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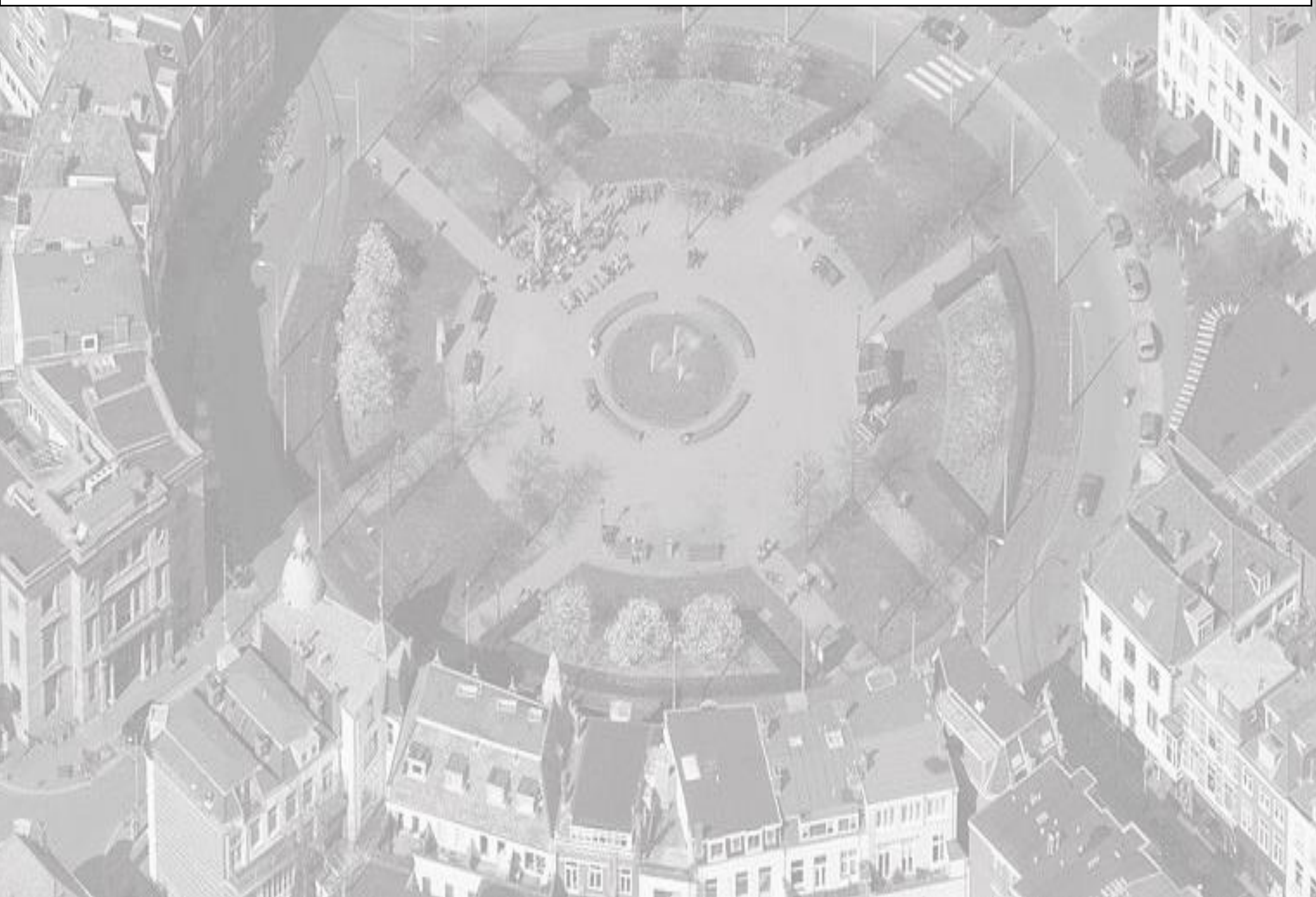
Requirements for sustainable heat storage in the Zeeheldenkwartier district of The Hague



Preface

This report has been written as a part of the The Hague University of Applied Science (THUAS) minor *'BE SMART. Strategies for smart sustainable cities'*. The report is focussing on an important element of the heat transition by which the built environment of The Netherlands should become fossil-free in 2030.

In a preliminary study, we made a roadmap for the energy transition in the Zeeheldenkwartier, a district of The Hague. By this roadmap, we recognized that an entirely new heating infrastructure is needed.

A crucial part for a new heating infrastructure is seasonal heat storage: there is plenty of heat in summer, bud virtually no demand, while in wintertime the situation is reversed.

In connection with the Zeeheldenkwartier, our aim was to study the requirements for seasonal heat storage. First we analysed the heat demand of the Zeeheldenkwartier and the resulting requirements for heat storage. Afterwards, different heat storage technologies have been analysed.

In order to analyse the suitability of heat storage technologies for the conditions in the Zeeheldenkwartier a decision tree has been added to this report. This tree can be used to select the best solution for heat storage in the Zeeheldenkwartier.

In our project, we had some help from the coaches Karel Mulder, Cees Verweij and Stephan van Berkel. We would like to thank them for their advice and support. Also, we would like to thank Johan Noordhoek from the municipality of The Hague for an informative interview assisting our research.

This report can be used for further research on the heat transition in general and for developing heat solutions for the Zeeheldenkwartier in particular.

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Summary

Global climate change, depletion of fossil fuels, and gas extraction induced seismicity in the North of The Netherlands necessitate a transition to sustainable sources for heating. The main problem for changing to sustainable sources of heat is that supply is low during the wintertime while there is a peak demand during the same wintertime. By using heat storage technology, the gap between energy supply and -demand might be bridged.

Zeeheldenkwartier is a densely populated area in the old part of The Hague. Most buildings in the neighbourhood Zeeheldenkwartier are pre-war buildings that are now heated individually by natural gas. Based on the characteristics of the district, requirements have been drawn up for future heating and for heat storage. Because of the poor insulation of most buildings, and limited options for improvement, higher-temperature heating is necessary to provide the residents with sufficient heat.

The more requirements a heat storage method meets, the better it will probably fit to the neighbourhood. The requirements can be divided in safety, end-user temperature, energy density, spatial demand, efficiency, and environmental impact.

The requirements for heat storage have been evaluated by a decision tree. This decision tree provides a clear insight into the different storage types for seasonal heat storage that are available at this moment. By following the requirements in the decision tree, the most suitable heat storage type can be identified.

The decision tree is used in a straight forward way, i.e. each requirement that is not met leads to a rejection of the option. However, heat storage technologies might be improved by innovations, and some requirements might be compensated by additional measures, or by over performance regarding other requirements. This is discussed in a final paragraph.

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1. Introduction

The Netherlands faces a major challenge: the transition from a fossil fuel based energy system to a sustainable energy system. Fossil energy sources will play a diminishing role in the energy supply. The need for this transition has arisen due to the depletion of fossil fuels, natural gas extraction induced seismicity in Groningen, the awareness of the rapidly changing climate, and the political desire to reduce resource dependence on foreign resources.

Renewable sources of heat are therefore needed to provide people with comfort. The use of sustainable heat involves a seasonal imbalance between heat production and heat demand. To have a comfortable climate inside buildings, the temperature needs to be around 19 to 20 degrees Celsius. In the climate conditions of The Netherlands, this implies that heating systems are required from October to May.

At this moment there are insufficient renewable heat sources to provide all dwellings with renewable energy during winter. Renewable energy sources might be solar heat, geothermal heat, heat extracted from the environment (air, open water, aquifers, soil, drinking water pipes, sewage pipes) by heat pumps, heat produced by biofuel and waste heat. The latter two are controversial, as:

- some biofuels production might ruin nature.
- It is sometimes unclear to what degree waste heat really is ‘waste’.

As such, there is sufficient sustainable heat; however, there is a shortage of sustainable heat during winter, when it is really needed. At the moment this shortage is compensated by burning natural gas. This causes emissions of carbon dioxide and other pollutants. On the other hand, there is a surplus of sustainable heat in summer, which is now regarded as a waste product.

Hence, the goal must be to find a way to balance this seasonal difference in sustainable heat production and -demand. The key to realize this could be the storage of sustainable heat in connection with a heat grid.

This study aims to provide an overview of the requirements for heat storage in the Zeeheldenkwartier district in The Hague. A district approach is important in order to take both the local heating conditions, as well as local options for heat supply into regard. This district is more difficult to supply with sustainable heat as most buildings are not well insulated, and often, there only few options for improvement.

It will also evaluate some potential storage types in the light of these requirements. To deal with the seasonal imbalance, long-term energy storage is necessary, which is why short-term energy storage has not been taken into account.

Citizen groups and city planners could use these insights on requirements for heat storage systems and potential heat storage types for further study.

This objective is explored by the following main question:

‘What are the requirements for a heat storage system that will balance the seasonal imbalance between the heat demand of dwellings/utility buildings and sustainable heat production in the Zeeheldenkwartier district of The Hague?’

To provide a complete answer to this main question, relevant sub-questions have been formulated:

Sub questions

1. Why is heat storage in the Zeeheldenkwartier necessary?
2. What is the demand for heat storage in the Zeeheldenkwartier in the course of a year?
3. What are the relevant characteristics of the Zeeheldenkwartier?

4. What are the requirements for heat storage methods in the Zeeheldenkwartier?
5. What are promising heat storage technologies?

We will first describe how we these question can be addressed. The main points are research type, sources, methods, and practicalities.

Research type

A qualitative research approach will be used to study which requirements are crucial to realize a heat storage system. It will be mainly explained in words and the key terms are complexity and understanding.

Primary and secondary literature sources will be used. Primary sources such as interviews with experts will be used to get more specific data for The Hague and the Zeeheldenkwartier. Databases and secondary data sources such as journal papers, previous student reports and research reports will be used for the general evaluation of heat storage methods.

The main data have been collected between 9th December 2019 and 12th January 2020. Moreover, interviews with experts were carried out to get specific data regarding heat storage types as there is little reported research on it. Databases were also used to gain summarized data.

The structure of this report will be described as followed. Chapter 2 describes the need for storage. Then, in chapter 3 an area overview is worked out. Chapter 4 describes the requirements for a heat storage system based on neighbourhood characteristics. Chapter 5 shows a decision tree. The conclusion & discussion are given in chapters 6 and 7. In the appendix all possible storage systems are detailed.

2. The need for thermal storage

Why is thermal energy storage important for the Zeeheldenkwartier? This chapter will explain the need for thermal heat storage.

2.1. Why is thermal energy storage necessary?

The Netherlands has a temperate marine climate. This is characterized by relatively warm winters and mild summers. More detailed information is given in chapter 3.2 Climate. In order to experience a pleasant temperature inside dwellings during winters, extra heat has to be added. In older neighbourhoods such as the Zeeheldenkwartier, due to the poorly insulated houses, more added heat is needed than in newer-built houses. Moreover, a stronger heat-flow is needed to guarantee that temperatures will reach 20⁰C within acceptable time. At this moment this is provided by burning natural gas.

Renewable heat sources that might replace gas heaters consist mainly of solar heat and geothermal heat. Heat might also be produced by using heat pumps that improve the quality of locally available heat such as heat from sewage, drinking water or aquifers. Geothermal heat and heat from sewage and drinking water is available all year, but in rather limited quantities. Aquifer storage systems are very limited as they require much space and their maximum temperature is no more than 25°C. Solar heat can only be produced during summer. This is due to the higher temperatures and greater number of hours of sunshine compared to winter. On the other hand, the demand for heat is much higher during winter than in summer. In figure 1 this imbalance has been sketched. This imbalance in heat demand and sustainable heat production needs not to be an important issue when a building is well insulated. Passive houses can be heated by the body heat of the users and their electricity consumption (Feist, W., et al., Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. Energy and buildings, 2005. 37(11): p. 1186-1203).

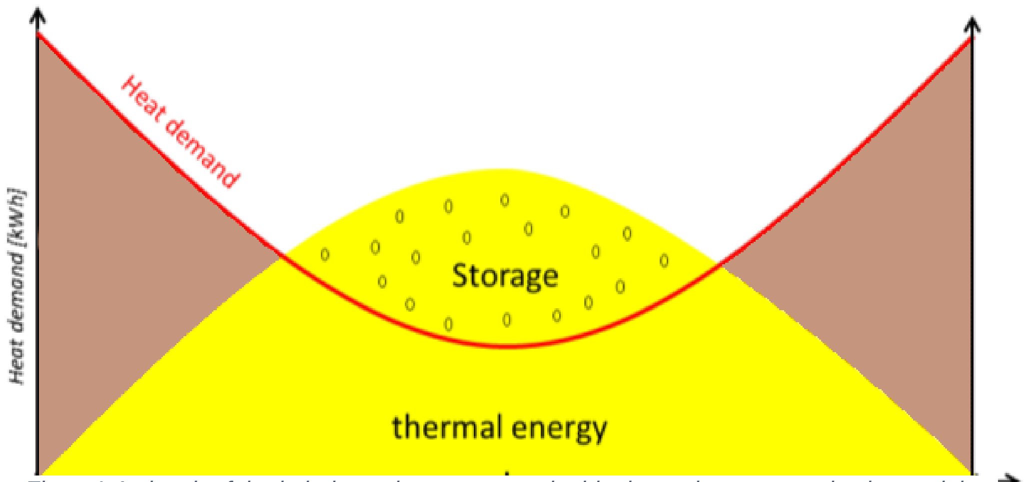


Figure1 A sketch of the imbalance between sustainable thermal energy production and the thermal energy demand (Rutz, Janssen, Ugalde, & Hofmeister, 2016).

However, a large part of the Zeeheldenkwartier consists of dwellings built in the years 1868 and 1890 (Gemeente Den Haag, 2002). These dwellings are often quite hard to insulate as they have no cavity walls that could be used for insulation. Hence, insulating layers take space on the inside, which is often unacceptable.

In order to be able to supply sufficient heat to these types of dwellings during the winter, excess heat from summer can be stored in order to replace natural gas based heat. However, the heat should be supplied at higher temperatures in order to be able to supply sufficient heat for each dwelling.

2.2. Heat demand and storage demand

The municipality of The Hague has the ambition to be climate-neutral by 2040. This is in line with the national climate targets and the phase out scheme for natural gas.

Phasing out natural gas from housing, utilities and industry is difficult. In this study only residential and non-residential buildings are considered. The cities industrial natural gas consumption is an interesting subject for further research.

''By storing heat, the demand for heat can be partially disconnected from the heat supply. This is necessary to maximize the use of local heat sources: the demand for heat is seasonal, but the supply of heat is often constant over time''. (Schilling, et al., 2019)

From an environmental point of view, low-temperature heating is to be preferred:

- The lower the temperature for heating, the less heat is lost in heat transport,

- The lower the temperature for heating, the more local renewable heat sources can be used as heat source.

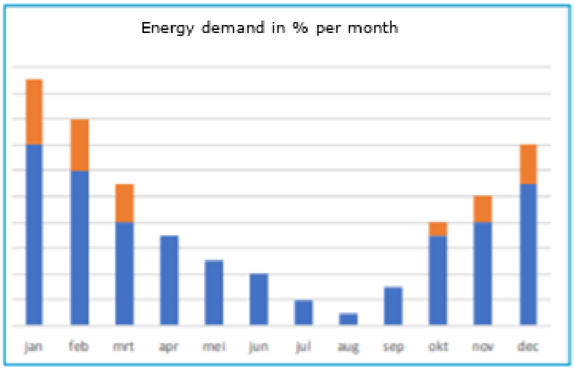
Hence, by low temperature heating less energy is needed to heat dwellings and utility buildings, and more heat might be available. However, it is not always possible to opt for low-temperature heating (LTH).

To provide (sustainable) heat to the dwellings and utility buildings in The Hague, a choice has to be made between heating at a high temperature (55-85°C) and a low temperature (35-55°C): The low temperature is more efficient but the high temperature requires a well-insulated dwelling.

2.2.1. Heat demand in The Hague.

With approximately 200,000 dwellings, 50,000 businesses and small enterprises, The Hague has a large heat demand. This heat demand amounts to 17 PetaJoule (PJ) (Noordhoek, 2019). Almost all of this thermal energy is currently produced by burning natural gas. More information about current heat consumption can be read in chapter 4.2. Besides heat by natural gas, there are some sustainable heat sources in The Hague (see Section 3.1).

The heat demand is divided into a base- and a peak load. The base load is the constant heat demand that can be supplied at any time of the day. Peak load is the fluctuating demand for heat that changes per day/week/season; The highest peaks in heat demand occur in the cold winter months, see Figure 2. CE Delft's study of hybrid heat grids in The Hague is based on a base/peak load volume ratio of 80/20 % (Schilling, et al., 2019). Newer heat systems are designed in a way that the baseload can be supplied by local renewable heat sources and, the peak load is supplied by fossil-fuel-powered installations. Such a system is called a



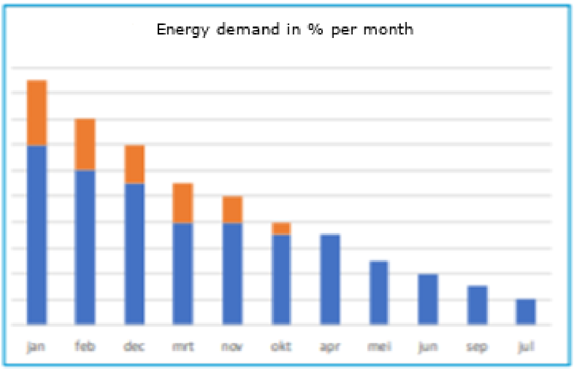


Figure 2. Indicative display of peak and base heat load. Blue indicates base load, orange indicates peak load. The left table shows heat demand per month. The right table shows a load/ duration curve of the same energy demand per month. (Schilling, et al., 2019)

hybrid heat network. This report describes how peak load can be provided with seasonal heat storage.

2.2.2. Heat demand of the Zeeheldenkwartier

Section 2.2.1. lists the base/peak load used to calculate the heat demand. This 80/20% volume ratio is described below to calculate the heat demand of the Zeeheldenkwartier.

Dwellings

In 2019, the number of dwellings in the Zeeheldenkwartier was 6553, see chapter 3. Figure 3 provides the basic data regarding current heat consumption in The Hague. Figure 4 gives an overview of the base load heat demand of the Zeeheldenkwartier in comparison to The Hague; If the Zeeheldenkwartier has a proportionate share in the total heat consumption, then the Zeeheldenkwartier consumes 0.24 PJ annually.

The annual natural gas consumption per dwelling in the Zeeheldenkwartier is 1070 m^3.

Residents	Dwellings		Utility buildings		Total	
Quantity	Quantity	Heat - demand	Surface	Heat demand	WEQ	Heat demand
502,000	249,000	9.3 PJ	8,780,000 m^2	4.7 PJ	308,000	14.0 PJ

Figure 3 Heat demand The Hague 2017 (Naber & Schepers, 2017).

(Gemeente Den Haag, 2018) This number multiplied by the number of dwellings and energy content of natural gas (31,65 MJ/m^3) gives a base load of 0.22 PJ, a little less than the result calculated above.

Utility

The number of utility buildings in the Zeeheldenkwartier is 205. (Zeeheldenkwartier voor speciale zaken, 2016) The surface area of this building type is ca. 48,892 m^2 (Pico.geodan , 2020). Figure 4 has been used to calculate that the base load of non-residential property is 0.03 PJ. See figure 5.

Basic and peak load

To calculate the peak load, the 80/20% rule of thumb (described before) is used. There is a total base heat demand of 0.22 PJ, and a peak heat demand of 0.05 PJ in the entire Zeeheldenkwartier.

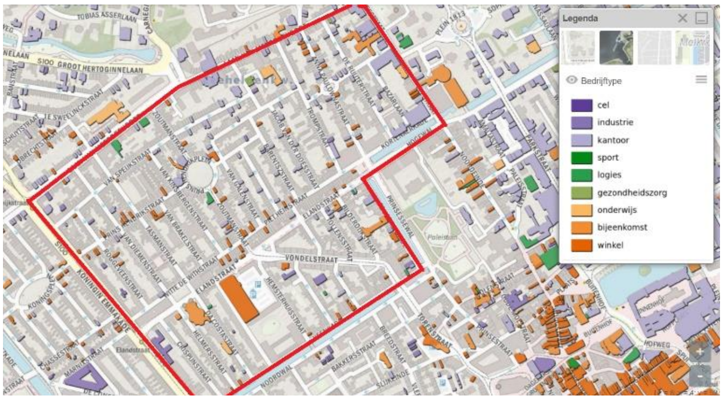


Figure 5 Amount of utility Zeeheldenkwartier, (Pico.geodan , 2020)

Location	Year	Dwellings		Utility Buildings		Total heat demand	
		Amount	Heat demand	Surface	Heat demand	Base load	Peak load
The Hague	2012	249,000	9.3 PJ	8,780,000 m^2	4.7 PJ	11.2 PJ	2.8 PJ
The Hague	2020	301,290	11.2 PJ	10,623,800 m^2	5.8 PJ	13.6 PJ	3.4 PJ
Zeehelden kwartier	2020	6,533	0.24 PJ	48,892 m^2	0.03 PJ	0.22 PJ	0.05 PJ

Figure 4 Heat demand in The Hague and in Zeeheldenkwartier

3. Area overview of the Zeeheldenkwartier

This chapter provides an overview of relevant characteristics of the Zeeheldenkwartier: the current heating system, buildings, climate and area density.

3.1. The current heating system

The current Dutch heating system is almost entirely based on natural gas. In 1959, the world's largest natural gas reservoir was discovered in the province of Groningen. Although this source is running out, and exports have been drastically reduced, the Dutch heating system almost entirely depends on natural gas.

To heat buildings, a finely branched grid covers the country and provides even the most remote hamlets with gas. Large gas pipelines transport the gas to the main population centres and smaller pipes distribute it to almost every household.

To convert the gas into heat, the gas is burned in a boiler. Individual boilers are about the size of a little refrigerator and are placed against a wall. The heat that is generated by the boiler is being transported by hot water. The hot water flows through the radiators or floor heating of the building. This heating method can deliver high-temperature heat (75 to 85 °C) to a building. This temperature is needed for the use of most radiators. Also when buildings are poorly insulated, high-temperature heating is needed to be able to reach comfortable temperatures.

In the current heating system, the peak load is relatively easy to manage. In the current heating system, gas is burned to receive heat. When more heat is needed, there is simply more gas burned to get the needed amount of heat. Gas is sufficiently available, even in cold winter days, although this is nowadays achieved by gas storage reservoirs.

In Zeeheldenkwartier the most common heating method is heating by natural gas, most of the buildings are old and poorly insulated. High-temperature heating is required to heat the dwellings during wintertime. Because the current heating system is based on the burning of natural gas, there is no real heat storage needed. In fact the gas system works as heat storage.

The organization "De Duurzame Zeehelden", consisting of inhabitants of the district, is promoting green solution for the district. This organization is scouting for potential fossil-free heating solutions.

3.2. Climate

The Zeeheldenkwartier as a part of The Hague has a temperate maritime climate (I am expat, 2020). Related to the Köppen-Geiger climate classification The Hague has the grading Cfb, as shown in figure 6, which means that the area has a humid climate. So the city has mild winters and short dry summers. The hottest month is August with an average temperature of 16.9°C, whereas January has the lowest average temperature of 2.6°C. The Hague has about 40 to 45 days per year with temperatures below 0°C, this number is about 20% lower than the Dutch average (Schilling, et al., 2019). The average yearly temperature

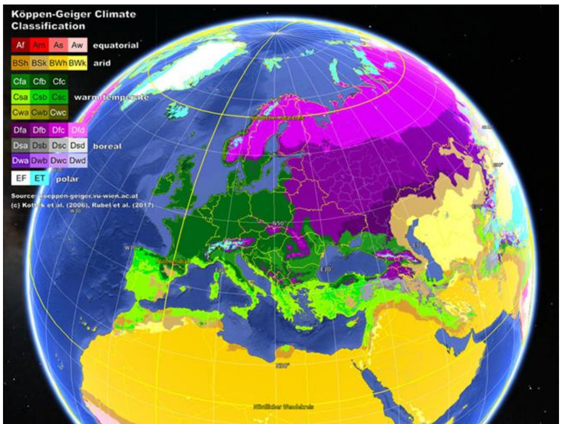


Figure 6 The Köppen-Geiger classification of climate types (World maps of Köppen-Geiger classification, 2017)

is 9.5°C in The Hague. Due to the fact that The Hague is located at the North Sea shore, it is often stormy, with much rainfall and no dry season. The amount of rain during the year is on average 777mm. The rainiest month is October with about 85mm; the driest month is April with about 45mm (CLIMATE-DATA.ORG, 2020). Moreover, the average humidity is 82% (Weather & Climate, 2020).

3.3. Buildings

The Zeeheldenkwartier contained 6533 dwellings at the beginning of 2019 (Gemeente Den Haag, 2019). These dwellings are mostly built before 1914, with a peak in 1902. See figure 7 (Gemeente Den Haag, 2002).

Most of the buildings are multi-family residential buildings or utility buildings smaller than 2500 m² as shown in building types in the appendix. Mostly little shops and cafes are located on the ground floor, above dwellings are located (Couvée, et al., 2019). The energy labels of these dwellings are mostly F or G or do not have a provisional label as shown in the appendix. In the west part of the district most of the better insulated dwellings, label B, are located. These houses have inter alia better insulation than buildings with a lower energy label. The bad insulation is related to the fact that most of these houses are in a monumental protection area, as shown in the appendix, which means that the buildings cannot be demolished or change their exterior.

Figure 7 Sum of houses per construction year in the Zeeheldenkwartier (Couvée, et al., 2019, S. 12).

3.4. Density

The Zeeheldenkwartier has been constructed starting from the year 1868. Private entrepreneurs bought meadows to build dwellings. They were commercial entrepreneurs seeking profits. Density of buildings was a strategy to optimise profits. As a result, the streets are narrow and there are relatively few open green spaces in the district.

3.4.1. GSI

The Ground Space Index (GSI) is an indication of how much area is developed (figure 8). In combination with the Floor Space Index, the GSI is used internationally as a unit to indicate the density of populated areas. In many countries, a minimum and maximum GSI is included in the Schedule of Requirements (Arjan Harbers, 2019). The GSI can be calculated using the following formula $GSI = \frac{Developed\ area}{Total\ area}$.

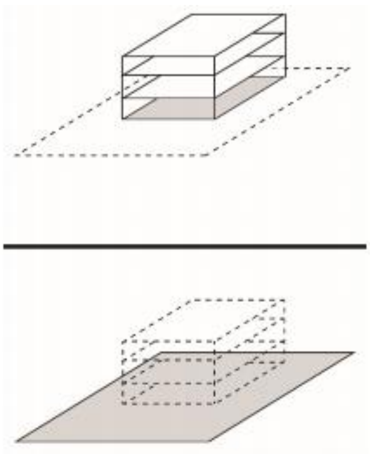


Figure 8 example of the Ground Space Index (Arjan Harbers, 2019).

3.4.2. OSR

The Open Space Ratio (OSR) is an internationally used indicator for the “building pressure” on the undeveloped area. This can be calculated by dividing the undeveloped land by the Gross Floor Area (GFA) of the area (Figure 9). A higher OSR indicates more open space than floor area (Arjan Harbers, 2019).

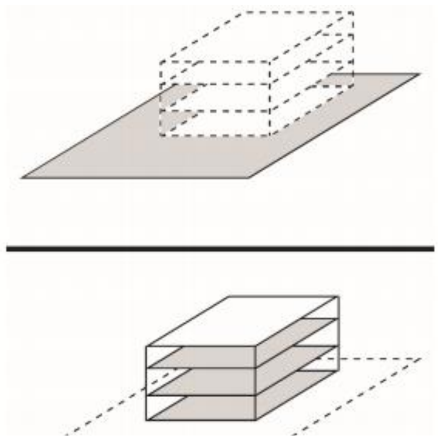


Figure 9 Example of the Open Space Ratio (Arjan Harbers, 2019).

4. Requirements for sustainable heat storage

In this chapter, the area characteristics will be linked to their requirements. In addition to area-specific requirements, the general requirements will also be explained.

4.1. General requirements

- *The supply source needs to be **sustainable.***

One of the main reasons to change the heating infrastructure is global climate change. The use of fossil fuels for heating causes high CO2 emissions; these emissions cause the greenhouse effect. To limit the greenhouse effect an energy transition is needed. Therefor climate goals have been set to make these big changes. When choosing a heat storage method the storage method must be sustainable. This means that the storage type must have very low greenhouse gas emissions and is made out of materials that have a long lifetime. Also, the charging and discharging of the storage needs to be sustainable. Sustainability is the main requirement in the decision tree. The Storage must be charged with a renewable source, storage types which are filled with fossil fuels or other non-sustainable materials are not mentioned in the decision tree.

- *The method needs to be above a certain **efficiency** level.*

High efficiency of the storage method is important, especially for long term heat storage (6 months or more). When a storage method has a low efficiency a lot of thermal energy will be lost during the storage period. This means that more heat needs to be produced to compensate for the losses. When the efficiency of heat storage is optimal the generated heat has more value. Also when the efficiency of a storage method is higher, there is less storage needed. Mostly this means that there is also less space needed. The value for the decision tree is set on 70% efficiency in half a year. This means that after half a year of heat storage, there should be at least 70% heat left of the heat input. If the efficiency is above 70% the storage method will pass with a yes in the decision tree. If efficiency is under 70% it will be a no in the decision tree.

- *The storage method shouldn't have a bad influence on the surrounding **environment.***

A heat storage method should not have a bad influence on the surrounding environment. When heat storage makes a lot of noise or smells very bad it has a bad influence on the direct environment. Some heat storage can be placed near dwellings or public areas, in this case, it is extra important to take a good look at the characteristics of the heat storage method.

When a storage method makes enough noise or smells bad enough that it disturbs the surrounding area it will be rated with a no at the decision tree. When it has almost no smell or makes almost no noise it will get a yes at the decision tree.

4.2. Area related requirements

In this paragraph the area related requirements will be described. These requirements are linked to the area characteristics described in chapter 3.

- *The storage needs to be **safe** enough for placement in the built environment.*

Due to the fact that the Zeeheldenkwartier is a densely populated district, the storage should be really safe for its surroundings. This means that it should not contain toxic components that could harm the people in the area. Also, components that could explode easily are not suitable for heat storage in a residential neighbourhood. Moreover, highly flammable elements are also risky to implement. The technology should not create any harmful risks, neither in a long-term perspective, nor in a short-term view. But not only should the storage type be safe, also the procedures/fuel which is used to charge the heat storage should be safe. Safety is an important characteristic of the quality of life in the Zeeheldenkwartier.

In the decision tree 'safety' is the absence of risk beyond a certain level. Risk is the probability of a certain loss, multiplied by the magnitude of that loss. As loss might be loss of human lives, but also financial-, ecological or social loss. So it is difficult to measure safety with a single number. For example, what is the risk of an explosion involving casualties, material damages and pollution?

- *The storage method must have **an energy density** of at least 840,55 MJ·m^{-3}*

When considering heat storage types, energy density plays an important role. The energy density means the amount of energy that a certain volume of material can contain. It is important to know the energy density of the material that is supposed to carry heat. When the energy density of a material is high, there is less material needed than when the material has a low energy density. In this report, the energy density is represented in MJ·m^{-3}.

For the decision tree, we have set the acceptable requirement limit at 840.55 MJ·m^{-3}. When the energy density of a storage type is below this level, it will be rated with a 'no' in the decision tree. When the value is above this level it will be rated with a 'yes'

The reason why there is chosen for this value is that this value of 840.55 MJ·m^{-3} is the average heat density of all heat storage types.

- *The **storage time** for heat must be 6 months.*

The peak load to be resolved by storing thermal energy is in winter. The energy to be stored is produced in summer. This means that the heat will have to be stored for at least half a year, without unacceptable losses.

- *The storage method must be able to deliver a minimum **temperature** of 75℃.*

The storage method must be able to deliver a minimum temperature of 75°C to the end-user. This temperature is necessary to provide the poorly insulated dwellings in the Zeeheldenkwartier with sufficient heat. At this moment the radiators in dwellings are made for temperatures above 75°C. Delivering a high temperature to the end-user can also be achieved by storing heat at a low temperature (35 °C - 55 °C), in combination with an additional heat pump to raise the temperature.

However, this solution is not desirable as the use of a heat pump requires extra investments and extra energy.

- *The **spatial demand** of the storage method needs to fit in the available space in the district.*

The spatial demand of a storage method is very important in a district such as the Zeeheldenkwartier. Due to the lack of parks, squares and wide streets, large storage systems are difficult to apply.

Spatial demand refers to the extent to which a system can adapt to this limited space. So for this district either modular heat storage units that can easily be fitted into this limited space, or heat units that can have various shapes, are most appropriate.

It is not only the spatial demand above ground that is important, but also the spatial demand below ground can be problematic. The soil beneath roads sidewalks and squares is filled with gas pipes, electricity cables, sewage pipes, water pipes, telephone cables, traffic controls, etc. Therefore, if a system can only be applied on a large scale, it will be difficult to fit it into the Zeeheldenkwartier. So if a system is modular and does not need much space, it will get a 'Yes' in the decision tree.

5. Decision tree

As a result of the area study, there are requirements set up for sustainable heat storage in the district Zeeheldenkwartier. Besides these requirements, various sustainable heat storage methods have been studied (see annex). By making a decision tree the requirements and the storage types are linked together clearly.

The decision tree is based on the requirements that have been developed. The order of the requirements in the decision tree is based on the importance of the requirements. Every storage type will be rated with a ‘yes’ or ‘no’ for each requirement. The ‘yes’ or ‘no’ is based on the criteria which are described in the previous chapter.

The decision tree is divided into fields of different colors. The fields from good (top) to bad (bottom). It has the same kind of principle as the energy label of dwellings, only, in this case, it is applied to energy storage systems.

The order of the requirements has been set as follows:

1- The operational temperature should be at least 75°C

Buildings in the Zeeheldenkwartier need high temperatures because they are poorly insulated. If the outside temperature is low much heat is needed to heat up again. For this reason the temperature of the heat storage has been set first.

2- Energy density above 840.55 MJ·m^{-3}

Less space is needed when the energy density is high. For making a decision the average of the energy densities of all long term storage types has been taken. Energy density is prioritised above efficiency as it is expected that renewable energy sources will be more common in the future. So if the storage material has a higher heat density it can store more thermal energy. In that case, the energy efficiency is not that important anymore, as there will more than sufficient heat during summer.

3- Efficiency over 70%

As the renewable energies are still a small part of the energy mix, energy needs to be used efficiently in order not to contribute to energy shortages. But this issue could change in the future when more renewable sources will be available.

4- Spatial development

Spatial development is important because the Zeeheldenkwartier is a dense area. This issue has not received a higher priority as there might be options to use heat storage space outside the district (e.g. by storage containers that could be moved into the district when needed).

5- Safety

Heat storages need to be safe, otherwise they will not be accepted by the people living and working in the area. So this could act as a number priority. However, smaller risks, even with casualties, are often accepted in practice: for example natural gas related accidents (explosions, fires, carbon monoxide poisoning) happen quite often (Netbeheer Nederland, 2019, *Registratie van gasinstallatie ongevallen achter de meter, 2018*. 2019).

). If a heat storage system has safety risks similar to the natural gas grid, it could be acceptable.

6- Environmental impacts

In general there are not many environmental impacts related to heat storage. Impacts like noise could be reduced by an additional noise canceller. Leakages could be prevented by proper inspection and maintenance schemes.

The decision tree has been divided in different areas to visualize the relevant categories for heat storage evaluation. It is similar to an energy label. The green colored area shows the preferred solutions related to the chosen requirements. The yellow and orange colored areas contain solutions that do not fulfil all requirements. In the red field are storage types which do definitely not fit to the requirements. The reader should keep in mind that this set of requirements is specifically chosen for the Zeeheldenkwartier district. For other neighborhoods the outcomes will be different. In this case, silicone heat storage fits the best to the set requirements.

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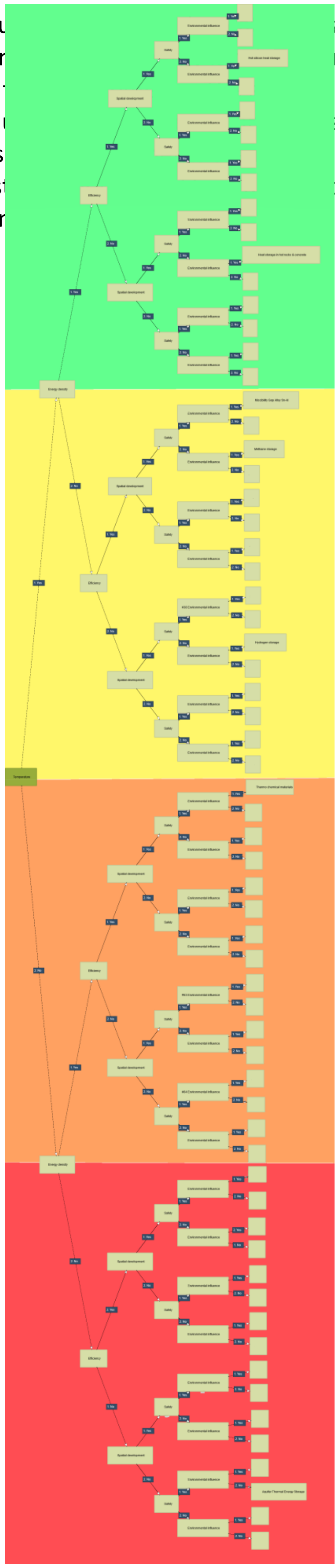

Figure 10 The decision tree with the 10 examined storage methods

6. Conclusion

This report provides an answer to the question: ‘What are the requirements for a heat storage system that will balance the seasonal imbalance between the heat demand of dwellings/utility buildings, and the sustainable heat production in the Zeeheldenkwartier district of The Hague?’ With this, a qualitative study has been carried out into potential heat storage methods.

The results of our analysis showed that heat storage is a necessity to achieve the ambition of the municipality of The Hague to be climate- neutral by 2040. Sustainable heat sources are needed to achieve this ambition. Heat storage systems are needed to store this sustainable heat, so when it's needed it can be delivered. With the cold winter and warm summer days, there is an imbalance in heat demand in the Netherlands, and therefore the Zeeheldenkwartier district. This imbalance is caused by the fact that in winter there is a shortage of heat, and in summer there is a surplus of heat.

Heat storage does not necessarily have to take place where the heat is consumed. In winter stored heat might be delivered to consumers by a city-wide heating grid. Heat might also be stored in containers outside the side, which might be brought into the city in winter. However, such solutions require large scale organisation and transport, and do not contribute to the self-reliance of a district.

For the Zeeheldenkwartier district the strong winter heat shortage is also based on the poor insulation of dwellings and utility buildings.

To answer the question regarding the heat demand, it can be said that: there is a baseload heat demand of 0.22 PJ in the whole Zeeheldenkwartier. The peak load heat demand is around 0.05 PJ.

To link the possible heat storage methods to the Zeeheldenkwartier district, the characteristics of the district were studied first. The following characteristics have been studied: the current heat system, buildings, density, and climate data.

This information regarding district characteristics was used to determine the requirements. The first general requirement of the particular storage method is that the supply of the heat source needs to be sustainable. Only sustainable sources and storage methods need to be studied to answer the main question. Besides the sustainability of the heat supply source, also the storage time is important. The time that the thermal energy can be stored must be longer than 6 months to make seasonal stores possible. If the storage method meets these requirements, the following points will be examined:

1. The storage method must be able to deliver a minimum temperature of 75 °C to the end-user.
2. The method needs to meet a minimum efficiency level.
3. The storage method needs to be modular as no large spaces are available in the neighbourhood.
4. The storage method must have an energy density of at least 840,55 $MJ\cdot m^{-3}$
5. The storage needs to be safe.
6. The storage method should not cause environmental harm to the surrounding environment.

A total of 10 storage options have been studied according regarding the requirements of the Zeeheldenkwartier. The storage options were rated YES or NO based on the criteria of the requirement; the end result is presented in a decision tree.

To answer the sub-question: ‘’Which heat storage method could meet the requirements of the Zeeheldenkwartier district?’’ it can be said that:

The results of this study lead to the conclusion that there is no perfect solution, which fits all of the given requirements. This is probably also the reason why large-scale heat storage is not yet established in the neighbourhood. It is difficult to realize a sustainable storage system that fits all the requirements of a specific district as the Zeeheldenkwartier. However, this study indicates the requirements that a specific heat storage system must comply with.

7. Discussion

To decide whether a storage method was the right one, the decision tree was chosen. This method shows whether the storage method meets a certain requirement. In hindsight, the disadvantage of this tool is that only 'yes' and 'no' can be chosen. Because of this, a certain method that does not meet for example a minimum energy density cannot compensate by having an over-average performance on another criterion. Moreover, small modifications might improve the situation: For instance safety might be improved by adding thicker walls to the system. The heat storage techniques, and the specific requirements for heat storage, are still very much in development. The 'decision tree' takes too little account of this.

Hence, the 'decision tree' is a too simple tool for a complex task of evaluating heat storage systems. In the end the decision tree gives an insight of the requirements that are important for choosing a heat storage method but it is not a tool that provides 'the best' end solution:

Some conditions such as 'safety' were very difficult to measure. If something was highly inflammable, toxic or explosive, something would be considered as 'not safe'. Now there are substances such as gas that have all these properties, but by taking sufficient safety measures their risks are still manageable. It would, therefore, have to be taken into account to what degree it is technically and sustainably economical to implement these safety measures.

Besides, waste heat has also been included in the calculation of energy demand. In this study, the starting point was that in the future situation the supply would only come from renewable energy sources. Waste heat will come from industry in the Rotterdam port area. At this moment this waste heat is 'sustainable' because otherwise the heat will be discharged in the North Sea. However, in the future heat generation and production might become much more efficient, which might lead to a drastic reduction of waste heat. In that case, such innovations might endanger heat supply, or the 'waste' heat could become a main product of this industry, which would imply that old fashioned/polluting industries will remain in business. Heat will then no longer be 'waste' and suddenly the heat for The Hague would no longer be sustainable. This also applies for waste incinerators: Developing a circular economy will imply that there is less waste to burn, and so less 'waste heat' from incinerators.

Therefore, one should be aware that waste heat is currently determined to be sustainable, but this could change dramatically in the future due to technical/legal developments.

In addition to considering a minimum temperature (75^{o}C degrees) for the storage options, a maximum temperature might also be appropriate. Too high temperatures require higher quality piping, and might create a risk for the user. Moreover, too high temperatures will create more heat losses, and thereby lower the efficiency of the system. Besides that, it is difficult to reach high temperatures with sustainable sources. Only waste incinerators are able to deliver high temperatures. Currently, a common maximum temperature is 120 ^{o}C. This is the maximum temperature that can be extracted from deep geothermal energy.

This research report does elaborate on costs and possible stakeholders. Costs and stakeholders can have a great impact on the realisation of any heat storage system.

In a follow-up study it might be interesting to study:

- Costs of investment and costs of exploitation of heat storage systems.
- Stakeholder requirements regarding heat storage systems.
- Likelihood of potential improvements of heat storage systems, in regard to requirements dealt with in this report, costs and additional stakeholder requirements.
- Improvement of the decision tree evaluation method, e.g. by combining 1) basic requirements to meet, and 2) a regular multi-criteria analysis

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Appendix

1. Potential heat storage methods

1.1. Miscibility Gap Alloy Sn-Al

Miscibility gap alloy (MGA) technology is a relatively new technology for storing heat. The technology is based on the heat that is needed to change the phase of a material. This heat is called latent heat. The temperature of the material does not change during melting or solidifying. For example, the amount of heat needed to turn ice of 0°C into water of 0°C is equal to 334 kJoule/kg. The amount of heat that is required to change 1.0 kg of a substance from the solid-state to the liquid state is called the "heat of fusion". This is denoted by L_F and is differs by material. The heat required to change a material from the liquid state to the gas state is called the "heat of vaporization" and is denoted by L_V (C.Giancoli, 2009) This added heat is not sensible and is therefore called latent heat. The heat that changes the temperature of a material is called sensible heat, because unlike latent heat it can be sensed. Figure 11 presents the temperature as a function of the heat. The MGA technology differs from other Phase Change Material (PCM) technologies like molten salt and paraffin-based technologies in the fact that they are made of metallic materials. The usage of metals include the following advantages (Heber Sugo, 2012):

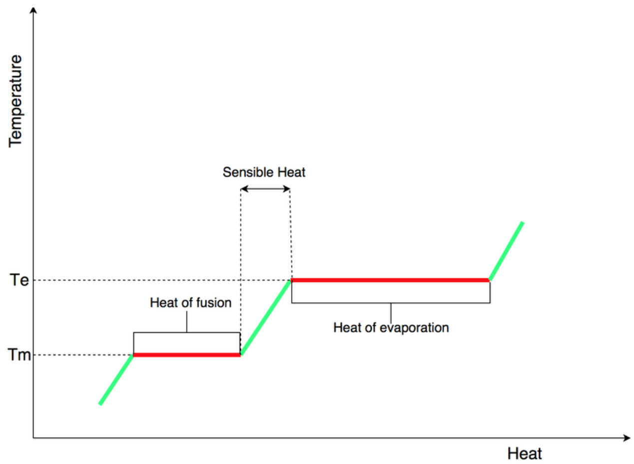

Figure 11 Phase change diagram: temperature as a function of heat added. Tm and Te indicates the melting and evaporation temperature, respectively. (Soibam)

1) High energy density per unit volume by capitalizing on the high latent heat of fusion per unit volume of metals.
2) A range of melting temperatures for active phases are available and therefore the materials may be individually matched to useful operating temperatures: 250 °C for space heating, 600 °C for steam turbine electricity generation and 1400 °C for high-temperature industrial processes.
3) Latent heat is delivered (or accepted) over a narrow temperature range allowing more precise control of process parameters and, in terms of steam-generation, would allow for easier matching of turbine-generator.
4) Since the heat is delivered and retrieved from the active phase by conduction alone, there is no need to transport the molten phase around the system and very high heat transfer rates are possible.
5) No special containment is necessary as the matrix phase remains solid at all times and encapsulates the active phase.
6) Chemical reactions between component materials are avoided as the two materials are thermodynamically stable and immiscible.

For further study the alloy of aluminum and tin has been chosen (Al-Sn). The charging temperature of this alloy suits the current heating systems in buildings the best.

Temperature

The charge-discharge cycle occurs in the temperature range of 224°C -246°C. This allows the heat delivery on a constant temperature (Heber Sugo, 2012).

Spatial demand

The MGA system can be build up in modular blocks of different sizes. This can vary from a cubic meter to several cubic meters. This makes them very easy to apply in the built environment.

Safety

Both Aluminium and Tin are very safe materials to use. There are no toxicological issues and the metals are very stable under normal circumstances (Fisher Scientific, 2009) (Carl Roth GmbH + Co KG, 2020). The temperature of the storage is controlled so the molten Tin particles will always be encapsulated by the aluminium. When the insulation of the alloy is intact the system will cause no harm.

Energy density

Al-Sn technology has a storing capacity of 0.43 $MJ \cdot L^{-1}$. So for example in a storage system of 1 cubic meter 430 MJ can be stored (Heber Sugo, 2012). Because this storage method is still under development, there is no information yet about the reduction in capacity over time of the Al-Sn alloy. There is information about other alloys, like the Al-Mg-Zn alloy. After 1000 charging/discharging cycles there is a reduction seen of 11.1% in latent heat of fusion. This reduction will lower the energy storing capacity over time.

Storage Time

Direct thermal energy storage (TES) can be made with almost no losses. The only losses are environmental losses through the insulation envelope. There is no exact percentage for MGA technology available. In (Heber Sugo, 2012) MGA technology has been compared with Concentrated Solar-Thermal plants. Tonnes of salt are molten in Concentrated-solar Thermal plants to store heat. By paying careful attention to insulation there are almost no losses. The efficiencies of those systems are about 99%. This efficiency rates can probably also be achieved by MGA technology when the same attention is given to the insulation.

Sustainability

The Al-Sn alloy needs to be charged by a temperature higher than 246°C. These temperatures can only be reached by using heat from industry or waste incineration.

The storage method uses large quantities of metal. Tin is present in the earth's crust at a concentration of 2.2 p.p.m. Aluminium is far more abundant than tin.

Efficiency

The MGA method is a direct thermal energy storing method. This kind of heat storage conducts no losses in thermal energy when being stored. There will only be losses if insufficient insulation is applied.

Environmental influence

The Al-Sn alloy does not have negative environmental impacts.

1.2. Thermochemical materials (hydration and dehydration of salts)

Thermochemical materials (TCM) are solid materials which can store energy in their molecular bonds. In the case of salt-based systems, heat is stored by hydrating and dehydrating the chosen salt or salt mixture. When a salt (e.g. $MgSO_4$) is hydrated, it will start releasing heat. One can use this property also the other way around. A hydrated salt can be dehydrated by adding heat that evaporates the water of the salt. When later the salt is hydrated again it will release the added heat.

There are two kinds of thermochemical energy storing systems, the open systems and closed systems. The closed ones have a little lower energy density than the open systems (Ding & Riffat, 2012). The downside of an open system is that some salts will react with the air. To overcome this problem closed systems have been introduced, that work under vacuum. In a 2017 study by Eindhoven University of Technology, in collaboration with TNO, 262 salts were evaluated as a thermochemical heat storage material. From these 262 salts, a shortlist of 25 salts was made. These salts were then assessed for energy density, volume variation, deliquescence vapor pressure[1], price, safety, chemical stability, and hydration/dehydration kinetics. After these salts were assessed, potassium carbonate, K_2CO_2, resulted as the best choice for heat storage (Donkers, Sögütoglu, Huinink, Fischer, & Adan, 2017).

Temperature

The hydration temperature of potassium carbonate is 59°C and the dehydration temperature 64°C. This temperature is not suitable for hot tap water according to (L.C. Sögütoglua, 2018).

Spatial demand

TCM's are easy to scale to the available space. Hence, a TCM system can be distributed in smaller units across the district, but a single large central storage might also be chosen.

Safety

Potassium carbonate is one of the safest salts for thermochemical energy storage. The salt is not highly flammable, non-toxic and is very stable. So there are no concerns about the safety of using potassium carbonate as thermochemical storing material (Donkers, Sögütoglu, Huinink, Fischer, & Adan, 2017).

Energy density

The TCM Potassium Carbonate can store 1.3 $GJ \cdot m^{-3}$ of latent energy. A storage system of 1 cubic meter can store 1.3 GJ of energy over a time span of 20 years according to (L.C. Sögütoglua, 2018). There are other salts with much higher energy densities, but those salts are either expensive or dangerous. However, an energy density of 1.3 $GJ \cdot m^{-3}$ is much higher than sensible heat and latent heat storage systems.

Storage Time

A year amount of energy can be stored for over at least a year (L.C. Sögütoglua, 2018).

[1] A measure for the ability to dry its surroundings

Sustainability

Potassium carbonate is a common salt on earth. Potassium is the seventh most abundant element in the earth's crust. It takes about 2.6% of the weight of the earth (Greenwood & Earnshaw, 1997). The system has a lifespan of over 20 years when charged/discharged monthly. However, if this system is used seasonal, the lifespan will be much longer than 20 years.

Efficiency

There are no losses between charge and discharge cycles over a long period according to (TNO, 2020).

Environmental influence

Storing energy by dehydrating salts does not have any negative environmental impacts. However, the systems require pumps to pump the transport media (water) from the storage to the end-user. Pumps can sometimes produce low-frequency vibrations. Most people will not be able to hear them.

1.3. Aquifer thermal energy storage

An Aquifer Thermal Energy Storage (ATES) can store thermal energy from the building and/or its surroundings in underground water. A heat pump is connected to almost all ATES systems to produce the right temperature for the building. By using the heat pump and passive cooling, an ATES system can save up to 60% of heating energy and 80%of cooling energy (RVO, sd). There are open and closed systems. Open systems use groundwater, closed systems do not. In this case, only open systems are considered, because open systems can store large quantities of heat/cold (Bouwmeester, 2013).

Temperature

The temperature to inject heat in an aquifer can only be a maximum of 25 °C (Duurzaam MBO, 2018). This maximum of 25 °C has been set by the government for environmental reasons: the subsoil life could be at risk by elevated temperatures. So the maximum stored heat is 25 °C. At some places the injection temperature can be increased to 30 °C, but this is not the case at every location (Deltaris, sd).

Spatial demand

Most of the existing ATES systems in the Netherlands have a storage volume of 500,000 cubic meters of water (H2O Waternetwerk, 2017). Several hundred systems are known with a volume of several million cubic meters. The system can be expanded, but they cannot just be placed next to each other. This is because the sources then influence each other. This can result in a negative output. As a result, there are many permits for this type of energy storage.

Safety

ATES is a very safe system. It does not work under high pressure and the system does not make use of dangerous or toxic materials...

Energy density

This section describes in what density the energy can be stored. So how much volume of the material is needed to store a certain amount of energy? The calculation is based on maximum storage potential. This is based on the maximum efficiency and the maximum temperature at which the water is stored. It must, therefore, be taken into account that in many cases this is not feasible and will, in reality, be lower. The energy density of this system is 104,28 $MJ \cdot m^{-3}$, according to the calculation in figure 12.

Storage time

An ATES system is used to overcome the seasons. In the summer there is cooling with cold from the winter and in the winter there is heating with excess heat from the summer. This means that the system can store energy at least from the beginning of summer until the end of winter. This is, therefore, a storage time from 9 and 12 months.

Calculation

m: 1 * 997 = 997 kg
c^{water}: 4184 $J \cdot kg^{-1} \cdot K^{-1}$
ρ: 997 $kg \cdot m^{-3}$
ΔT: 25 K

$Q = c * m * \Delta T = 4184 \cdot 997 \cdot 25 = 104{,}28$ $MJ \cdot m^{-3}$

Figure 12 The calculation for energy density of ATES.

Sustainability

No fossil fuels are used during the storage of energy and no greenhouse gas emissions are produced. As can be seen under the heading 'efficiency' the storage has a high Seasonal Performance (SPF) and an efficiency of 80 %. The manufacturer indicates that the service life of his sources is at least 25 years (Geotherm, sd). The lifespan of the wells depends entirely on their construction, maintenance, and choice of materials. This kind of thermal energy storage system is not infinite and can, therefore, be defined as 'not completely sustainable'. After the source is no longer tenable after 25 years, it is infused with a certain non-toxic substance that separates the various groundwater layers again.

Efficiency

The ATES can achieve a high efficiency in which about 50 % of primary energy is saved. This saving can only be achieved if the source of heat and cold from the building or another source is added to the soil (RVO, 2010). The energy efficiency of ATES is expressed as the (SPF). The annual heat and cold produced are divided by the added primary energy. The SPF of an ATES is 20 (RVO, 2010). If there is a large bubble of injected water, a large source distance, and no background flow, the efficiency will be high (about 80 %) (Bot, 2013).

Environmental influence

The risks with such a storage system are the unsuitability of the soil or no permission to drill, the presence of soil contamination or reservation for drinking water supply, among other things. In the case of phased construction, there is uncertainty about the realization of construction plans after investment in a thermal energy system (RVO, 2010).

In the case of an ATES, drilling has to be carried out in the ground. These drillings can have all kinds of consequences for the environment. During the maintenance of the wells or due to leakage, a limited amount of oxygen from the air can get into the groundwater. Because the groundwater is intensively circulated, existing groundwater contaminants might spread. Also, undesirable geochemical and microbiological effects can result from mixing different groundwater layers with different values. These geochemical and microbiological processes can lead to iron precipitation and anaerobic corrosion. As a result, the source can become clogged. Aggressive chemicals such as chlorine bleach lye, hydrogen peroxide, and strong acids are sometimes used to regenerate clogged wells. In Lelystad, several reference wells were studied. Several systems had very few microorganisms. This also indicates a negative effect of the ATES installation (Beelen, 2011).

1.4. Thermal energy storage in tanks

To store heat, heat storage tanks can be used. These tanks are primarily made of steel and are highly insulated to prevent heat loss. Inside the tank, there will be hot water or steam located. The water or steam functions as a heat carrier by this storage method. By using high pressure, heat storage will be more efficient. This is because high pressure makes particles move faster, as a result of this there will be heat generated. This storage type is mostly used to store heat for a few days and manage peak loads in the heating system. The heat will be transported by water to and from the storage tank. Storage tanks like this are available in different sizes, from fifty litres up to thousands or even millions of litres. The variety in size makes it easier to adjust this storage type in different situations. The heat storage tanks can be placed in both vertical and horizontal directions. It frequently happens that these tanks are buried. The underground placement saves space in the environment. There are a few differences in characteristics between the horizontal and the vertical storage tanks. The horizontal tank can be filled with hot water where this is not possible with the vertical tank.

Temperature

A vertical tank has a maximum fill temperature of 95°C, the reason why it cannot be filled is that there is an expansion space at the top of the tank. (Hogervorst, van Steekelenburg, & van Antwerpen)

Spatial demand

To build a big heat storage tank (not the ones in homes) there is a building permit needed. The maximum height is established at 10 to 12 meters. This might vary per municipality, and there can be some exceptions too. (Hogervorst, van Steekelenburg, & van Antwerpen)

Safety

Heat storage tanks can be considered safe, they do not use materials that are toxic, flammable or explosive.

Energy density

The heat carrier by this storage method is water. The energy density of water is about 399 $MJ \cdot m^{-3}$. This means that one cubic meter of water can contain 399 MJ of energy.

Storage time

Storage tanks are made for short storage time, usually for a few days.

Sustainability

Heat storage tanks are a sustainable way to store heat. This heat storage method is based on the storage of hot water. When the hot water is heated by sustainable sources it can be considered even more sustainable.

Efficiency

According to (Hogervorst, van Steekelenburg, & van Antwerpen) the storage will lose 1,33% to 1,87% of heat per day (figure 13).

rg, & van

	Delta T	Energy loss per day
Vertical buffer	60	1.3%
Horizontal buffer	60	2.87%

Environmental influence

A heat storage tank has almost no environmental influence. Only the high temperature might harm the environment. Underground heat losses might kill invertebrates and microbes.

The table underneath shows the delta T in degrees Celsius and the energy loss per day for a vertical and horizontal storage tank

1.5. Thermal energy storage in hot rocks & concrete

Rocks or concrete have a lower thermal capacity in comparison to water. Where water has a thermal capacity of 4200 $J \cdot kg^{-1} \cdot K^{-1}$ the thermal capacity of concrete is just one-third of that (about 1000 J $J \cdot kg^{-1} \cdot K^{-}$). The reason why rocks or concrete are still interesting heat carriers is that the temperature in rocks or concrete can be heated too much higher temperatures (around 1200 °C in some cases). A Norwegian company named Energy Nest has developed a storage method where heat can be stored in concrete. The storage type is based on concrete cylinders (batteries) that have pipes inside of them. By pumping hot fluid through these pipes, the concrete cylinders as seen in figure 14 can warm up to a temperature of 450°C. Because of the characteristics of concrete, the heat will stay in the concrete cylinders. When the heat needed it can be extracted from the concrete batteries by pumping colder fluid through the pipes. The cold fluid will warm up and then can be used for

multiple purposes. (De Ingenieur, 2018)

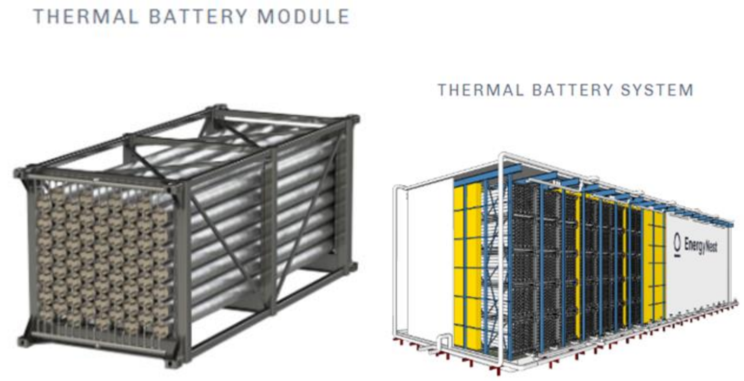

Figure 14 A unit of concrete tubes for thermal energy storage and a container unit filled with concrete tubes for the storage of thermal energy (Energy-Nest, 2020).

Temperature

For both rocks and concrete there are different temperatures that can be used for the storage of heat. For concrete the highest temperature might be around 450 °C and for rocks this is about 1200 °C. In reality these temperatures will not be reached all the time so it is likely that the storage temperatures will be a bit lower than these maximum values.

Concrete: up to 450 °C

Rocks: up to 1200 °C

Spatial demand

It is possible to make storage units as big as you want. The company Energy-Nest makes storage modules as big as sea containers; these can be connected to create one big heat storage. Figure 6 provides an example of such a storage unit.

Safety

The storage method is relatively safe; the only dangerous part of this storage method is the extremely high temperature of the storage.

Energy density

The maximum storage capacities of these systems can be found underneath. These capacities are the absolute maximum, in reality; these values can be a bit lower.

Rocks: 2,760 MJ·m^{-3}

per sea container size (76 m^3): 209.760 MJ

Calculation Rocks

m: 1 * 2000 = 2000kg
c^{Rocks}: 1000 $J \cdot kg^{-1} \cdot K^{-1}$
ρ: 2000 $kg \cdot m^{-3}$
ΔT: 450 K

Q = c * m * ΔT = 1000·2000·450 =900 $MJ \cdot m^{-3}$

per thermal battery system (7600 m^3): 20,976,000 MJ = 0,021 PJ

Concrete: 900 $MJ \cdot m^{-3}$

per sea container size (76 m^3): 68,400 MJ

per thermal battery system (7600m^3): 6,840,000 MJ =0.0068 PJ

The above values have been calculated using the given values of (greenspec, 2019)

Storage time

Because of the passive high-temperature heat storage, this storage method is for the long term. Rocks or concrete are bad heat conductors, this means that it takes a long time for them to absorb heat. Also, the extraction of heat goes slowly with these methods. Exact numbers about the storage time are barely available.

Sustainability

Heat storage in rocks or concrete can be considered sustainable because there are no fossil fuels used for this storage method. Only the making of concrete/rock storages can be unsustainable, this also counts for the transport of the materials.

Efficiency

The efficiency of these storage types is about 50% according to (Charles W. Forsberg, 2018).

Environmental influence

The environmental impact of rock and concrete heat storage is minimal. It has no smell and makes almost no noise; the only noise is produced by the pumps that pump the water through the stone or concrete. When using big volume installations there can be an amount of shadow that is caused by the storage installation. This can be prevented by lowering the installation but this takes more space in the environment. Also because of the high temperature storage the system could have an effect on the life in the underground when not properly insulated.

Calculation Rocks

m: 1 * 2300 = 2300kg
c^{Rocks}: 1000 $J \cdot kg^{-1} \cdot K^{-1}$
ρ: 2300 $kg \cdot m^{-3}$
ΔT: 1200 K

Q = c * m * ΔT = 1000·2300·1200 =2,760 $MJ \cdot m^{-3}$

1.6. Electric thermal storage heaters

This is a form of heat storage that uses electricity to generate heat. The system consists of a heat storage material that is electrically heated. The heating material is stored at night so that the heat can be given during the day. These heating elements often consist of clay bricks or other ceramic materials. These materials are known for long term heat retention and slow heat delivery. Feolite is also a known proper material for this storage method.

Electric heating elements are placed in the heating system that can heat the storage medium, and therefore store energy. The stored heat is continuously emitted by thermal radiation and convection of air. To speed up the heat transfer, mechanical fans are often placed in the storage element, which can move the hot air faster and further.

Storage heaters with high heat storage are the latest development in technology. This technology with new advanced software is often used in new construction and renovation work. High heat storage heaters can retain more heat than traditional storage heaters, at least 45% heat is retained after 24 hours of full charge (DECC, 2012). When the system is used, 98% of the electricity is converted to heat (Siemens gamesa, 2020). The high-temperature heat storage heaters are often combined with smart measuring equipment or well-designed climatic conditions. Storage heaters with high heat storage comply with LOT 20, which is a regulation list/legislation of heaters that may be installed in the EU member states (Glen Dimplex Heating & Ventilation, 2020).

Storage heaters are usually used in combination with a two-rate electricity meter that registers the electricity used during the off-peak period so that it can be charged at a lower rate.

Storage heaters often have two regulators, one that regulates heat input and one that regulates heat output, also known as draft control. These regulators can be operated manually or set automatically with a thermostat.

Environmental influence

An opportunity for a more sustainable solution is to combine green generated energy (locally) with the electrical storage option ETS. Also, connecting the storage options to a smart grid is another possibility.

The surplus of electricity in off-peak hours can be used by storage facilities such as ETS. This is a supply and demand system, which can have a dynamic and financial perspective. In the end, the storage heaters give a lower peak load on the energy network.

Temperature

This heating system does not give heat to the end-user using water as a transport medium. This system is based on the convection and radiation of heat by transporting heat through air. The temperature delivered is a comfortable 21 °C.

Spatial demand

The size of the system is comparable to existing radiators; the size depends on the surface that is heated. The ETS system is a house specific system and cannot be used in large utilities or industry. To get an idea of the dimensions see figure 15.

Input Power kW	Storage Capacity kWh	Max Heat Output kW	Dimensions m	Installed Weight lbs (N)
2.4	13.5	3.5	0.76 x 0.62 x 0.27	267 (1188)
3.6	20.3	4.3	0.94 x 0.62 x 0.27	376 (1673)
4.8	27.0	5.8	1.12 x 0.62 x 0.27	478 (2126)
6.0	33.8	6.2	1.30 x 0.62 x 0.27	585 (2602)
7.2	40.5	6.5	1.47 x 0.62 x 0.27	692 (3078)

Figure 15 Characteristics of thermals storage heaters (Steffes, 2020).

Safety

This system is installed within dwellings, so there are no outside dangers that the system has to deal with. Indoors, the only danger is the high temperature of the system. The product contains 2 layers of insulation, both used to resist the heat transfer. This insulation makes the product more efficient, but also safer in using. The inside of the feolite stones reaches a temperature of up to 1000 °C, while the outer layer of the stones does not get warmer than 180 °C. (South Kentucky Rural Electric Cooperative Corporation, sd) With all insulation and packing, the system is user-friendly. When the system is applied to a house, there should be always space between the appliance and the surrounding surface, because the heater must lose its heat.

Energy density

There is no information available in public sources on the energy density of feolite, therefore this has been calculated using the heat capacity and density of the material. This determines the energy density of feolite at 3512,65 MJ·m-3. This calculation can be seen in figure 16.

Storage time

An ETS system can retain its heat 24 hours a day if properly installed on the corresponding room content. Once the brick core of the system has warmed up, it can retain its heat for a long time due to its good insulation. (Madison Electric, 2016) However, this storage method is not suitable for seasonal storage, only for day and night storage.

Calculation

m: $1 \cdot 3900 = 3900$ kg
$c^{feolite}$: $920\ J \cdot kg^{-1} \cdot K^{-1}$
ρ: $3900\ kg \cdot m^{-3}$
ΔT: $1000-21 = 979$ K

$Q = c * m * \Delta T = 920 \cdot 3900 \cdot 979 = 3512{,}65\ MJ \cdot m^{-3}$

Figure 16 The calculation of energy density for feolite.

Efficiency

The efficiency of an ETS is at least 45% with high-temperature storage over 24 hours. This means that there is a loss of 65% heat after 24 hours (DECC, 2012). When the system is used, the efficiency is 98 %, including the electricity to heat transfer. In figure 18 you can see the efficiency changes.

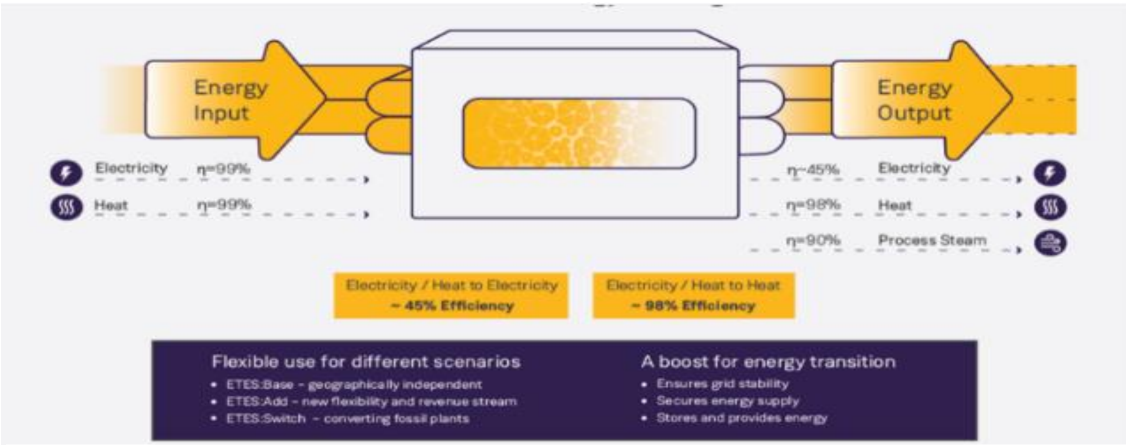

Figure 17 ETS efficiency, (Siemens gamesa, 2020)

Sustainability

Electric power for the ETS system is produced using electric heating in a power plant that burns fossil fuels. This is not environmentally friendly because of the greenhouse gas emissions. The materials where the system is made of are not harmful to the environment, besides that they are also non-toxic.

Environmental influence

The storage system does not smell. This is important because it has to be taken into account that the system is placed in a room where people work or live. This method contains no toxic materials and does not emit harmful gasses.

1.7. Hot silicon heat storage

''Thermal energy is the largest consumer of energy in our society, it is larger than transport and electricity generation. If you want to tackle energy efficiency and make a difference to emissions, you need to look at the thermal energy usage and not just electricity.'' Dr. Kevin Moriarty (1414degrees, 2018).

This form of heat storage is based on heating silicon. The technology of this system is still in its developmental stage, and experiments are being done with it today. The green electricity generated by wind or solar energy, for example, can be stored in the hot silicon. This storage method uses heat as a storage method, but the most important reason for this storage method is to provide electrical energy. Company 1414 Degrees who is mentioned later on, also produces heat with this system.

A team of researchers at the Massachusetts Institute of Technology (MIT) proposed a new energy storage concept, claiming that this technology would be much more economical than contemporary storage methods (Willuhn, 2018). Such a system could power up to 100,000 homes.

The system is based on renewable energy which is converted into heat; this heat is converted into hot-white melted silicon. The technology consists of two 10 meter large graphite storage tanks, which are heavily insulated and filled with liquid silicon. The 'hot' tank stores silicon at a temperature of 2370 °C. The 'cold' tank, at 1926 °C, is connected via pipes and heat elements to the 'warm' tank, allowing the system to circulate and release heat.

When electricity is needed, the molten white-hot silicon is passed through a series of tubes. In these tubes the glowing silicon emits a lot of light (500 x as strong as regular solar cells); this light is received by high-efficiency solar cells 'multi-junction photovoltaic cells'. This is used to generate electricity. The cold silicon is reused in this circular process (Willuhn, 2018).

Silicon is a chemical element with the symbol Si in the periodic table. The chemical element has a melting and boiling point of 1414 °C and 3265 °C. Silicon is the 8 most common element on earth, and rarely occurs as a pure element. Silicon has an extremely high energy density due to its latent heat properties. Silicon is available in large amounts, making the technology sustainable and affordable. It is also non-toxic and fully recyclable. It is not flammable due to its liquid form, it can only be considered 'caustic'. (Carlroth, 2015)

1414 Degrees is an Australian company experimenting with energy storage using silicon technology. The company is different from others, in addition to electricity; it also supplies heat using silicon, without having to convert it back into electricity. This Thermal Energy Storage Solution (TESS) of 1414 Degrees uses combined heat and power. Testing an average prototype has led to an efficiency of 80%, 1414 Degrees expects to reach an efficiency of up to 90% in large-scale systems. 'With this, TESS offers an alternative to gas, coal or electricity from fossil fuels by using electricity from renewable sources.'

(1414 Degrees, 2019). A neighborhood-specific TESS-GRID system strives for 57% electrical efficiency in combination with advanced electrical power plants, when working together with heat consumers such as producers or industries a CHP can lead to 90% efficiency in a TESS-GRID. The heat storage time is about 1 week. This allows energy to be extracted from the installation at any time. This does not make it a seasonal storage installation. Because there is no burning during phase change, TESS does not produce any greenhouse gases. The lifespan of a TESS installation is 20 years.

Temperature

Calculation

m: $1 \cdot 2400 = 2400$ kg
$c^{Silicon}$: 760 $J \cdot kg^{-1} \cdot K^{-1}$
ρ: 2400 $kg \cdot m^{-3}$
ΔT: 1414-120= 1294 °C

$Q = c \cdot m \cdot \Delta T = 760 \cdot 2400 \cdot 1294 = 2360{,}25$ $MJ \cdot m^{-3}$

Figure 18 The calculation of energy density for silicon.

Because of the high boiling point of silicon (1414 degrees), this temperature level of heat can also be extracted from the system. This is done by using a heat exchanger. The losses with the use of a heat exchanger are minimal because of the efficiency of 85-90%.

Spatial demand

The storage heat system has great applicability. For example, the system can be connected to or removed from the electricity system. In this way, the system can be placed anywhere where heat is needed (1414 Degrees, 2019). An average system (10 MWh) is as big as a 40-foot sea container; a larger system is as big as a 2 story building.

Safety

1414 Degrees insists that the system is safe. This is because of the thick insulation of the system, in order to contain the hot silicon. The graphite storage tanks create a chemical reaction with the silicon, creating an extra protective layer on the inside. (1414 Degrees, 2019) The only danger is that silicon is highly flammable when it is solid (rating 3 serious hazard), and the melting point is about 1414-1420 degrees Celsius. Silicon may create some slight hazards or minor injuries (Gelest enabling your technology , 2015).

Energy density

There is no information available in public sources on the energy density of the hot silicon method; therefore this has been calculated using the heat capacity and density of the material. This determines the energy density of the hot silicon at 2360,25 $MJ \cdot m^{-3}$. This calculation can be seen in figure 18.

Storage time

Standard insulation can store the heat for a week. Extra insulation may increase this period, but this will increase the cost. The heating system circulates its heat daily.

Sustainability

The silicon is heated with electricity or burning gas (biogas or natural gas). When electricity is not produced sustainable, it will cause emissions of CO^2 and some other pollutants. Burning 1 gallon of natural gas produces about 19.6 pounds of CO^2 (U.S. Energy information administration, sd). Biogas is sustainable as it is of biologic origin.

Efficiency

The efficiency of a similar heat storage system (TESS) is 85-90% heat efficiency and 10-50% electrical efficiency. The real efficiency depends on the size of the system, and the type of energy you want to generate after storage. This allows you to choose between electrical energy and heat.

Environmental influence

Silicon is not dangerous to the environment. (Carlroth, 2015) In addition, silicon is non-toxic. It does not produce any harmful emissions such as particulate matter or greenhouse gasses, because there is no combustion. (1414 Degrees, 2019)

1.8. Molten salt technology

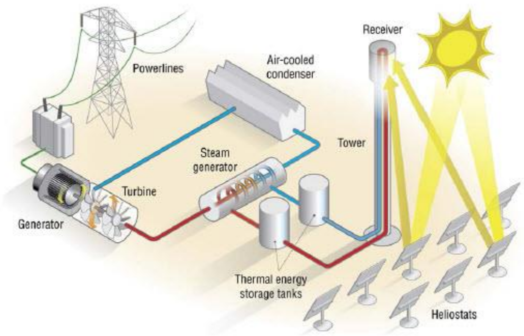

Figure 19 – Molten salt storage function (Cleanleap,

The molten- salt technology is mainly used in solar thermal power plants and uses a physical process to store sensible heat (Loeper, et al., Potenziale der Integration thermischer Energiespeicher in Dampfkraftwerke, 2019). Sensible heat means that the temperature is measurable by a thermometer (Spektrum, 2001). The heat can be used for generating electricity but also for heating. Mostly two-tank molten salt storages are used without pressure inside. The two tanks have different temperatures. One tank has an inside temperature of about 290°C. The temperature of the other tank depends on the power plant. A solar tower power plant contains temperatures up to 560°C. Whereas storages for parabolic through power plants only need temperatures about 390°C (Loeper, et al., Potenziale der Integration thermischer Energiespeicher in Dampfkraftwerke, 2019). These tanks contain liquid nitrate and nitrate salt mixtures (Kraftwerkforschung, 2016) mixed with some natural stone to reduce the needed amount of salt (energy 4.0 , 2016). This salt mix is three times more efficient than storage based on water with the same volume (Urbansky, 2017).

As shown in figure 20 the cold salt mix gets heated up by the sun in the receiver. The heated fluid flows through the hot storage tank to the steam generator where it exchanges the heat to the water cycle. The water vaporizes to steam which runs the turbine to generate electricity. This electricity could also be used for heating purposes. The cooling steam runs through an air-cooled condenser and flows back to the steam generator. Also, the condensate salt mix goes back through the cold storage tank to the receiver (Cleanleap, 2016). In the whole salt fluid circle, it is important that the temperature of the salt mix does not fall below the crystallization temperature. Therefor a trace heating is included mostly (Loeper, et al., Potenziale der Integration thermischer Energiespeicher in Dampfkraftwerke, 2019). There is also another system possible to store heat with molten salt, the thermocline system. This system has only one tank with a vertical temperature gradient which separates the hot and cold salt. The storage is charged if the cold salt heats up through the heat exchanger and flows into the hot side of the tank. To use the stored heat the hot salt flows out of the tank to heat up water for running a turbine to generate electricity. The remaining heat can also be used for heating purposes. This kind of storage is in development but has the advantage that it is cheaper as less filling material is needed (Dodaro, 2015).

Temperature

The stored heat is used for generating electricity. The temperatures are about 100°C to generate water steam for running the turbine in the power plant. The waste heat can be used for heating as in a normal combined heat and power plant for e.g. district heating (Loeper, et al., Potenziale der Integration thermischer Energiespeicher in Dampfkraftwerke, 2019).

Spatial demand

Due to that the fact that the storages are placed next to a solar thermal power plant the whole construction needs a lot of space. It also depends if a single tank system is used or a two tank system. The area also needs to be flat (TADIJANOVIĆ & BOŠNJAKOVIĆ, ResearchGate, 2019)

Safety

Advances of this technology are that it works without pressure and no toxic or flammable materials. It is also easy to pump in the pipes.

Energy density

A storage capacity of up to 5 GWh might be created. The calorific value depends on the kind of salt which is used in the storage. For example, Potassium nitrate has a calorific value of 935 $MJ \cdot m^{-3}$ (Bauernfeind, 2018).

Sustainability

A disadvantage is that a lot of salt is needed to fill the tanks. For example for a power plant with 50MW power about 30,000 tonnes liquid salt is needed. In the future also one tank storage system will be developed to reduce the needed amount of salt and also to reduce costs (energy 4.0 , 2016). Also, electricity is needed to run the pumps. This power needs to be from renewable energies if the storage type should be sustainable.

Storage time

The storage system can be used short term for overnight storage. For example, the 110 MW Crescent Dunes power tower from SolarReserve can store heat for 10 hours. Normally the heat is stored at least 30 minutes up to 12 hours (Deign, Energy storage, 2017).

Efficiency

It has a storage efficiency of 90 to 99% (Epp, 2018) but the losses are 1-5% per day. The expected lifetime of the storage is 20 years or 10,000 cycles (Bundesverband Energiespeicher, 2017).

Environmental influence

The molten salt storage has no mentionable environmental influence. The pumps of the storage make some noise but are not as loud as the processes in for example coal power plants (TADIJANOVIĆ & BOŠNJAKOVIĆ, ResearchGate, 2019).

1.9. Hydrogen(electricity)

A future compensation for natural gas could be hydrogen. It can be used as an energy source itself or can be converted into another energy source such as Methane, Methanol or other fuels to be used in the present infrastructure. Hydrogen can be made of surplus electricity which is added to some water and an ion transportable liquid. The electricity splits it up into hydrogen and oxygen, so electrical energy is converted to chemical energy. This method can produce sustainable hydrogen without using fossil fuels. In a fuel cell, the chemical energy can be converted back into electrical energy which also can be used for heating (Ausfelder, et al., Energiespeicherung als Element einer sicheren, 2015).

Temperature

The temperature for heating depends on the fuel cell. Proton Exchange Membrane fuels, also known as PEMFC can reach temperatures between 70 and 90°C. Whereas Solid Oxide fuel cells (SOFC) can heat up from 650-1000°C. The type which will be used depends on the application area (Simons & Franken, Modernisieren und Bauen, 2017).

Spatial demand

Smaller amounts of hydrogen can be stored in underground storage. Bigger amounts might be stored in cavern storage facilities without any problems, whereas pore storages could lose hydrogen. The existing natural gas pipe infrastructure can also be used to a share of 10% hydrogen. Only the industry and natural gas fuel stations are not able to use the mix. Higher amounts of hydrogen are not possible at the moment as the hydrogen has a lower calorific value than natural gas and other burning qualities. For example, the compressor in the gas grid would have to be adapted (Ausfelder, et al., Wiley Online Library, 2015). So hydrogen storages can be scaled from small to really big sizes.

Safety

Hydrogen is highly flammable and explosive. Moreover, it can be deadly for people if they inhale too much hydrogen (Lenntech, N.A.).

Energy density

Hydrogen storages itself have a capacity of about 0.005 – 200,000 MWh. The lower calorific value is about 10.8 $MJ \cdot m^{-3}$, whereas the higher calorific value is about 12,744 $MJ \cdot m^{-3}$ (Meier, 2014).

Sustainability

At this moment, the hydrogen which is available at the market is mostly a by-product of refined natural gas (Internationales Wirtschaftsforum Regenerative Energien, 2005). So using hydrogen as storage for energy is only useful with renewable sources.

Storage time

Hydrogen can be stored for hours until months and the storage has a lifetime of 15 years (Bundesverband Energiespeicher, 2016).

Efficiency

At this moment the efficiency of producing hydrogen from electricity and back to electricity is about 43% (pro-physik, 2019). The efficiency of the storage is 55%.

Environmental influence

Hydrogen does not smell. The long-term impacts of storing hydrogen in underground storages as caverns are not studied so far. Hydrogen itself is a gas that already exists in the environment (Lenntech, N.A.).

1.10. Hydrogen (based on methane/methanol)

Temperature

The temperature for heating depends on the fuel cell. Proton Exchange Membrane fuel cells, also known as PEMFC can reach temperatures between 70 and 90°C. Whereas Solid Oxide fuel cells

(SOFC) can heat up from 650-1000°C. The type which will be used depends on the application area (Simons & Franken, co2online, 2017).

Spatial demand

The existing natural gas structure can be used as well as underground storage. The methane can be used as natural gas in a power plant to generate electricity and heat for district heating (Ausfelder, et al., Wiley Online Library, 2015). Another possible product from hydrogen is for example methanol. In the catalytic process hydrogen and CO_2 react to methanol. This process is already well known and used in bigger plants. To use the methanol for storing energy, smaller plants are needed. These fit better to smaller amounts of surplus electricity from locally and timely different generation locations. A huge advantage of methanol is that it can be transported easily by pipelines, trains and also in trucks over large distances. It can be used in gas power plants as natural gas (Ausfelder, et al., Wiley Online Library, 2015).

Safety

Methane is highly explosive and flammable (Keppler & Röckmann, 2006). So there are serious safety issues involved, however, methane is already used in our built environment.

Energy density

The storage itself has a lifetime of about 20 years and the size is from 0.001 – 4,000,000 MWh_{out} (BVES, 2016). Methane has a higher calorific value of 39.708 $MJ \cdot m^{-3}$, whereas the lower calorific value is about 35.784 $MJ \cdot m^{-3}$ (Meier, 2014).

Sustainability

If the hydrogen is produced with at least 80% of electricity from renewable energies it is recognized as biogas. With some added CO_2 it will react to create methane. This converting process has the disadvantage of additional losses (Keppler & Röckmann, 2006).

Storage time

Methane can be stored for hours until years (Bundesverband Energiespeicher, 2016).

Efficiency

Methane storage has an efficiency of about 79% (Bundesverband Energiespeicher, 2016).

Environmental influence

Methane has no smell. Moreover, the storages do not affect the environment negatively (Keppler & Röckmann, 2006).

2. Building types

Figure 20 Building types of houses in the Zeeheldenkwartier (Couvée, et al., 2019).

3. Energy labels

Figure 21 Provisional energy labels of the buildings in the Zeeheldenkwartier (Couvée, et al., 2019, S. 13).

4. Monumental protection

Figure 22 Map of the monumental protected area in the Zeeheldenkwartier (Gemeente Den Haag, 2002).