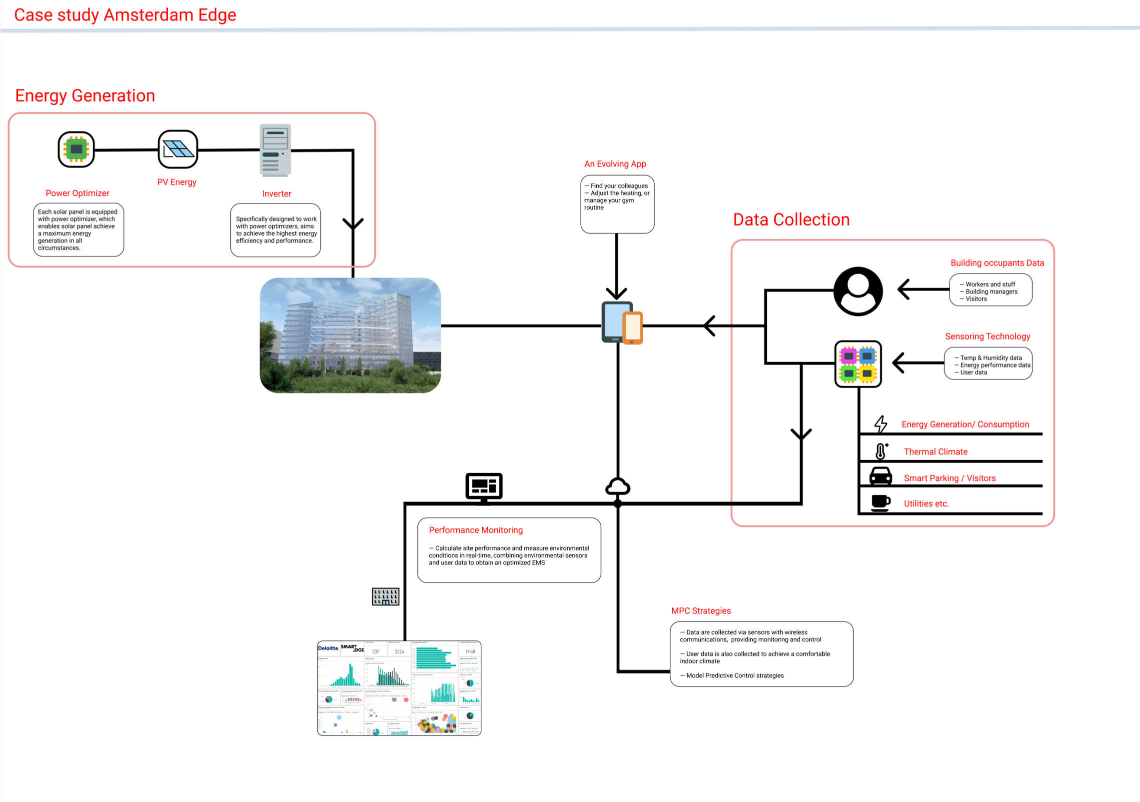


Figure 9 Integrated system of the Edge Amsterdam

<u>Building usage</u>

Smart application

The smartphone is the passport to the Edge. Users could adjust temperatures, the light density of the office room, planning meetings or finding their colleagues, even ordering recipes (Randall, 2015). The lighting of the building is supplied by Philips Ethernet-Powered LED connecting lighting system, this system is supported by the app to set the light to the personal preferences (DGBC, n.d.).

Data Collection:

28000 sensors are installed in the Edge building to collect data. These data collect information such as: availability of car parking, energy consumption, amount of visitor, personal thermal comfort and utilities. All the data will be sent to the monitor platform, all the data will be visualized in real-time on a dashboard, this aims to provide information about building performance and energy consumption (Randall, 2015).

Usage of rainwater

In the development of the building the choice was made to integrate a rainwater storage facility. The rainwater is collected at the roof top terrace. This collection of rainwater in reservoirs is used for flushing the toilets and for irrigating the plants at the roof top (OVG, 2014).

To conclude, the Edge is a very innovative building where energy generation, usage of sustainable sources and heating within the building. The designers of the Edge made good use of the orientation, glass and atrium for heating and energy generation of the building. The Edge is not only about a sustainable energy sources combined with a heat pump, as mentioned it is much more than that. The sensors in the building measure everything and control the building in that sense for an optimal building performance. We could conclude from the analysis of the Edge, which is a big sized office building, the integration of many systems and working together towards a good energy performance and an optimal use for the users. For smaller buildings, like single-housing units, the number of solar panels and data sensors need to be scaled back a lot. But the integration of heat pumps, sensors, solar panels in combination with glass could be advised for a smaller scale building as well.

4 Morphological chart

In this chapter the morphological charts will be presented per category. In the previous chapters heating, generation and storage systems are already discussed in how they operate. The first part of this chapter is a description of the criteria for testing the selected systems and gives answer to the third sub-question; "which criteria are important for the selection of the integrated system?". The second part are the morphological charts, where conclusions are drawn from the scorings.

4.1 Definition of criteria

The definition of the criteria is split up in the categories of systems; HVAC, heating distribution system, generation and storage. Each category has its own important criteria, depending on the literature study in chapter 2. Every criterion per category are explained in Appendix I and defined which points are rewarded based on the performance of the system. In general there are several aspects that are assumed for every part of the HVAC and storage and generation system. For example, sustainability, comfort, costs and scalability are aspects repeating itself in the criterion. Systems which function the best will come out of the morphological chart as best functioning system, but this does not mean it is the best system for the BSD application combined with all the other systems needed.

The goal of the designed system is to have an integrating, self-supporting and flexible system. Which may have the opportunity to be up-scaled to bigger size buildings. With keeping this goal in mind, the criterion were developed and scored.

Criteria for Heating systems.
Several heating systems were selected in the literature review in chapter 2. All these systems have their own functioning and performance in terms of sustainability, comfort and costs for example. This heating part is specifically on delivering the heat to the users with different systems. The following parts are selected for scoring the heating systems:

- Sustainability (Lifespan)
- Thermal comfort
- Room adjustment
- Costs (first cost, operating costs & maintenance)
- Efficiency (overall and scalability)

Criteria for HVAC operation systems
In the literature review there were several operation systems for HVAC, for example the heat pump or rooftop units. These units operate the HVAC and operate by transforming heat and cooling into a certain temperature and distribution methodology. Together with the heating and cooling facilities this should work simultaneously together for supporting the most efficient way of heating, cooling and ventilating the building. The following aspects are mentioned as important:

- Sustainability (Energy performance & Usability)
- Costs (investment, operating and maintenance costs)
- Flexibility (scalability)
- Reliability (Lifecycle)

Criteria for generation
The four generation aspects where all scored on the below mentioned aspects. Where for HVAC systems the level of comfort and usability are important, the sustainability and geographical aspects are more important. For example, solar energy is depending on the sun to generate energy which is an important point for scoring.

- Sustainability (pollution)
- Costs (first cost, operating costs & maintenance)
- Flexibility (scalability)
- Reliability (weather dependency & lifespan)

- Geographical dependency

Criteria for storage

The last criteria are for the storage facility that needs to be implemented in the neighborhood and buildings. Storage is important to combine with the energy generation in terms of seasonal storage opportunities and the mismatch between supply and demand of energy. According to the literature review, the storage facilities are more depending on scale and materials than other systems. Therefore, some geological and efficiency aspects are more deeply researched in the morphological charts.

- Geological (dependency on ground circumstances, harmful substitutes)
- Flexibility (scalability, durability)
- Reliability (service life, response time)
- Costs (first cost, operating costs & maintenance)
- Discharge
- Efficiency (overall, energy density, cycles)

4.2 Morphological chart heating systems

The first part of the morphological charts is the heating system, where the nine heating systems are evaluated and scored on the criteria. The chart in table 35 gives an overview of the scores of the heating systems

Table 35 Morphological chart heating systems

Heating systems								
	Efficiency		Costs		Lifespan	Thermal comfort	Room adjustment	
	Overall	Scalability	Investment	Operation and maintenance				
Electric heating	5	2	4	3	1	4	4	23
Electric baseboard heating	5	3	4	2	2	4	3	23
Furnace heating	4	4	3	2	3	5	4	25
Radiant heating	4	5	2	4	5	5	3	28
Wamr air heating	4	3	2	3	4	4	3	23
Hot water heating	4	3	2	3	1	5	3	21
Steam heating	3	4	2	3	3	3	4	22
Reverce cycle cilinder	5	4	2	4	2	5	4	26
Solar collector	2	4	2	3	2	3	3	19

The best scoring heating system is the radiant heating system which is especially scoring good on its scalability, efficiency, lifespan, operation and maintenance costs and thermal comfort. The part which should be considered are the investment costs and the room adjustment. With integrating the heating duct in the floor, beforehand adjustments in the design need to be made. The advantage of heating in the floor is that it does not have problems with placement of furniture within the rooms.

Another attractive heating system is the reverse cycle cylinder which is scoring good on the efficiency, scalability, operation and maintenance costs, thermal comfort and room adjustment. And worse on the lifespan and investment costs. This makes the system, in economic terms less attractive, but remains good for application due to its good scores on efficiency and comfort.

The solar collectors are scoring worse, especially because of its lifespan and overall efficiency. This system is not attractive in functioning for heating by itself. The solar energy generation will be descripted in chapter 4.5 where other scoring criteria are used.

4.3 Morphological chart cooling system

The cooling systems researched are combined in the chart in table 36. To compare, the maximum score for the cooling systems is 40 points.

Table 36 Morphological chart cooling

Cooling/ventilation systems									
		Usability		Costs					
	Thermal comfort	Adjustable	Flexibility	Investment	Maintenance	Disrubtive	Scalability	Lifecycle	Score
Vapor compression refrigeration	4	3	3	2	4	3	4	2	25
Exterior wall unit	2	3	4	4	3	2	2	2	22
Central air conditioning	4	4	2	2	3	4	4	1	24
Packaged air conditioning	4	4	3	2	3	4	4	2	26
Splitt system	3	4	2	3	3	3	3	1	22
Ductless system	2	3	2	4	3	2	2	1	19

It could be concluded that the packaged air conditioning system is the best functioning system. But to compare the scores compared to the maximum of 40, all the systems do not score that well and are closely related. It is therefore, hard to make a choice between the systems in their best performance. The smaller systems, like the exterior wall unit and ductless system are not performing that well on the scalability and flexibility. For all the systems we could conclude they score worse in terms of lifecycle compared to the heating systems which makes them less durable and sustainable.

The packages air conditioning and compression refrigeration are the ones scoring the best in terms of their score in the chart. Mostly the thermal comfort and scalability are important for both systems. With the system that needs to be developed these two aspects are important, so that makes them advisable for the Brainport Smart District.

4.4 Morphological chart operation system

The last part of the HVAC systems if the operation system. Based on the criteria, the morphological chart in table 37 can be assumed.

Table 37 Morphological chart operation systems

HVAC operation system							
	Sustainability		Costs		Flexibility	Reliability	
	Energy performance	Usability	Investment	Maintenance	Scalability	Life cycle	Score
Heat pumps	4	4	3	4	3	4	22
Geothermal heating and cooling	4	4	3	4	3	5	23
Rooftop units	3	3	4	1	4	4	19

It could be concluded from the morphological chart that the geothermal heating and cooling system is the most attractive operating system. With scoring high on the usability, energy performance, maintenance and operating costs and life cycle most of the scores are high. The only part that is scoring lower is the investment costs, which remain high for operating systems. The same is for scalability, which has the problem with operating underground and the need for boring deeper whenever the scale is bigger which brings risks.

Geothermal heating is followed by heat pumps, which have a similar performance. The only part where heat pumps are scoring worse is the life cycle of the system. With comparing the two systems it would be more attractive to integrate a geothermal heating system because of its life expectancy and further, similar performing system for approximately the same price class.

The less attractive operating system is the rooftop unit, which has especially high maintenance and operating costs. The usability and the energy performance of the system are scoring worse compared to the other systems, which make the rooftop units less attractive.

4.5 Morphological chart generation systems

With scoring the four generation systems; solar, wind, geothermal and biomass energy on the criteria the morphological chart combines the scores into the most optimal solution based on scoring. In table 38 the morphological chart for generation systems is visible. A maximum score of 35 can be achieved with the total amount of criteria.

Table 38 Morphological chart generation

Energy generation system								
	Sustainability	Costs		Flexibility	Reliability		Geographical	
	Pollution	Investment	Operation and maintenance	Scalability	Weather dependency	Lifespan		Score
Solar energy	5	5	4	5	1	4	5	29
Wind energy	5	5	3	2	1	3	2	21
Geothermal energy	4	1	2	4	5	5	3	24
Biomass energy	2	4	1	2	5	4	1	19

The best score is rewarded for the solar energy, which scores on every criterion a high score. Solar energy is widely used for both solar collectors as PV panels. The only point where solar energy is not scoring as high as 4 or 5 points, is the weather dependency. This is a big disadvantage of the solar energy system, at night no energy can be generated and therefore, storage is needed to supply households with energy. While looking at the public buildings, the weather dependency is less affecting because of different operating times of the building. But with the best score, it could be assumed that solar energy is a good suggestion for application in a multi-use neighborhood with different scale buildings. This is especially advices because of the scalability of the system.

The second scoring system is the geothermal energy generation. With its high costs for investment and operating and maintenance it seems not that interesting. But with the lifespan and no weather dependency the systems score quite high. Geothermal energy is already discussed with heating operating systems where it scores the highest of the operating systems. With the combination between energy generation, heating and storing energy this could be a good solution for energy generation, but should probably be supported by another generation system.

The third scoring item is the wind energy, which is not scoring as high as solar energy. This has specially to do with the weather dependency and the geographical dependency of the system. What is already discussed with solar energy systems, is happening in the same way for wind energy where wind force is needed to generate energy. The second part, the geographical issues, are scoring bad as well. This mainly has to do with the visual and disrupting issues wind energy is associated with. At the moment large wind energy farms are used to generate energy but not places in a neighborhood because of the risk associated. Smaller scale wind farms or single wind energy systems can be places but still are associated with noise and visual pollution. For a small-scale neighborhood like the Brainport Smart District the wind energy is probably not that interesting due to the reasons mentioned before.

4.6 Morphological chart storage systems

The above- mentioned categories are integrated in the morphological chart and scored on the performance of all the researched storage systems. As already mentioned in chapter 2, some of the systems suffer from having big scales or dependency of geographical features. In table 39 the morphological chart for storage systems is shown.

Table 39 Morphological chart storage systems

Storage system (Individual building & Neighborhood)													
	Geographical		Costs			Flexibility		Reliability		Efficiency			
	Ground	Harmfull substitutes	Investment	Operating & maintenance	Discharge	Scalability	Durability	Service life	Response time	Overall	Energy density	Cycles	Score
Hydro power	1	5	1	1	4	1	5	5	1	2	1	5	32
CAES	2	5	1	3	5	2	5	3	1	1	1	3	32
Flywheel	4	5	2	3	1	3	1	2	3	2	3	5	34
Sodium sulfar	3	3	1	1	4	3	3	2	5	4	3	2	34
Lithium ion	5	1	1	4	2	4	3	2	5	4	5	3	39
Lead acid	4	1	3	4	2	3	3	2	5	4	3	1	35
Flow battery	4	3	1	4	5	3	3	2	5	2	2	4	38
Hydrogen	3	5	1	3	5	3	5	2	2	2	4	2	37
Phased change materials	2	5	5	4	3	5	5	3	1	3	5	4	45
Molten salt	2	4	5	4	1	3	5	3	4	5	3	1	40
Pumped heat	2	5	3	4	3	5	5	3	1	3	4	4	42
Liquid air	1	4	1	1	1	2	3	3	1	1	4	2	24

While looking at the chart the best scoring system is the Phased changed materials, followed by the pumped heat. Both systems are part of the thermal storage operating systems. These systems score especially good on their durability and scalability aspects while the ground circumstances and response time score worse. Especially the ground circumstances have to do with the deepness of the system into the ground. This system is especially functioning great in combination with the heating devices because of the interconnected heating possibilities.

Looking at the other types of systems, the chemical energy storage, the lithium ion scores best. The biggest disadvantage of almost all the chemical storage facilities seems to be the service life and the number of cycles of the system. These seem to be worse compared to other systems. One of the great advantages of all the battery, chemical storage, facilities is the response time of these systems. This is extremely quick. Depending on the preferences of the user, this could be an important solution for quick responses at a small scale with less geographical necessities.

And the last category, the mechanical systems, score the lowest. Especially the CAES and Hydro storage score as one of the lowest systems. The biggest disadvantage of the system is the scale necessary for operating these systems and depending on water in the neighborhood with big amounts. But these systems have some advantages that can be concluded from the morphological chart; the service life and durability of these systems is quite high which makes the investment relative. The other mechanical storage facility, the flywheel, did not score much better and is especially underperforming on the discharge times and its efficiency.

5 Distribution

In this chapter the researched systems and outcomes of the morphological chart will be combined into a function system. The starting point of the research was to integrate the generation, storage and HVAC aspects into one operational system which has the flexibility of scaling within the Brainport Smart District. Within this chapter the developed system will be discussed. First the distribution within the private building, the house, will be presented. After this the possibilities of scaling the systems will be discussed and afterwards the functioning of the system in the neighborhood will be discussed.

The result is an advice that aims to deliver sustainable energy and smart HVAC solution for every type of buildings, ranging from a private house, public building to a neighborhood level. In order to give a clear impression of the distribution in every type of building, three diagrams are created:

5.1 Distribution within private building

The distribution of a smart HVAC system for a private house is illustrated as figure 10, the full picture on bigger scale are visible in appendix II. The components and functions of the components are described in table 40.

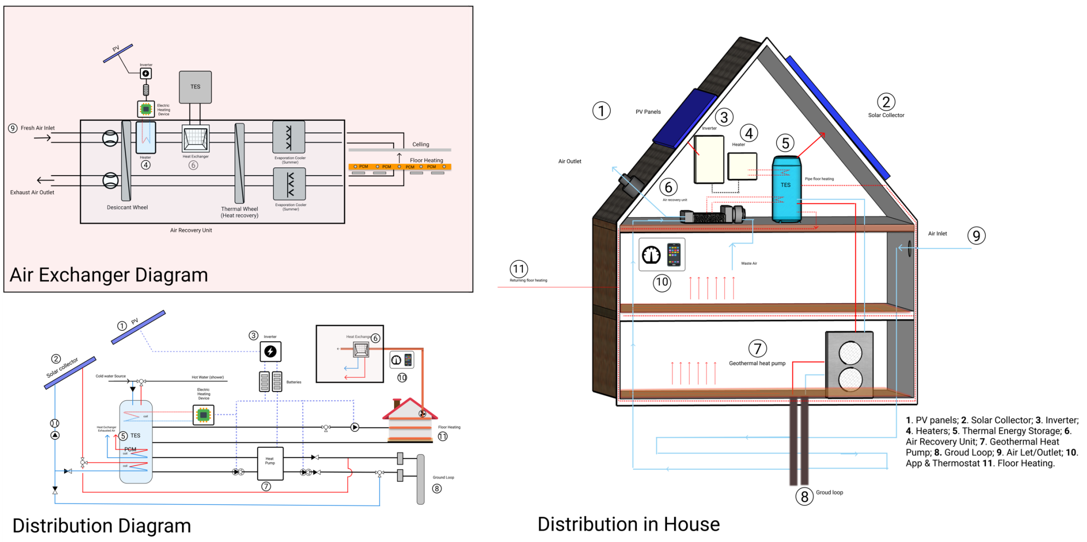


Figure 10 Distribution diagram
(left bottom); air recovery unit diagram (left up) and visualization of distribution of HVAC systems in a house

Table 40 Components and functions of the system

NO.	COMPONENT	FUNCTIONS
1	PV panels	Generate electricity for heaters and TES
2	Solar collector	Heat up the water
3	Inverter	Inverts DC to AC
4	Heater	Heat up TES when heat pump and solar collector perform insufficiently
5	PCM TES	Store thermal energy
6	Air Recovery Unit	1) Ventilation 2) Heat up / cool down the indoor air
7	Geothermal Heat Pump	Circulate waterflow
8	Ground Loop	Heat up inlet air
9	Air inlet/Outlet	Ventilation
10	Smart Thermostat / APP	Monitor HVAC system for building owners
11	Floor Heating	Provide heating

In terms of energy generation PV panels are selected, they generate sustainable and clean energy for two electric heaters (TES heater and Air recovery Unit). An inverter is installed between PV panels and heaters which serves to invert DC to AC.

TES (thermal energy storage) is used to storage thermal energy and the PCM (Phase changing materials) are used to fill the inside of the TES. PCM has the advantage that it stores more heat and is capable of maintaining a constant temperature during usage. Furthermore, water is used as a medium to transfer heating and cooling through the system. Cold water is heated up by the solar collector and the heated water will be stored in TES, which allows thermal energy to be used when energy demand is higher than the supply. The current problem with the demand mismatch can also be solved because the storage cycle can be daily, weekly and seasonal depending on the usage of the system. The TES is deployed with an electric heater as well and therefore the system always has a back-up for functioning. The electric heater is connected to a battery which can operate simultaneously to destress the TES.

The heat pump is chosen to be the heating operation equipment to circulate hot and cold water. The ground loop via the air is used to heat up the water which can be distributed in the house via the radiant floor heating. Which is selected because it not only distributes heating equally in various places in a house, but also delivers a more comfortable thermal climate because it warms up the construction of the building, therefore the indoor climate can remain relatively stable.

An air recovery unit is installed to offer ventilation and heat up/cool down the indoor air. When inlet (cold) air enters the building, it will firstly go through group loop and be heated up before it arrives to the air recovery unit. Two wheels are equipped inside of the air recovery unit, the desiccant wheel is for removing particles and dehumidification (first device in the Air Recovery Unit), then the heater and/or exchanger heat the air when necessary and the thermal wheel for heat recovery. Next to the thermal wheel, there are two air conditioners that help to cool the air when needed. The thermal wheel, as descripted in chapter 2, is useful for the recovery of heat by the interchange between incoming fresh air and exhausted air (which is either hot or cold). This already changes the temperature a little and therefore makes the system more efficient.

Last but not least, smart sensors are deployed in these systems, data will be generated and sent to a central monitor system which allows energy usage to be more sufficient. The system can make smart decisions regarding to energy demand, weather condition and user behaviors.

While looking back at the morphological charts we could conclude the following aspects in terms of performance; Almost all the systems which were preferred by the morphological chart are integrated in the system, which makes the overall performance rather good. All the aspects are good functioning in terms of scalability, which gives the system the possibilities to become scalable in size. The aspects where the complete system is scoring worse on, is the investment costs of the system. They will be initially high for all the elements; the maintenance costs are depending on the separate elements but score high which means the operation and maintenance of the system is relatively low in price.

Furthermore, the system incorporated the solar collectors for heating water. This system is scored as lowest due to its efficiency. The overall efficiency of the system decreases a bit with this, but it is useful to incorporate for the direct heating of the water.

5.2 Distribution within an apartment or public building

Distribution for an apartment or public building with a bigger scale:
The advice for a house can be also applied in a shared building. The distribution of HVAC can be displayed as in figure 11, the more detailed version is visible in Appendix III. Every element has its own function, this is displayed in table 41.

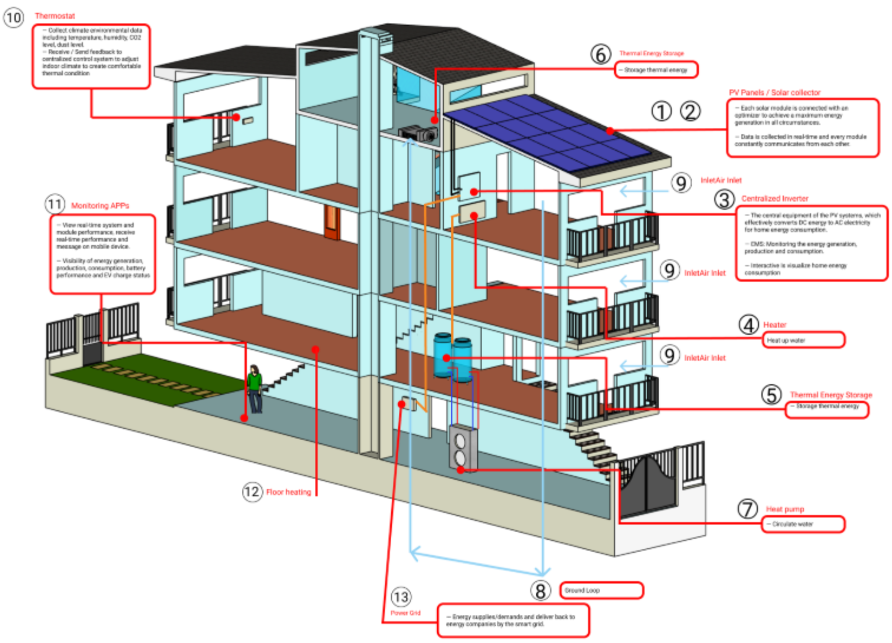


Figure 11 Visualization of distribution of system in shared building

Table 41 Components of shared building

NO.	COMPONENT	FUNCTIONS
1	PV panels	Generate electricity for heaters and TES
2	Solar collector	Heat up the water
3	Centralized Inverter	Inverts DC to AC
4	Heater	Heat up TES when heat pump and solar collector perform insufficiently
5	TES	Store thermal energy
6	Air Recovery Unit	1) Ventilation 2) Heat up / cool down the indoor air
7	Heat Pump	Circulate waterflow
8	Ground Loop	Heat up inlet air
9	Air inlet/Outlet	Ventilation
10	Smart Thermostat	Monitor HVAC system for building owners
11	Monitoring app	Monitoring HVAC systems
12	Floor Heating	Provide heating
13	Smart grid	Consume or feedback energy from the grid

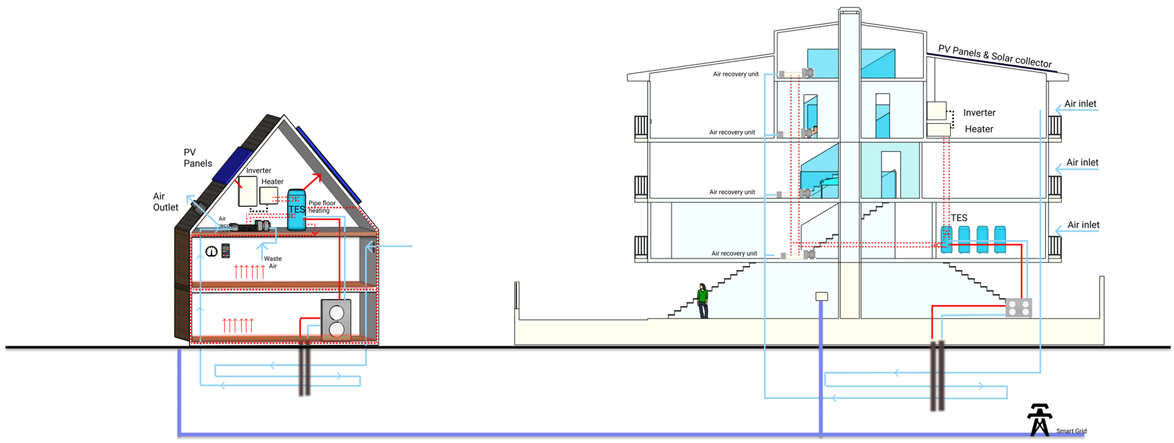


Figure 12 Scalability of proposed solution

The distribution of HVAC systems for houses can also be applicable and scalable in a shared or public building. The difference is that shared or public buildings have multiple owners, which results in a lower level of ownership. This requires a higher level of security and privacy requirement. Usually a building manager will take these responsibilities to not only monitor and control the indoor climate, but also the building security and safety. In such buildings, an advanced monitoring platform can be added to increase building performance in terms of the energy management system and HVAC system.

The monitoring system should provide functionalities that allow users and building manager to track and review energy performance, HVAC performance and financial performance. Additionally, the monitoring platform also featured with self-diagnosis function, fault detection and accurate maintenance, when an abnormal occurs, the monitor platform should rapidly responses to building owners and technical team to minimize the consequence.

Since not everyone is trained to be a technician to operate the entire building automation system, therefore a smart thermostat and app should be also added to help users and building manager to easily operate these systems, for example in our case study, every user who works in the Edge uses an app to change their thermal climate, additionally, the user interface of such apps should be designed user friendly to reduce the threshold of learning and adapting process.

Last but not least, the smart grid should also be integrated in this energy ecosystem. The smart grid aims to improve overall energy performance by intellectually collecting and providing energy from each grid. The most popular approach is to deploying sensors everywhere in the building to collect performance data (e.g. Edge building, Amsterdam). These sensors are communicating each other via wireless network, the generated data will be stored and transferred to the monitoring platform. The monitor platform interacts with the smart grid system to obtain a tradeoff between energy sufficient, prices and thermal comfort.

For upscaling the system not only, data is important. In figure 12 the size of the building is increased. With multiple owners and users in the building it is likely that there is a higher demand for heating and cooling and simultaneously for energy and storage. For scaling up the systems enormously it could result in multiple heat pumps which have their own storage unit. For the energy generation there should be more PV panels to operate the size of the systems.

5.3 Distribution within the neighborhood

In a neighborhood level, the focus should be given more on the data analytic perspective. Based on the literature review, collaborative data analytical can be used to monitor the energy management system in a neighborhood. In the Brainport smart district, buildings with similar characteristics in terms of energy performance can be given a cluster, by categorizing different buildings in a neighborhood allows us to obtain a clustering system, where data analytical can be applied in this system, this enables the estimation of energy consumption both at individual and group level and then aggregating them to predict the overall energy generation and demand.

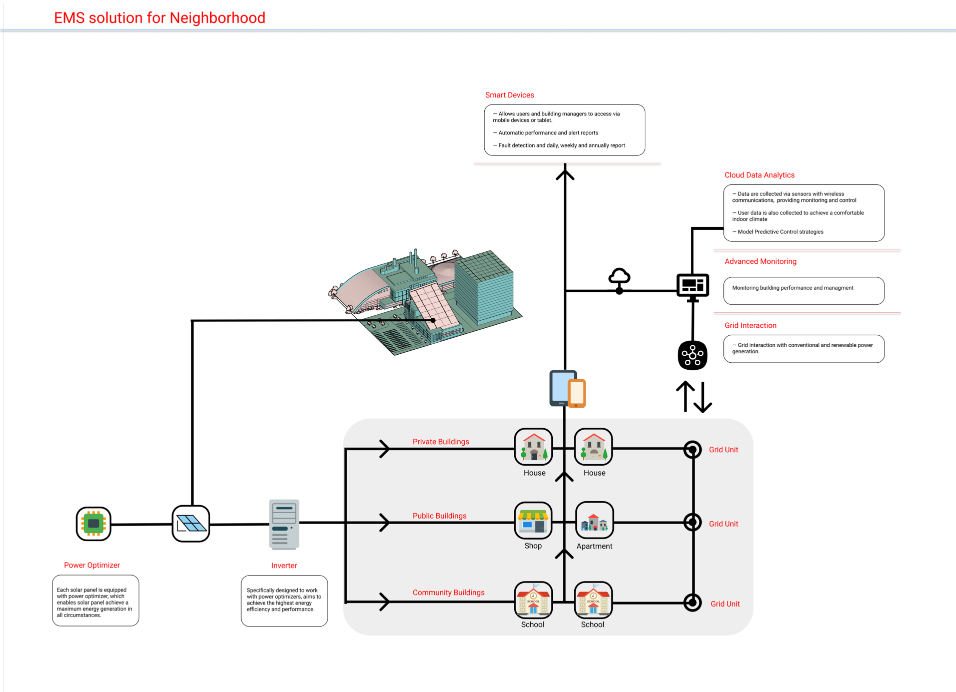


Figure 13 Distribution in a neighborhood

As is visible in figure 13 (see appendix IV for detailed version) the several building types are functioning on its own in the neighborhood but are connected to the neighborhood grid. The HVAC systems are developed to function on its own with several back-up systems within the building available, with the connection to the neighborhood smart grid energy problems could be removed.

One of the points of importance in the Brainport Smart District is the data collection and optimizing the neighborhood for the best performance.

6 Conclusion and recommendations

The proposed solution needs to present an innovative and adaptive approach of HVAC systems design and installation, since the buildings in Brainport Smart District are of different characteristics and scale. In addition, the proposed solution should balance the tradeoff between sustainable energy generation and consumption, price and thermal comfort. These factors were taken into account and shaped our vision for a suitable Smart HVAC system in combination with an energy management system for BPS. More specifically, the proposed energy management system should be self-efficient in terms of energy generation, storage and consumption, the HVAC system should deliver comfortable indoor climate and eventually both systems are scalable and equipped to adapt to different types of building contexts.

First, the bottom-up approach was used to understand the types and operations of energy management systems and HVAC systems. The existing technologies and HVAC solutions that could be applied in BSD were analyzed; the division was made into the mechanism of these systems. The division was made between heating systems, cooling systems and HVAC operation systems. It could be concluded that according to a certain set of criteria, the radiant heating system would be suitable based on criteria as thermal comfort, costs and scalability. For the cooling system similar criteria are used and the packaged air conditioning system would be more suitable according the final assessment based on morphological charts. However, it is interesting to point out that the cooling systems score lower in their performance compared to the heating systems. All things considered; it is shown that the geothermal heat pump is the most interesting solution in terms of HVAC operating systems.

Second, the energy generation systems are evaluated. The geothermal heat pump still presents positive characteristics but is not the most optimal option in terms of energy generation. Instead, the use of solar energy seems to be the most efficient and scalable solution. Through PV panels, electricity can be generated for heaters and TES and through solar collectors, water can be heated up. In addition, storing the generated energy and heating can be achieved through the phased changed materials and heat pump which constitute the best thermal storage facilities. Mechanical storage and chemical storage have their own disadvantages in terms of scaling and geographical necessities which make them less suitable.

It is crucial though, that the above-mentioned systems can be combined in order to form a new integrated system. In table 42, the systems that are selected as the best in their categories in terms of their function are presented.

Table 42 components of the flexible system

NO.	COMPONENT	FUNCTIONS
1	PV panels	Generate electricity for heaters and TES
2	Solar collector	Heat up the water
3	Inverter	Inverts DC to AC
4	Heater	Heat up TES when heat pump and solar collector perform insufficiently
5	PCM TES	Store thermal energy
6	Air Recovery Unit	1) Ventilation 2) Heat up / cool down the indoor air
7	Geothermal Heat Pump	Circulate waterflow
8	Ground Loop	Heat up inlet air
9	Air inlet/Outlet	Ventilation
10	Smart Thermostat / APP	Monitor HVAC system for building owners
11	Floor Heating	Provide heating

The proposed combined system consists of multiple components interacting with each other to perform in the best way in terms of energy, heating and cooling a building. This system has the possibility to be scaled-up easily with adjustments in terms of size or amount. The most important point for scaling up the system is the data collection system and usability integration for multiple users.

The development of the integrated system is based on literature review and the assessment of the performance of the individual components. For further development of the Brainport Smart District and the integrated heating systems, the following recommendations have emerged from the research:

- Simulate the system as fully functioning system and see whether there are lacking aspects in the system where improvements can be made.
- Determine the eventual costs of the system for integration in single-households houses. If the individual aspects are of high investment costs, then the initial costs for developing the houses would be expensive.
- Determine the size of separate parts of the systems and the size of the up-scaled system through further calculations.
- Since the systems installations are a technical aspect of the construction of houses and other buildings, specialized parties should be involved in the development process from the earlier stages. This could result to interesting innovations for the construction and to a more efficient construction process.

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Appendix I: Description of criteria

The criteria of the different sub-parts are divided into smart HVAC systems, the operating of heating and cooling within the building, the generation and storage. For all the parts a morphological chart will be developed, where the criteria will be scored on a 5-point scale. Every criterion has its own way of testing; therefore, every criterion will be descripted in their meaning and how the 5 point need to be interpreted.

Criteria for heating systems

Efficiency

The efficiency is of the systems is depending on the percentage they are scoring. Some of the chosen systems have a very high efficiency of heat transfer, for example the electric (baseboard) heating system where other systems have a lower performance.

1 = < 65%
2 = Between 65 and 74%
3 = Between 75 and 84%
4 = Between 85 and 94%
5 = > 95%

Scalability

For the development of a heating system which can fit multiple types of building the scalability of the heating system is important. The scores of the heating systems are depending on 5-point scale and scored on whether they are scalable or depending on vert large scales. For example, electric heating systems are only usable for small spaces and therefore not scalable.

1 = Only operational in very small or very big spaces
2 = Only operational in relatively small or big spaces, not scalable
3 = Hardly scalable system
4 = Easy to scale
5 = Very easy to up-scale

Investment costs

For the buyer and developer, the investment costs of the buildings (both private and public buildings) have benefit from a lower investment cost. The exact numbers of the heating systems are not known but are scored based on the knowledge of high or low investments costs coming from the literature review done in chapter 2. For definite numbers the size of the building and the installation of the system play an important role in the price.

1 = Very high investment costs
2 = Relatively high investment costs
3 = Medium investment costs
4 = Relatively low investments costs
5 = Very low investment costs

Maintenance and operation

Not only the investment costs have influence on the costs, also maintenance and operation costs need to be evaluated. Some of the systems, like radiant heating do not need maintenance, while others (baseboard heaters) need more maintenance. With these maintenance expectances the costs during the years rise. Just like the investment costs, the exact numbers are not known, the assumptions are made based on the literature available.

1 = A lot of maintenance needed, and operating costs are high
2 = One of the two has a very high amount (maintenance/operation)
3 = Acceptable amount of maintenance needed for the system & medium operating costs
4 = Both maintenance and operating are low
5 = No maintenance needed and very low operating costs

Lifespan

After evaluating the investment and maintenance of the system, the lifespan of the system can be scored on the 5-point scale. This score is given on the expected number of years where the system can function. For some systems, like the steam heating system the expectation was between 20 and 30 years of lifespan. In these cases, the average is considered and used for the scoring. [1]

1 = < 15 year
2 = Between 16 – 20 years
3 = Between 21 – 25 years
4 = Between 26 – 30 years
5 = > 30 years

Thermal comfort

After discussing the technical parts of the operating system, the level of comport achieved by the user is maybe more important. The four most important parts of the thermal comforts; humidity, temperature (radiant/air) and air velocity (HSE, n.d.). The choice is made to combine the four aspects because the individual scores were not available for the general systems and are depending on the supplier and installation within the building.

1 = Bad thermal comfort, not scoring well on either one.
2 = Relatively low thermal comfort, scoring good at only one point
3 = Medium thermal comfort, scoring good at two points
4 = Relatively high thermal comfort, scoring good at three points
5 = High thermal comfort, scoring good on all four points

Room adjustments

The adjustment of the room is evaluated at last, the systems need to be places in the building and maybe require placement in floors or walls but also within the space, for example radiators. Other systems have the characteristics that no furniture can be places in front. The room adjustment is scored on the adaptability of the room (whether changes need to make) and the level of easy placement in the room

1 = No adaptability and difficulties with placement
2 = Relatively difficult adaptability and placement
3 = Adaptable or placement are good
4 = Relatively easy placement and adaptability
5 = Easy placement and adaptability within the rooms/buildings

Criteria for cooling systems

Disruptive

For the level of comfort, it is important for the users that the cooling system does not disrupt by making a lot of noise or being extremely visible in the rooms.

1 = Very noisy and visible
2 = Very noisy *or* visible
3 = One of the aspects is at a medium level
4 = Nearly noisy and visible
5 = No noise and no visibility

Thermal comfort

Just like the comfort of the heating system, this is also important for the cooling the aspects of temperature, air flow and humidity are considered for cooling.

1 = Bad thermal comfort, not scoring well on either one.
2 = Relatively low thermal comfort, scoring good at only one point
3 = Medium thermal comfort, scoring good at two points
4 = Relatively high thermal comfort, scoring good at three points
5 = High thermal comfort, scoring good on all four points

Flexibility of the system

[1] The numbers are based on literature study but change per supplier, so changes can apply by choice of specific suppliers and countries.

Some of the cooling systems have the ability to be changed during use or be places afterwards, this makes the flexibility of the system a lot higher. Also, the flexibility of the building increases in this way which makes it more sustainable.
1 = No changes possible
2 = Hardly any changes possible
3 = Change is possible but not preferable
4 = Upgrade or lay-out are possible to change
5 = ability to be upgraded and changed in lay-out

Adjustability
An adjustable system is important for every user, thermal preferences can be modified and settled according to the user. It is not preferable to don't have the ability to do this adjustment in the system.
1 = No control
2 = Hardly any control by end users
3 = Methods for adjustability possible
4 = Relatively easy adjustable
5 = Able to be controlled very easy

Scalability
The choice is made to score the cooling system on its ability to be scaled. The scores 1,3 and 5 are only given because of the functionalities of the systems.
1 = Only very big or small scales are possible
3 = Between certain ranges of sizes applicable
5 = Everywhere applicable

Investment costs
For the buyer and developer, the investment costs of the buildings (both private and public buildings) have benefit from a lower investment cost. The exact numbers of the cooling systems are not known but are scored based on the knowledge of high or low investments costs coming from the literature review done in chapter 2. For definite numbers the size of the building and the installation of the system play an important role in the price.
1 = Very high investment costs
2 = Relatively high investment costs
3 = Medium investment costs
4 = Relatively low investments costs
5 = Very low investment costs

Maintenance and operation
Not only the investment costs have influence on the costs, also maintenance and operation costs need to be evaluated. With these maintenance expectances the costs during the years rise. Just like the investment costs, the exact numbers are not known, the assumptions are made based on the literature available.
1 = A lot of maintenance needed, and operating costs are high
2 = One of the two has a very high amount (maintenance/operation)
3 = Acceptable amount of maintenance needed for the system & medium operating costs
4 = Both maintenance and operating are low
5 = No maintenance needed and very low operating costs

Lifespan
After evaluating the investment and maintenance of the system, the lifespan of the system can be scored on the 5-point scale. This score is given on the expected number of years where the system can function.
1 = < 15 year
2 = Between 16 – 20 years
3 = Between 21 – 25 years
4 = Between 26 – 30 years

5 = > 30 years

Criteria for smart heating operation systems

Energy performance

The energy performance is for every operating system important. It is not interesting to have a system which uses a lot of energy which is renewably generated. Therefore, the choice is made to score the operating systems on their energy demand combined with the efficiency.

1 = Uses a lot of energy during heating and cooling
2 = A lot of energy needed but performance is relatively good
3 = Low usage or high efficiency
4 = Minor energy combined with energy efficiency
5 = Uses no energy is highly efficient

Usability

Where the energy and costs are important, the final usage of the inhabitants or occupants is important as well. The assumption that nobody likes a system which is noisy, uncomfortable and extremely visible is made. The three systems are scored on these three aspects.

1 = Extremely visible, noisy and not comfortable for user
2 = All three of the above-mentioned aspects at certain level
3 = Two components at a certain level
4 = One component at a certain level, other two are good
5 = Not visible, not disturbing and noise

Investment costs

The importance of the investment costs is evaluated already with the heating systems. But for the operating systems the costs for placement are known, but still depending on the size and usage.

1 = > 20000 euro
2 = Between 12500 and 20000 euros
3 = Between 5000 and 12500 euros
4 = Between 2500 and 5000 euros
5 = < 2500 euros

Maintenance and operation costs

The systems are also evaluated on their costs for operating and maintenance depending on the yearly costs.

1 = > 500 euros/year
2 = Between 400 – 500 euros/year
3 = Between 300 – 400 euros/year
4 = Between 200 – 300 euros/year
5 = < 200 euros/year

Scalability

For the development of a scalable system, the operation system needs to be easily scalable between the different scale buildings. The scores are given on their ability to be scaled during development, the very large-scale systems are not preferred for individual buildings and therefore scored low.

1 = Not scalable, depending on very large scale
2 = Hardly possible to scale and requires a lot of space
3 = Many systems and operations need to work to make scaling happen
4 = Easy scalable
5 = Easily scalable even during functioning of the building

Life cycle

The sustainability of the system can be scored on their lifespan, the investment costs will decrease relatively with a longer performance of a system. Furthermore, the assumption that it improves the value of the building supports the importance.
1 = < 5 year
2 = Between 5 – 10 years
3 = Between 10 – 15 years
4 = Between 15 – 20 years
5 = > 20 years

Criteria for generation
Sustainability (pollution)
The renewable energy generation is already a sustainable solution for energy, but between the generation types differences could be made. At first, the pollution of the system, this aspect is scored on whether it is responsible for air or water pollution
1 = Major amounts of pollution and waste
2 = Major amount of pollution or waste
3 = There is pollution and waste during the process
4 = Minor pollution or waste
5 = No waste and pollution during the process

Investment costs
The costs are separated between investment costs of the system, operating costs and maintenance costs. The first, investment costs are evaluated in the investment that has to be made for the building/neighborhood to integrate the generation method[2]. The costs are depending on how many kW systems are places.
1 = High (+3500 euro/kW)
2 = Relatively high (between 3000 and 3500 euro/kW)
3 = Medium between (between 2000 and 2500 euro/kW)
4 = Relatively low (between 1500 and 2000 euro/kW)
5 = Low (-1500 euro/kW)

Operating and maintenance costs
The operating costs are evaluated in a way where the costs for operating the systems are evaluated. Within these operating costs, all financial aspects and materials needed for operating and maintaining the systems are evaluated. The scores are given depending on their costs per kW/year, so the scale is not important in this criteria.
1 =High costs for operating and maintenance the system (+ 110 euro/kW/year)
2 = Costs for operating and maintenance between 65 – 110 euro/kW/year
3 = Costs of operating and maintenance between 20 – 65 euro/kW/year
4 = Low costs for operating and maintenance the system (-20 euro/kW/year)
5 = No costs associated after installing

Flexibility (scalability)
Energy generation is needed for every building in the neighborhood as well as the services within the neighborhood, like the street lightning. The flexibility of the system is evaluated with the scalability of the system. Question like; is it easy extendable? Can the system be implemented everywhere and within every building? Arise within this score.
1 = Scaling is not possible
2 = Scalability is a difficult aspect
3 = Scaling the system is possible but not easy
4 = relatively easy scaling and implementable
5 = Easy implementable within every building and easily up-scalable

[2] Costs are based on data from the USA in 2018, changes and costs need to be considered for usage in the Netherlands.

Reliability (weather dependency)

Some of the generation system have the dependency on the weather, for example the sun or wind are necessary for operating the system. For this criterion the scores 1 and 5 are the only ones given because there is no other way of operating the system

1 = Always depending on the weather
5 = no weather dependency

Lifespan

As mentioned earlier the lifespan of the systems supports the sustainability. The generation systems are scored on their expected number of years operating.

1= below 15 years
2= between 15-19 years
3= between 20-24 years
4= between 25-29 years
5= above 30 years

Geographical dependency

Within the geographical subject, the dependency on nature and scale are evaluated. In terms of major changes in the environment and dependency of large scales in the area. As well as the visual representations of the generation systems are considered

1 = Large scale and geographical dependency is high with high disturbance
2 = disturbing system for environment and inhabitants
3 = there are geographical changes needed but don't disturb living and working
4 = minor visual and geographical aspects need to be considered
5 = no geographical changes necessary

Criteria for storage

Overall efficiency

The efficiency of the system is important for the energy losses during usage of the storage. The distinction is made between the overall efficiency, where the efficiency of the overall process is evaluated on their score in the percentage of efficiency.

1 = percentage below 65%
2 = percentage between 65 – 75%
3 = percentage between 75 – 85%
4 = percentage between 85 – 95%
5 = percentage above 95%

Energy density

Depending on the system, the energy density can be determined. Systems with low energy density have more space needed to store the same amount of energy as higher densities.

1 = < 20 MJ/m3
2 = Between 20 – 100 MJ/m3
3 = Between 100 – 750 MJ/m3
4 = Between 750 – 1250 MJ/m3
5 = >1250 MJ/m3

Cycles

The number of cycles counts for the amount of cycles (discharge and recharge) can be applied during their operational life. The expectation is that lower cycles have a shorter life expectancy for highly used storage systems.

1= < 1000 cycles
2 = Between 1000 – 5000 cycles
3 = Between 5000 – 10000 cycles
4 = Between 10000 – 20000 cycles
5 = > 20000 cycles

Discharge periods

The term seasonal storage is already discussed. In some months the generation of energy is higher and especially the demand for heating is lower. It is preferred to have a system that offers this opportunity to store energy for a longer period of time without losing (much) energy during this period.

1 = sec – min
3 = min -days
5 = hours - months

Ground circumstances.

The first part is the dependency of ground circumstances that need to be considered for the application of the storage system. Due to the geographical necessities, not every storage system is applicable for the situation of Brainport Smart District. The district did have an area available for food production and energy necessities.

1 = Enormous impact on environment and major changes in geographical area
2 = Major geographical necessities needed
3 = average geographical necessities
4 = minor geographical necessities
5 = no geographical necessities needed for installation of the system

Harmful substitutes

1= Materials used are harmfull for the environment
3= Some of the materials are not good for the environment
5= No harmfull substitus

Flexibility (scalability, durability)

Flexibility is in all the criteria already mentioned. Also, for the storage system this is also important. The first aspect is the scalability of the system, which is already mentioned before, the multi purposes in the neighborhood have all different demand and preferences.

1 = Not scalable and depending on big scale
2 = Hardly scalable
3 = Scalability is possible
4 = Easily scalable and small scale
5 = Scalability is no problem

Discharge

With the discharge of the storage system is meant; in what time the whole system is discharged. Preferably it is better to have a high discharge time, so the system can support with more energy for a longer period of time.

1 = < 15 minute
2 = Between 15 minutes – 1 hour
3 = Between 1 hour and 8 hours
4 = Between 8 hours and 24 hours
5 = > 24 hours

Lifespan

The reliability of the system is an important aspect as well, the reliability can be split up in two terms. First the service life is scored, whether the lifetime of the storage systems functions long enough

1 = < 10 years
2 = Between 10 – 20 years
3 = Between 20 – 30 years
4 = Between 40 – 50 years
5 = > 50 years

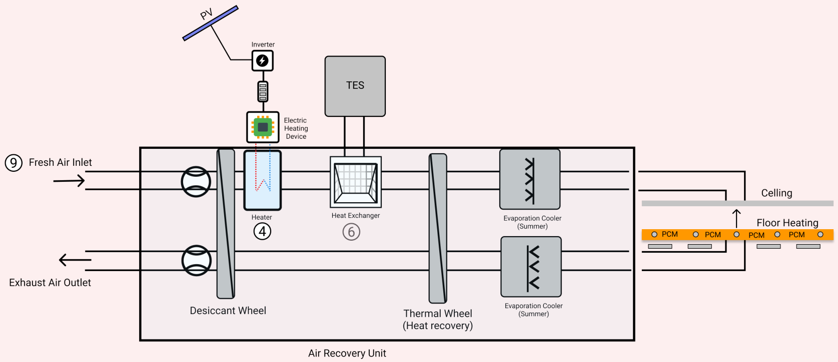
Response time

The second part of reliability is the response time of the system. Some of the storage systems have the characteristic of first starting up the system or have a longer delivery time of heat or electricity.
1 = 3 >
2 = Between 2 – 3 minutes
3 = Between 1 – 2 minutes
4 = Between 30 sec – 1 minutes
5 = < 30 seconds

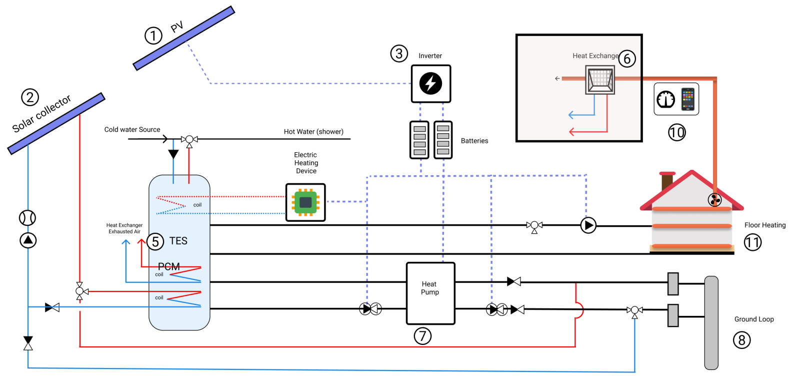
The investment costs:
Just like the generation part, the amount of kW stored has its own investment costs.
1 = > 400 euros/kW
2 = Between 300 – 400 euros/kW
3 = Between 200 – 300 euros/kW
4 = Between 100 – 200 euros/kW
5 = < 100 euros/kW

Maintenance and operation costs
Maintenance costs are not evaluated in terms of economic values but in terms of necessities for maintenance during the life time.
1 = > 35 euros/kW
2 = Between 25 – 34 euros/kW
3 = Between 15 – 24 euros/kW
4 = Between 5 – 14 euros/kW
5 = < 5 euros/kW

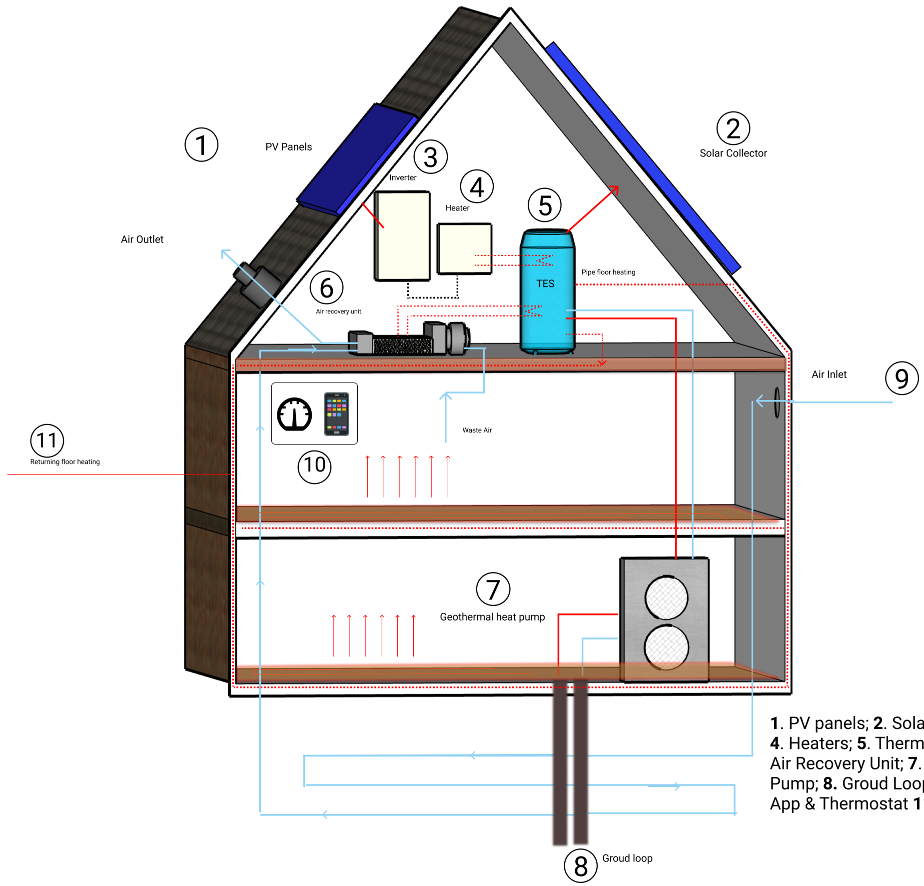
Appendix II: Integrated system



Air Exchanger Diagram



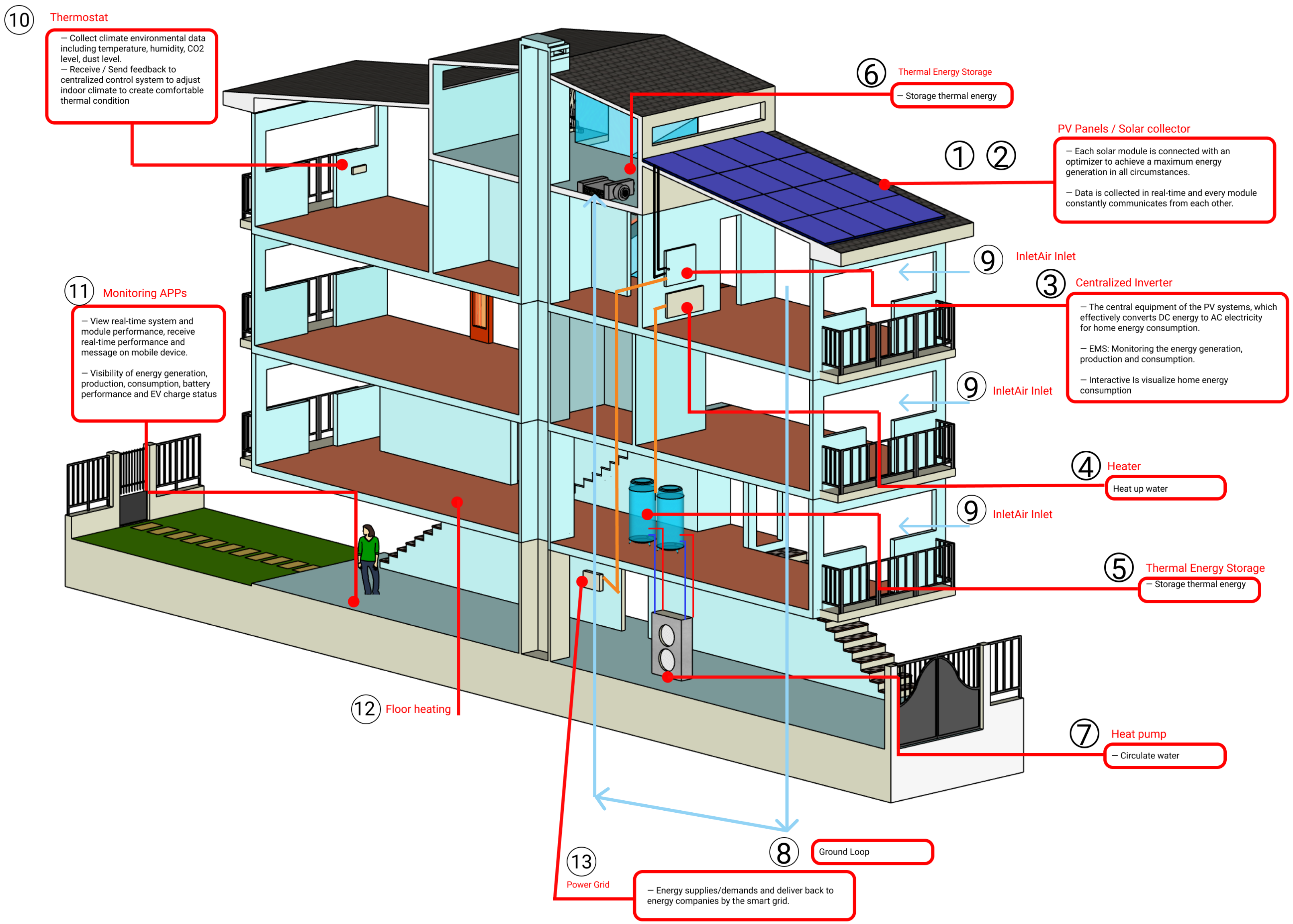
Distribution Diagram



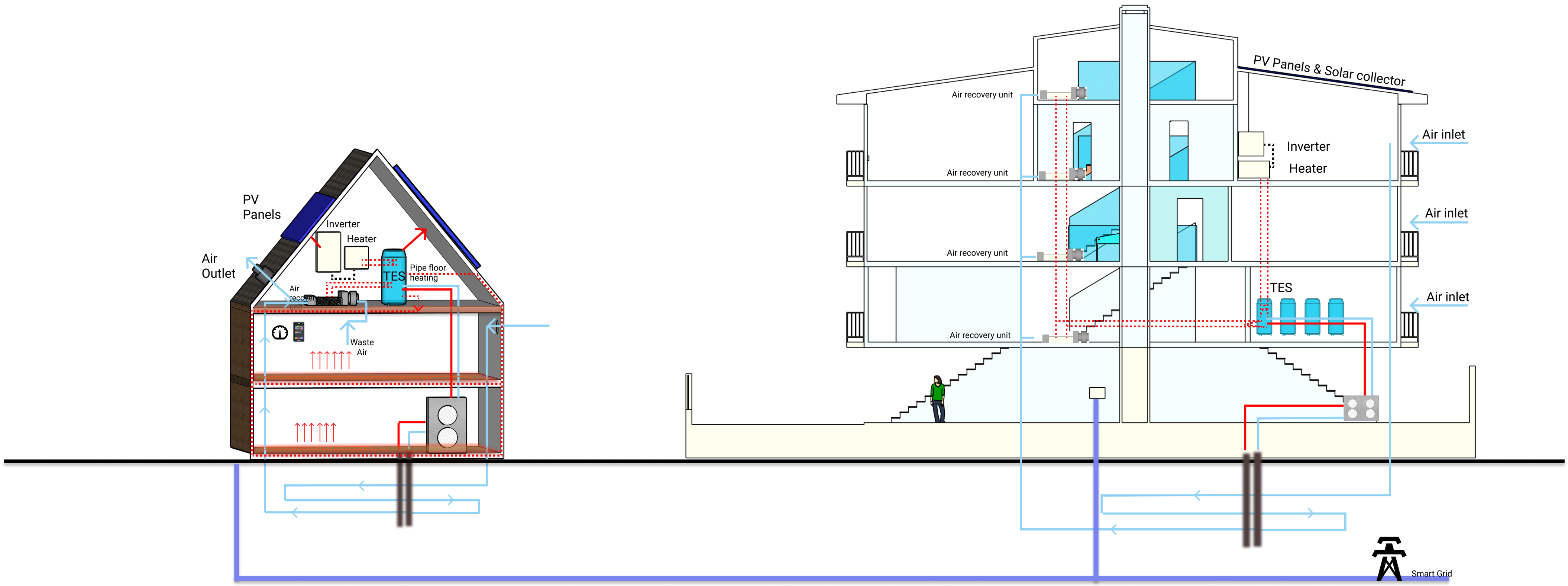
1. PV panels; **2**. Solar Collector; **3**. Inverter; **4**. Heaters; **5**. Thermal Energy Storage; **6**. Air Recovery Unit; **7**. Geothermal Heat Pump; **8.** Groud Loop; **9**. Air Let/Outlet; **10**. App & Thermostat **11**. Floor Heating.

Distribution in House

Appendix III: Integrated system public building



10 Thermostat
— Collect climate environmental data including temperature, humidity, CO2 level, dust level.
— Receive / Send feedback to centralized control system to adjust indoor climate to create comfortable thermal condition
6 Thermal Energy Storage
— Storage thermal energy
1 2
PV Panels / Solar collector
— Each solar module is connected with an optimizer to achieve a maximum energy generation in all circumstances.
— Data is collected in real-time and every module constantly communicates from each other.
9 InletAir Inlet
3 Centralized Inverter
— The central equipment of the PV systems, which effectively converts DC energy to AC electricity for home energy consumption.
— EMS: Monitoring the energy generation, production and consumption.
— Interactive Is visualize home energy consumption
11 Monitoring APPs
— View real-time system and module performance, receive real-time performance and message on mobile device.
— Visibility of energy generation, production, consumption, battery performance and EV charge status
9 InletAir Inlet
4 Heater
Heat up water
9 InletAir Inlet
5 Thermal Energy Storage
— Storage thermal energy
12 Floor heating
7 Heat pump
— Circulate water
8 Ground Loop
13 Power Grid
— Energy supplies/demands and deliver back to energy companies by the smart grid.



PV Panels
Inverter
Heater
Air Outlet
TES
Pipe floor heating
Waste Air
PV Panels & Solar collector
Air recovery unit
Air recovery unit
Inverter
Heater
Air inlet
Air inlet
Air recovery unit
TES
Air inlet
Air recovery unit
Smart Grid

Appendix IV: Neighborhood system

EMS solution for Neighborhood