IEA HPT ANNEX 57

Task 2: Potential future and conventional waste heat sources

BASED ON THE RESULTS FROM THE MEMPHIS 2.0 PROJECT

Stefan Reuter

Ralf-Roman Schmidt

Nicolas Marx

Philipp Ortmann

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1 INTRODUCTION

This report has been prepared in course of the IEA HPT Annex 57 and is based on the results of the project 'Memphis 2.0' that consists a research project conducted at the AIT in the timeframe August 2021 to end 2022, financed by the IEA DHC within Annex XIII. This report addresses task 1 of the international Annex 57 work program.

The structure of this report is as follows: chapter 2 provides an overview on conventional waste heat sources while section 3 discusses potential future waste heat sources.

2 CONVENTIONAL WASTE HEAT SOURCES

2.1 Industrial Waste Heat

For high temperature heat pumps, energy-intensive industrial sectors with a large heat demand in the temperature range up to 200°C are the most relevant for waste heat usage. The paper, chemical, refinery and food industries can be considered the most suitable for the integration of heat pumps.[1]

The pulp and paper sector is responsible for a large variety of products. Despite the diverse product range and the different use of raw materials, there are only minimal differences in the underlying processes. The energy demand of the sector is mainly determined by paper drying and the mechanical energy for pumps, compressors, fans and machine drives. [1]

The chemical and refining industries are responsible for converting numerous raw and feedstock materials into numerous end products. Although the products produced are very different, both sectors are based on similar process units.

Distillation is the most commonly used process in the chemical and refining industries. It is also considered the most energy-intensive process in the chemical industry. The large heat requirement for distillation processes is often at temperatures below 200 °C. [1]

The food sector has very wide variations in production processes. The need for simultaneous heating and cooling in the food sector provides an opportunity for heat pump applications where the heat output of the cooling system can be used as a heat source, which can improve the overall coefficient of performance of the entire system. [1]

Marina et al. found the overall waste heat potential from the sectors described above in the EU28 to be close to 1200 PJ per year. With the majority being low temperature waste heat up to 100°C. Figure 2-1 below shows the share of waste heat of each sector and the respective waste heat temperature. The refinery sector has the largest share of waste heat with also a greater variety of the waste heat temperatures. [1]

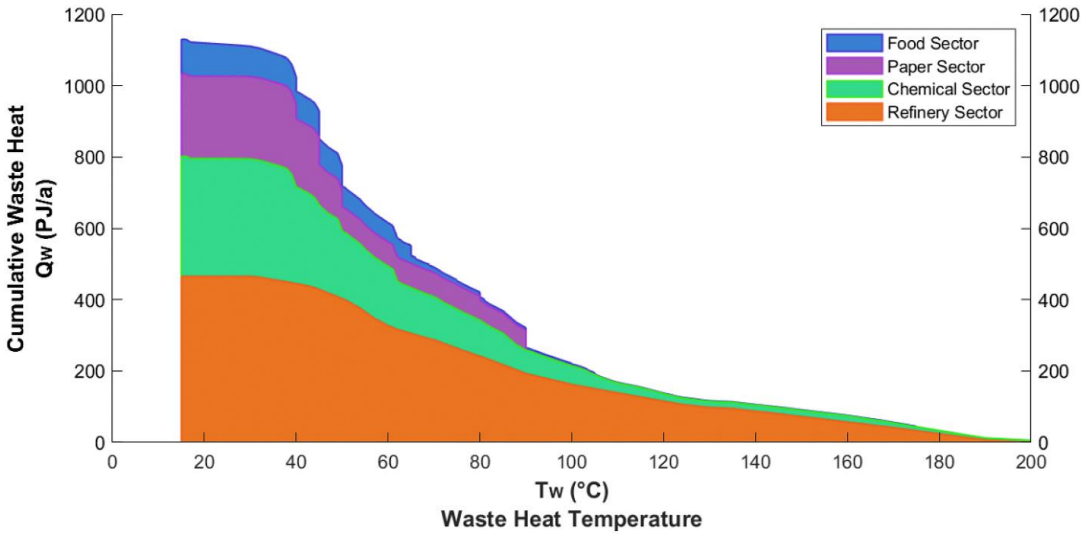


Figure 2-1: Cumulative waste heat <200°C in EU28 identified in processes which make up the heat pump market study. [1]

Table 1 below gives an overview on the waste heat potential of different energy sectors. It is distinguished between low temperature waste heat (<100°C), medium temperature waste heat (100 – 500°C) and high temperature waste heat (>500°C). The table originates from the Memphis project. [2] For the purpose of flexibility provision of heat pumps and the use of waste heat by heat pumps, obviously, temperatures below 100°C are most relevant.

Table 1: Overview of the waste heat of different industry sectors [2]

Main Sector	Detailed Sector	low_temp (<100°C)	medium_temp (100-500°C)	high_temp (>500°C)	Processes	Notes
Production of food and feed	Production of meat products	x			Smoking; Refrigeration	Smoking 20 - 80 °C Scalding 50 - 90 °C Waste heat refrigeration plant 45°C
	Dairy	x	x		Pasteurizing	Pasteurization 50 - 100 °C Pasteurization involves heating the milk to 62° C to 65° C for about 30 minutes to kill germs and achieve a longer shelf life.
	Bakery	x	x		Smoke gases; Refrigeration	The hot flue gases from the furnace heating can be used to heat process water, for example, just as the waste heat from the refrigeration plant provides thermal energy at a temperature level of around 45 °C.
	Manufacture of sugar	x	x		Cleaning / Juice extraction --> process steam Drying process	First, the beets are cleaned, crushed and then the raw juice is obtained by extraction. The subsequent juice purification, evaporation and crystallization produce the sugar. The multi-stage process requires large amounts of process steam and is very energy-intensive.
Beverage production	Manufacture of beer	x	x		Mash (hot water), Cooking	About 50 % of the total heat consumption occurs in the brewhouse, mainly for mashing and boiling.
	Manufacture of malt	x			Drying process	
Manufacture of articles of wood, of straw and of products of wood and cork, except furniture	Sawmill	x			Drying process compressed air	Pickling 40 - 70 °C Steaming 75 - 95 °C Pressing 120 - 160 °C Drying 40 - 150 °C
Manufacture of paper, paperboard and articles thereof	Pulp and paper	x				Wastewater paper machine 20 - 40 °C Wastewater Stock preparation with deinking 40 - 60 °C Wastewater stock preparation without deinking 30 - 50 °C Wastewater from grinding/TMP plant 60 - 70 °C Exhaust air production hall 30 - 40 °C Exhaust air vacuum pumps 40 - 50 °C Exhaust air vacuum blower 130 - 160 °C Exhaust air dryer section paper machine 60 - 80 °C Exhaust air dryer section coater 100 - 140 °C
Production of printed products	Printing		x			
Production of chemical products	Manufacture of chemicals	x	x	x	Biochemical reactions	Biochemical reactions 25 - 55 °C
Production of pharmaceutical products	Manufacture of basic pharmaceutical products	x	x	x		
Manufacture of rubber and plastic products	Manufacture of rubber and plastic products		x			
Manufacture of other non-metallic mineral products, except	Manufacture of glass and glassware		x	x		
	Manufacture of ceramic products			x		

machinery and equipment	Manufacture of bricks	x		x	Drying process	
	Manufacture of cement			x		
	Manufacture of lime and plaster			x		
	Manufacture of refractory products			x		
Manufacture of basic metals and fabricated metal products	Manufacture of basic iron and steel			x		
	Aluminum production			x		
	Foundry			x		
Manufacture of fabricated metal products	Surface Technology		x			
Mechanical engineering	Manufacture of machinery		x			
Manufacture of motor vehicles, trailers and semi-trailers	Manufacture of motor vehicles	x	x	x		
Other personal service activities	Laundry	x			Drying, Washing, Bleaching	Drying 60 - 100 °C Washing 30 - 100 °C Bleaching 40 - 100 °C

2.2 Wastewater heat recovery

Wastewater heat recovery is a mature technology. First publications, patents and implemented projects date back to the mid-1970s.[3]

Throughout the year, gray water flows through the wastewater pipes at a temperature of between 10 and 20°C. With the means of a heat pump, the contained heat can be utilized for heating purposes. Wastewater heat recovery is possible in 3 ways: directly from the sewer, via the wastewater treatment plant, or in the building itself. The smaller the distance between wastewater and heat utilization the better. The use is particularly recommended from an economic and technical point of view in buildings with high heat demand, such as public institutions, because of the consistent high temperature and continuous flow of wastewater. In wastewater heat pumps, the heat exchanger is equipped with an additional heat transfer circuit, so the evaporator does not come into direct contact with the gray water. Suspended solids and impurities could significantly reduce the efficiency of the heat pump. The annual performance factor of a wastewater heat pump is around 5 for new buildings and 4 for existing buildings. [4]

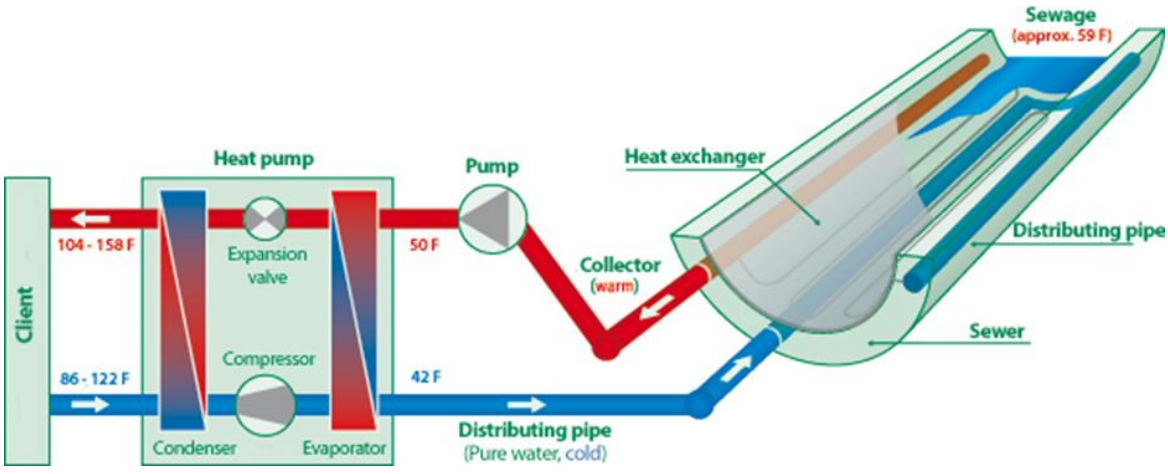


Figure 2-2: Example of heat recovery from wastewater [5]

2.2.1 Use in wastewater treatment plants

In this type of use, a heat exchanger is installed directly at the outlet of a wastewater treatment plant and operated with treated wastewater. Prerequisites for use here are, among other things, a large heat demand in the immediate vicinity. Wastewater treatment plants supply a very large and constant amount of wastewater. However, there is an expenditure because of the authorizations, in addition, a periodically accruing cleaning expenditure. Since wastewater treatment plants usually have no direct heat consumers in the vicinity, there can be high heat transport losses and costs for heat transport. [3]

2.2.2 Sewage System

This type of use is particularly recommended in cities, as it is underground and invisible. Heat exchangers are either installed in the sewer itself, attached to a pressurized sewer, or the wastewater is fed into an external manhole. Installation is particularly worthwhile in the case of new sewer construction or renovation. The prerequisites for this are sufficiently large sewer diameters and sufficient flow rates. The proximity to potential heat consumers shortens the heat transport distances. However, this can also involve considerable organizational effort. [3]

2.2.3 Internal use in buildings

The thermal energy of the gray water in buildings is recovered via a heat exchanger. This is done with a collection tank for wastewater. After heat extraction, the wastewater is fed into the public sewer system. The prerequisite here is a sufficiently large heat demand. In addition, the wastewater temperature near the house is still high enough and only a short distribution network is required. The disadvantages of this method include the fluctuations during the day and the low volume of waste heat, which is often only sufficient for hot water use, but not for heating requirements. [3]

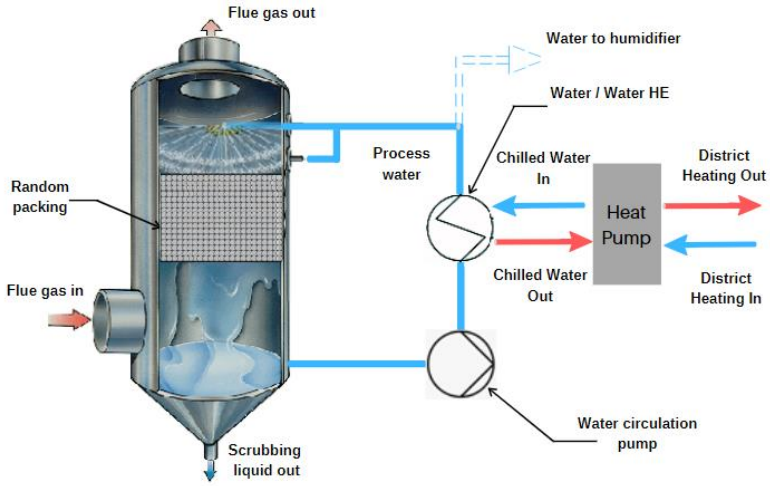
2.3 Flue Gas Condensation

Flue gas is a mixture of combustion exhaust gases. Many companies regard it as a waste product and discharge it unused into the environment. Valuable heat energy is lost in this way. With a flue gas heat recovery system, the waste heat can be utilized. The system is usually installed in the chimney. In general, a flue gas heat recovery system can reduce the cost and consumption of heat, less energy is required for the same temperature and heat effect, and it also does not cause any changes in the production operation time.[6]

Flue gas condensation plants are a well-known and proven technology, for example for biomass combustion plants from 1 MW_{th} for heat recovery, dust reduction and deflashing of the flue gas. The more the flue gas is cooled below the dew point, which is usually between 50°C and 60°C, the more efficient flue gas condensation is. The latent energy released can be utilized.

Due to the mostly constant temperatures throughout the year and with the use of industrial compression heat pumps, the low-temperature heat of the flue gas could be raised to a temperature level that could be fed directly into the conventional heating returns of district or process heating systems. The basic concept is illustrated in Figure 2-3. [7]

Figure 2-3: Water/District Heating Water Heat Exchanger - including Heat Pump [8]



2.4 Thermal use of lakes and rivers

Heat pumps are used to utilize the low-temperature heat of lakes and rivers. The lake/river water circulates in a primary circuit and a secondary circuit brings the heat transfer fluid to the user. After the heat is released, the cooled water is returned to the water body. Special attention should be paid here to the influence of water temperature on the ecology of the water body. The great thermal potential of lakes and rivers has been little exploited so far due to lack of experience, inherent obstacles of the respective water bodies or difficulties in implementation, plus the problem of possible aquatic fouling and the associated performance losses. High costs also extend the payback period, making such projects more suitable for the public sector. In the long run and with good planning, thermal use of a body of water can be made both economically and ecologically sustainable. [9]

2.4.1 Lakes

The thermal use of a lake is based on the assumption that the temperature of a certain volume of water changes by a certain value in a given period of time. The volume of water available is determined so that the impact on the lake is small. The temperature changes should not cause temperatures that would not naturally occur in the lake and are mostly around 1°C. For heat extraction between October and March, the optimal location of the water intake is at about 15-40 m depth at temperatures between 4 and 10°C. [9]

2.4.2 Rivers

For thermal utilization of rivers, it is assumed that the temperature will change by a certain temperature value at a certain discharge rate. In the case of rivers, care must be taken to ensure that the temperature conditions of the watercourse are not changed in such a way that the self-purification capacity is reduced or the water quality is no longer sufficient for the thriving of the biotic communities typical of the watercourse. For heat extraction between October and March, the optimal location of the water catchment is in the downstream of a low-lying lake at temperatures between 4 and 12°C. [9]

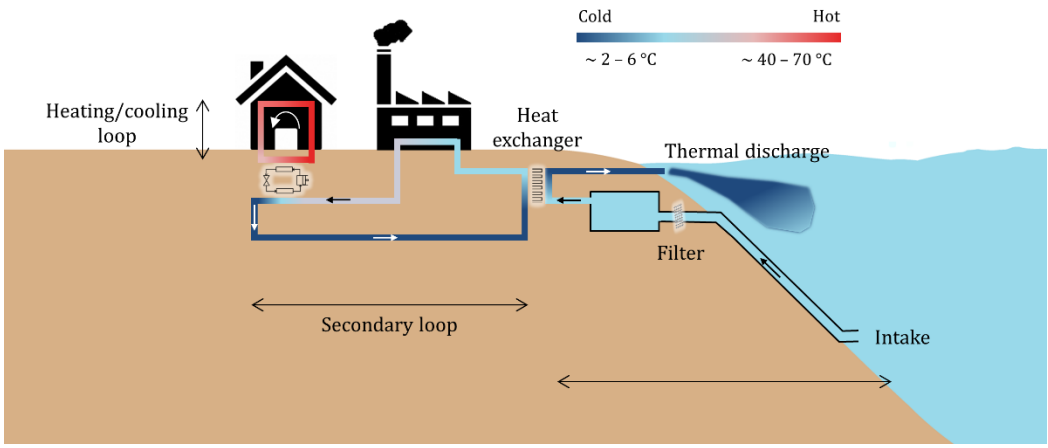


Figure 2-4: Example System for Thermal Use of Water Body [10]

3 POTENTIAL FUTURE WASTE HEAT SOURCES

Due to the decarbonization of the entire energy system, it is to be expected that new waste heat sources for heat pumps will emerge. This will include waste heat from data centers, tunnels and transformers among others. In the following section, heat sources will be addressed with a qualitative description, their role in a future energy system will be highlighted and ways how they can be tapped for increased flexibility are discussed.

3.1 Waste heat from food supermarkets

Food supermarkets have the highest energy intensity in the commercial building sector, represented as energy consumption per square meter. Values documented in studies range from 150 kWh/m²/a to 1,500 kWh/m²/a [11]. Energy consumption is significantly dependent on the size of the store, the ratio of refrigerated to non-refrigerated products, climatic conditions, opening hours, and equipment used, resulting in large differences within the sector. Decisive for the high energy demand is the refrigeration system and the room conditioning. Refrigeration typically accounts for 35-50% of total electricity consumption [12], while HVAC accounts for 20-25% of total energy consumption [11].

The cooling demand does not show significant seasonal variations, but contributes to a base load energy consumption outside of opening hours [13]. The total energy consumption shows particular seasonal effects for areas that require heating in winter or air conditioning in summer. Accordingly, the available waste heat may also show seasonal variations.

While cooling demand per cooled area has decreased in recent years due to various efficiency measures, there is a trend toward a higher proportion of cooled areas [14], partially offsetting efficiency gains. The current state-of-the-art for refrigeration systems in supermarkets are CO_2 trans-critical booster systems, which combine both medium-temperature (1°C to 14°C) and low-temperature (-12°C to -18°C) cooling, as well as air-conditioning supply and waste heat provision in one integrated system (see Figure 3-1). Due to the high temperatures at the compressor outlet, these systems can provide waste heat temperatures of up to 70°C, allowing integration into district heating networks without the need for an additional heat pump [12]. An estimate of the available waste heat potential of European of food retail stores, assuming widespread use of CO_2 trans-critical booster systems, gives a value of about 44 TWh/a for 41.832 stores [12].

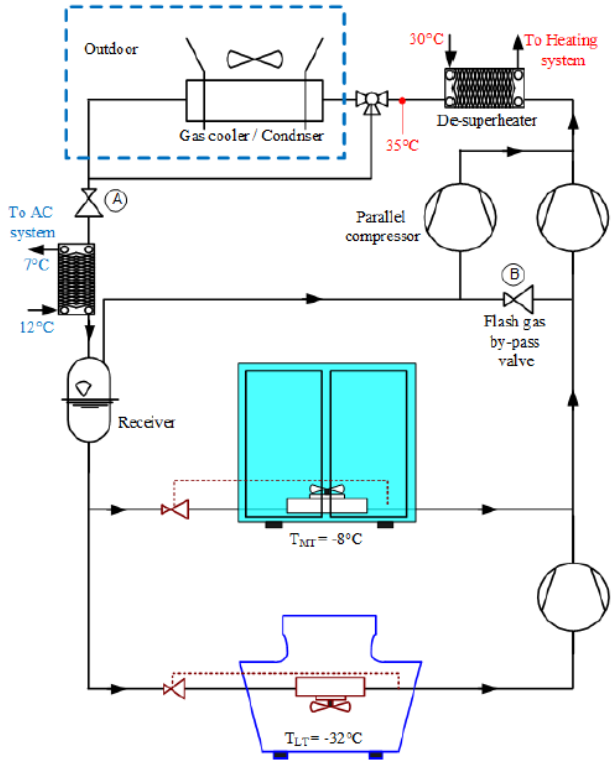


Figure 3-1: Schematic of a CO_2 trans-critical booster system [15]

In Denmark the project Super Supermarkets aims at evaluating, demonstrating and implementing the full potential of district heating production and system services that are available in Danish supermarkets. A large proportion of this remains untapped to this day. Currently only approximately 10 supermarkets in Denmark have a basic heat recovery system. Based on a study from 2015, 6 – 8 TWh of waste heat from supermarkets could be supplied to the district heating network in Germany. [16]

It is assumed by the project, that when the cooling system is using trans critical CO_2 and the nominal cooling capacity is above 25 kW the supermarket would already have the possibility to generate its own heat. In case the supermarket is close to a district heating network, there would also be the possibility to sell the generated heat. On the website an Excel-based tool to evaluate the heat recovery potentials of a supermarket is available and can be found here. [17]

3.2 Waste Heat from cooling of residential and service sector

According to the RHC Technology platform, cooling demand is expected to triple by 2050 compared to 2006. This trend is confirmed by the 600% rise of the cooled floor area in the EU between 1990 to 2010. Furthermore, the number of space cooling units, mostly room air-conditioners, grew 24 times in the same period at 3% per year. [18]

Kranzl et al. also estimated a three-fold increase of the cooling demand by 2050 [19].

An issue with excess heat from residential and service buildings is its seasonality. The availability mismatches with the heat demand of buildings. Thermal heat storages could improve the competitiveness for urban excess heat sources, although additional investments could weigh out the benefits. [20]

The excess energy, comprised of heat and the electricity added by the chiller, which is removed from a building to maintain a certain indoor temperature is equal to the cooling demand. High potential is seen in the usage of excess heat from service sector buildings, like offices, hospitals or educational facilities, as these are mainly supplied by a central cooling device. Therefore, these types of buildings are regarded as more suitable for large-scale recoveries of rejected heat, compared to the residential sector, which, in most cases uses individual cooling units. These individual cooling units make up about 65% to 95% of national market sales in the EU28, while the remaining share is made up of central cooling systems. These systems, chillers with a capacity greater than 400 kW, can be considered for large scale heat recovery. Also, the saturation rates, the actual use of cooling technologies to meet building cold demands, is with 21.3% for service sector buildings, compared to residential at 6.3% significantly higher. Overall, the available excess heat potential in the EU28 from rejected heat in service building processes is currently estimated at 150 TWh/y. For the

residential sector this value is estimated at 24 to 56 TWh/y. Naturally, the largest potential for the usage of excess heat from cooling is in southern Europe. [21]

Low temperature district heating networks, also referred to as 5th generation district heating or anergy networks are generally considered a way to better integrate waste heat from residential or service sector cooling. Front runners of this technology are Germany and Switzerland, where the ETH Zurich has already successfully implemented an anergy network at their Campus Hönggerberg.

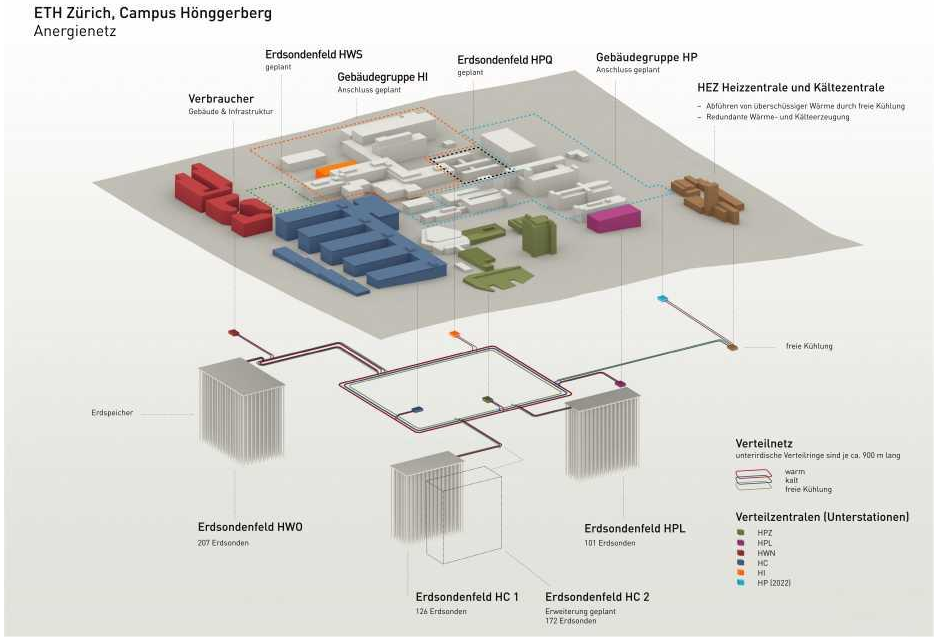


Figure 3-2: Anergy Network at ETH Zürich, Switzerland

The network consists of a ground storage and 5 distribution centers. 14 buildings are supplied with heat and cold from the ground. While other buildings require heating in the winter, others, like server buildings require cooling all year around. The excess heat is then stored 200 meters below the ground in water filled earth probes. Excess heat can be used for heating in winter. With constant usage, the temperature in the ground storage will drop and be used for cooling in summer then. [22]

3.3 Waste heat from tunnels

The idea the usage of waste heat from tunnels revolves around the water which drains through the man-made hole in the mountain. Rain penetrates the mountain and seeps downward. With increasing depth, the rock temperature increases. The approximate gradient is 3°C/100m. An example in this field is the Brenner base tunnel, which should be finished by 2030. Above the tunnel are 1800 meters of mountain, leading to water with temperatures around 35 to 40 degrees, collected by drainage pipes. Due to a gradient, the water then runs towards Innsbruck. [23]

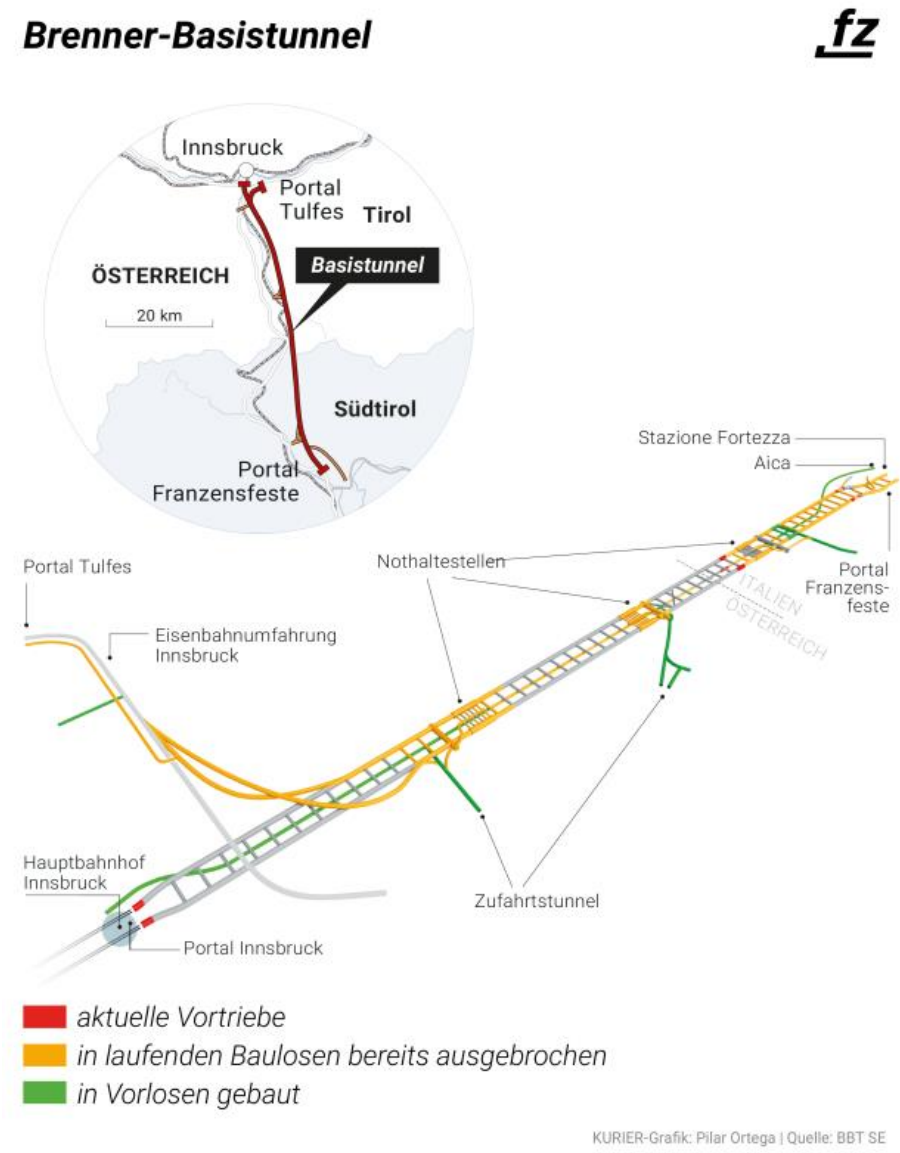


Figure 3-3: Layout and Location of the Brenner Base Tunnel [23]

The removal of excess heat from metro tunnels usually happens close to station platforms via exhaust ventilation air shafts. Excess heat is generated by the electricity used to power the drive of trains, from auxiliary systems and from the breaking process of trains in front of platforms. The total assessed potential for excess heat recovery from a total of 1994 metro stations in the EU28 is estimated at around 98 TWh per year. [21]

A promising project in this area is in the UK. The tunnels of the London metro usually have a temperature in the range of 22°C to 28°C all year around. This heat comes from breaking, mechanical and drivetrain losses, while only a small part is generated by passengers. Around 90% of this heat is absorbed by the walls and 10% is removed by a ventilation system, which discharges the heat via ventilation systems all over London. The CELSIUS project aims at demonstrating heat recovery from the underground ventilation system through electric heat pumps. The heat can then be used for local district heating. Within the framework of the CELSIUS project, the Bunhill Energy Centre in Islington wants to expand an existing district heating network with 454 homes and include excess energy from the London Underground to further supply another 1000 homes. Removing the heat in winter, when it is mostly needed, can help lower the overall temperature and will enable more absorption capacity of tunnel walls in the summer.

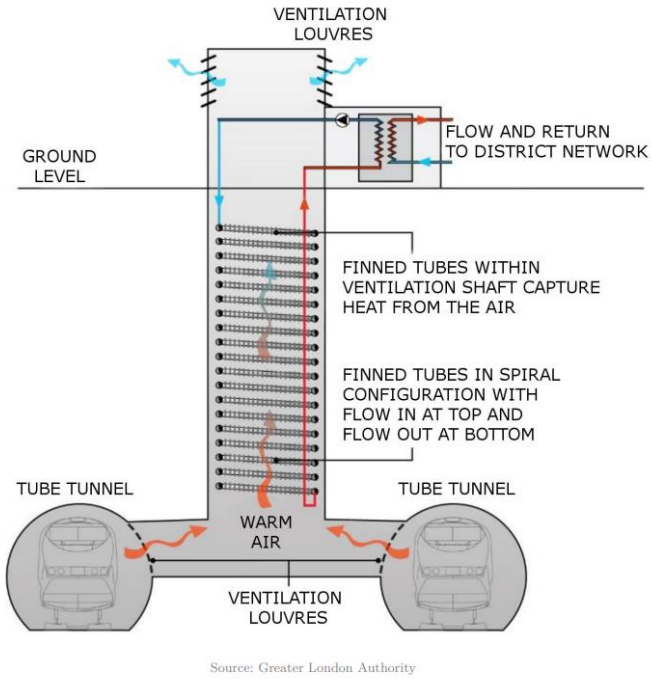


Figure 3-4: Waste Heat Extraction from London Underground

3.4 Waste heat from converter stations

Electricity and therefore, power converters will play a vital role in the future energy system, this opens opportunities to utilize their thermal losses. As this is a new topic, little information is available. Large transformer stations typically have very high efficiencies, often above 99%. Nevertheless, losses of as little as 0.5 % can provide a significant amount of waste heat from large systems. [24] In Denmark the theoretical excess heat from power transformers 0.28 TWh per year. Of this 0.07 – 0.21 GWh can be supplied below the average DH price. This potential will be utilized by heat pumps. Waste heat from converters could supply up to 2% of the Danish DH demand. As converter stations are in most cases in the vicinity of heat consumers, they could become an important option on a local level. On average each 132 kV transformer provides 985 MWh of EH per year and each 165 kV transformer 865 MWh per year. The larger 400 kV transformers generate on average 4.3 GWh of EH a year. There are several outliers – the largest transformer located in Viborg generates 50 GWh of heat per year. [25]

Due to the increasing number of high-voltage direct current (HVDC) converter stations worldwide, there is a significant potential impact of efficiency improvements in the MW scale. In 2019, around 0.2 GW of HVDC interconnector power stations were installed worldwide. The majority of losses of the converters originates from the AC/DC conversion, which results in the production of heat. [26]

As the HVDC converters are in most cases developed for power in the MW range, efficiencies of 95% and above still mean significant heat losses. This opens up opportunities to recover this, mostly low-temperature waste heat. [27]

Many HVDC converter stations are used in the transmission of power between countries. A collaboration by a Danish (Energinet) and a Dutch (TenneT) transmission system operators implemented the COBRA cable for energy transmission between their countries. The HVDC converter station in the Danish town of Endrup, near Bramming provides excess heat to the local district heating network. The converter station has a voltage of 320 kV and a transmission capacity of 720 MW. The surplus heat generated by the converter station, which has a full load capacity of 3150 kW, will reach around 35°C. To reach the temperatures of the district heating network, heat pumps are used. Due to the origin of the heat, there is no tax involved, which benefits the project.[28]

Facts about this case

Heat source: Excess heat from a converter station (35 °C).
Heat pump COP: Expected above 6.0
Temperatures: Surplus temperature from the converter station is expected to be 35 °C.
Period: Expected to be finished in 2019

District heating network: 2500 consumers
Link to web page: https://energinet.dk/ http://www.brammingfjernvarme.dk/

Contact information:
Steen Thøgersen, Bramming Fjernvarme, post@brammingfjernvarme.dk

Figure 3-5: Facts about Excess heat from Converter Stations

3.5 Data centers

3.5.1 Overview and outlook

With an increased rate of digitalization, the need for data centers increases as well. Since 2010, the global internet traffic has shown a 15-fold growth, accompanied with an 8-fold growth of data center workload [29], see Figure 3-6. The energy consumption associated with data centers was 200 - 250 TWh in 2020 [30], corresponding to around one percent of the global electricity demand. A different source states a consumption of 350 TWh for the year 2017 [31]. As the current consumption estimations show some variety, so do the forecasts for the next decade. The range is between a constant consumption due to further increases in energy efficiency and figures of up to 3,000 TWh in the year 2030 [31].

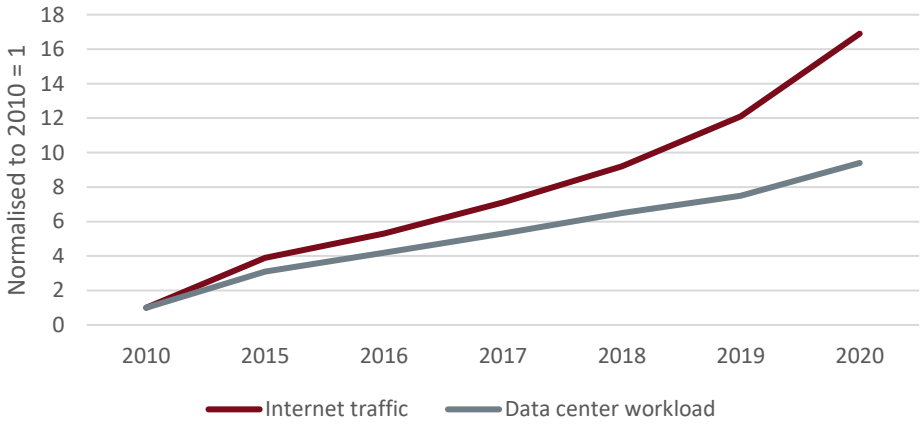


Figure 3-6 Trend of internet traffic and data center workload from 2010 to 2020. Adapted from [29].

A commonly used indicator for the energy efficiency of data centers is the power usage effectiveness or PUE. It is defined as the quotient of the total energy consumption of the data center facility and the consumption of the IT equipment. Although this indicator does not provide information about the energy efficiency of the actual computing devices, it gives an overview on the efficiency of the facility. A survey among data center managers revealed a prominent decline of PUE values in the years between 2007 and 2014, see Figure 3-7. However, this trend was not continued in the following years. An explanation for this trend is that easy gains for old data centers have been implemented, but further improvements would require drastic efforts (e.g. exchange of the entire cooling system) that are not economically feasible [32]. Nonetheless, modern data centers with PUE values as low as 1.1, meaning that only 10% of the needed energy of the data center is used as overhead for non-IT equipment, do exist [33].

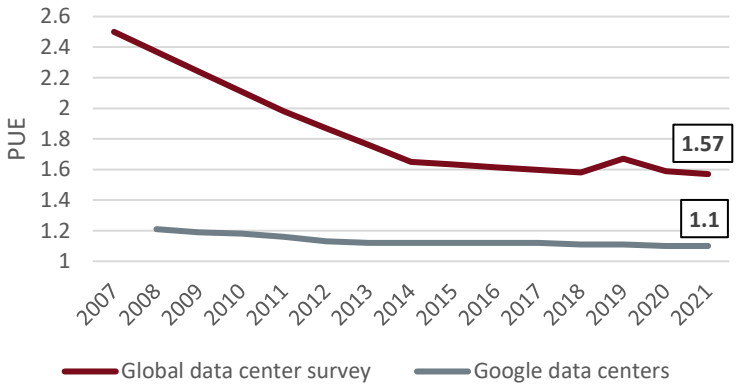


Figure 3-7 Trends of data center PUE from 2007 to 2021. Adapted from [32], [33].

While the PUE gives an indication about the general efficiency of the data center facility, it does not directly correspond to the availability of waste heat. More efficient operation of the auxiliary systems reduces the overall energy consumption of a data center. However, the heat produced by the computing equipment still needs to be cooled away, making it possible to extract waste heat for district heating also in very efficient data centers. An assessment of the waste heat potential from European data centers that are within 2 km of urban district heating areas revealed a potential of approximately 50 TWh annually [12]. With the continued extension of data center infrastructure this potential will rise, offering a potential contribution to the green transformation of district heating networks.

3.5.2 Sources for waste heat

Data centers are designed for continuous operation and can therefore provide constant heat [34]. Typical specific power densities are in the range of 250 to 1,500 W/m² IT area [35], resulting in high power requirements for larger data centers. An average, European data center has an area of 2,616 m² [36], which, assuming a power density of 750 W/m² and continuous operation, means an electricity demand for the IT hardware of about 17.2 GWh/a. Since the electricity used is completely converted into waste heat, this heat must be cooled away. Most of the heat is dissipated into the environment by means of cooling units, but it is possible to recover the waste heat and use it for district heating. Depending on the cooling concepts used, there are different possibilities for recovering waste heat.

CRAC – Computer room air conditioner

CRAC units are mostly used for the cooling of small data centers [37]. The CRAC unit is located within the server room and collects the hot air from the IT hardware. The racks containing the servers are usually organized in rows of alternating hot and cold aisles. Heated air from hot aisles is collected and directly fed into the evaporator of a direct expansion unit, where heat is transferred to a refrigerant. The cooled air is then distributed through the floor of the server room and delivered to the cold aisles, where is cools the IT hardware [38]. Downsides of CRAC units are the needed cooling of the entire server room and high operational costs [37].

With CRAC units, waste heat extraction is possible from the hot air before entering the evaporator at a temperature level of 25 – 45°C [37].

CRAH – Computer room air handler

CRAH units are preferred cooling option for larger data centers as they tend to have lower operational expenditures compared to CRAC units [37]. The working principle is similar to CRACs with the difference that the hot air coming from the IT hardware is cooled through chilled water**.** The heated water is transported outside of the data center where it is cooled by a chiller.

With CRAH units, waste heat extraction is possible at two points. Extracting heat from the hot air before entering the CRAH unit yields identical temperatures of 25 – 45°C as with CRAC units. The second option is to extract heat from the condenser of the needed chiller, where temperatures between 40°C and 50°C are reached [37].

In-row / rear door cooling

These cooling techniques commonly share the use of an air-to-liquid heat exchanger near the server racks. The IT equipment is still air-cooled, but the heat is transferred to chilled water in a heat exchanger either between (in-row) or in the front (rear door) of the server racks. As the cooling is focused on the heat producers and not the entire server room, these cooling concepts offer efficiency gains [38]. The cooling water is conditioned outside of the data center in a chiller, allowing two possible heat extraction locations. Waste heat can be extracted at temperatures of 20 – 30°C from the warmed cooling water or at the condenser of the chiller in the temperature range of 40 – 50°C [37].

Liquid cooling

Liquid cooling techniques limit the cooling to the hottest parts (e.g. CPUs and memory chips). While there are concepts where the liquid indirectly cools the components (cold plates), immersion cooling techniques offer the best efficiency as the cooling liquid (dielectric fluid) is in direct contact with the components. The temperatures of the cooling liquid can reach values of 50 – 60°C that can be used for waste heat extraction [38].

Air cooling techniques are still widely used and the standard technology for cooling data centers. However, the share of liquid cooling is increasing and will continue to grow in the future, especially for data centers with high power densities. The average power density in 2020 was 8.4 kW/rack, with larger data centers in particular having higher power densities [39].

Another trend is towards free cooling, where cooling of the infrastructure works directly via an external heat sink. There are different approaches to this, with various advantages and disadvantages. The simplest and least costly approach is direct cooling using fresh air, whereby air quality and humidity requirements must be considered. For large cooling loads, it is possible to use free cooling in parallel with an existing chiller to cool the cooling water. Depending on the external conditions, cooling can be provided entirely by free cooling or by a combination of free cooling and the chiller [40]. The use of free cooling results in significant savings in the power consumption of the refrigeration supply and is therefore commonly used in facilities with low PUE.

3.5.3 Successful implementations in DHN

There are already some successful implementations of waste heat recovery projects from data centers in district heating networks, which are presented below.

Open District Heating in Stockholm, Sweden

The local district heating network operator Stockholm Exergi has launched Open District Heating, a project in which companies can feed waste heat into the district heating network at a competitive price. The focus is on data centers, but all companies with surplus heat can participate in the project. The remuneration for the waste heat fed into the network depends on the model selected: feed into the supply with a temperature level dependent on the outside temperature, feed into the supply with a constant temperature of 68°C or feed into the return with a temperature difference of at least 3 K [41].

Several data centers already feed into Stockholm Exergi's network. The Pionen data center from the company Bahnhof is centrally located in Stockholm and has two heat pumps installed with a cooling capacity of 694 kW and a heat output of 975 kW. The heat pumps provide chilled water, which cools the warm exhaust air in the server rooms. In normal operation, the data center thus feeds approx. 600 kW of heat at a temperature of 68°C into the district heating network. In addition to the heat pumps, there is also a chiller as a back-up solution, see Figure 3-8 [42].

Bahnhof's Thule data center goes one step further and relies on a flexible cooling system that can feed waste heat into the district heating network on the one hand but is integrated into the district cooling network on the other. This combined approach has made it possible to oversize the cooling system to be prepared for a later expansion of the data center. In normal operation, three heat pumps provide a cooling capacity of approximately 1,200 kW at 5.5°C and a heat output of approximately 1,600 kW at 68°C. Excess cooling capacity is thereby fed into the district cooling network, see Figure 3-9 [43].

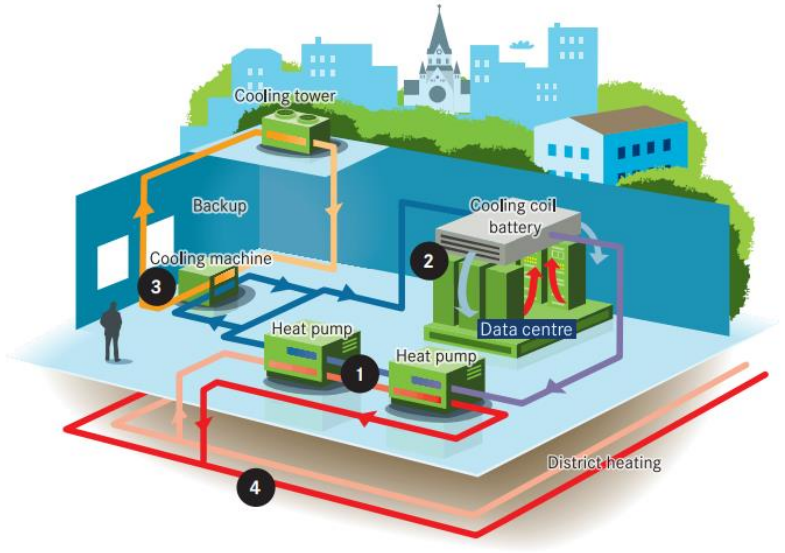


Figure 3-8 Waste heat implementation Bahnhof Pionen [42]

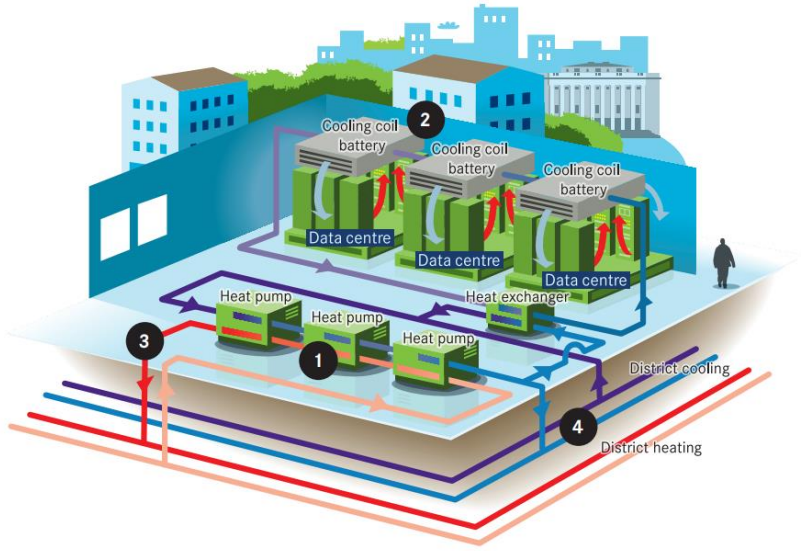


Figure 3-9 Waste heat implementation Bahnhof Thule [43]

Yandex Data center in Mäntsälä, Finland

A 4 MW heat pump was installed in 2015 to utilize the waste heat of the data center, supplying ca. 30 GWh heat to the local district heating network [44]. Hot air at a temperature of ca. 40°C serves as waste heat medium and is boosted in the heat pump to a temperature of 85°C. With the implementation of the heat pump, approximately 75% of the needed electricity for the data center can be recovered as useable heat [45].

Facebook Data center in Odense, Denmark

Facebook is operating a data center in Odense with a size of about 85,000 m² since 2019. Together with the local district heating network operator Fjernvarme Fyn, a concept was developed to utilize the waste heat of the facility. Warm water from the cooling coils of the server halls is transported to a nearby heat pump facility operated by Fjernvarme Fyn, where the heat is upgraded and supplied to the district heating network. With this installation approximately 165 GWh heat can be supplied annually [46]. As an expansion of the data center to a size of 200,000 m² is planned, the heat delivery may be further increased in the future [47].

3.6 Electrolysers

3.6.1 Overview and outlook

It is commonly agreed upon that hydrogen will play a significant role in the decarbonization of an integrated energy system as the link between previously separated sectors of power, gas, mobility, industry and households. Currently, hydrogen is mostly used as feedstock for industrial processes and predominantly produced from natural gas with steam reforming. The global hydrogen demand was at 90 Mt H2 in 2020, stemming from refineries, the chemical industry and steelmaking processes. Globally installed **electrolysis capacities** were at **290 MW in 2020**, producing 30 kt H_2 corresponding only to 0.03% of the overall production [48]. The installed capacity is expected to increase significantly in the next decade with estimations ranging from 25 GW [49] to 90 GW [50] by the year 2030. The European Hydrogen strategy [51], adopted in July 2020, sets the ambitious goals of the construction of **40 GW electrolyser capacity** and the production of **10 Mio. tons of green H_2 by 2030**. The international Energy Agency expects in their Net-Zero Emissions scenario a hydrogen demand of up to **530 Mt in 2050** [48].

While currently the production of H_2 predominantly takes place in **temporal and spatial coherence** with the demand, that coherence will change with increasing production and demand volumes of green hydrogen. The production of green hydrogen will shift from the demand centers to the generation sites of renewable electricity. Here, large-scale electrolyser capacities are expected to emerge, producing hydrogen that is then transported to the off-takers. To foster the transition to a smart energy system, synergies within the energy systems will be utilized. By positioning the electrolysers in proximity to the renewable electricity generators, capacity constraints of the electrical grid can be circumvented. Additionally, the generated waste heat of electrolysers will need to be considered, as it amounts to a significant potential for providing heat to residential applications.

3.6.2 Sources for waste heat

The production of hydrogen from water and renewable electricity with electrolysers is the preferred production path in the future. There is a multitude of different technologies available at varying technology readiness levels. However, three electrolyser types are the most promising: Alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEM-EL) and solid oxide electrolysis (SOEL) [52]. As these technologies operate at different temperatures and with different efficiencies, the waste heat potential is assessed for each technology individually. An overview of the key parameters for the technologies is given in Table 2.

Table 2 KPIs of electrolysis technologies, based on [49], [52]–[55]

	AEL	PEM-EL	SOEL
TRL	9	8 - 9	6 - 7
Operating temperature [°C]	60 - 90	50 - 80	650 - 900
Electric efficiency (LHV)	50 - 71	50 - 68	75 - 85
Recoverable waste heat (% of electricity input)	16 - 30	20 - 30	-
Waste heat temperature [°C]	50 - 80	50 - 80	-

Alkaline electrolysis

Alkaline electrolysis is the most mature water electrolysis technology with multiple commercial installations in the MW range [56]. Similar to PEM electrolysis the operating temperature is below 100°C, allowing liquid water as input for the process. Benefits of this technology are the low capital costs, high lifetime of the components and the availability. Contrary, disadvantage are the limited operating pressure, resulting in higher costs for subsequent compression of the produced hydrogen, low current densities and limited flexibility for dynamic operation [52].

Considering the availability of waste heat, literature values imply that **16% of the electricity input** can be recovered at a **temperature of 50°C**. By 2024, the temperature of the available waste heat is expected to increase to 70°C [54].

PEM electrolysis

PEM electrolysis is seen as one of the most promising solutions for efficient hydrogen production from renewable energy sources and has already reached a commercial level. The compact design, the high current density and efficiency, the low operating temperature (50-80°C) and the possibility of a flexible operation (fast cold start-up times) make it an attractive solution [56]. Due to the usage of expensive catalysts and limited production capacities, capital costs for PEM-EL are higher than for AEL. Additionally, the stack of current systems has a limited lifetime, resulting in additional expenses when replacement is needed [52].

Similar to AEL, **waste heat** can be recovered at a **temperature of 50°C** (expected to increase to 70°C by 2024). The available **share of waste heat** is expected to reach values of **26% of the electricity input** [54].

SOEL

Contrary to the other two technologies, SOEL is operating at high temperatures (650 – 900°C) and with the input of steam. While the overall energy demand of splitting water in hydrogen and oxygen is increasing slightly with increasing temperature, the electricity demand is decreasing as more heat is utilized [57]. Therefore, high electrical efficiencies in the range of 81 – 86% (lower heating value) can be achieved with SOEL [52]. Existing challenges with this technology are material degradation due to the high operating temperature and limited flexible operation due to the long start up times [57].

Whereas the other electrolysis technologies are generating waste heat that can be utilized in a district heating network, SOEL is relying on an external heat input. A possibility to provide the thermal energy input is industrial waste heat: The European project “GrInHy2.0” is demonstrating the implementation of a high-temperature SOE plant in an integrated steel production facility, utilizing waste heat from the steel making processes as heat input to the SOE. With this configuration, hydrogen is produced with electrical efficiencies of 84% (considering the lower heating value) [58].

3.6.3 Successful implementations in DHN

MPREIS Hydrogen

The Austrian supermarket chain MPREIS is generating green hydrogen in their headquarter in Völs, Tyrol. The 3.2 MW plant is the largest single-stack electrolyser in Europe. Alkaline pressure electrolysis is used for the generation. The generated hydrogen is used in their bakeries and as fuel for their own truck fleet. The waste heat is reused in their production processes. 70% of the input electricity is converted to hydrogen while about two thirds of the heat losses are reused. [59]

Pilot project „Power to Gas“ Ibbenbüren

In the city of Ibbenbüren, in Germany, a plant for hydrogen production by PEM electrolysis with a rated power of 150 kW is being tested since 2015. The aim of the test is to proof the functionality of an electrolizer in interaction with the fluctuating electricity production from renewables under real-life conditions. This plant is the first one in Germany with a multiple waste heat utilization at a temperature of around 56°C. The overall efficiency of the system is at 86%. [60] [61]

WindGas Falkenhagen

In Falkenhagen, Germany Uniper has built a demonstration plant for the generation of green hydrogen by alkaline electrolysis fed by wind power. The 2 MW plant is in operation since May 2018. The hydrogen is supplied to a high-pressure natural gas grid. The heat from the process is used in an adjoining veneer factory. [62] [63]

Green Hydrogen Esslingen

For a newly developed city quarter with a size of 120,000 m², a climate-neural energy concept was developed that includes the production and usage of green hydrogen. The 1 MW electrolyser, capable of producing 400 kg of hydrogen per day, is powered by excess electricity from the rooftop PV installations and a nearby wind turbine. The hydrogen is used for different applications: feed-in into the local gas grid, mobility applications and for the generation of electricity in times of low renewable production. The waste heat of the electrolyser is utilized for heating the quarter, raising the overall efficiency of the system to around 90% [64].

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