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Heat Roadmap Europe: Potentials for Large-Scale Heat Pumps in District Heating

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Executive Summary

This report is an overview of the role and potential for large-scale Heat Pumps (HPs) in the current DH systems and in future Smart Energy Systems (SES). It is based of several studies and especially on results from the Heat Roadmap Europe (HRE4) project that modelled the thermal installed capacities needed for increasing the share of renewables and reuse of excess heat in the different systems. HRE4 covers about 90% of the heat market in Europe.

The heating sector corresponds to half to the total energy demand in Europe, thus improving its efficiency would have an important impact in the overall energy system in the continent. One of the most efficient ways to improve heating efficiency in dense urban areas is by integrating or expanding District Heating (DH) Systems. These have been used for many decades in some European countries and their efficiency could be highly improved with the integration of large-scale HPs.

The decarbonisation of the DH systems already started with the CHP changing from fossil fuel to biomass, however, biomass resources will not be enough for the heating sector in a scenario with 100% renewable energy system. Therefore, it is important to also recover excess heat from industry and power generation into the DH networks and to electrify the heating sector via large-scale boilers and large-scale HPs, in order to integrate more electricity from RES, while leaving biomass resources to be used in the transport or industrial sectors.

Large-scale Heat Pumps in Smart Energy Systems

In order to decarbonise the heating sector, it is important to integrate more intermittent renewables and for that the energy system has to become more flexible. Flexible energy systems, with synergies between the transport, electricity and heating sector, and with a variety of different technologies and energy sources, are able to respond to the quick variation of intermittent renewable production and absorb their energy as soon as it is generated. The key to create these Smart Energy Systems (SES) is to integrate large-scale HPs. Figure 1, on the right, is a representation of a SES, where large-scale HPs have a central role.

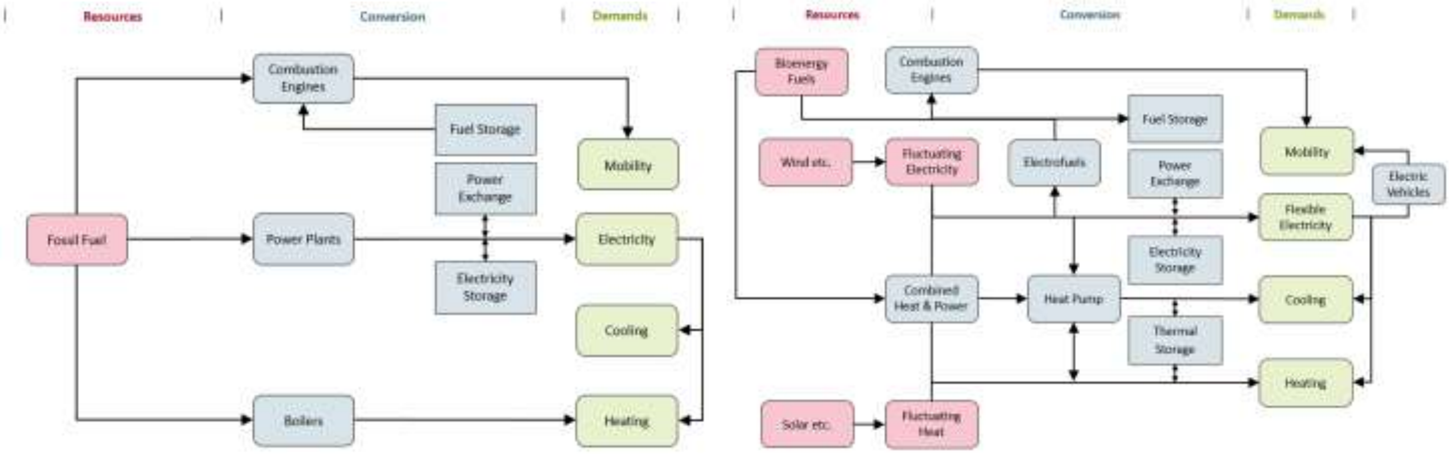

Figure 1

Figure 1: Current Energy System (on the left) mostly characterized by linear paths from fuel to end-use, and Smart Energy System (on the right) where the transport, electricity and heating sectors are connected and where large-scale HPs have a central role.

The combination between the large-scale HPs, the CHP and thermal storage is what creates a link between the heating and the electricity sector and what makes it possible to absorb low-price electricity as soon as it is produced and to use other fuels in a flexible and efficient way. When there is excess of power generation from RES, excess electricity produced can be stored and used in different ways. A very efficient way to temporarily store this energy is to convert it from electricity to heat, by means of large-scale HPs, and deliver the heat directly to the DH network or to a thermal storage. In this way, HPs, DH and thermal storage can represent short-term energy storage solutions, while the gas grid and liquid fuels can be left for long-term storage options and with secondary priority for the heating sector.

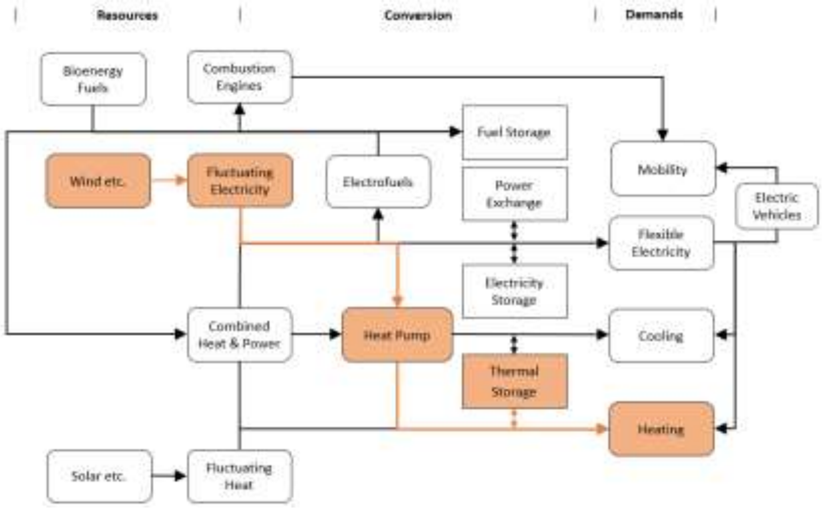

Figure 2: Operation of a Smart Energy System when there is integration of wind power.

In a SES the large-scale HPs are mostly used when the electricity prices are low, meaning that they will not be used continuously all the time. This leads to the fact that in a SES there should be an over installed thermal capacity of large-scale HPs that would be used in discontinued periods during the year. Figure 2 illustrates the energy path in hours where there is high levels of excess electricity production from wind. During these hours, instead of only supplying the electricity storage, the excess electricity can supply large-scale HPs, which in turn can supply Thermal Storage and the DH demand.

Large-scale HPs can also have a role on the future cooling systems, which nowadays consists mostly on individual electric HPs/chillers. In a SES, a more sustainable alternative is the district cooling, which currently covers only 1% of the total cooling demand in Europe, where central chillers (or large-scale HPs) would be implemented and some of the HPs used for heating could deliver cooling at the same time. This would lead to a much complete synergy between the heating and cooling sector and the electricity sector.

Most of the DH systems existing nowadays share the same characteristics as what it is described as 3rd generation DH. In some places a development towards 4th generation DH has already begun. This report shows that by using existing technology it would be possible to improve the efficiency of these DH systems with the use of large-scale HPs.

Large-scale Heat Pumps potential in 3rd generation DH

The HRE4 project showed that, for the vast majority of European urban areas, DH is a cost-efficient solution and can provide at least half of the total heat demand in the 14 countries studied, while efficiently reducing CO_2 emissions and the primary energy demand of the heating and cooling sector. Based on its results, it is also suggested that large-scale HPs will have a big role to play in future DH systems in order to develop flexible and supply safe systems.

According with this project, the European share of DH in the heating sector should increase from 12% (current values) to **50% by 2050**. This is an important shift in the heating sector in Europe and shows that DH can be cost-effective and essential to significantly reduce CO_2 emissions in the energy sector.

In the HRE4 project, three main scenarios were developed:

- **BL 2015** –baseline scenario representing the current situation of the heating and cooling sector, based on data from 2015;
- **BL 2050** – This scenario represents the development of the baseline scenario under the current agreed policies regarding savings and RES, etc., but without any additional measures to improve the decarbonisation of the system.
- **HRE 2050** –scenario representing a highly decarbonised energy system with redesigned heating and cooling sector that also includes energy savings. This scenario is based solely on proven technologies and does not depend on unsustainable amounts of bioenergy.

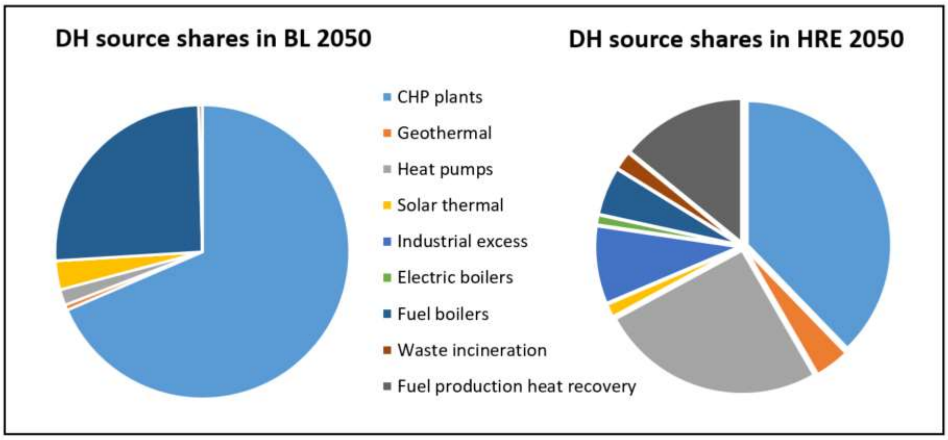

Figure 3: DH source share for BL 2050 and HRE 2050 scenarios (Source HRE4 project)

In the modelled energy efficiency scenario for 2050 (HRE 2050), DH is supplied mostly by decarbonised energy sources and **25% of the total DH demand is met by large-scale HPs** (Figure 3). This scenario would bring a higher variety of energy supply to the DH, increasing the flexibility of the system as well as it security of supply.The HRE 2050 scenario shows that it would be possible to achieve a much more decarbonized DH in 2050 than in the BL 2050 scenario, **reducing CO_2 emissions in more than 70%**.

In order to provide the DH demand for the HRE 2050 scenario (1100 $TW_{th}h$/year), the total installed thermal capacity of DH technologies would have to be around 400,000 MW_{th}, where **95,000 MW_{th} corresponds to the total installed capacity of large-scale HPs, representing a share of 23% in the DH network** (Figure 4).

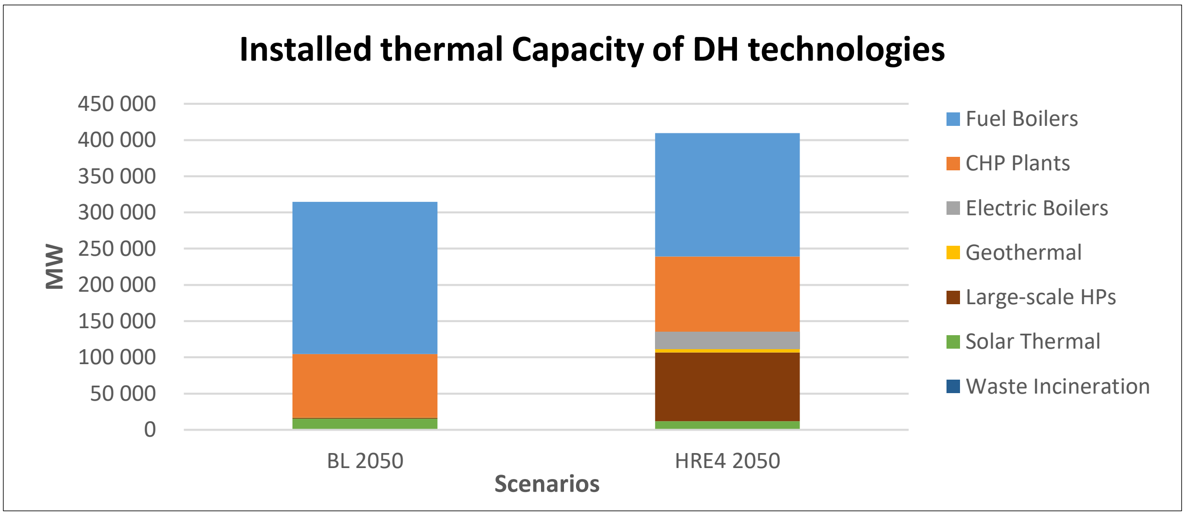

Figure 4: Installed thermal capacities of DH technologies in the BL 2050 and HRE 2050 scenarios (Source HRE4 project)

The Potential for large-scale HPs to supply DH is very high and it is, nonetheless, based on conservative estimations from the HRE4 project.

In the existing DH systems, large-scale HPs installed operate close to 100% of the time in full capacity, which differs greatly from what happens in the HRE 2050 scenario. If large-scale HPs would be allowed to work only either at full capacity or being turned down, in the HRE 2050 scenario they would work only 33% of the time during a whole year. This means that in a SES there is always an overcapacity of large-scale HPs installed in order to enable them to work in a flexible way. However, having a large-scale HP operating only 33% of the time is a conservative way to model this technology in the energy system. This is how the DH system was modelled in the HRE 2050 scenario, however there is potential to increase these levels. It is recommended that large-scale HPs operate on full load hours for about half of the time during a year. This means that without increasing the installed capacities in the HRE 2050, large-scale HPs could have a much higher share in the heat market while still being able to operate in a flexible way. In the HRE 2050 scenario, if large-scale HPs would operate in full load capacity half of the time during a year, their **heat market share could increase from 25% to up to 38%** of the DH production.

Other way to improve the estimations of the HRE4 project would be by integrating unconventional low-temperature heat sources in the system. In 3rd generation DH networks, large-scale HPs can improve the efficiency of the system by upgrading low-temperature heat sources (between 5°C and 40°C) in order to achieve the necessary temperatures to deliver them to the DH grids (around 80°C). In the HRE4 project, only common low-temperature heat sources were used (water bodies and water sewage), however there is a high potential to recover heat from unconventional heat sources in urban areas such as data canters and metro stations. The heat recovered by means of HPs could replace even further fuel boilers and some of the CHP capacity and reduce even more the primary energy consumption of the system.

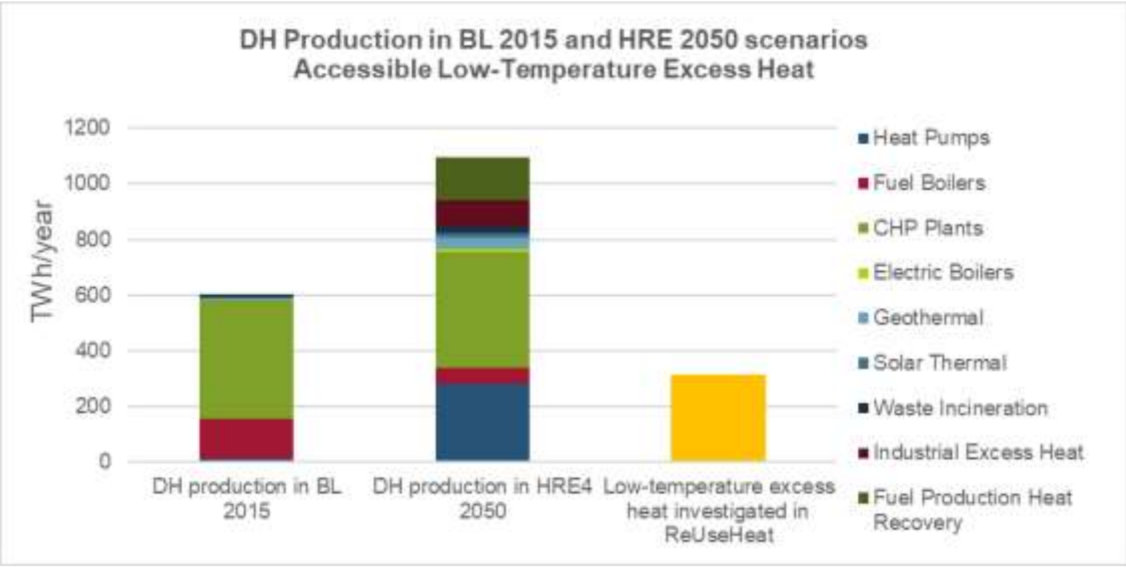

Figure 5: Comparison between the DH production in the BL 2050 and HRE 2050 scenarios and the accessible low-temperature excess heat in the 14 HRE countries (Source HRE4 project and [15]).

Figure 5 shows that the amount of accessible low-temperature excess heat from unconventional sources is very high in comparison with the DH produced in the HRE4 scenarios. However, this value is merely indicative and further analysis would be necessary in order to establish exactly how much of this extra heating source could be integrated in the DH scenario for 2050 and how much of the other technologies it would replace.

Notwithstanding, the results shows that without the need of advanced technologies, higher installed capacities of large-scale HPs in the DH in Europe could already allow energy systems to work flexibly, enabling a higher integration of low-temperature heat sources, a higher integration of renewables and a higher overall flexibility and energy efficiency of the system.

Large-scale Heat Pumps potential in 4th generation DH

4th generation DH systems, besides being characterised by the active synergy between the heating and electricity sectors, are characterised by low-temperature DH grids and the interconnection with the district cooling systems. In these future DH systems, large-scale HPs end up being an essential element.

low-temperature DH systems (between 50°C and 60°C), besides their intrinsic advantage of presenting lower distribution heat losses, they also allow large-scale HPs to work with much higher COPs. As the difference of temperature between the heat sources and the DH would be lower, HPs would need less electricity input in order to lift the temperatures to the desired levels. In this way, the use of large-scale HPs would be even more profitable and their potential in a 2050 DH system would be even higher than the values presented before.

Besides, the near future might bring advanced technology developments in the large-scale HPs market and it is expected that they will be able to present higher COPs, even when operating intermittently; meaning that more heat could be recovered with less electricity consumption.

According with the HRE4 project, district cooling will not have a significant growth until 2050 and will account for less than 5% of the cooling market in the HRE 2050 scenario, being mainly used for the industry and services sectors. Cooling is growing rapidly and faster than any other thermal sector, nevertheless its relatively smaller demands compared to the heat sector will keep its impacts on the whole energy market very limited. However, in 4th generation DH systems, heating and cooling should be designed together and large-scale HPs would be the critical technology to link both systems, by operating simultaneously to supply heating and cooling.

Overcoming barriers for the implementation of large-scale Heat Pumps

In future SES large-scale HPs are expected to operate in a flexible way, by increasing or decreasing their heat output depending on the availability of intermittent renewables. This could represent a technical barrier as the HPs nowadays were mostly designed to operate continuously. Frequent start-ups might cause wear on the HP's components and increase their operation and maintenance costs. Nevertheless, this barrier could be overcome with technology developments in the near future.

Besides their lower operation costs, especially due to the relatively lower energy consumption, HPs have high investment costs compared with other heating system components, such as electric boilers. This is one of the reasons why large-scale compression HPs are still not a very common technology in DH systems, and are most of the times custom built, making them even less accessible. However, in the future, it is expected that engineering processes to build HPs become more standardized which would reduce their investment costs.

Policy limitations and cost of fuels also affect the market share of HPs and might have a bigger impact on their market development than technological limitations. When fossil fuels are cheap, or while biomass, although a limited resource, still have higher financial incentives, it might be more difficult for HPs to penetrate the market. Because of the lack of incentives, large-scale HPs end up with higher investment costs than their competitors. If the fuel prices are high or there are more subsidies to encourage the use of HPs, these ones would be more profitable even with low COP. At the end, it is a matter of making large-scale HPs more known and policy-makers aware of their high socio-economic benefits in order to be considered for tax exemptions or other promoting schemes to help expanding this technology.

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1 Introduction

The heating demand in EU corresponds to around 50% of its total energy demand [1]. The electricity sector has seen many improvements in the last few decades in terms of savings and energy efficiency measures. However, the heating sector still has a long way to go to become decarbonized and several studies have shown that the potential to make it more efficient and renewable is very high.

In Europe, a big share of the residential heating is still based on individual systems where water-based radiators supplied by gas-based individual boilers provide heat for each flat. Natural gas is the most imported fuel to the EU, and in total, three quarters of the energy imports for heating and cooling are in the form of fossil fuels, indicating a strong dependency on non-EU countries [5].

There are different strategies that can be used to improve the decarbonisation of the heating sector. Although much attention has been given to the demand side (by retrofitting the building stock) in the past, the focus has lately changed to the type of heat supply [5], which would also enable the EU to have more renewable and geo-political independent systems. District heating (DH) is an important solution in these regards, since its fundamental idea is to use local fuel and any available source of heat that would be wasted otherwise, and to integrate Renewable Energy Sources (RES). DH systems in urban areas allow the wide use of CHP and Waste-to-Energy (WTE) solutions, as well as the integration of surplus heat sources such as excess industrial heat, and renewable heat sources like geothermal and solar thermal heat [6]. Studies have indicated that the amount of surplus heat from industries and power production in Europe could provide enough heat to cover almost the entire heating demand in Europe [7].

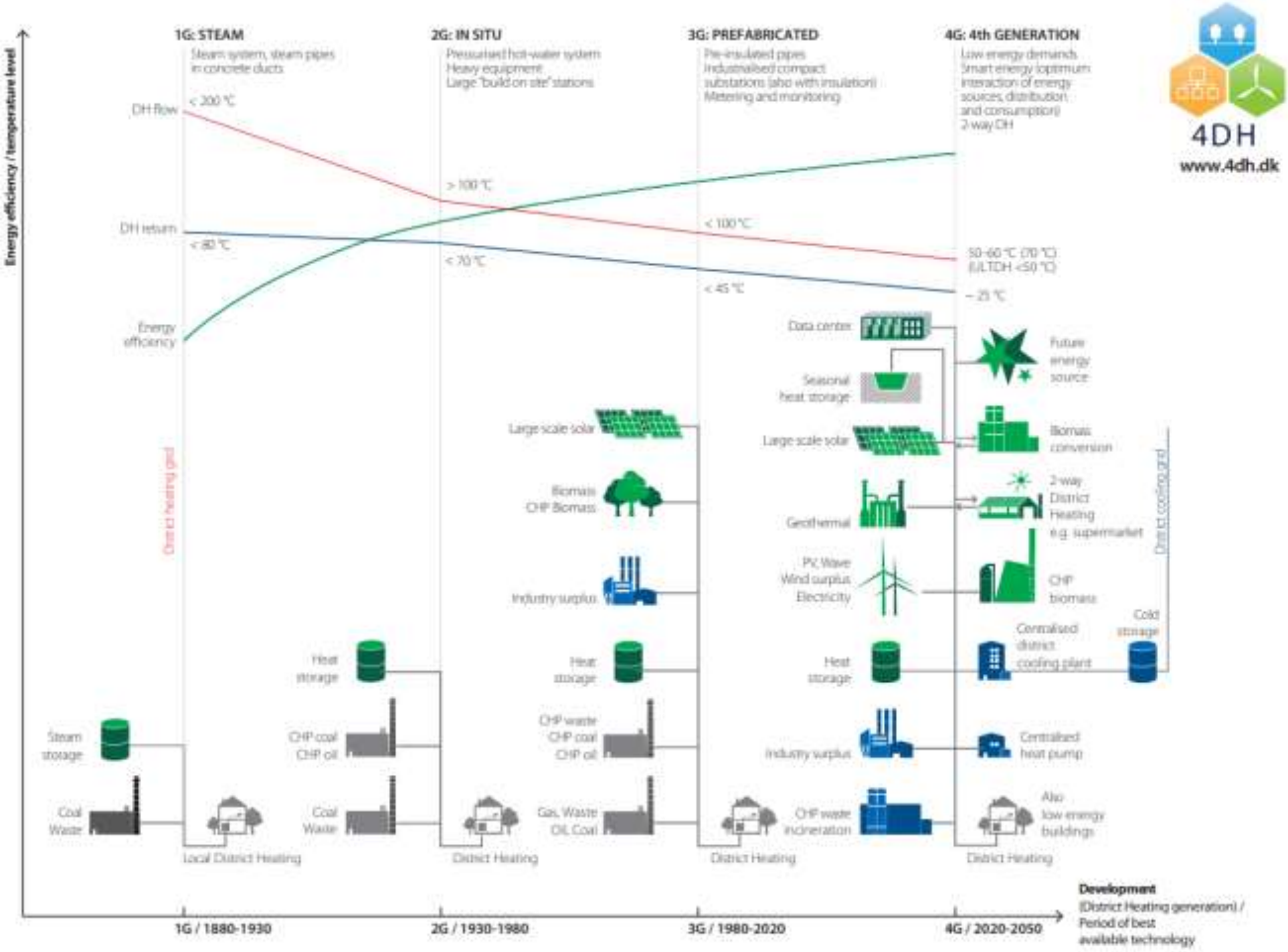

Figure 6: District heating technology evolution (source 4DH research centre, www.4dh.eu)

DH systems have been evolving with a trend towards lowering supply temperatures and introducing different producing units. As shown in

Figure 6, it is possible to identify 3 distinct generations of DH until nowadays, while we are currently going towards the 4th one [6].

The 4th generation DH is characterised by an integration of both thermal and electricity systems with low supply and return temperatures, based on CHP, power-to-heat solutions that together with large-scale heat pumps (HPs), allow the absorption of more RES. In this way, DH is becoming more than a system to distribute heat; it is becoming increasingly important to also integrate intermittent RES [5].

Studies have suggested that DH, together with thermal storage and large-scale HPs are more feasible, fuel-efficient and cheaper than individual solutions in areas with high urban density. Large-scale electric HPs are then an important technology to make DH systems even more efficient and renewable. HPs are an essential to develop a 4th generation DH, but can also be useful to improve a 3rd generation DH system, in case there are low-temperature heat sources available that need to have their temperatures lifted in order to integrate the DH [8].

In this report only electric compressor large-scale HPs are considered as they are one of the most efficient technologies to integrate intermittent renewable energy in the DH systems [8]. In order to define what large-scale means, in this report it was decided to consider only HPs with thermal capacities above $1MW_{th}$.

2 Large-scale Heat Pumps in District Heating Systems

Previous studies, like Heat Roadmap Europe 1 and 2 [9][10], show that the development of more DH networks in Europe will reduce the energy imports and increase the efficiency of both the thermal and electricity sectors. These studies also point out for the fact that biomass resources would not be enough for the heating sector, in a scenario with 100% renewable energy system. Therefore it is important to make use of excess heat from industry and power generation and to electrify the heating sector via large-scale boilers and large-scale HPs, while leaving biomass resources to be used in the transport or industrial sectors [3]. When the temperatures of the heating sources are not high enough to be incorporated directly in the DH grid, compressor HPs can be used to upgrade their temperatures. This is a very efficient solution (e.g., compared to electric boilers) and provides the opportunity for using inexpensive sources of heat that might be available nearby the DH grid [5]. It is in this way that large-scale HPs could already improve the existing DH networks by making use of low-temperature heat sources available naturally or from surplus heat.

2.1 The Role of Large-Scale Heat Pumps in Smart Energy Systems

In future energy systems it is expected a higher level of integration of intermittent RES and therefore a higher need for Smart Energy Systems (SES).

"*A Smart Energy System is defined as an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system*" [10].

In this sense, SES are not only focused on the electricity grids, but mostly on the integration of energy sectors and in the flexibility of response to inconstant energy demands. While the current energy systems are characterized by linear paths from fuels to energy demand, with traditionally separated electric, thermal and gas grids (Figure 7); in a SES there are active synergies between the three grids, where electric large-scale HPs gain a central role linking the electricity and the heating sector (Figure 8).

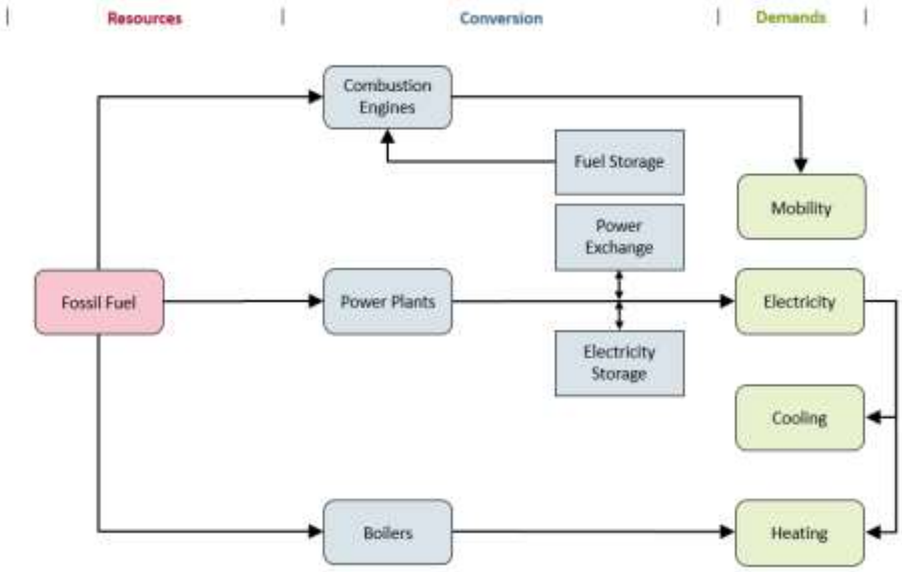

Figure 7: Current Energy Systems mostly characterised by linear paths from fuel conversion into end-use [11]

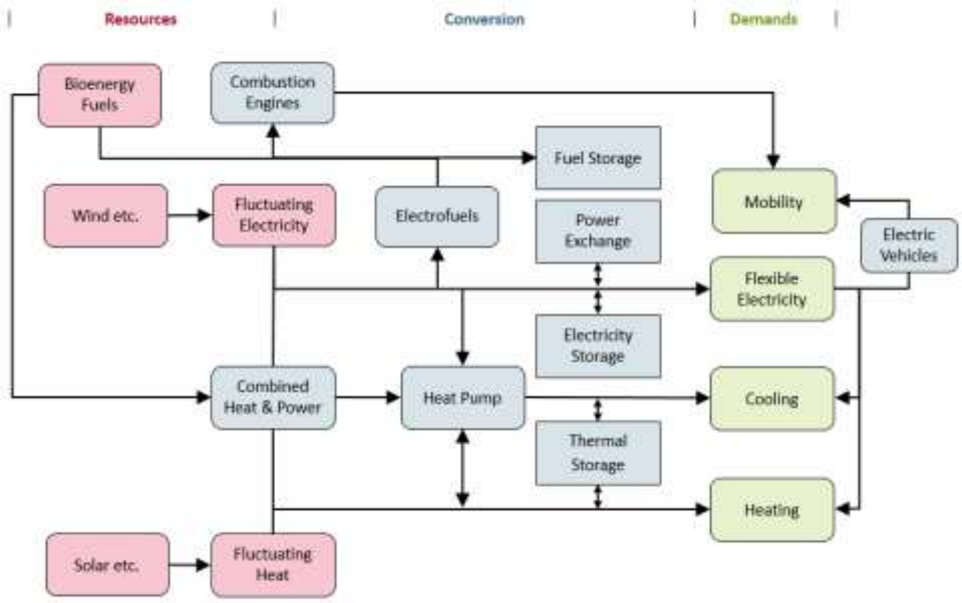

Figure 8: Smart Energy System [11]

Figure 8 shows how a SES becomes more complex and how the transport, electricity and heating sectors become interlinked. SES are able to integrate large amounts of intermittent RES with the synergy between different storage options and new energy demands, such as: a) the use of gas storage (long-term storage); b) the production of electrofuels for transport, which represent a new form of electricity storage; c) thermal storage and DH with CHP and large-scale HPs that represent short-term thermal storage; and d) electricity demand from large-scale HPs and electric vehicles, representing short-term electricity storage [12].

In a SES the most important step is the creation of a link between thermal and electric systems, where electric large-scale HPs have a central role to enable **the flexible and efficient integration of large amounts of fluctuating and intermittent electricity from RES** while maintaining the overall efficiency of the network [5][7][12].

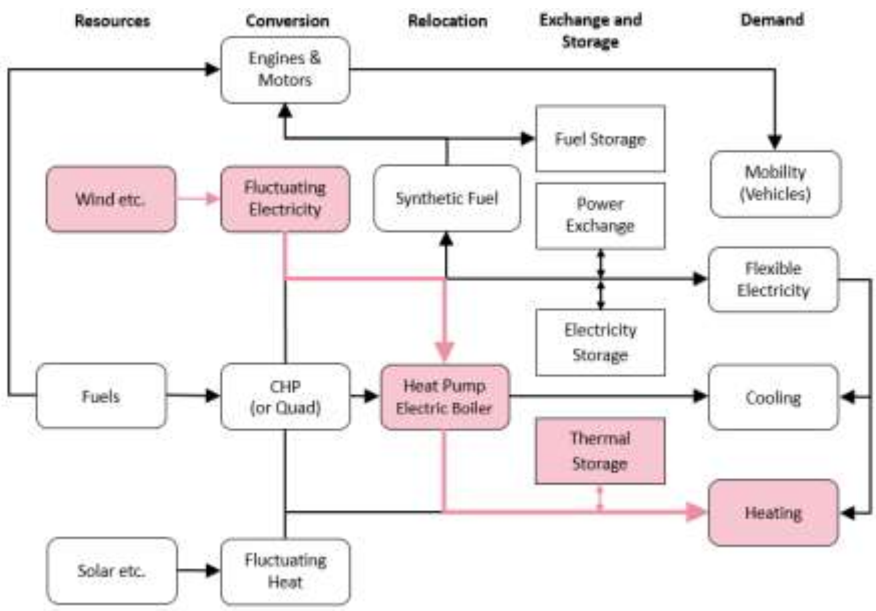

Figure 9: Operation of a Smart Energy System when there is integration of wind power [11]

In energy systems with high levels of intermittent renewables, like wind, one of the most efficient solutions is to install HPs to absorb the excess electricity production. These large-scale HPs should be designed to operate during periods of high production of electricity from variable electricity generation from renewables and should reduce operations during periods of low RES production [12]. As an example, Figure 9 illustrates the energy path in hours where there is high levels of excess electricity production from wind. During these hours, instead of only supplying the electricity storage, the excess electricity can supply large-scale compressor HPs, which in turn can supply Thermal Storage and the DH demand.

Large-scale compression HPs have then a very important role in future RES, as besides enabling the recovery of low-temperature heat sources, they also enable the connection between the electricity sector and the heating sector in a very efficient way. Large-scale compression HPs, in combination with electric boilers, are very useful to incorporate excess electricity production from intermittent RES (like wind and solar) in the energy system and transform it into heat supply that can later be storage in large-scale and relatively cheap thermal storage systems. Because HPs are much more efficient than electric boilers, the first ones should be prioritised. However, since electric boilers are still much cheaper than HPs, they represent a good solution to capture peak productions from renewable electricity sources. The optimal balance between these two technologies in DH systems is still not specified and might depend on each case. Nevertheless, large-scale HP would be only necessary to incorporate surplus production of electricity if there is a large share of wind or solar PV capacity already installed in a country [13].

In a SES, HPs work in a flexible way and absorb excess electricity production in hours of the year when there is too much wind and solar power production, transforming it into heat to fill in the large thermal storages [1]. In scenarios of highly electrified energy systems and increased DH shares, the role of power-to-heat technologies, such as HPs, become even more significant. Large-scale electric compressor HPs will be actually critical components of a SES and their use combined with CHP can enable the integration of the electricity and thermal sectors, the use of low price electricity and the flexible use of fuels (e.g. waste and biomass) [5].

In a SES, the combination of CHPs and HPs is what allows the integration of sectors and the following figure illustrates the process.

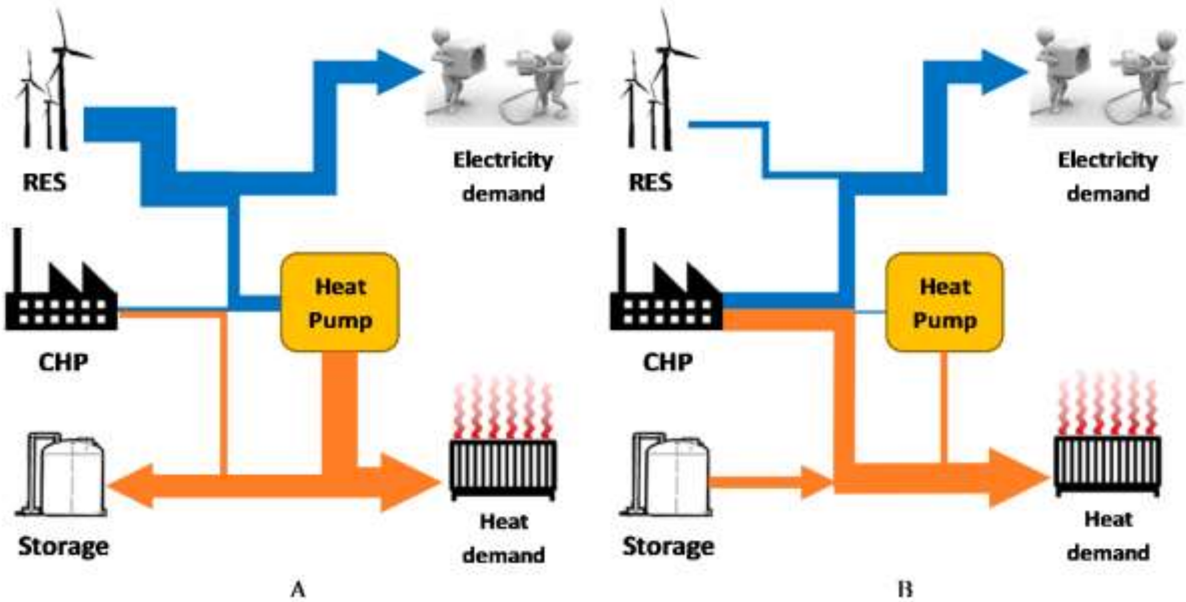

Figure 10: Large-Scale HPs used with high share of RES (A) and HPs used with low share of RES (B) [2].

In Figure 10 A, there is a high share of RES leading to a peak of electricity production with low price. In this situation, the CHPs can be turned down since there is enough electricity to supply the grid. However, once the cogeneration is turned down it brings the heat production down as well. In this way, the excess electricity produced by wind turbines can be used to feed in HPs that will increase the temperature from a heat source. The heat output from the HPs will then be delivered to the thermal grid while the excess heat will be stored in large-scale storage systems.

On the other hand, in Figure 10 B, when there is low RES share of electricity production, the CHP will be operating more intensively in order to produce the electricity needed to cover the demand. At the same time, the CHP will be producing heat and there is no need to utilise electricity (which will have a higher price at this moment) in the HPs. If the heat produced by the CHP is not enough the heat in the thermal storage can also be used at this point.

The electricity from RES, like wind and solar PV, is not always available and for that it is very important to develop a flexible system that can absorb it and use it as soon as it is produced. However, when there is excess of power production from RES (like in Figure 10 A), it is a good idea to store the excess electricity produced until it is needed. An efficient way to temporarily store this energy is to convert it from electricity to heat, by means of large-scale HPs, and deliver the heat directly to the DH network or to a thermal storage. In this way, HPs, DH and thermal storage can represent short-term energy storage solutions, while the gas grid and liquid fuels can be left for long-term storage options and with secondary priority for the heating sector [5].

In energy systems with high capacities of wind power installed, the higher the amount of wind power produced, the more HPs can facilitate its integration and reduce primary energy consumption. When the wind power covers more than 20% of the total electricity demand, if there is a large extra share of wind capacity installed in the country, it is possible to use excess wind power production to replace some of the CHP production, allowing to save CHP fuel [12].

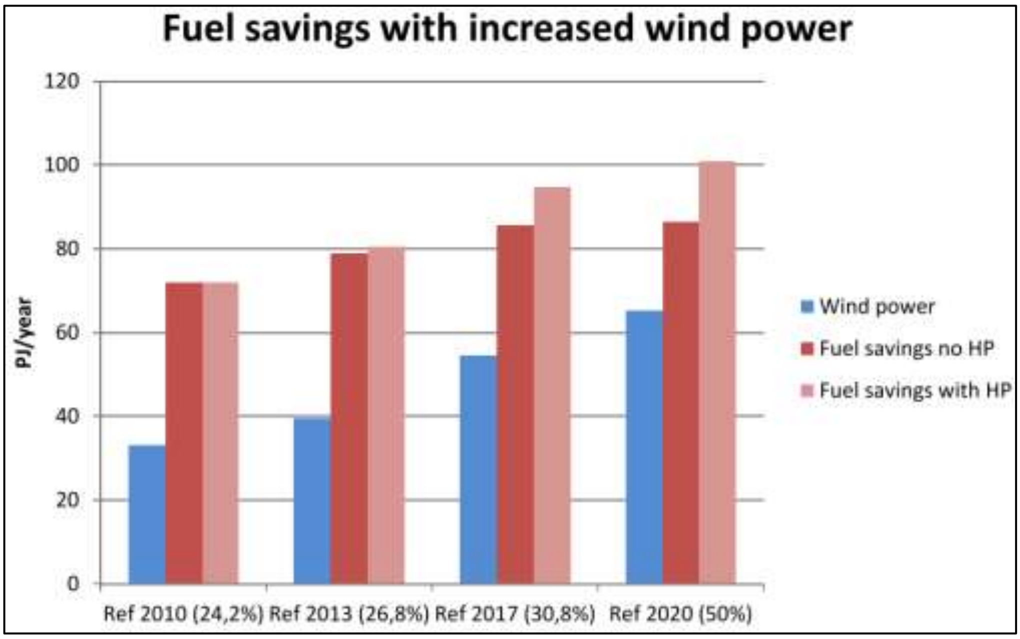

Figure 11: Wind power production in four energy systems with increasing percentages of wind power (in parentheses), and fuel savings with and without large-scale HPs. For 2013 it is modelled a system with 50 MWe of HPs installed capacity, 300 MWe in 2017 and 450 MWe in 2020 [11].

As illustrated in Figure 11, the amount of fuel savings increase the more wind power is produced but also the more HPs are installed. One of the biggest benefits of large-scale HPs in SES is in fact the possibility of saving large amounts of primary energy consumption by replacing it with renewables, which also corresponds to large financial savings in fuel [12].

Large-scale HPs can also have a role on the future cooling systems, which nowadays consists mostly on individual electric HPs/chillers. In a SES, a more sustainable alternative is the district cooling, which currently covers only 1% of the total cooling demand in Europe [13], where central chillers (or large-scale HPs) would be implemented and some of the HPs used for heating could deliver cooling at the same time. This would lead to a much complete synergy between the heating and cooling sector and the electricity sector [1].

Other advantage of a SES is the fact that the combination of HPs and CHPs allows for the integration of "low-temperature storage" in the system, where flue gases (containing excess heat from the CHP operation) are stored during the operation of the CHPs. The flue gases can later be recovered by the HPs operating with a high COP due to the relatively high temperature of this heat source. These type of operations allow for a high degree of flexibility in the system, opening the opportunity to constantly integrate surplus electricity for heat production in a very efficient way [5].

Future district heating networks, as 4th generation DH systems, might be based on low-temperature distributions, with delivered temperatures of around 50° C, and return temperatures of 20° C. A low-temperature network would bring several benefits besides of the reduced distribution heat losses. Some of those benefits are related with an overall higher efficiency of the system, such as better COP of HPs, higher capacities in thermal storages and higher share of low-temperature heat sources like the low-temperature heat storages as mentioned before, geothermal and industrial excess heat [6].

In a SES the large-scale HPs are mostly used when the electricity prices are low, meaning that they will not be used continuously all the time. This leads to the fact that in a SES there should be an over installed thermal capacity of large-scale HPs that would be used in discontinued periods during the year. It is important to note that so far HPs have not been designed to operate with frequent start-ups and that that would probably wear out its components. However, if future developments solve this issue by designing HPs for smart energy systems, or if the maintenance and operation costs are low enough to encourage the use of HPs when electricity prices are low, then the frequent start-ups would not be a problem anymore [5].

3 Characteristics of large-scale Heat Pumps

Heat Pumps can deliver both heating and cooling simultaneously, however they are most of the times only used for one of the purposes. For DH systems, large-scale HPs are used to deliver heat and to recovered heat from a lower temperature heat source.

3.1 Coefficient of Performance

Coefficient of performance (COP) of a heat pump is calculated by the ration between the thermal output and the power input. In Europe, large-scale HPs used for district heating have an average COP between 3 and 9, depending on the temperature of the heat source and other factors. This value is calculated without accounting the power input used by auxiliary HPs to pump the heat source. As a general rule, the COP of a HP will be higher for smaller temperature increases [5].

In the case of HPs not operating continuously, their COP will be lower during start-ups, which makes HPs operating in a continuous basis and with a stable electricity supply more profitable, also considering the wear of their components due to the numerous start-ups [5].

Although there is limited knowledge on the life-time of large-scale HPs' components, it is common knowledge that the most vulnerable components to suffer from mechanical wear are the compressor's elements. After that, the electrical engine, gears, coupling, tubes and computer system also require retrofit after 20-30 years of operation. Also it is important to note that the existing large-scale HPs in Europe operating in an intermittent basis were not designed to function with numerous start-ups per year and future developments might solve some of the problems concerning the wear of their components [5].

3.2 Refrigerants

Since 2015, ozone depleting chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants have been phased out and nowadays the use of natural refrigerants like hydrocarbons (HCs, e.g. propane), ammonia (NH_3), and carbondioxide (CO_2) are becoming more popular, whilst CO_2 and NH_3 seem to be the most promising for future HPs [8]. In some European countries, regulations have already forbidding the use of synthetic refrigerants for large-scale HP, and only natural refrigerants are allowed (e.i. hydrocarbons, carbondioxide, ammonia and water vapour) [4].

There is a global tendency of moving from synthetic to natural refrigerants in the newly-developed projects, as a consequence of regulation changes and a higher maturity of the technologies using natural refrigerants. HPs using NH_3 as refrigerant can present higher COP if the heat source is above 10-15°C. On the other hand, HPs using CO_2 as refrigerant are more efficient when there is a large temperature difference at the warm side and a small temperature difference at the cooling side (3-4°C) [8].

There are however some HPs manufactures considering the use of a new family of synthetic working fluids – hydrofluoroolefins (HFOs) – that have a low GWP amongst other benefits since they would be able to replace HFCs. However, due to its toxicity when released in the environment, some HFOs have been already prohibited in some countries, such as Denmark, that placed them in the same category as HFCs [5].

Each one of these working fluids present different properties, and are chosen depending on the HPs applications. The following table summarizes the properties of different refrigerants.

Table 1: Properties of different working fluids [5][8][4]

Refrigerant characteristic	Synthetic		Natural		
	HFCs	**HFOs**	**HCs**	**NH3**	**CO_2**
GWP 100 year	Very high 125-1900	Low 4	Low 3-5	Non 0	Very low 1
Toxicity	Non to moderate	Very high	Non	high	low
Flammability	no	Very high	Very high	High (moderate)	no
Pressure	moderate	moderate	moderate	High pressure	Requires very high pressure
Familiarity	Good	Good	Good	Good	Low
Applications/ Capacity	Suitable for very large-scale capacities	Suitable for very large-scale capacities	Medium-scale, 0.2-1.2 MW	Medium to large-scale HPs, not larger than 6MW	Not suitable for HPs larger than 2 MW
Temperatures	Good for high temperature lifts	Good for high temperature lifts	Up to 85° C	Good for both low and high temperatures, Up to 95° C	Good for high temperature lifts, up to 90° C
COP	Over 3	Lower than HFC's HPs	*Similar to HFC's*	Over 3, higher COP for heat sources above 10° C	The lower the temperature in the inlet, the better the COP
Retrofitting of HPs using HFCs	-	Can replace HFCs	*Possible.*	Corrosive properties, cannot retrofit HPs with HFCs	Non-corrosive
Future Potentials	It is expected to be phased out	It is expected to be prohibit	They are ideal for services (like supermarkets)	It might continue to be widely used	Generally a waste product, so very low-cost

HCs (i.g. propane and isobutene) are used in medium size HPs and can be used with standard commercial available components. However, due to its high flammability, the HPs often installed outdoors [4].

Water vapor can also be used as working fluid; however, its application on large-scale HPs is still in the demonstration phase. Several low-temperature demonstration projects are being developed and in the near future it will be possible to have results on this new refrigerant [4].

A lot of large-scale electric compressor HPs built nowadays and used for district heating have average capacities around 3 MW_{th}. When a higher capacity is needed, these large-scale HPs are built in parallel. There are large-scale HPs with heating capacities up to 25 MW but only when using HFCs as refrigerant, meaning that those are no longer permitted in Europe [5] [4].

Due to the GHG emissions from HFCs and the uncertain future of HFOs, NH_3 is at the moment considered the safest refrigerant for the future expansion of electric large-scale HPs, with CO_2 in second place. However, due to the high toxicity of ammonia when released in the environment, its systems must comply with high security measures to avoid environmental and health damages [5] [4].

3.3 Heat sources suitable for Heat Pumps

In Europe there are mainly seven different types of heat sources used by large-scale electric HPs that can be used to deliver heat in DH grids. Most of those heat sources are used locally in the DH networks and would otherwise be wasted. Although there is more waste heat in Europe than the necessary to supply the entire heat demand, not all heat sources have the required temperature to be directly connected to the district heating network. HPs are thus good solutions to lift the temperature of the heat sources [2].

Sewage water is considered a long-term stable and locally available heat source, being the most used by large-scale HPs in Europe. It is also regarded and the most advantageous one due to its relative high temperatures [2]. It is estimated that 5% of the heat demand in cities can be recovered from sewage water by using large-scale HP, when the population is higher than 10.000 inhabitants [14].

Ambient water is also a long-lasting and stable heat source but is not always close enough to urbanized areas. Nevertheless, when urban areas are located in the proximity of rivers, lakes or coastal areas, these water bodies can represent a stable heat source throughout the year, even with average temperatures are as low as few Celsius degrees. Ambient water and the output of District Cooling can be two successful low-temperature heat sources for HPs that can still reach COPs of 3 [2].

Studies show that although industrial excess heat has been somehow neglected in the past, it represents a vast amount of heat source, both with low and high temperatures, that is most of the times located in the proximity of urban areas. The downside of this heat source is that it is depended on the industry activity, which had led to the decommission of several HPs in Europe when the industrial activity ceased [2]. Other unconventional excess heat sources from other sectors, like services or specific buildings, are likely to be abundant low-temperature heat sources in the future and will be most of the times be generated near high DH demands regions. These unconventional heat excess heat sources are analysed further in section 4.2.

Other heat sources have been used in the last two decades in Europe and are added in the table bellow where their characteristics are summarized.

Table 2: Characteristics of the heat sources used by large-scale HPs in Europe [5]

Type of Heat Source	Temperature	Stability/Security	Proximity to Urban Areas
Sewage water	▲	▲	▲
Ambient water	—	▲	▲
Industrial waste heat	▲	▼	—
Geothermal water	▲	▲	▼
Flue gas	▲	—	—
District cooling	▼	—	▲
Solar heat storage	▲	▲	—

3.4 Output Temperatures

The delivered temperature of a HP has to be in accordance with each DH network requirements, and can go up to 80-90°C. However, there is a general trend in the evolution of the different generations of DH networks to lower the distribution temperatures due to their lower heat losses. This trend is beneficial for the integration of more large-scale HP in the DH systems since they operate with better COP when the temperature lifts are lower [2].

Table 3: Output temperature ranges with number of HP units in Europe, total capacity and COP [5]

Output Temperature Ranges (°C)	< 70	71–80	> 80
Units	19	57	34
Capacity (MW)	40	725	425
Average COP	4.5	3.6	3.7

The output temperatures are depended of different factors, such as the working fluid used, the temperature of the heat source, and type of operation. With the technology in use nowadays, it is possible to achieve temperatures as high as 90° C with natural refrigerants [2].

3.5 Type of operation

Heat pumps can supply the DH network by operating as the primary or as the secondary load, which is reflected on their operating hours. The HPs that supply as the primary load of heat operate on a continuous basis (7000-8000 h/year), which also enables them to achieve a shorter payback time. HPs supplying as secondary load operate only few hours per year (4000-7000 h/year) and operate mainly during the cold season, some of them can operate in an intermittent way, depending on the price of electricity [5].

The large-scale HPs existing nowadays were not specifically designed to operate with numerous start/stop or load changes, so operating a HPs in an intermittent way might wear its components in a faster way and reduce their lifetime [4]. Nevertheless, the future DH systems, will require HPs to work in a more flexible way so the technology development might evolve in that direction and the wear of components will not be a problem.

3.6 District Cooling

The existing district cooling networks in Europe are concentrated especially in the Nordic countries and supply mostly the service and industry sectors. Large-scale electric HP are able to deliver both heating and cooling at the same time, they have been already used in some district cooling networks in Europe while also supplying to the district heating network. District cooling in Europe covers only 1% of the cooling demand, which is mostly supplied by individual HPs (chillers). Nevertheless, the heating demands in Europe are much higher than the cooling demands, even in the southern countries, so the development of large-scale HPs should not be defined by the need of supplying both heating and cooling, but by the need of integrating intermittent renewables according to local strategies [5].

4 Future potentials for large-scale Heat Pumps

According with a survey from 2016 [2], there are 149 units of large-scale HPs, with thermal capacities higher than 1 MW_{th}, operating in DH systems in 11 European countries. Figure 12 is a result of this survey and shows when the HPs were installed in the seven countries with higher installed capacities. Sweden is the country with more thermal capacity installed, and also the one with older large-scale HPs. Other countries, like France and Denmark, have only recently started to install these elements in their DH systems.

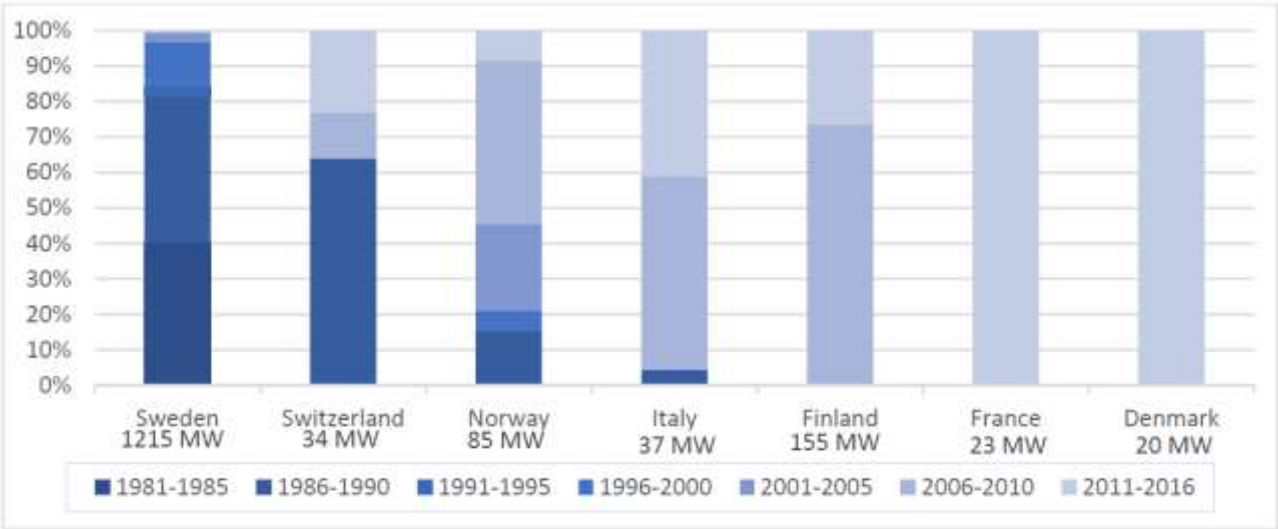

Figure 12: Overview of installed capacity of HPs in Europe and total thermal capacity in each country [2]

Sweden built most of its installed capacity during the 80's, when there were high levels of excess electricity production from the nuclear power plants and a limited export capacity. During that time, HFCs refrigerants were still in use, which allowed the installation of very large HPs with average capacities of 19 MW_{th} by the end of the decade. Nowadays, approximately 1000 MW_{th} of these large-scale HPs are still operational [2].

Table 4 presents the aggregated installed capacity and the number of units for, each five years, and shows that the average installed capacities have decreased during the years in Europe. This, is not only due to the fact that, with the natural refrigerants used nowadays, HPs can only have lower thermal capacities (1-6 MW_{th}), but also for the fact that there is a competition from other types of heat production and there is a lack of surplus electricity to enable HPs to operate continuously in full capacity [2].

Table 4: Overview of installed large-scale HPs in Europe from 1981 to 2016 [2]

Year	Capacity (MW_{th})	Number of Units	Average Capacity (MW_{th})
1981–1985	490	37	13
1986–1990	533	28	19
1991–1995	35	3	12
1996–2000	157	10	16
2001–2005	59	8	7
2006–2010	173	20	9
2010–2016	121	37	3
Total	1568	143	11

In current DH systems, large-scale HPs are used in full capacity most of the time, meaning that it would make sense to install them if: a) there is a constant surplus of electricity production in the system; b) if the price of electricity makes the use of HPs feasible; or c) if, the social and environmental gains are high enough to compensate the extra costs. In this sense, there is still space to improve the current DH systems by introducing large-scale HPs to lift temperatures from low-temperature heat sources, or to reuse excess heat from industries or power production.

4.1 Current and future potentials for District Heating

The Heat Roadmap Europe 4 (HRE4) project[1] modelled the heating and cooling sectors of the 14 EU countries[2] with higher heat demands, which together represent 90% of the total European heat market. The following figure presents the current share of DH in each of the modelled countries and the recommended shares DH should represent in 2050 according with the results from the project.

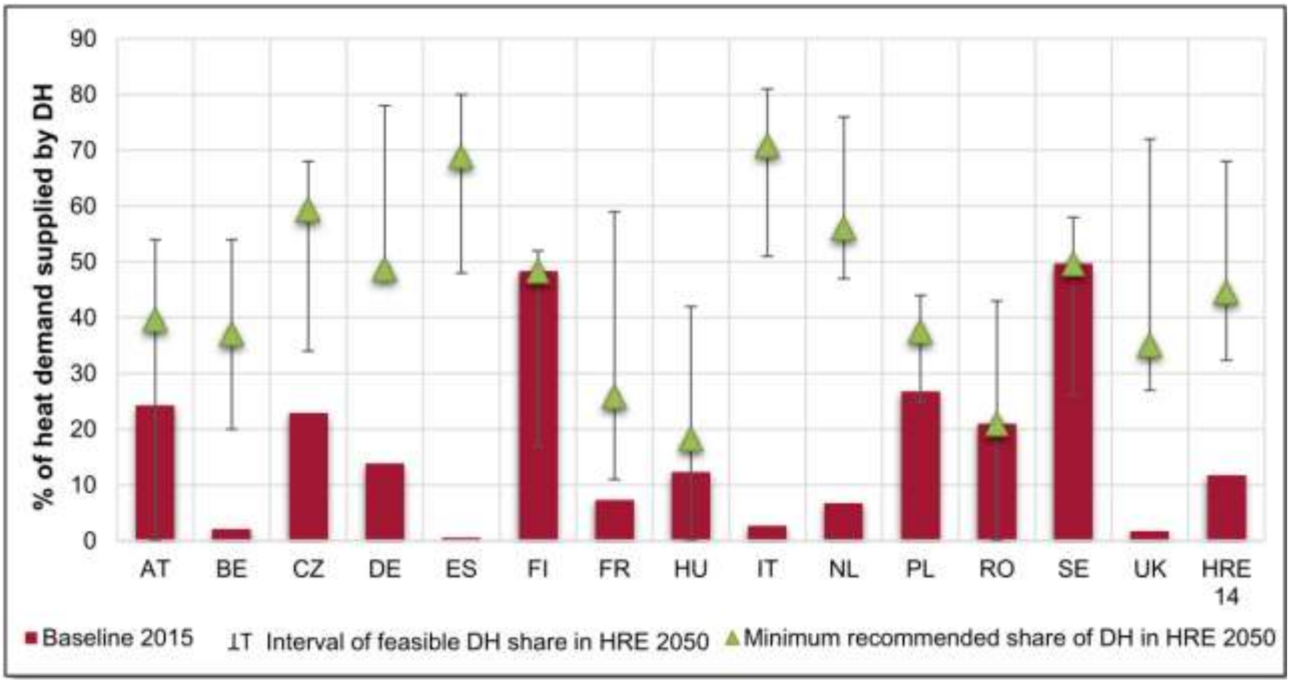

Figure 13: Share of district heating in 2015 (BL 2015), recommended level of district heating share in HRE 2050, and the range of economically feasible district heating within a 0,5% total annual energy system cost change sensitivity [1].

As presented in Figure 13, the current share of DH in the heating market in Europe is 12% (according to the Baseline 2015 scenario). HRE 2050 scenario recommends a share of DH of about 50% of the heat market, which would enable major savings in primary energy supply and CO_2 emissions in the heating sector, opening an opportunity for a full-decarbonised energy system. Having around half of the heat demand in Europe covered by DH would be a major shift for the markets in most of the member states, which shows the importance of a new and integrated approach towards supporting DH as a mean of achieving deeply decarbonised energy systems [1].

Nevertheless, depending on the country, going beyond the recommended values towards the maximum feasible DH levels might bring more benefits such as jobs and industrial development, security of supply and reduced geopolitics tensions, for allowing higher use of domestic fuels. Also, a very high share of DH in the heat market is more cost efficient than a full electrified heating system, which would not enable the recovery of excess heat, neither the creation of a link between the electricity, heating and thermal storage, which would limit the overall efficiency of the system [1].

[1] www.heatroadmap.eu

[2] Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, Netherlands, Poland, Romania, Spain, Sweden and United Kingdom

The scenarios developed in the HER4 project and used in this report are:

- **BL 2015** – this baseline scenario represents the current situation of the heating and cooling sector, based on data from 2015;
- **BL 2050** – This scenario represents the development of the baseline scenario under the current agreed policies regarding savings and RES, etc., but without any additional measures to improve the decarbonisation of the system.
- **HRE 2050** – this scenario represents a decarbonised system with redesigned heating and cooling sector that includes energy savings as well. In this sense, this scenario, includes a high level of performance from buildings and extensive savings in the industry sector, besides including the reuse of excess heat, use of efficient renewables and the use of individual HPs (in rural areas) and large-scale HPs (in district energy networks in urban areas). This scenario is also based on only proven technologies and does not depend on unsustainable amounts of bioenergy [1].

Figure 14 shows the DH shares in the BL 2050 scenario, the range of economically feasible DH shares in the HRE 2050 scenario, as well as the DH level actually modelled in the HRE 2050 scenario.

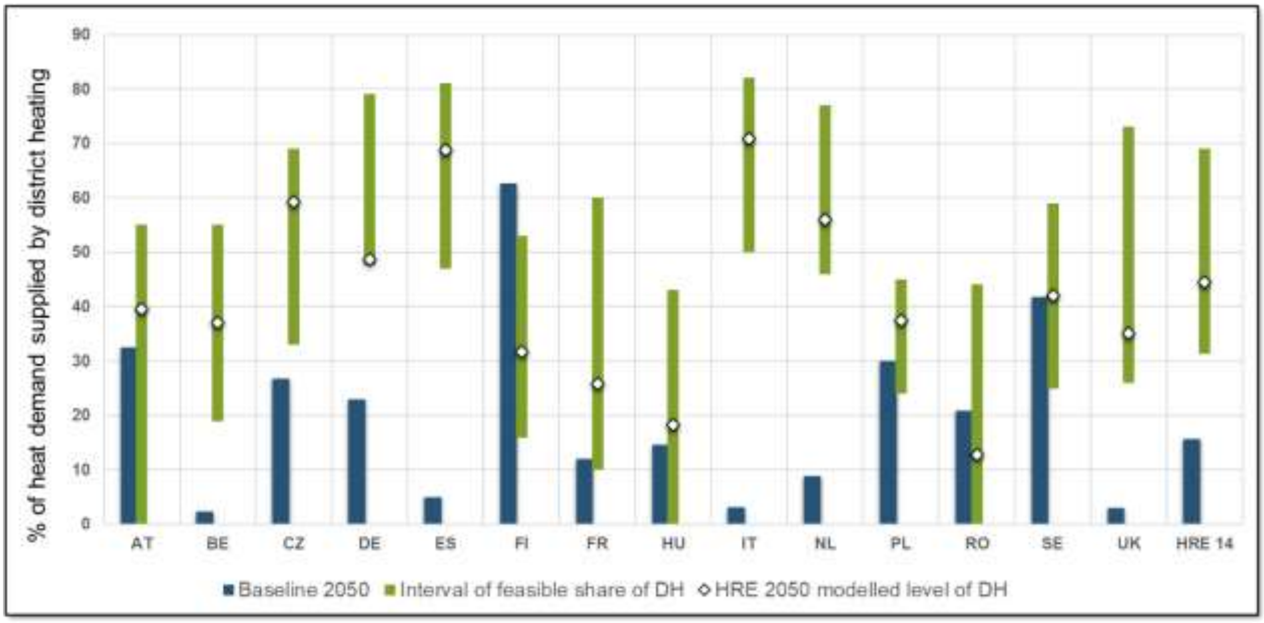

Figure 14: BL 2050 share of district heating, modelled share and interval of economically feasible DH in the HRE 2050 scenario [1]

If we assume that the current trends, policies and goals will not change until 2050, the DH share in the 14 HRE countries will increase but not significantly, reaching around 16% of the heat market (BL 2050 scenario), which represents a very limited development from the current value, which is 12%. On the other hand, the HRE 2050 scenario is modelled with DH covering about 50% of the heat demand in the 14 countries accounted in the project. However, this is a conservative approach, meaning that with additional strategic energy planning measures the DH share could be expanded up to almost 70% of the total heat demand. Although the costs would increase, the higher the share of DH the higher would be some other benefits such as security of supply, jobs creation and industrial development. A very high share of DH in some countries could also mean a decrease of possible geopolitical tensions related to energy supply and the creation of more fuel-efficient systems when it would be possible to recover more excess heat from different sources and to integrate more renewables [1].

The values of DH modelled for the HRE 2050 scenario are based only on economic metrics. Looking at the graphic, the modelled DH levels for Finland and Romania are below the BL 2050 levels due to a "least-cost approach" used. The main reason for the high or low levels of DH in each country is the spatial density of the heat demand in the urban areas and the excess heat available nearby [1].

4.1.1 District heating supply

The DH supply for the HRE 2050 scenario is designed in order to avoid the direct use of fossil fuels. However, although excess heat from industries and cogeneration might be of fossil-fuel origin, it is accounted in the scenario in order to make use of heat sources that already exist and improve the overall system's efficiency [1].

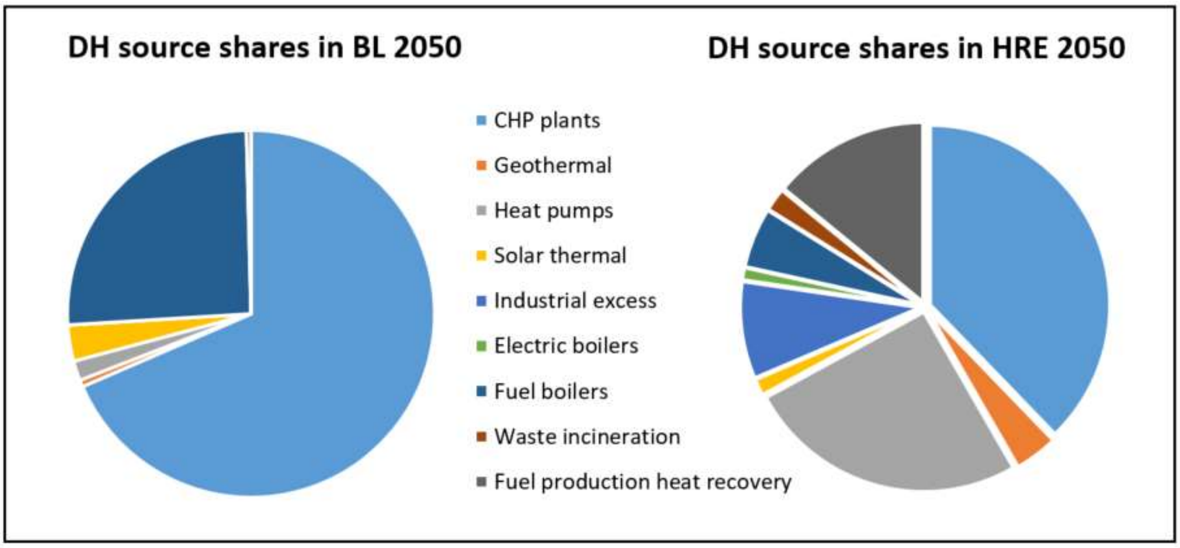

Figure 15: District heating sources share for BL 2050 and HRE 2050 scenarios (Source HRE4 project)

Figure 15 shows the shares of the DH supply for the BL 2050 and HRE 2050 scenarios, respectively. If there would be no changes in the current trends of heating and cooling policies, according with the **BL 2050** scenario, the **total DH production in the 14 countries would be 550 TW$_{th}$h/year**. 69% of this amount would be supplied by CHP, 26% would still be supplied by fuel boilers, 17% by solar thermal and only **2% would be supplied by large-scale HPs**. The BL 2050 scenario would not be a scenario favourable to a decarbonised energy system and neither would it improve the penetration of renewables.

On the other hand, the **HRE 2050** scenario shows that, even with conservative projections, it would be possible to achieve a much more decarbonized DH in 2050. With **a total of 1100 TW$_{th}$h/year of DH production**, 38% would be supplied by CHP, **25% by large-scale HPs**, 14% would have origin in recovered excess heat from fuel production and 9% from industrial excess heat. Renewables would be also integrated in higher scale in this scenario, with 4% of geothermal, 1% of solar thermal and electricity from wind being used to feed in the large-scale HPs. **This scenario would bring a higher variety of energy supply to the DH, increasing the flexibility of the system as well as it security of supply**.

Since HRE4 modelled 90% of the European heat market, the results of this project are actual references to what all European members states should aim for when designing heating and cooling systems for the future. In the following section the potentials for large-scale HPs in the BL 2015, BL 2050 and HRE 2050 will be presented, giving an indication of what should be the future market share for this technology in Europe.

4.2 Large-scale HPs in the HRE scenarios

As Figure 15 shows, large-scale HPs have a very important role in the HRE 2050 scenario. With a **market share of 25%** in the HRE 2050 scenario, the DH supply from large-scale HPs would **increase from 10 $TW_{th}h$/year, in the BL 2050, to 280 $TW_{th}h$/year, in the HRE 2050 scenario**. The reason behind this major increase is the fact that large-scale HPs can deliver heat with high efficiency while creating a link between the heat and the electricity sector with the use of intermittent RES – enabling an overall decarbonisation of the energy system and the possibility to make DH an integrated part of a SES. However, in order to integrate variable renewable sources, the HPs would have to operate in a flexible way, using most of their capacities during the hours when wind and solar electricity are abundant. When the heat demand is already covered, their work could be used to fill in thermal storages, allowing for further integration of intermittent renewables [1].

The characteristic of the large-scale HPs modelled in the HRE4 scenarios are based on the most common technologies available in Europe nowadays, but excluding HFCs as working fluids, limiting the COP to around 4. Using a relatively low COP is part of the conservative approach of the HRE 2050 scenario, meaning that there is technical potential to improve the share of heat produced by large-scale HPs when new ways to improve the COP are found. As heat sources, large-scale HPs in the HRE project used only water bodies, rivers and sewage water as low-temperature reservoirs [1].

In the existing DH systems, large-scale HPs installed operate close to 100% of the time in full capacity, which differs greatly from what happens in the BL 2050 and HRE 2050 scenarios. If large-scale HPs would be allowed to work only either at full capacity or being turned down, in the BL 2050 scenario large-scale HPs would work 67% of the time while in the HRE 2050 scenario they would work only 33% of the time during a whole year. What happens is that in the 2050 scenarios, with more wind capacity installed, large-scale HPs always work at least at a minimum capacity (5% of the total capacity), and when wind power is abundant, they work with higher capacities, depending on the amount of wind available or on the heat demand at that time [1]. The following figures illustrate the process for the case of Sweden.

The case of Sweden (SE) was chosen because it is the country with higher share of large-scale HPs in the baseline scenario and has abundant onshore wind.

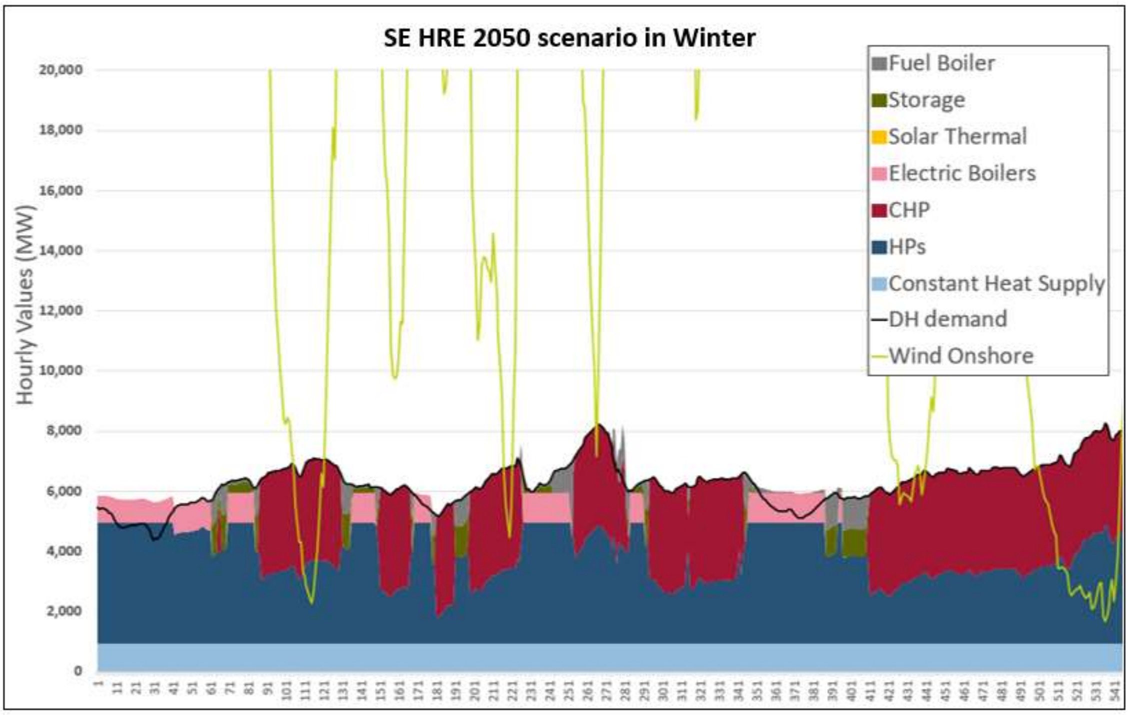

Figure 16: CHP and large-scale HPs heat production, onshore wind power and DH demand during the first hours of the year in the SE HRE 2050 scenario (Source HRE4 project)

Figure 16 is a section of the first days of January 2050 in Sweden in the SE HRE 2050 scenario. In the graphic, "Constant Heat Supply" refers to the combination of heat from waste incineration, geothermal, industrial excess heat recovery and fuel production heat recovery. It is assumed that this amount of heat will be constant throughout the year and covers the minimum DH demand needed, which is the amount of DH needs during the Summer months.

In general, the wind is stronger during the Winter, which is also when there is higher DH demand and therefore HPs are working in higher capacities. When large-scale HPs are working at full load, CHP are shut down, which happens during hours when more wind is available. When the heat delivered from HPs at full load still does not cover the DH demand, electric boilers are turned on, also to make use of the excess electricity production during these peak hours. When the combination of heat from "Constant Heat Supply", with HPs and Electric Boilers covers more than the DH demand, there will be excess heat transferred to thermal storages.

In hours where the wind power production levels are not high enough to make HPs work at full load, the CHP are turned on. Is these cannot meet the DH demand, there heat used from thermal storage and finally, Fuel Boilers are turned on in order to meet the DH demand.

In the SE BL 2050 scenario, the onshore wind installed capacity is 5 times lower than the values modelled for the SE HRE 2050 scenario. Nevertheless, it is still possible to see, in Figure 17, that large-scale HPs are used in a flexible way but without much variation between minimum and full load operations.

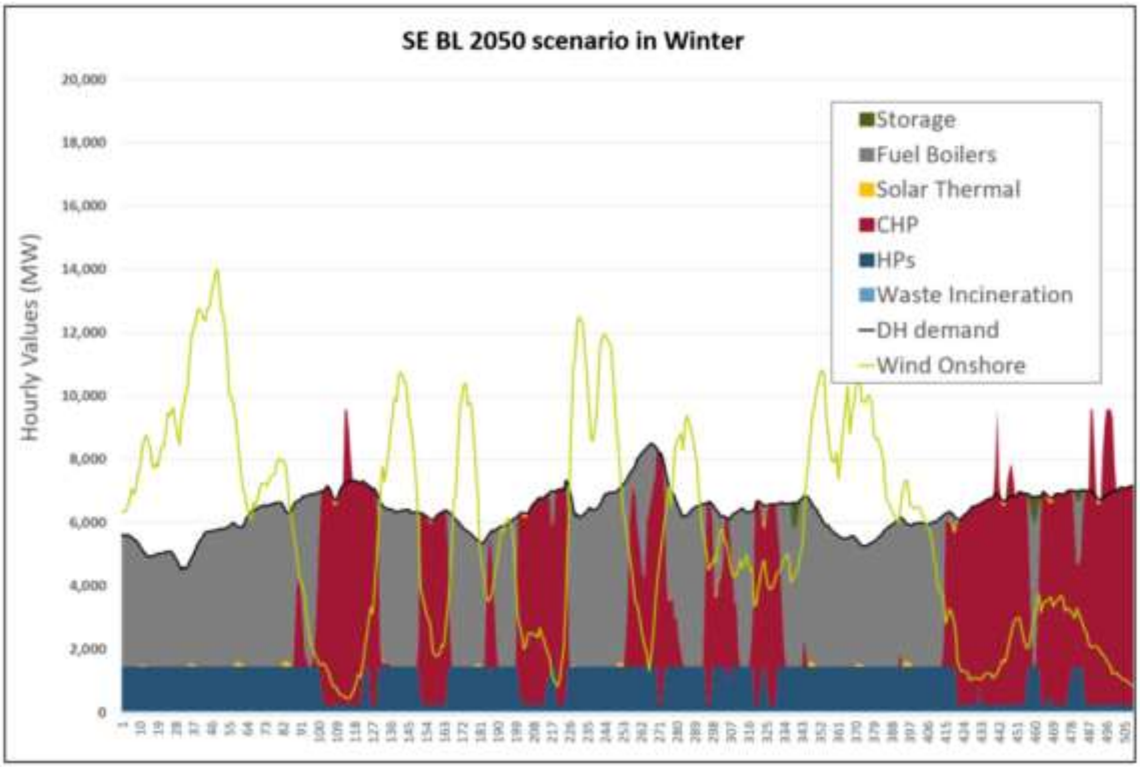

Figure 17: CHP and large-scale HPs heat production, onshore wind power and DH demand during the first hours of the year in the SE BL 2050 scenario (Source HRE4 project)

Because there is not much large-scale HPs capacity installed, neither electric boilers, during the hours with high wind power production Fuel Boilers have to cover most of the DH demand.

In hours where there is a low level of wind power, the HPs are turned down to the minimum load and are replaced by CHP to cover the total DH demand. CHP will in produc excess heat in hours with very low levels of wind, in order to feed in the electricity greed, and the excess heat will feed in thermal storage. The heat from thermal storage is used when there is a need to cover DH demand in hours with low wind power.

There is a constant heat supply from waste incineration, however its value is very low and difficult to find it on the graphic, which is placed bellow the HPs heat supply.

By the end of the Spring, the DH demand decreases until it reaches a constant minimum during the Summer months.

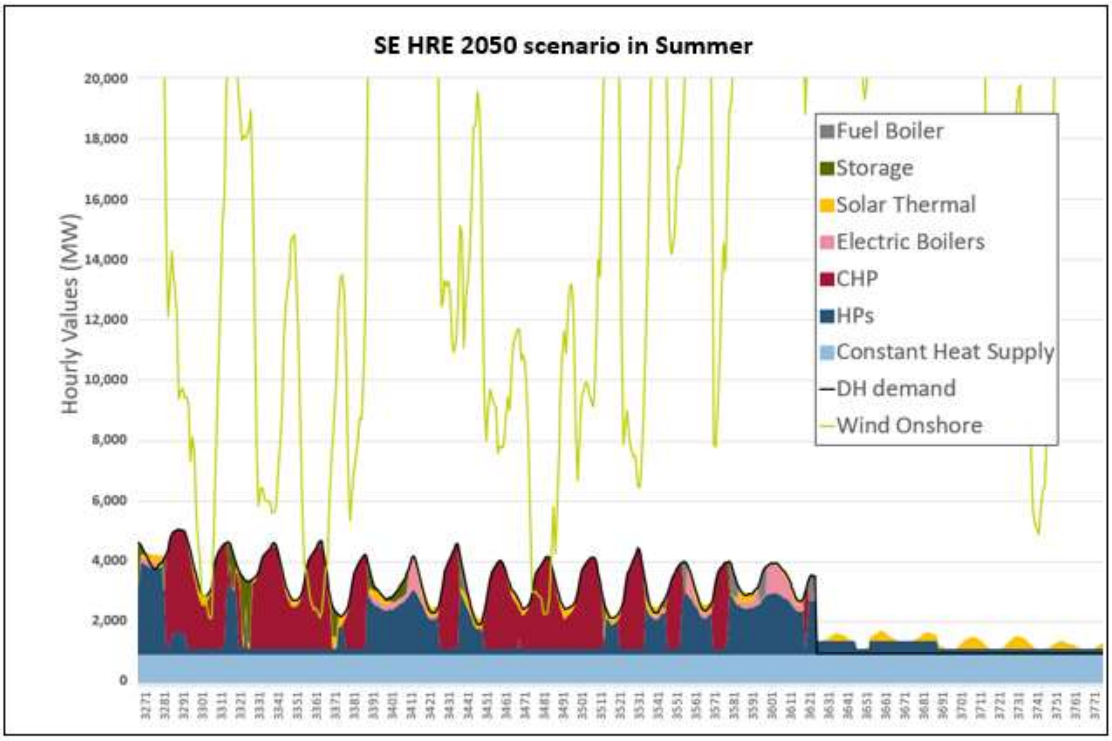

Figure 18: CHP and large-scale HPs heat production, onshore wind power and DH demand between the middle of April and the middle of May 2050 in the SE HRE 2050 scenario (Source HRE4 project)

As shown in Figure 18, in the SE HRE 2050 scenario, large-scale HPs are still in use during high levels of wind power production until they are kept to a constant minimum load (190 MW), during the time that the DH demand also reaches its constant minimum. It is also possible to see that the levels of wind power production decrease during the Summer months, not enabling the HPs to function at full capacity.

The levels of solar thermal are now higher and used to cover part of the DH demand before this one decreases to the minimum levels.

In the Summer in the SE BL 2050 scenario, the tendency is similar to the one presented in the previous figure, with the main difference that Fuel Boilers still cover a high share of the DH demand, although there is also solar thermal available during the warm months.

By comparing the graphics representing the SE HRE 2050 and the SE BL 2050 scenarios, it is possible to see that in the HRE scenario, the high share of HPs installed capacity is used in a more flexible way, not operating simply at full or minimum capacities only. In the SE HRE 2050 scenario, HPs and CHP work together to supply most of the DH demand.

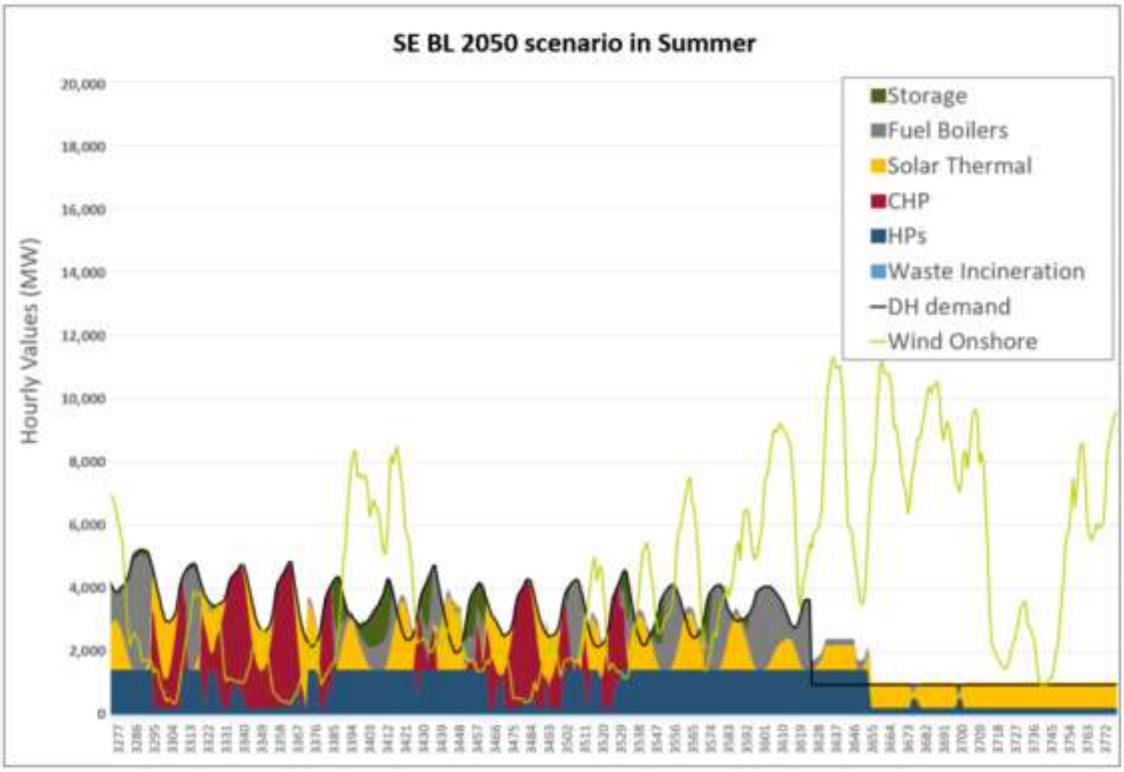

Figure 19: CHP and large-scale HPs heat production, onshore wind power and DH demand between the middle of April and the middle of May 2050 in the SE BL 2050 scenario (Source HRE4 project)

4.2.1 Large-scale HPs installed capacities

In order to provide the DH demand for the HRE 2050 scenario, the total installed thermal capacity of DH technologies would have to be around 400,000 MW_{th}, where **95,000 MW_{th} corresponds to the total installed capacity of large-scale HPs, representing a share of 23% in the DH network** [1].

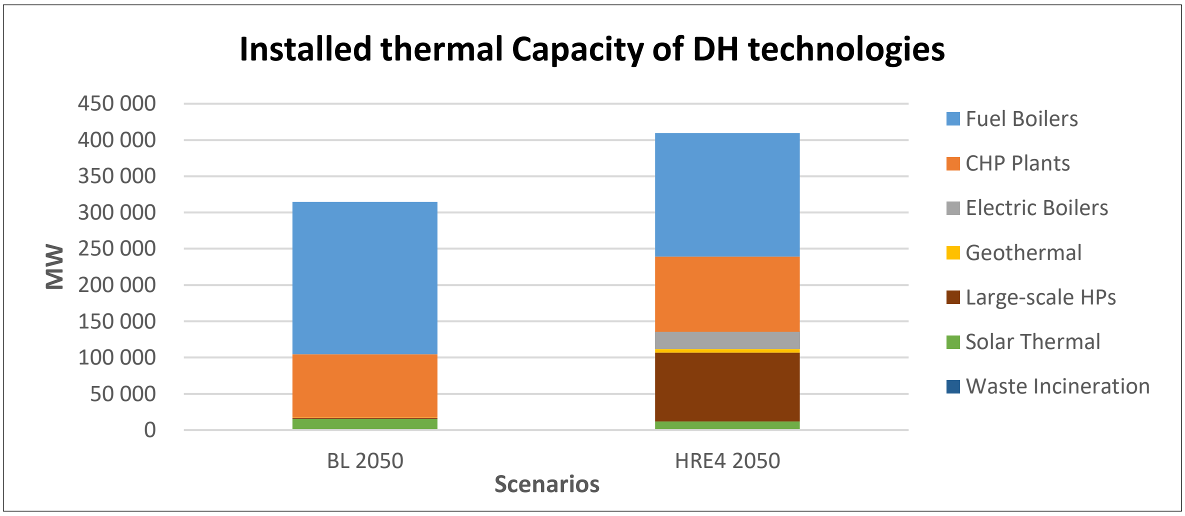

Figure 20: Installed thermal capacities of DH technologies in the BL 2050 and HRE 2050 scenarios (Source HRE4 project)

When comparing the installed capacity for DH in the BL 2050 scenario and the HRE 2050 scenario, as presented in Figure 20, it is possible to see that large-scale HPs have the biggest increase of installed capacity, showing the importance HPs will have in the future to build decarbonised and efficient DH systems. In fact, in the HRE 2050 scenario there is an intentional overcapacity of large-scale HPs installed to allow them to function in a flexible way. The following table presents the installed capacity of large-scale HPs in each HRE country, as well as the heat they produced and the percentage of full load hours they operate per year.

Table 5: Installed capacity and heat produced by large-scale HPs, percentage of full load hours HPs operate per year and DH production in the HRE 2050 scenario (Source HRE4 project)

Country	Installed capacity of large-scale HPs (MW_{th})	Share of Installed capacity of HPs in the DH	Heat produced by Large-Scale HPs ($TW_{th}h$/year)	Share of heat produced by HPs in the DH ($TW_{th}h$/year)	Percentage of full load hours HPs operate per year	Total DH production ($TW_{th}h$/year)
AT	4,800	37%	10	34%	24%	30
BE	4,000	31%	9	27%	26%	34
CZ	4,000	28%	10	27%	29%	38
DE	22,000	24%	64	24%	33%	265
ES	8,000	29%	21	26%	30%	81
FI	2,800	22%	11	36%	43%	30
FR	6,400	29%	13	16%	24%	85
HU	1,000	19%	3	26%	36%	12
IT	10,400	11%	48	23%	53%	210
NL	5,600	21%	19	28%	38%	66
PL	6,800	26%	16	26%	28%	62
RO	1,600	27%	4	31%	28%	13
SE	4,000	33%	12	34%	33%	34
UK	13,600	29%	38	28%	32%	136
HRE14	**95,000**	**23%**	**279**	**25%**	**33%**	**1,097**

From Table 5, according with the HRE 2050 scenario, it is possible to see that in some countries large-scale HPs will cover higher shares of the future heat market, such as in Austria, Finland, Romania and Sweden. It is worth to mention that the total heat produced by HPs is not directly proportional to the installed capacities because for each country HPs operate on full capacity during different periods. This is how the DH systems in each country were modelled, however there is potential to increase these levels. It is recommended that large-scale HPs operate on full load hours for about half of the time during a year. This means that without increasing the installed capacities, large-scale HPs could have a much higher share in the heat market while still being able to operate in a flexible way. In the HRE 2050 scenario, if large-scale HPs would operate in full load capacity half of the time during a year, they would have **a heat market share of 38%** of the DH production (Table 6).

Table 6 shows how much would be the heat market for large-scale HPs in each country if they would operate half of the time at full load hours, in the HRE 2050 scenario. According with these values, there is potential to optimize the operation of large-scale HPs in the DH systems modelled in the HRE 2050 scenario. Without increasing the installed capacities of this technology, it would be possible to have higher shares of heat produced by large-scale HPs if they would operate for more hours during the year at high capacities, while still maintaining their flexible way of operation in connection with the operation of CHP.

Table 6: Installed capacity and heat produced by large-scale HPs, percentage of full load hours HPs operate per year and DH production in the HRE 2050 scenario (Source HRE4 project)

Country	Total Heat produced by large-scale HPs ($TW_{th}h$/year)	Share of heat produced by HPs in the DH system ($TW_{th}h$/year)	Percentage of full load hours large-scale HPs operate per year	Total Heat produced by Large-Scale HPs when operating half of the year at full load hours ($TW_{th}h$/year)	Share of heat produced by large-scale HPs when operating half of the year at full load hours in the DH system ($TW_{th}h$/year)
AT	10	34%	24%	21	70%
BE	9	27%	26%	18	51%
CZ	10	27%	29%	18	46%
DE	64	24%	33%	96	36%
ES	21	26%	30%	35	43%
FI	11	36%	43%	12	41%
FR	13	16%	24%	28	33%
HU	3	26%	36%	4	36%
IT	48	23%	53%	46	22%
NL	19	28%	38%	25	37%
PL	16	26%	28%	30	48%
RO	4	31%	28%	7	55%
SE	12	34%	33%	18	52%
UK	38	28%	32%	60	44%
HRE14	**279**	**25%**	**33%**	**416**	**38%**

The HRE 2050 scenario included conservative estimations also related to the installed capacities. For the DH systems, only electric compressor large-scale HPs were considered in this project, with output temperatures of 80-100° C, and using as heat sources bodies of water available nearby urban areas. To make the system more efficient, excess heat from industry or power production that has temperatures high enough to be directly incorporated in the DH grid were also included, which is the cheapest heat source. However, low-temperature excess heat sources that would require HPs to upgrade the delivered temperature were not included in the analysed scenarios. Although low-temperature heat sources in urban areas are available, they are not considered in the HRE project because this would require further geographical data and analyses. Nevertheless, there is a high potential for the use of large-scale HPs to upgrade low-temperature heat sources in order to increase their share in the DH [1].

Low-temperature excess heat sources are defined as excess heat from services, industry or specific buildings, and have temperatures between 5°C and 40°C. These excess heat sources need to have their temperatures lifted in order to be integrated in 3rd generation DH systems that, on average, operate with supply temperatures above 80°C. This low-temperature heat sources were investigated under the project ReUseHeat and are divided into four indicative unconventional excess heat sources, not representing the total diversity and amount of low-temperature heat sources available [15].

Table 7 presents the potentials for low-temperature excess heat sources in Europe that could be recovered to DH grids, while being upgraded with the use of large-scale compressor HPs with COP of 3. This low-temperature heat sources were investigated under the project ReUseHeat[3] and are divided into four indicative unconventional excess heat sources, not representing the total diversity and amount of low-temperature heat sources available [15].

[3] www.reuseheat.eu

Table 7: Accessible low-temperature excess heat in HRE14 countries, from four type of unconventional sources, within 2 km from urban DH networks [15]

Country	Data Centres 25°C - 35°C (TWthh/year)	Metro stations 5°C - 35°C (TWthh/year)	Service Sector Buildings 30°C - 40°C (TWthh/year)	Waste-water Plants 8°C - 15°C (TWthh/year)	Total 5°C - 40°C (TWthh/year)
AT	2.0	0.3	0.8	6.6	9.8
BE	2.5	0.3	2.3	4.0	9.1
CZ	1.8	0.3	0.5	5.5	8.0
DE	16.3	2.0	7.4	33.7	59.3
ES	4.8	2.9	16.5	6.3	30.5
FI	2.6	0.1	0.6	3.4	6.7
FR	12.7	3.1	13.9	23.8	53.5
HU	1.3	0.3	1.1	4.5	7.2
IT	5.7	1.6	19.1	11.1	37.5
NL	2.3	0.2	0.7	4.3	7.4
PL	4.3	0.2	2.2	18.6	25.2
RO	1.4	0.3	2.2	5.1	9.0
SE	3.7	0.3	1.5	5.6	11.1
UK	7.7	0.8	6.7	25.9	41.1
HRE14	**69.1**	**12.7**	**75.5**	**158.1**	**315.4**

In Table 7, only the unconventional low-temperature heat sources that exist within 2 km form urban areas are accounted [15]. These extra potential to recover excess heat into the DH systems means that the installed capacities of large-scale HPs might be even bigger in the future than what has been estimated by the HRE project, if they will be also used to recover heat from unconventional heat sources. In fact, the amount of heat that could be theoretically recovered from these unconventional sources is so significant that could replace completely the need of fuel boilers in the BL 2015 and HRE 2050 scenarios and still reduce the need for other energy demanding heat sources. However, it is not possible to conclude on the financial benefits of, for instance, replacing completely the fuel boiler without further analyses of the whole energy system. For reference, Figure 21 presents the level of accessible low-temperature excess heat in the 14 HRE countries compared with the DH production in the BL 2015 and HRE 2050.

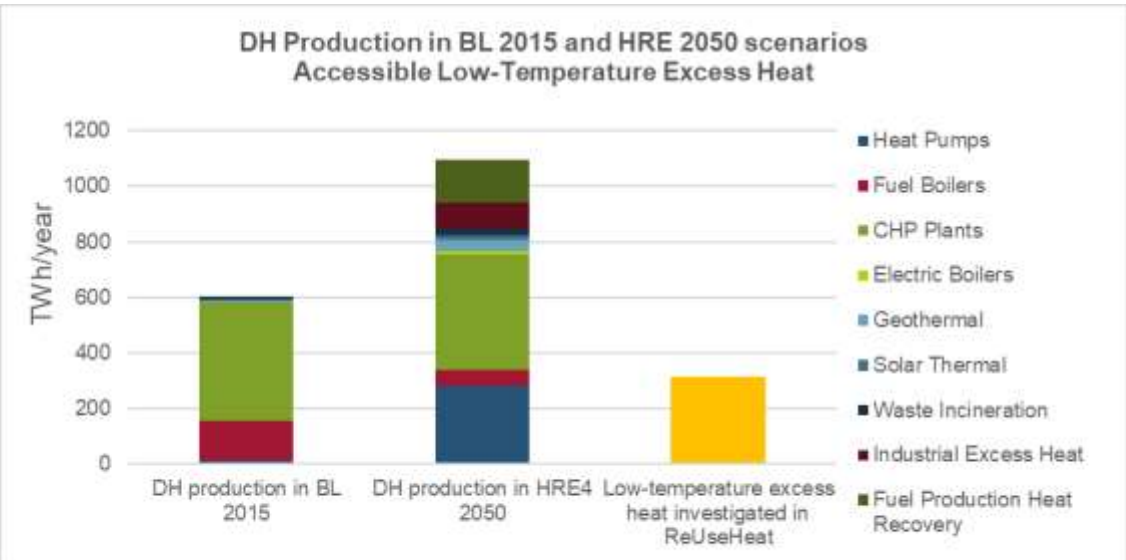

Figure 21: Comparison between the DH production in the BL 2050 and HRE 2050 scenarios and the accessible low-temperature excess heat in the 14 HRE countries (Source HRE4 project and [15]).

Figure 21 shows that the results for the large-scale HPs potential in the HRE 2050 scenario (where only water bodies, rivers and sewage water are used as low-temperature heat sources) are likely very conservative compared with the real potential. The amount of accessible low-temperature excess heat from unconventional sources in Figure 21 is merely indicative of the fact that the potential for large-scale HPs in future energy systems might be much higher than the one predicted in the HRE project. Besides, further technology improvements are possible, especially when aiming for low-temperature DH and a 4th generation DH. If the required temperature for DH would be lower, between 50°C and 60°C, it would be possible to recover a higher amount of heat from unconventional low-temperature heat sources, while still using large-scale HPs with a COP of 3 to uplift the temperatures.

4.2.2 More integration of renewables

In the HRE 2050 scenario the electricity production is much higher than in the baseline scenarios because it is assumed a very high level of electrification of the industry and transport sectors and there is also a high demand of electricity for the production of electrofuels. This broader diversity of electricity sources is what gives the system a high level of flexibility and it is only possible due to the synergy between the electricity and heating sectors, created with the use of large-scale HPs [1].

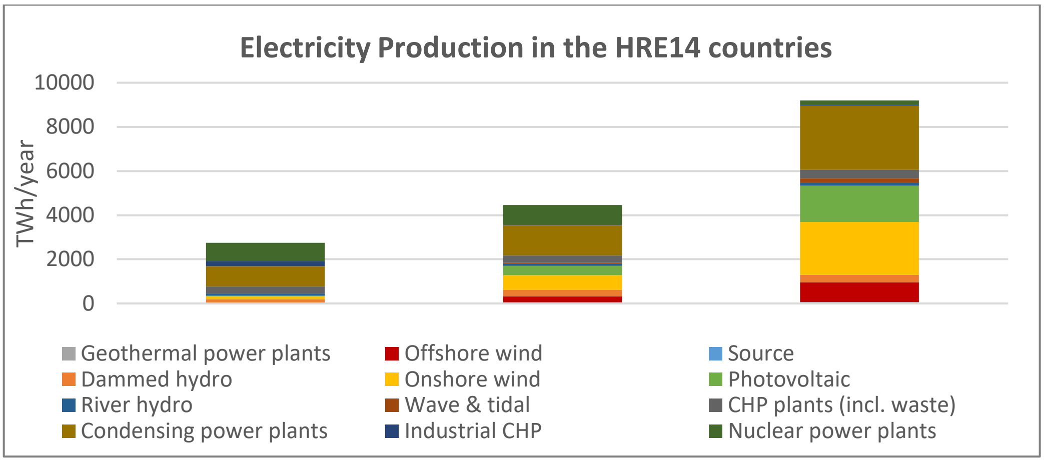

Figure 22: Electricity production in the BL 2015, BL2050 and HRE 2050 scenarios (Source HRE4 project)

As presented in Figure 22, renewables account for a higher share in the HRE 2050, representing 64% of the electricity production, while in the BL 2050 they only account for 42%. Onshore wind is the RES with higher share in the HRE 2050 scenario.

The higher share of renewables being integrated in the energy system, will lead to lower CO2 emission levels. As it can be seen in Figure 23, HRE 2050 scenario represents a deeply decarbonised system with much lower emissions compared with the baseline scenarios.

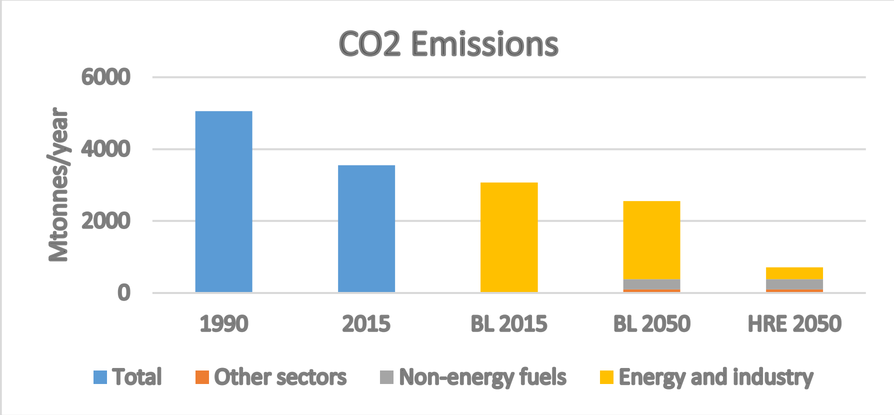

Figure 23: CO_2 emissions for the HRE14 countries (Source HRE project)

4.2.3 DH Implementation Costs

The HRE 2050 scenario has a high degree of decarbonisation and its high level of energy efficiency measures makes it the scenario where more investments have to be made in the DH networks. Expanding the DH grids and achieve the installed capacity modelled in the HRE 2050 scenario requires some significant investments. However, these investment would only represent 14% of the total investments necessary in the heating and cooling sector (which includes very high level of investments in savings) [1]. The annualized costs of the investments for all the components needed to expand the DH grid can be found in Figure 24.

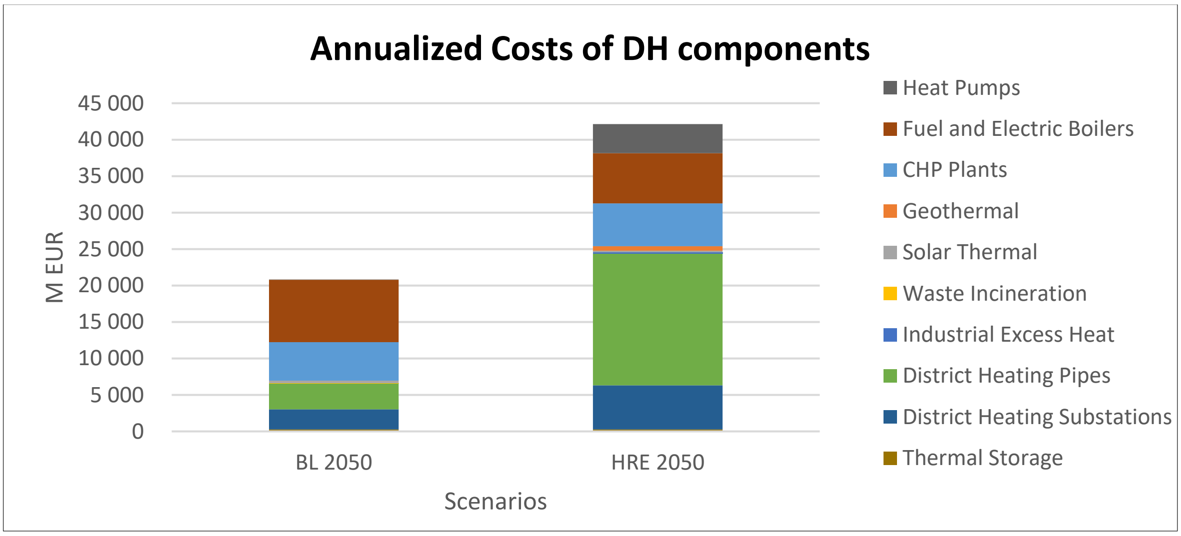

Figure 24: Annualized costs of DH components in both BL 2050 and HRE 2050 scenario (Source HRE4 project)

Although HPs will play a very important role in the future DH systems and that their installed capacity has to increase significantly, the biggest investments will be allocated to DH pipes (more than 40% of the investment) for the grid expansions. The investment in increasing the installed capacity of HPs in DH will represent 10% of the total annualized costs.

It is important to mention that, compared with other traditional technologies in the heating sector, large-scale HPs can be considerably expensive but at the end might enable considerable savings in the operation costs [8].

Policy limitations and cost of fuels also affect the market share of HPs and might have a bigger impact on their market development than technological limitations. When fossil fuels are cheap, or while biomass, although a limited resource, still have higher financial incentives, it might be more difficult for HPs to penetrate the market. Because of the lack of incentives, large-scale HPs end up with higher investment costs than their competitors. If the fuel prices are high or there are more subsidies to encourage the use of HPs, these ones would be more profitable even with low COP. At the end, it is a matter of making large-scale HPs more known and policy-makers aware of their high socio-economic benefits in order to be considered for tax exemptions or other promoting schemes to help expanding this technology [5].

4.3 District cooling

In the HRE 2050 scenario, district cooling accounts for less than 5% of the cooling market and it is mainly used for the industry and services sectors. However, this result is based on estimations, that besides being based on a conservative approach, they lack the rigorousness used to analyse the heat market. This means that this result is an underestimation of the share district cooling could have in the future, leaving space for further research. Cooling is growing rapidly and faster than any other thermal sector, nevertheless its relatively smaller demands compared to the heat sector will keep its impacts on the whole energy market very limited [1].

Nevertheless, the more district cooling networks are installed, the higher the demand would be for large-scale HPs, and if the energy systems are designed with a SES approach, there would be potential to have those HPs operating simultaneously to supply the DH and the district cooling grids in order to optimize the system performance [16].

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