OULUN YLIOPISTO

FACULTY OF TECHNOLOGY

A review of heat storage technologies: Utilizing industrial waste heat for residential heating

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ENVIRONMENTAL ENGINEERING
Bachelor’s thesis
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Tiivistelmä

Teollisuus tuottaa paljon hukkalämpöä, jota ei hyödytetä. Tätä energiaa voitaisiin käyttää esimerkiksi kaukolämpöverkossa vuoden kylmempinä aikoina, kun lämmityksen tarve on suurempi. Lämpövarastojen avulla tuotettu hukkalämpö voitaisiin varastoida myöhempää käyttöä varten, mikäli lämmityksen tarve ei ole hukkalämmön syntyhetkellä korkea.

Tämän työn tavoitteena oli etsiä tietoa lämmönvarastointi teknologioista, jotka ovat sopivia teollisen hukkalämmön varastointiin. Pääasialliset lämpövarastoteknologiat ovat havaittavan lämmön sekä sitoutuneen lämmön varastointiteknologiat. Lisäksi myös kemiallinen lämmönvarastointi on lupaava teknologia, mikä on vielä tutkimusvaiheessa. Työssä käytiin läpi myös projekteja, jotka liittyvät lämmön varastoinnin ja hyötykäytön pilotteihin ja mitoitukseen.

Työssä myös selvitettiin myös asuintilojen lämmitystarve Suomessa, lämmityksen tuotantomäärät ja –tavat, sekä teollisuuden hukkalämmön tuotannon määrä. Talojen lämmöntarve Suomessa vuonna 2017 oli noin 45,35 TWh josta 13,4 TWh oli kaukolämpöä. Kaukolämpöä tuotettiin Suomessa vuonna 2017 38,29 TWh. Samalla teollisuuden hukkalämmön arvioitiin syntyvän vuosittain 54 TWh, josta 4 TWh olisi taloudellisesti kannattavasti käytettävissä. Taloudellisesti käytettävissä olevaa hukkalämpöä verrattaessa kaukolämmöntarpeeseen nähtiin, että hukkalämmön käytölle kaukolämmössä olisi potentiaalia. Jos teollisuuden hukkalämpöä pystyttäisiin käyttää tehokkaasti tilojen lämmityksessä, voitaisiin saavuttaa huomattavia päästövähennyksiä.

Muita tietoja

ABSTRACT
FOR THESIS

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A review of heat storage technologies: Utilizing industrial waste heat for residential heating

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Abstract

Industry produces large amounts of waste heat, which is not utilized. This thermal energy could be used for an example in residential heating in the colder seasons of the year, when the heating demand is larger. Using heat storage technologies, waste heat could be stored for later use.

In this thesis, heat storage technologies were reviewed. The main technologies reviewed for heat storages were sensible heat storages and latent heat storages. In addition, chemical heat storage is a promising technology, which is currently in the research phase. Furthermore, some heat storage pilot projects were reviewed reviewed as well.

The heat demand for space heating, heat production and industrial waste heat production in Finland are also reviewed. Heat demand for space heating in 2017 was some 45,35 GTWh in total, and 13,88 GWh of that was district heating. The production of district heat in 2017 was 38,29 TWh in total. At the same time, annual industrial waste heat production in Finland was estimated to be 54 TWh. Although of this, only 4 TWh was estimated to be commercially usable; notwithstanding, it can be concluded that utilizing industrial waste heat for space heating could lead to substantial emission reductions.

Additional Information

SISÄLLYSLUETTELO

1 INTRODUCTION

Roughly one third of the energy consumed by industry is wasted as industrial waste heat. In Finland, this means that the waste heat released by industry was estimated to be 54 TWh. About 4 TWh of that waste heat could be utilized in a commercially viable way, which would be enough to cover the annual heat consumption of over 200 000 houses. (Motiva 2013)

A lot of industrial waste heat is produced, that could be used, but the heat demand does not equal heat production at all times. This creates the problem of utilizable waste heat being produced when there is no demand for it. That waste heat could be used later on, when the demand rises and heat production could be reduced by using the formerly produced waste heat.

For an example in Finland, the temperature varies greatly from season to season. Winters are very cold when compared to the summer time, therefore much more heat is needed to heat living spaces. Industrial waste heat produced in the warmer months of the year, when space heating is not needed so much, could be used in the winter to warm before mentioned living spaces.

Thermal energy storages are systems that can store and release thermal energy at command. They use different different properties of material, such as specific heat capacity, to store heat. Using thermal energy storages, the differences between peaks of heat production and demand can be evened out. When heat is produced at a time it is not needed, it can be stored in thermal energy storage to be used when heat demand rises. Seasonal thermal energy storages can be used to store waste heat, produced in the warmer seasons of the year. That heat could then be used in the colder seasons of the year for space heating purposes.

The purpose of this thesis is to review the thermal energy storing technologies compatible with storing industrial waste heat. Heating demand of households in Finland and industrial waste heat production in Finland are also reviewed, so that the heat demand and waste heat production can be compared. This makes the evaluation of the viability of storing industrial waste heat for later usage easier. In addition, some projects with connection to the reviewed technologies and heat storage systems, are also reviewed.

2 HEAT AND WASTE HEAT

In 2017, the heat usage for living space heating in Finland was 45 349 GWh. This heating was produced using wood, peat, coal, heavy fuel oil, light fuel oil, natural gas, heat pump energy, district heating and electricity. The three largest heat sources were district heat, electricity and wood. Of all the used energy sources, district heating was the dominant heating method for living spaces. (Suomen virallinen tilasto 2018b) Table 1 presents how much heat was produced for living space heating, and with what energy source.

In 2017, the production of district heating was 38 292 GWh. In addition, 53 655 GWh of industry heat was produced (Suomen virallinen tilasto 2018a). Table 2 presents the district heat production and the industry heat production in correlation with the used energy sources.

Table 1. Energy sources in space heating (Suomen virallinen tilasto 2018b).

Energy source	**Space heating, GWh**
Wood	12 539
Peat	27
Coal	2
Heavy fuel oil	22
Ligh fuel oil	2 922
Natural gas	239
Heat pump energy	4 989
District heat	13 882
Electricity	10 727
Total	45 349

Table 2. Production of district heat and industry heat in Finland in 2017 (Suomen virallinen tilasto 2018a).

Energy source	**District heat, GWh**	**Industry heat, GWh**
Oil	926	2 179
Coal	8 642	873
Natural gas	3 693	3 802
Other fossile fuels	1 378	713
Peat	5 382	3 282
Waste liquor from forest industry	176	27 050
Other wood fuels	12 491	12 390
Other renewables	1 624	1 059
Other energy sources	3 979	2 307
Total	**38 292**	**53 655**

Approximately 37 % of energy used in industry is estimated to be wasted as industrial waste heat. This is equal to 54 TWh of energy, of which 4 TWh is commercially utilizable (Motiva 2013). This heat could be used, for an example, in district heating.

Waste heat is usually commercially viable, if it is used in the same location where it is produced. This means that the waste heat would be used in the facility’s own processes, and is usually done with heat exchangers and heat pumps. In situations, when it is not possible to use the produced waste heat in the same place it is produced, it can be sold to be used in district heating. If the waste heat is over 55 °C, it can be directed in to the district heating distribution network with just a heat exchanger. In cases where the waste heat is under 55 °C, the temperature must be increased with heat pumps to the required level. This kind of co-operation between industry and district heating is still quite rare in Finland. In 2012, the portion of industrial waste heat in district heating production was 2%. (Motiva 2013)

For waste heat to be used efficiently in district heating, the problem of waste heat production and heat demand variance must be solved. Industry, in general, operates all year round. The heat demand, in countries such as Finland, can vary significantly; the difference in average temperature in January and July is over 20 °C (Ilmatieteen laitos 2019). This should mean that the heating need for living spaces varies a lot during the year.

This problem could be ideally solved, if the industrial waste heat produced in the warmer seasons was stored, and used in the colder seasons of the year. This stored heat could then be used in space heating, when the demand is higher.

3 HEAT STORAGE MATERIALS AND SYSTEMS

In this chapter, different heat storage materials and technologies, will be reviewed. There are three main categories of heat storage materials: sensible, latent and chemical. Sensible and latent heat storage materials are main material types used in heat storing, and therefore are the main subject of the materials part of this bachelor's thesis. In the technology part, thermal energy storage technologies and systems that are compatible and usually used with industrial waste heat, will be reviewed. This narrows down the list of technology types to two: seasonal or long duration heat storages and mobile heat storages.

3.1 Sensible heat storage

Sensible heat storage is a thermal energy storing method, where heat is stored in to the specific heat capacity of the material. Absorption of the thermal energy raises the temperature of the material and no phase change happens during this process. How much thermal energy can be stored in to the material is proportional to the properties of the material. Such properties are density, volume, specific heat and variation of temperature of the storage material. (Alva et al. 2017, p. 694) Overall desirable properties for the storage materials are high specific heat capacity, long term stability under thermal cycling, compatibility with its containment and low cost. Sensible heat storages can be divided in to two groups based on the storage medium, liquid medium storage and solid medium storage. (Hasnain 1998, p. 1127-1128)

Sensible heat storage is the most used method for high temperature heat storage applications. This is because sensible heat storage materials are thermally stable at high temperatures. They are also usually low-cost storage materials, excluding liquid metals and thermal oils. The main drawback of sensible heat storage is that the outlet temperature during discharge process is unsteady. The outlet temperature starts to decrease when the discharge process continues with time. The specific heat of sensible heat storage materials is also 50 to 100 times smaller compared to latent heat, but sensible heat storages can still possess large thermal energy storage density due to the large operating temperature range and high density of sensible heat storage materials. (Alva et al. 2018, p. 353)

3.1.1 *Liquid storage materials*

Water

Water is a good choice for a heat storage medium, not only for its properties, but because warm water is a necessity that is used in a variety of household applications. The properties that make water one of the best thermal energy storage medium are high specific heat capacity, low cost, high availability and it can be used over a wide range of temperature (25 – 90 °C). Water is one of the best medium at low temperatures, but it is also used in high temperature applications. When it is used in high temperature applications, insulation and pressure withstanding containment is required. (Hasnain 1998, p. 1128) Water storage tanks are made from a variety of materials, such as steel, aluminium, reinforced concrete and fiber glass, and these tanks vary from hundreds of liters to thousands of cubic meters. Storage tanks are insulated with glass wool, mineral wool or polyurethane. Water can also be used in large scale heat storage applications, such as underground aquifers where heat can be stored for seasonal use. (Alva et al. 2017, p. 694)

Thermal oil

Thermal oils are organic fluids with good heat transfer capabilities. They remain in liquid phase at higher temperatures unlike water, and they have a wider range of operating temperature (12 – 400 °C) and they can be used in higher temperatures. Thermal oils can be used as heat transfer fluid at the same time as they are being used as the thermal energy storage material due to their low viscosity and good flow properties. Thermal oils do not freeze in pipes unlike molten salts, because the melting point of thermal oils is very low (below 12 °C). Disadvantages of thermal oils are lower specific heat than water (around 2 kJ/kg K) and they are costly. (Alva et al. 2018, p. 349-350)

Molten salts

Molten salts are used in solar power plants, and in chemical and metals industry as heat transport fluid. Molten salts are liquid at atmospheric pressure, and they are an efficient heat storage material considering their heat storing capabilities and low cost. The operating temperature of molten salts is compatible with the high-pressure and high-temperature steam turbines used today. In addition, they are non-flammable and non-toxic. (Gil et al. 2010, p.37)

Liquid metals

Some metals and alloys have a low melting point and a high boiling point. This makes them well suited for heat transfer fluids in high temperature thermal energy storages. These kinds of metals and alloys have no freezing problems and almost zero vapor pressure at high temperature, unlike water. In addition, the wide gap between the melting point and boiling point gives a high heat storage capacity. Liquid metals also have outstanding heat transfer capabilities. On the other hand, liquid metals are very expensive and they are also prone to corrosion. (Alva et al. 2018, p 351)

3.1.2 *Solid storage materials*

Earth materials

Rocks, sands, gravel etc can also be used as a heat thermal energy storage material. They are used as fillers in thermocline energy storage systems. In these kinds of systems they are arranged in a packed bed structure. Heat storing is achieved by forcing heat transfer fluid to flow through the bed, exchanging the heat through direct contact. (Alva et al. 2018, p. 351) More specifically, hot heat transfer fluid flows through the bed and heats the storage material during the charging process and during the discharge process, cold heat transfer fluid flows through the bed and is heated by the hot storage material. (Alva et al. 2017, p. 695) Earth materials are cheap, easily available, non-toxic, non-flammable and act as both heat transfer surface and storage medium, but their specific heat is quite low and their thermal conductivity is quite low (Alva et al. 2018, p. 351).

Concrete

Concrete has many advantageous qualities that makes it a competent sensible heat storage material. Concrete is cheap, its production is easy and little thermal energy is lost in the heat transfer between exchanger and concrete. It also has a few disadvantageous properties. Concrete can suffer from long term instability and its effective reachable charge level can be low. The construction process of concrete heat storage also includes the process of dehydration, which is slow. Dehydration process eliminates the occurrence of dangerous vapour pressures in the storage material. (Salomoni et al. 2014, p. 306)

3.1.3 ***Summary of sensible heat storage materials***

Table 3 presents a list of sensible heat storage materials discussed in this work and also the pros and cons of those materials.

Table 3. Pros and cons of sensible heat storage materials.

Material	Pros	Cons
Water	High specific heat capacity Low cost High availability Can be used over wide range of temperature	Pressure and insulation are problems in high temperature applications
Thermal oil	Good heat transfer properties Remain in liquid phase at higher temperatures Wide range of operating temperature Low melting point	Low specific heat High cost
Molten salts	Good heat storing capabilities	High melting point

	Low cost High operating temperature Non-flammable and non-toxic	
Liquid metals	Minimal vapor pressure at high temperatures Wide gap between melting point and boiling point	High cost Prone to corrosion
Earth materials	Cheap Easily available Non-toxic and non-flammable Can act as both, heat transfer surface and storage medium	Low specific heat Poor thermal conductivity
Concrete	Cheap Easy production Little loss of thermal energy in heat transfer	Long term instability Low reachable charge level

3.2 Latent heat storage

Latent heat means the thermal energy that is absorbed in to the material during a phase change. When a material is heated, at first it absorbs the thermal energy as sensible heat, thus raising the temperature of the material. When the material reaches a phase change temperature, for an example the melting temperature, the absorbed thermal energy does not raise the temperature of the material anymore. Instead, a large amount of energy is absorbed to carry out the phase change. This phenomenon is used to store energy as latent heat. The process also works in the same way when cooling. Stored energy can be recovered from the material at a constant temperature.

There are three types of phase changes, solid-solid, solid-liquid and liquid-gas. The latent heat is the highest in a liquid-gas phase change. Because the volume of the material increases so much when transformed in to gas from liquid, it is not used in thermal energy storage systems due to the system becoming overly complex and impractical. Solid-liquid is the most used phase change in latent heat storages. Increase of volume in solid-liquid phase change is much lower when compared to liquid-gas phase change, therefore producing fewer problems. Because the material is in liquid form at times, the material has to be contained in capsules to prevent leakage. This reduces the energy density of the system. The phase change material also has a low thermal conductivity, when using solid-liquid application. This problem can be solved using systems that utilize solid-solid phase change materials. Even though solid-solid materials eliminate the need for containment, they still have a lot smaller latent heat of transition compared to solid-liquid materials. (Cárdenas and León 2013, p. 725-726)

Probably the biggest advantage of latent heat storage is that latent heat is approximately 50 to 100 times larger than sensible heat. This feature results in more compact thermal energy storage systems. Latent heat storages also give out heat at a steady temperature during the discharging process. Phase change materials are also non-toxic in general, but organic phase change materials are flammable and can’t be stored in plastic containers. Inorganic phase change materials on the other hand are corrosive to metal containers and therefore can’t be stored in them. The main drawback of phase change materials is their poor thermal conductivity. (Alva et al. 2018, p. 359) Table 2 presents a list of latent heat storage materials discussed in this work and also the pros and cons of those materials.

3.2.1 *Organic phase change materials*

Paraffins

Paraffin waxes are a mixture of mostly straight chain n-alkanes and the crystallization of the (CH3)-chain is capable of releasing a large amount of latent heat. The melting point and latent heat of fusion increases with the number of carbon atoms in the chain. Paraffins are available in a large temperature range, safe, reliable, predictable, non-corrosive, chemically inert and stable under 500 °C. They also have a low vapor pressure in melt form, show little volume change on melting, melt congruently and have good nucleating properties. Paraffins also have a few negative properties, such as low thermal conductivity, non-compatibility with plastic containers and moderate flammability. (Sharma et al 2009, p. 323)

Non-paraffins

In addition to paraffins, other organic materials are used as phase change materials, such as fatty acids, esters, alcohols and glycols. Fatty acids are low cost and have low supercooling, are chemically stabile and they do not undergo phase segregation. On the other hand fatty acids have a strong odor, low density, low thermal conductivity and large volumetric changes during phase change. The melting point of fatty acids increase with the number of carbon atoms in the chain. They are also weak acids and the acidity decreases with the number of carbon atoms in the chain.

Some esters of fatty acids have a lower phase change temperature, when compared to their corresponding fatty acids, which makes them suitable to be used as phase change materials. Esters have low supercooling, are chemically stable and undergo no phase segregation, but they have a strong odor, low density and low thermal conductivity.

Sugar alcohols are suitable for medium temperature heat storage applications due to their high melting point and high latent heat. They are non-toxic and low cost, but their application in thermal energy storage systems is negatively impacted by polymorphism. This is because different polymorphs can have different physiochemical properties.

Among glycols, polyethylene glycol has the most potential to be used in thermal energy storages as a phase change material. The phase change temperature of polyethylene glycol is close to room temperature and it dissolves in water, which is rare among organic phase change materials. Polyethylene glycol has a few undesired properties, such as highest supercooling among organic phase change materials and the difference between its melting point and freezing point can be as high as 30 – 40°C. (Alva et al. 2018, p. 353-354; Sharma et al. 2009, p. 324)

3.2.2 *Inorganic phase change materials*

Salts

Pure salts can be used as a latent heat storage material, in addition to being a sensible heat storage material. If a correct salt is selected, with a melting temperature within the operational temperature of the thermal energy storage, to be used as storage material the latent heat of phase change can be utilized in the storage system. This can greatly increase the heat storage capacity of the system. Pure salts have high melting points, which makes them suitable for high temperature thermal energy storages, but they have poor thermal conductivity. The high melting points of pure salts can be brought down for lower temperature applications with eutectic mixtures of salts. The problem with eutectic mixtures is that their properties can be hard to predict. Eutectic compositions and density can be predicted reasonably well, but latent heat and thermal conductivity are hard to predict. (Alva et al. 2018, p. 354)

Salt hydrates

Salt hydrates are alloys of salts and water, which form a crystalline solid. The solid- liquid phase change of salt hydrates is actually the dehydration of salt hydrates, which resembles the process of melting or freezing. Salt hydrates are an important group of phase change materials, because of their high latent heat of fusion per unit of volume, relatively high thermal conductivity, small volumetric changes when melting. They are compatible with plastics, sufficiently low cost to be used in thermal energy storages and not very corrosive. Salt hydrates have a few problematic features, such as incongruent melting and poor nucleating properties, which produces the problem of supercooling. (Sharma et al. 2009, p. 325)

Metals

Among phase change materials, metals and their alloys have the highest heat capacity per unit volume and highest thermal conductivity per unit volume. These qualities make them good candidates, when available system volume is low. Metals and their alloys are costly, which limits their use. They also have a low heat energy storage capacity per unit weight, which results in weight problems in thermal energy storage applications. Repeated thermal cycles also can change microstructure, which can affect phase change temperature and latent heat. Changes in microstructure can be battled with an inert atmosphere, but then the inert gases can be absorbed in to the metals, which can change the thermo-physical properties of the storage material. Supercooling is also an issue with metals and their alloys. (Alva et al. 2018, p. 359)

Table 2. Pros and cons of latent heat storage materials

Material	Pros	Cons
Paraffins	Low vapor pressure in melt form Little volume change on melting Congruent melting Good nucleating properties	Low thermal conductivity Non-compatibility with plastic containers Moderate flammability
Fatty acids	Low cost Low supercooling Chemically stable No phase segregation	Strong odor Low density Low thermal conductivity Large volumetric changes during phase change

Esters	Lower phase change temperature compared to fatty acids Low supercooling Chemically stable No phase segregation	Strong odor Low density Low thermal conductivity
Sugar alcohols	High latent heat Non-toxic Low cost	Polymorphism causes different physiochemical properties
Glycols	Dissolves in water	High supercooling Difference between melting point and freezing point can be high
Salts	High melting point makes salts suitable for high temperature systems	Poor thermal conductivity Properties of eutectic mixtures can be hard to predict
Salt hydrates	High latent heat of fusion per unit of volume High thermal conductivity Small volumetric changes when melting	Incongruent melting Poor nucleating Supercooling

	Low cost Compatible with plastics Not very corrosive	
Metals	High heat capacity per unit of volume High thermal conductivity per unit of volume	High cost Low heat storage capacity per unit of weight Supercooling

3.3 Chemical heat storage

Chemical thermal energy storages use reversible chemical reactions to store heat. The direction of this reaction depends on temperature and pressure. Operating temperature ranges from 200 °C to 400 °C. The heat is stored, when the system is charged and the material in use decomposes and new materials are produced. These products of decomposing are then store separately. During the discharging process, separated products are brought back together in contact to release stored heat. The chemical reaction goes back in the opposite way and the two separate products form the material that was first decomposed. Chemical heat storage has the highest thermal energy storage per unit mass and per unit volume, among all the thermal energy storage technologies. The separate decomposition products can also be stored infinitely without heat losses. Chemical heat storage still has a few problems. During the charging process, some storage materials might undergo sintering, which results in grain growth and therefore lower porosity. Lower porosity negatively affects dehydration rate during the charging process. Chemical heat storage is a technology still in research and not in commercial use. (Alva et al. 2018, p. 359-360)

3.4 Seasonal heat storage systems

Seasonal or long-term thermal energy storages are used in situations, where the heat need varies seasonally. A good example of this is space heating in the norther areas of the earth.

During the summer, space heating is not needed anywhere as much as in the winter, and therefore the heat demand is small in the summer time and the other way around in the winter. Industrial waste heat is generated during the whole year, and to be able to use that waste heat in space heating in the winter time, long term heat storages are used.

3.4.1 *Water-based systems*

Water tanks

Water tanks are artificial structures, that are usually made of steel or reinforced concrete, which are then surrounded by thick insulation. They can be placed underground, on the roof a building or outside of a building. Water tank storages utilize the thermal stratification phenomenon. Water at lower temperatures is denser than at higher temperatures, which causes the hotter water to flow to the top part of the water tank, and the colder water to flow to the bottom of the tank. This is called thermal buoyancy. When this happens, the hot water at the top of the tank can be extracted to be used. Temperature gradient inside the tank can cause unwanted mixing of the water, decreasing the temperature of the water at the top of the tank, therefore negatively impacting the storage system efficiency. This kind of mixing can be battled by partitioning the inside of the tank horizontally into different chambers. Water inside the tank is able overflow, from the first chamber to the next, through a gap between two plates that separate the two chambers. This way the hot water at the top of the tanks flows to the next chamber, meanwhile the water at lower temperatures stays at the chamber in its lower regions. System efficiency can also decrease through heat loss. Heat loss can be decreased by optimizing the tank design and selection of insulation material. Glass wool and polyurethane are widely used insulation materials in water tanks. (Xu et al. 2014, p. 614)

Aquifers

Aquifer thermal energy storage is a system where naturally occurring underground saturated aquifer is used as a storage medium and the groundwater within it is used as the heat carrier fluid. Aquifer thermal energy storages have a huge heat storage capacity, which makes them a good choice for seasonal heat storing. This kind of system is made by drilling at least to thermal wells in to the aquifer, where one of them acts as the hot well and the other one acts as the cold well. Charging of the storage is achieved by pumping cold water from the cold well, heating it with a heat exchanger and an available heat source, and then injecting the heated water to the hot well. Discharging of the system is achieved by pumping hot water from the hot well, utilizing the heat via a heat exchanger and then pumping the now cold water to the cold well. Most existing aquifer thermal energy storages are low temperature aquifer storages, which operate in temperature range of 5-30 °C. Aquifer storages operating at temperatures greater than 30 °C are called medium-to-high-temperature storages. Medium-to-high-temperature storages have a larger storage capacity, greater applicability and a greater feasibility to connect with different thermal energy sources, such as solar, industrial waste heat and surplus heat from cogeneration plants. (Gao et al. 2019, p. 898; Xu et al. 2014, p. 615-616)

3.4.2 *Soil- or rock-based systems*

Rock beds

Rock bed storage systems use rock material, such as pebbles, gravel, bricks or sand, as the heat storage medium. Heat transfer fluid is usually air, but also water can be used as heat transfer fluid. Using water as the heat transfer fluid combines the concepts of water tank and conventional rock bed storage, compromising between the high construction expenses of a water tank system and the low thermal capacity of rock materials. Rock bed systems require a much larger storage volume compared to water-based systems, due to the aforementioned low thermal capacity. On the other hand, rock bed systems can endure much higher temperatures, compared to water-based systems. (Xu et al. 2014, p. 617)

Soil storages

Soil storages, also called borehole thermal energy storages, use ground material as the heat storage medium. Ground storages consist of boreholes that are drilled in to the ground and vertical or horizontal pipes that are put in to the drilled holes. The pipes act as heat exchangers. Water is used as the heat transfer fluid. These kinds of heat storages require drillable ground and groundwater presence is preferred. Ground material also needs to have a high heat capacity and thermal conductivity. Ground storages are suitable for small and large applications and ground is highly available to be used as storage medium. Storages can also be easily extended by drilling more boreholes. Borehole thermal energy storages are no feasible if there is groundwater flow present in the ground. Soil storage systems also suffer from high initial cost and the lower energy density of ground material compared to water creates the need for 3-5 times larger storage volume to carry the same heat amount as a hot-water system. In large-scale systems, also an auxiliary water buffer store unit is required. (Shah et al. 2018, p. 39-40; Xu et al. 2014, p. 617-619) High-temperature storages need a 3-4 year start-up time to reach typical performance. This is due to required initial heating of the storage and the surrounding ground to increase the temperature to a design level (Lundh and Dalenbäck 2008, p. 703).

3.5 Mobile heat storage systems

Mobile heat storage systems can be used in situations, where a pipe-line connection between the heat source and demand site is not feasible. In these cases, the heat can be supplied through mobile thermal energy storages, which can be transported with trucks. There are two types of mobile thermal energy storages, mobile sorption heat storage and mobile latent heat storage.

Sorption systems use physical sorption pairs, such as zeolite/water or silica-gel/water, as heat storage medium. During the charging process, heated air is blown through the zeolite bed, dehydrating it. The bed absorbs the heat, the water inside the bed is vaporized and flows out of the bed with the heated air. During the discharge process, humid air is blown through the hot zeolite bed, rehydrating the bed, and heating and drying the air.

Mobile heat storages can also be done with phase change materials. In phase change material mobile heat storages, a phase change material is chosen with a suitable phase change temperature for the charging process. The phase change material is heated during the charging process, undergoing phase change and storing heat. During the discharge process, heat transfer fluid is heated with the stored latent heat from the phase change material. The phase change material undergoes phase change again, but in the opposite direction, releasing heat. (Alva et al. 2018, p. 365-366)

3.6 Heat storage projects

In this section, two heat storage projects using industrial waste heat as their heat resource, will be reviewed.

3.6.1 *REslag project*

REslag project aims to find new technologies to provide more efficient ways to generate or consume the primary resources of industry, raw materials and energy. Particularly steelmaking industry has been addressed, since its waste heat potential has been identified as one of the largest among industrial sectors.

In the dominant steel production route, electric arc furnace, around 50 % of the input energy is lost in different forms, and 15 % of this amount is contained in the sensible heat of the exhaust gases. To exploit this waste heat, a thermal energy storage system, using packed beds where slag would be used as the storage material, was designed to obtain a continuous heat supply from the discontinuous, high temperature heat producing, electric arc furnace process. The stored heat could then be used, for an example, to pre-heat the scrap metal used in the casting process.

A double storage tank application was proposed for this system. These tanks would operate simultaneously, one tank in charge mode storing heat from the electric arc furnace and the second tank would be in discharge mode. Charging and discharging processes would be inverted when both tanks attain their charged or respectively discharged state.

The charging time for the storage tank would be 45 minutes, in correspondence with the electric arc furnace operation time. This charging period would be followed by a 15 minute idle period. The discharge time would be 60 minutes, which is how long one casting process takes, so that continuous heat supply would be achieved for the casting process.

Through analysis and optimization of the model, the storage system achieved efficiency values around 65 % and 85 %. The final target of this particular work is to construct an experimental pilot facility in the electric arc furnace of ArcelorMittal steelworks in Sestao (Spain), based on the design and operation parameters derived from this work. (Ortega-Fernández and Rodríguez-Aseguinolaza, 2019)

3.6.2 *A demonstration plant of a mobile energy storage working with Zeolite*

ZAE Bayern and Industrienlagen Hoffmeier GmbH developed and built a pilot mobile heat storage system. This system uses waste heat from an incineration plant as a heat source. The heat demand site would be an industrial drying process. The mobile heat storage system would have to be road-legal for the transportation between the source and demand site.

Two heat storages were built for the pilot plant. These storages use zeolite as the heat storage material. Charging process is done by heating ambient air to 130 °C, with extraction steam from the turbine in the waste incineration plant. This heated air then charges the zeolite bed. Discharging process is done by blowing humid exhaust air from the gas fired drying process through the zeolite heat storage. Exhaust air is then heated by the heat storage to 160 °C. This air then heats the ambient air used in the drying process.

The storage built for this project achieved an energy capacity of 2,3 MHw and the system achieved carbon dioxide savings of 616 kg per cycle. Analysis of the system showed that the zeolite bed must be charged with high enough temperature, which is in this case 130 °C. Prime energy costs for the mobile heat storage system was 73 €/MHw. In comparison, prime energy costs for conventional energy sources, such as oil or gas, are 36 €/MHw. However, a larger zeolite heat storage, which would be transported within factory premises, could bring down the prime energy costs of the zeolite heat storage to 30 €/Mhw. (Krönauer et al. 2015)

4 DISCUSSION AND CONCLUSIONS

The heat usage for space heating in 2017 was 45 349 GWh in total. Of this amount, 13 882 GWh was from district heat. District heat production in 2017 was 38 292 GWh in total. When the district heat use and production numbers are compared, it can be seen, that the production number is a lot higher than the usage. When doing this comparison it should be taken in to account that not all the energy is consumed or used when district heating is used. The water in district heating distribution network retains heat after usage.

About 54 TWh of industrial waste heat was produced annually. Of this, about 4 TWh, or 4 000 GWh, was commercially usable in a profitable way. When this number is compared to the annual district heat use of 13 882 GWh in 2017, it can be seen that the amount of waste heat produced from the industry is almost 30 % of the annual district heat use.

The two main types of storage materials are sensible and latent heat storages. Sensible heat storages store heat in the specific heat capacity of the material. When the heat is absorbed in the material, the temperature of the material rises, but no phase change happens. The heat storage capacity is determined by the properties of the material, such as density and volume. Sensible heat storage materials are stable at high temperatures and are usually low cost. Latent heat storages use the latent heat of phase change of materials. When a material undergoes a phase change, a large amount of thermal energy is absorbed to carry out the phase change. The temperature of the material does not rise during this phase, although the heat stored in latent heat storages before and after the phase change is stored as sensible heat.

Chemical heat storages are primary candidates for future heat storages and technologies, and are currently under research. Chemical heat storages use reversible chemical reactions to store heat. Chemical heat storage happens when the heat storage material transforms to new materials in a reversible reaction. The new material is then stored until the discharging process releases the stored energy. Chemical heat storages have the highest thermal energy density among all the thermal energy storage technologies.

Finally, it has to be noted that, finding data concerning the variation of heat demand during the year was hard to find. This should be researched more in the future, so that the waste heat production and the heat need could be compared at different times of the year.

If this comparison could be done, better viability evaluation for using heat storages to utilize industrial waste heat would be possible. If all the industrial waste heat that is commercially usable would be utilized, substantial emission reductions could be achieved.

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