Perspectives of deployment of Large Heat Pumps (LHPs) combined with waste heat recovery and powered by renewable green electricity in fourth-Generation District Heating (4GDH)

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Abstract. The decarbonization of the heating sector is a central component of the European Union's energy and climate strategy, as reinforced by the revised Energy Efficiency Directive (EU) 2023/1791) [1] and the Renewable Energy Directive (RED III) [2]. These frameworks mandate the progressive deployment of heating and cooling efficient systems, in all sectors, which must integrate increasing shares of renewable energies, high energy efficiency technologies and possibly allow waste heat recovery. Within this legislative landscape, beside the wide range of individual heating solutions for the different fields of residential, commercial and industrial applications, fourth-generation district heating (4GDH) systems are emerging as a very valuable solution for the future, in particular if they will be able to provide low primary energy space heating and cooling inside buildings and use innovative technologies to recover waste heat. In this paper we investigate the possible solutions of waste heat recovery trough the adoption of Large Heat Pumps (LHPs), more commonly known as HTHP (High Temperature Heat Pumps) and VHTHP (Very High Temperature Heat Pumps), alimented as much as possible by green electricity coming from renewable energy sources.

1 Introduction

In recent decades EU guidance on urban energy planning, specifically for space heating and cooling inside buildings, emphasizes the integration of heat pumps, low-temperature networks, large use of renewable energies and waste heat sources as key enablers for reducing greenhouse gas emissions and enhancing system efficiency, including industries and energetic communities. A new vision related to individual (residential, commercial and industrial) heating from renewable energies sources and district heating is taking place.

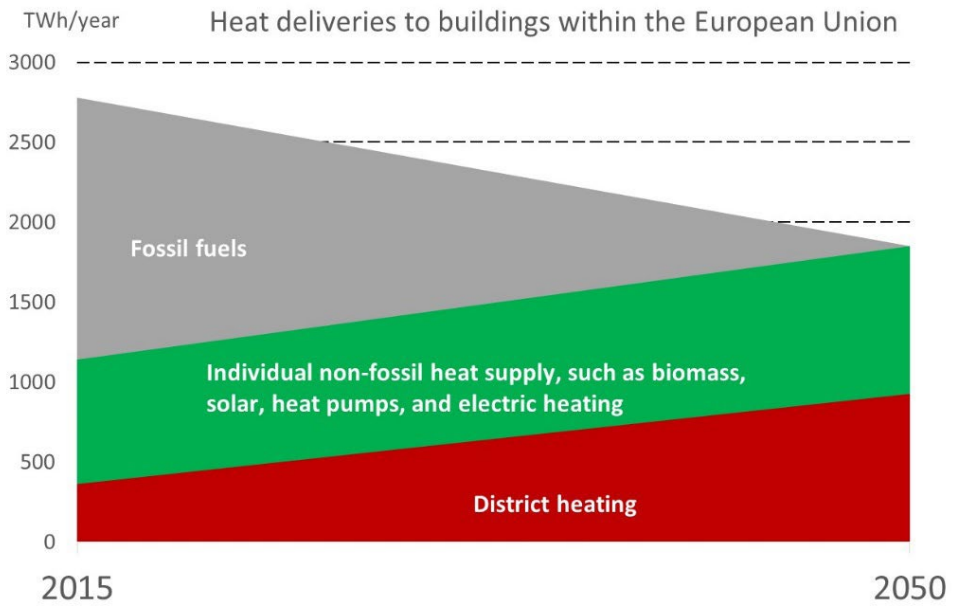

Diagram 1. Possible transition from the current heat supply (expressed with the origins of the supply) to buildings within the EU being fully decarbonised by 2050, according to the Heat Roadmap Europe cluster project. Source: Implementation of low-temperature district heating systems.IEA DHC Annex TS2 [3]

Within this landscape district heating, and in particular fourth-generation district heating (4GDH) systems, operating at substantially reduced supply and return temperatures, have emerged as a highly suitable platform for enabling large-scale integration of industrial and urban waste heat, renewable energy in air, water and ground (that can be captured by heat pumps) as well as green electricity from Variable Renewable Energy Sources (VRES) such as wind and solar. Lower network temperatures reduce distribution losses, improve the coefficient of performance (COP) of heat pumps and allow efficient harvesting of low-temperature resources, thereby supporting sector coupling between electricity and heat. In general, Northern EU countries, and in particular Denmark, provides some of the most advanced operational examples in Europe. A flagship Renewable District Heating installation is the Esbjerg (Copenhagen, DK) [4] seawater large heat pump, comprising two 50 MW CO_2 , for a total peak capacity of 100 MW. Powered primarily by nearby offshore wind resources, in terms of energy, the system delivers approximately 350 GWh of heat annually and replaces a former coal-fired plant, supplying heat to around 25.000 households while reducing CO_2 emissions substantially.

These deployments align with findings from European demonstration projects such as REWARD Heat [5] and LIFE4HeatRecovery [6], which show that low-temperature DHC networks combined with heat pumps and distributed waste-heat sources can substantially reduce system-level emissions.

Fig 1. Example image, not exhaustive, just for illustrative purpose of MAN Industrial Heat Pump installed in the modern heat pump hall near the Esbjerg Harbor (Denmark) [4] which houses the world's largest seawater (Renewable Energy Source according to RED Directive) heat pump, which replace coal-fired heat plant for district heating application. Electricity for the heat pumps is generated by giant offshore wind farms producing an abundance of clean energy, making the district heating 100% based on renewable energy.

2 District heating generations main characteristics

Since a few years ago (e.g. before 2010) the world was simple when it came to describing District Heating Systems (DHS). The systems were generally based on steam, hot water or warm water. The pipes were either laid in concrete channels or pre-insulated, and the supply temperature was from 70°C to more than 200°C. District heating was based on relatively few production technologies.

The scientific community is nowadays identifying four generations of DHS, which describe the historical development of these solutions since the introduction of the first systems in the 1880s in the USA to the modern low-temperature systems (called 4th Generation DH) introduced recently in many countries. The generation dividers are the periods when each generation's technology was used as the best available technology.

The 1st generation of DH systems (1GDH) was based on steam distribution systems and was recognized as the best available technology between 1890 and 1930. Steam distribution is still found today in parts of larger urban DHS. In most cases, however, plans exist for gradually transforming these parts into hot water systems.

The 2nd generation of DH systems (2GDH) uses hot water with rather high supply temperatures above 100 °C as a heat carrier and was recognized as the best available technology between 1930 and 1980.

The 3rd generation of DH systems (3GDH) was characterized by further temperature reductions below 100 °C, but also the introduction of pre-insulated pipes and pre-fabricated substations. This 3GDH technology is recognized as the best available technology since about 1980 and is currently utilized in all European district heating systems.

The expression of 4th generation DH systems (4GDH) was introduced by an IEA DHC (District Heating and Cooling) expert group in the late 2000s. 4GDH stands for a family of many different network configurations that apply new technological features and concepts using low temperatures below 70 °C and which are considered best available from 2020 onward. In the first three generations of DHC systems, the supply temperature and capacity in the distribution networks was always high enough to satisfy local heat demands in all points of the network. This concept can be labelled as warm district heating (WDH). The 4GDH extends the variety of distribution concepts to so called cold district heating systems (CDH) or thermal source networks (TSN). In these cases, an additional decentralized heat supply (e.g. decentralized proximity HP) can be required to cover the customer temperature demands.

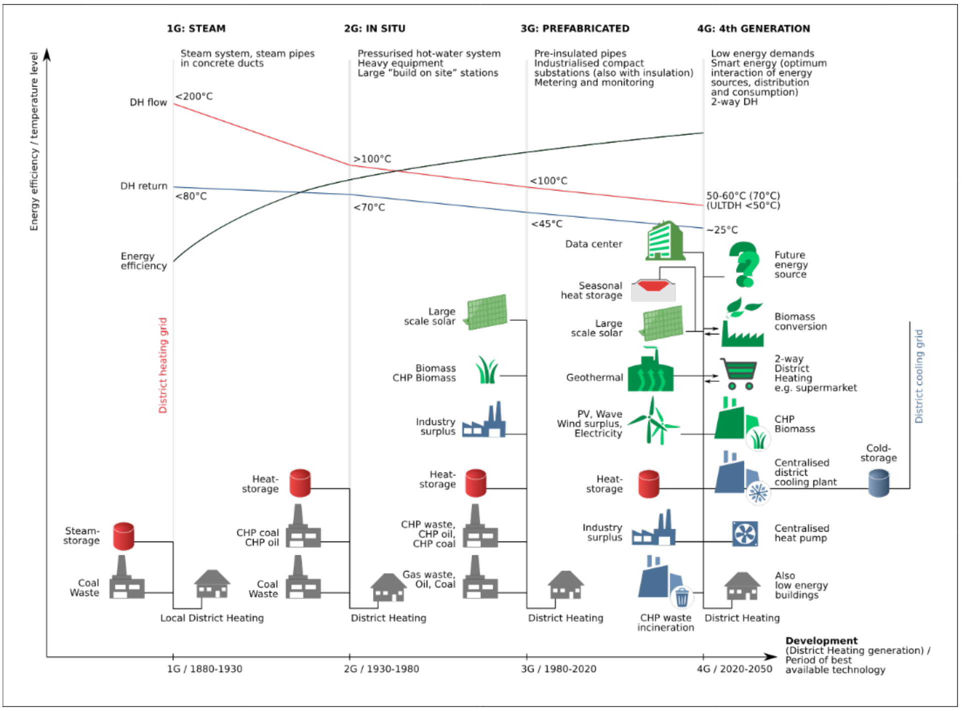

Fig. 2. The different types of District Heating according to the article: 4th Generation District Heating (4GDH) Integrating Smart Thermal Grids into future sustainable energy systems [7]

It is very important to consider that recent definitions expressed by IEA [8] also introduces the concept of 5th generation District Heating Networks DHNs as "thermal source networks" (TSNs) including cooling beside heating energy.

5G District Heating and Cooling Networks (5GDHCNs) consist of a warm and a cold pipe with temperatures close to ground temperature (5-30 °C) [9], [10], [11], [12], [13]. In heating mode, heat-pumps (HP) extract heat from the network, and the cooled water is returned to the cold pipe. Water temperature in the building is raised using the extracted heat [12]. The inverse principle is used to deliver cooling, injecting heated water back to the warm pipe. This strong coupling between warm and cold sides induced by the usage of decentralized HP is the essence of 5G networks. This supports electrification, allows the integration of decentralized renewable energy (RnE) and ultra-low temperature waste-heat [9]. Each customer becomes a prosumer. IEA also express the important concept that 5G District Heating and Cooling Networks (5GDHCNs) are often considered a separate generation of district heating. It has been shown that so-called “5th generation district heating networks” can be in many ways less beneficial than the “4th generation district heating networks”[14], [15] if only heating is considered.

3 Possible sources of “waste heat” that can be efficiently used for district heating

Industrial waste heat represents one of the largest untapped energy resources globally and constitutes a strategic pillar for the decarbonisation of heating systems. According to the International Energy Agency (IEA), a substantial share of the primary energy consumed in industrial processes is ultimately discharged as waste heat, often at low and medium temperatures.

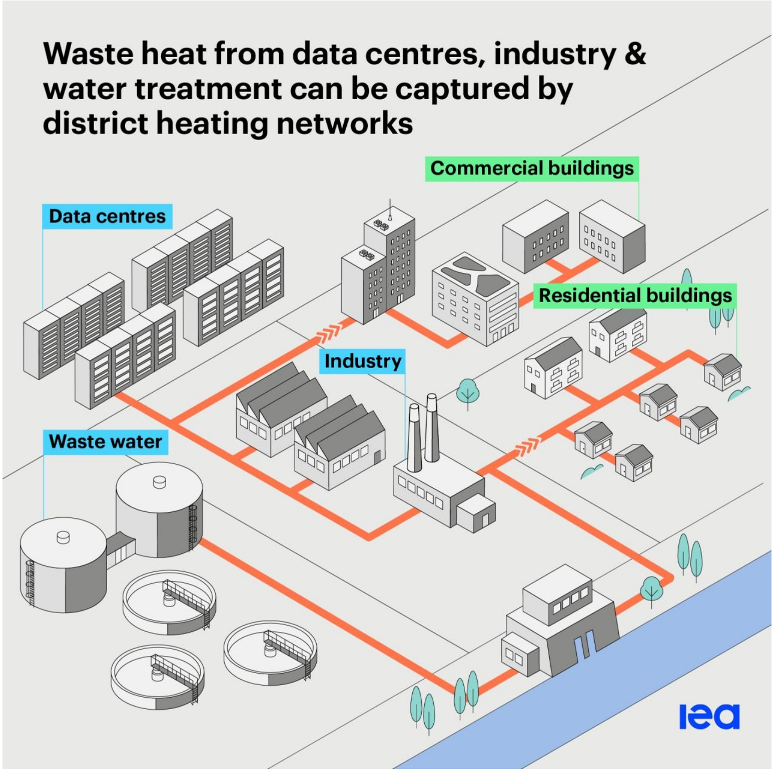

Fig 3. Example, not exhaustive, for illustrative purpose from IEA (international Energy Agency) showing how “waste heat” from undesired subproduct of industrial processes can become precious source of energy for Large Heat Pumps and the permit its reuse at higher level of temperature in several applications [16]

According to the International Energy Agency (IEA), the main waste heat sources suitable for district heating, when upgraded at the desired temperatures using heat pumps, can be summarized as (non-exhaustive):

3.1 Industrial Waste Heat

From: manufacturing processes, steel, cement, chemicals, refineries, food industry
Temperature range: 20–100 °C

Role: Largest technical potential, especially for large district heating networks

3.2 Data Centres

From: server cooling systems
Temperature range: 25–80 °C
Role: Rapidly growing urban heat source, especially in cities

3.3 Wastewater & Sewage Systems

From: sewer networks and wastewater treatment plants
Temperature range: 10–25 °C
Role: One of the highest-potential urban heat sources, widely available in cities

3.4 Metro Systems & Underground Infrastructure

From: tunnels, stations, braking systems, ventilation exhaust
Temperature range: 15–35 °C
Role: Important urban source, especially in dense metropolitan areas

3.5 Power Plants & Flue Gas Condensation

From: exhaust gases, cooling water, condensers
Temperature range: 30–60 °C
Role: Key transitional source, especially in existing thermal plants

3.6 Commercial Refrigeration Systems

From: supermarkets, cold storage, shopping centres
Temperature range: 25–40 °C
Role: Distributed urban heat source, ideal for local networks

3.7 Electrolysers (Hydrogen Production)

From: hydrogen electrolysis processes
Temperature range: 30–80 °C
Role: Emerging future source, as hydrogen production expands

4 The role of large heat pumps in recovering "waste heat" and increasing its temperature levels to make it suitable for district heating

This waste thermal energy, typically released into the environment through exhaust gases, cooling systems and wastewater streams, remains largely unexploited, despite its significant recovery potential. The systematic recovery and upgrading of industrial waste heat, particularly through the deployment of advanced heat pump technologies, can therefore provide a major contribution to sustainable energy systems.

A particularly important fraction of industrial waste heat lies in the low-temperature range, typically below 100 °C and often between 40 °C and 80 °C. These temperature levels are common in numerous industrial sectors (Diagram 2), including chemical manufacturing, food and beverage processing, pulp and paper production, cement and steel manufacturing, data centres, and wastewater treatment facilities.

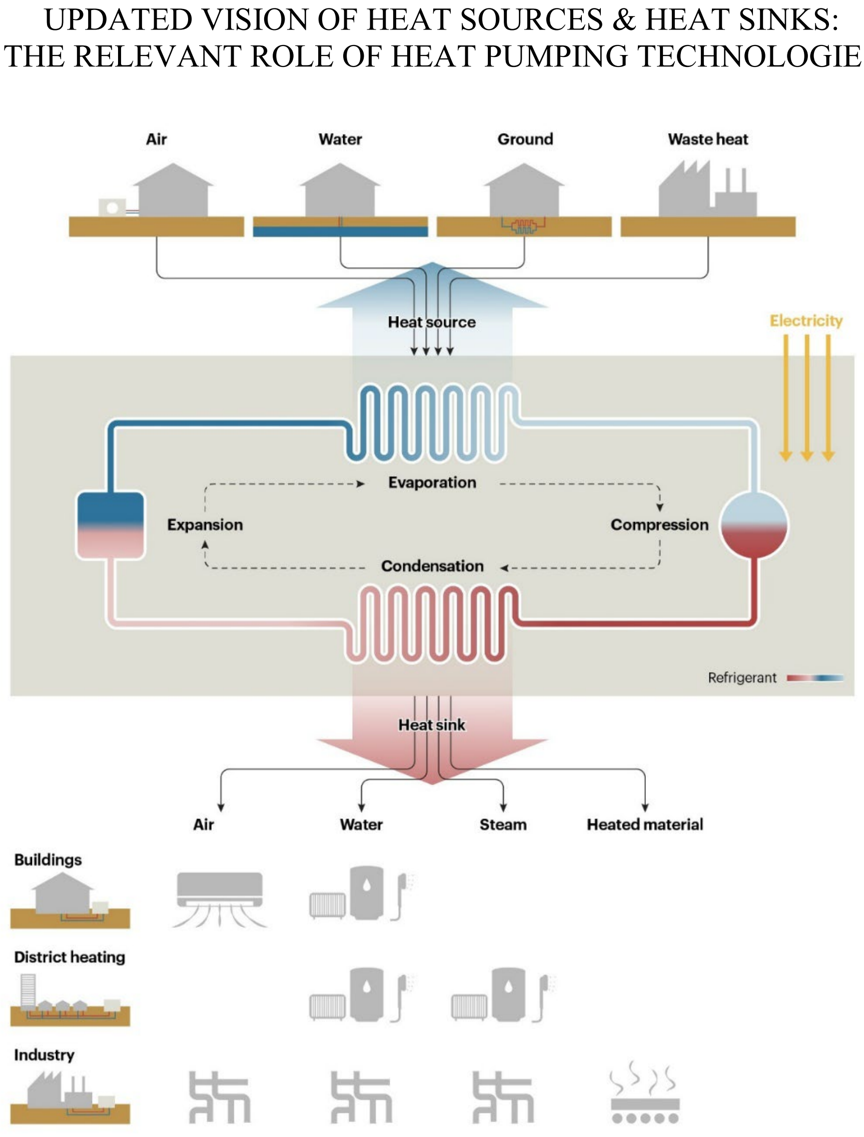

Fig. 4. Waste Heat is considered valuable as the traditional renewable energies sources (air, water and ground), as expressed in the recent (2022) IEA publication 'The Future of Heat Pumps' [17]

Although low-temperature waste heat has historically been considered of limited practical value, technological advancements in large-scale heat pumps now allow this energy to be efficiently upgraded to temperatures suitable for industrial processes, space heating, and district heating networks. This technological progress effectively transforms low-grade waste heat into a high-value energy carrier, enabling its integration into modern energy systems. The IEA reports that, in major industrial economies, waste heat flows can reach levels comparable to or exceeding total final heat demand. Heat pump technology plays a central role in enabling the large-scale utilisation of industrial waste heat. Modern Large Heat Pumps can achieve output capacities of 1-2 MW (and multiple of it) and temperatures from traditional 40-60-80 °C up to 100-140–160 °C (and even beyond 200 °C depending on the heat source) in the most challenging solutions.

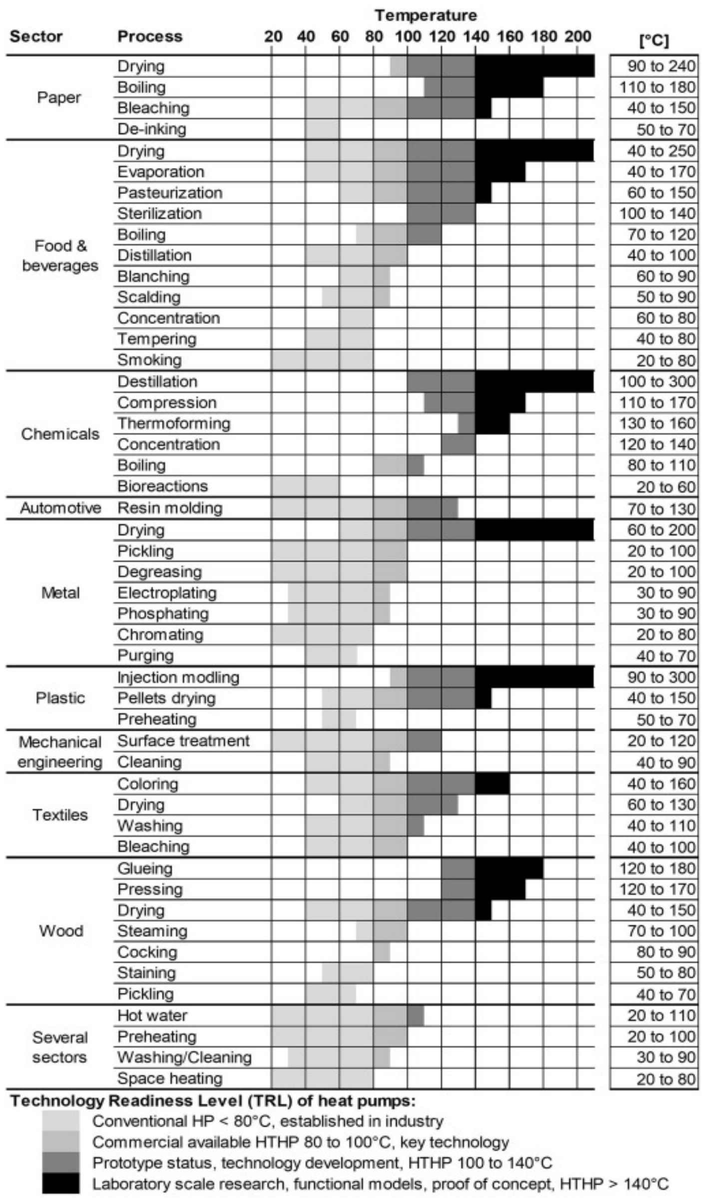

Diagram 2. Temperature required in the different industries and sectors. Source: Publication "High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials", autors C. Arpagaus, F. Bless, M. Uhlmann, J. Schiffmann and S. S. Bertsch [18]

From a system perspective, industrial waste heat recovery contributes to the formation of highly efficient, resilient, and low-carbon energy infrastructures. By capturing energy that

would otherwise be dissipated, waste heat utilisation reduces primary energy demand and mitigates thermal pollution. That is why IEA indicates (see Figure 4), in its publication "The Future of Heat Pumps", Waste Heat at the same level of Air, Water and Ground which are considered [2] renewable thermal energy sources.
Regarding industrial applicability of Heat Pumps, looking at Diagram 2, it is immediately evident that the range of applications for heat pumps is certainly very broad and suitable for many sectors and processes. The light grey areas can be satisfied with High Temperatures HP, largely available nowadays, while the dark grey and black areas (from 100-140 °C onward) are still firmly dominated (in the industrial stock) by traditional combustion applications but a growing number of HTHP (High Temperature Heat Pumps), VHTHP (Very High Temperature Heat Pumps) are more and more considered in many installations, or retrofit, as a more energy efficient alternative to boilers.

5 Available heat pumps technologies

Large heat pump technologies available in the industry can provide many solutions for different sectors and applications, according to the different needs and the different heat sinks and heat sources. In general, when it comes to heat recovery uses, there are 3 types of heat pumps which are normally described as: HP, HTHP & VHTHP.

GRAPHIC SIMPLIFIED REPRESENTATION OF SOURCE AND SUPPLY TEMPERATURES OF THE 3 DIFFERENT TYPES OF HEAT PUMPS NORMALLY USED IN THE HEAT RECOVERY SECTOR

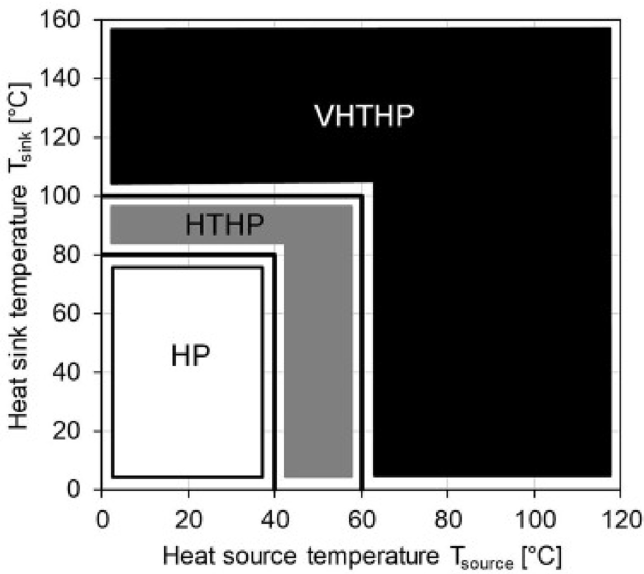

Diagram 3. Source: Publication "High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials", autors C. Arpagaus, F. Bless, M. Uhlmann, J. Schiffmann, and S. S. Bertsch [18]

• **HP** Traditional Heat Pumps (HP = Heat Pumps). These are widely used in several commercial and industrial installations and technologically stable. They are typically used in all comfort sectors, both in residential and commercial buildings and, due to decrease of supply temperatures required in 4th GDH (water temperature in general up to 70°C), they can also be used in such field also taking advantage from waste heat recovery from Data Centers, AI infrastructures, etc. Sometimes for medium-to-low temperature processes (e.g., 35-45-65 °C) they can be used also in the industrial field (see Diagram 2, light grey area, normally called "Commercial HP"). These kinds of Heat Pumps can reach in general heating temperatures of 75°C, the application field in which they can be used is becoming very wide, for the following 2 main reasons (non-exhaustive):

1. Because 4th generation District Heating is increasingly using low temperatures around 70 °C, and these commercial units can represent a reliable and modular scalable solution, instead of going for (sometimes) high CAPEX custom made HTHP & VHTHP;
2. Because, as it is possible to see in Diagram 2, many processes in the industry are based on temperatures below 80°C and secondly because many waste heat sectors mapped by IEA (see chapters 3.2 – 3.3 – 3.4 – 3.5 – 3.6 – 3.7) can offer usable waste heat temperatures from 25-30-40-60 °C) which are perfectly compatible with these units.

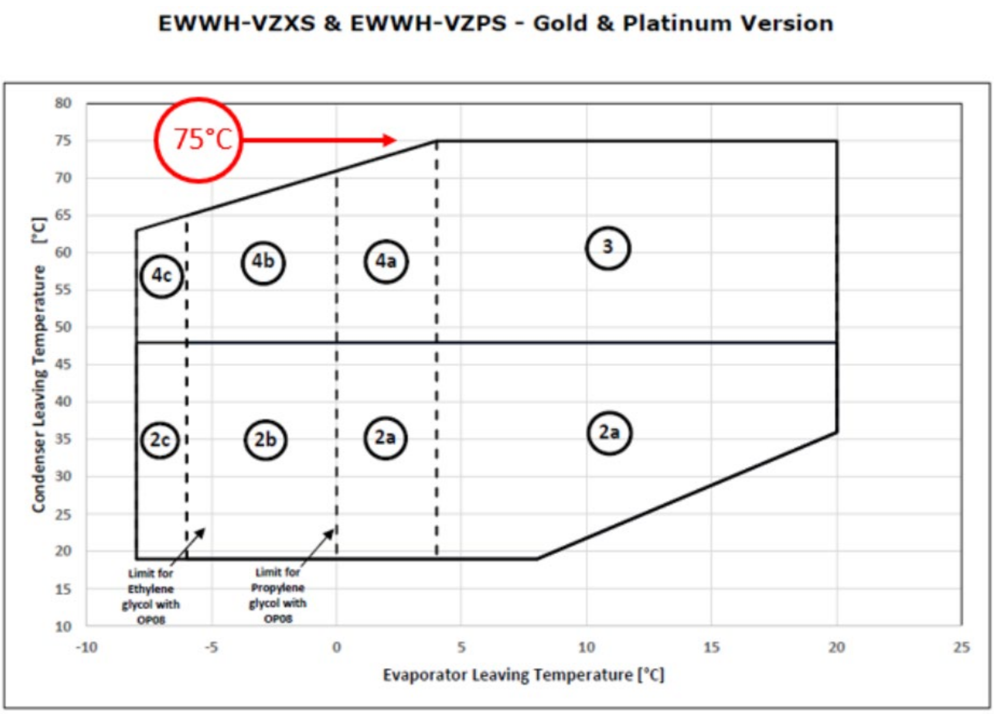

Diagram 4. Operational Envelope of a commercial Heat Pump (example from Daikin Applied Europe S.p.A. range EWWH) which can nowadays be suitable for being used in several applications of waste heat recovery and 4th Generation District Heating (4GDH) as supply temperatures can reach 75°C [19]

Fig. 5. Picture for illustrative purpose (non-exhaustive) from Daikin Applied Europe S.p.A. of High Temperature HP Water to Water EWWH- VZ with nominal heating capacity (depending on the size and features selected) from 400 – 1900 kW, using low GWP Refrigerant, R-1234ze, with Inverter driven Screw Compressor. It can be suitable for being used in several applications of waste heat recovery. With "modular combination" they can scale from 2 to 10 MW and more of heating capacity with stable and reliable technology [19]

• **HTHP** High Temperature Heat Pumps (HTHP = High Temperature Heat Pumps) [12]. These can generally reach 100-140 °C. They are sometimes at the prototype level and not yet widely distributed.

• **VHTHP** Very High Temperature Heat Pumps (VHTHP = Very High Temperature Heat Pumps) [20]. They can reach and exceed 160-200 °C, but are sometimes still in laboratory research development stage. To be highly efficient, it is expected that they will need several more years to see widespread development and adoption.

Single-unit VHTHP systems continue to present technical challenges, especially at temperatures exceeding 160 °C. Consequently, many applications are increasingly shifting toward a "two-stage system" configuration, also known as a Templifier (Temperature Amplifier). For example, combining a High Temperature Heat Pump (See Figure 7) able to deliver Hot Water up to 90°C (See Diagram 5) together with a VHTHP unit as a Booster system (up to 200 °C and above) can create a continuous thermal chain capable of efficiently and fully electrifying process-heat demands up to 200 °C. The HTHP can act as the 1st Stage unit (see "STAGE 1" in Figure 6) for pre-heating or for directly supplying medium-temperature utilities (>75-90°C), while the VHTHP unit serves as the 2nd stage (see STAGE 2 in Figure 6), producing hot water up to 200 °C.

Such systems have the opportunity to become more and more frequent as they combine technology largely available, modular and standardized, for the 1st stage (see STAGE 1 in Figure 6) up to 90°C like indicated in Figure 6, leaving the second stage only to the need of very high temperatures, with a specific dedicate VHTHP in 2nd Stage (see STAGE 2 in Figure 6) in most of cases custom made for the specific process.

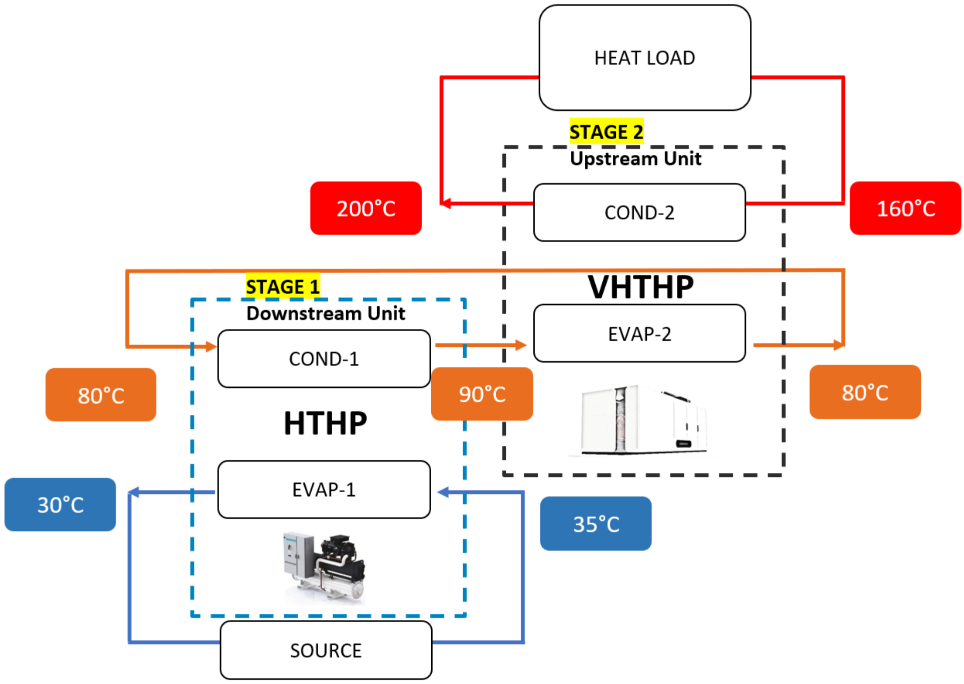

Fig. 6: Functional non-exhaustive scheme of the combination between HTHP & VHTHP in a "two-stage systems" that can constitute (economically and technologically) a very interesting, industrialized, efficient feasible alternative to a "single VHTHP unit approach", which can lead to too high CAPEX custom solutions.

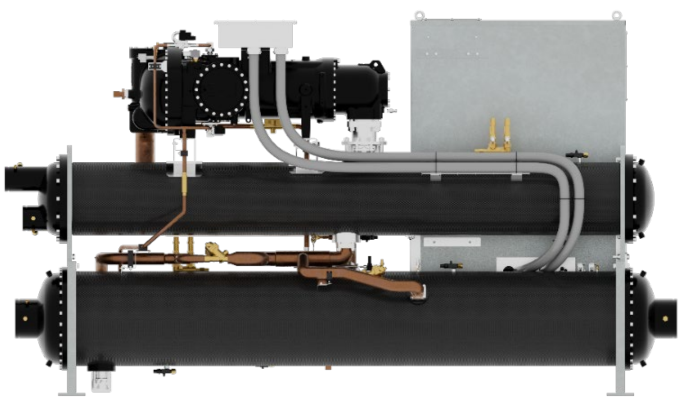

Fig. 7. Picture for illustrative purpose (non-exhaustive) from Daikin Applied Europe S.p.A. of High Temperature HP Water to Water EWWH- VZ with nominal heating capacity (depending on the size and features selected) from 600 – 2200 kW, using low GWP Refrigerant, R-1234ze, with Inverter driven Screw Compressor. It can be suitable for being used in several applications of waste heat recovery. With "modular combination" they can scale from 2 to 10 MW and more of heating capacity with stable and reliable technology [19]

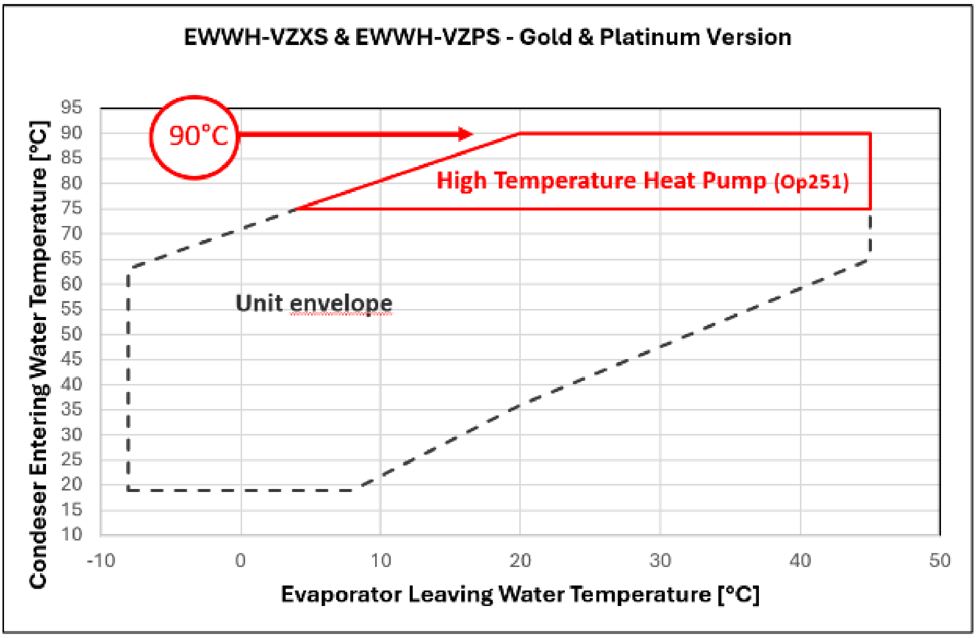

Diagram 5. Daikin VZ Series in HTHP version for Hot Water Production up to 90°C, as a single unit able to manage within the relevant operating envelope allowed to be included in a so called two-stage systems or traditionally speaking, Templifier system (example from Daikin Applied Europe S.p.A. range EWWH) [19]

6. Large heat pump adoption perspective in the district heating with green electricity

Given the right, stable framework conditions, district heating could undergo a dramatic shift in supply structure. From supply being dominated by production from thermal plants (biomass, waste, gas, etc.) to a strong electrification (and thus a strong reduction of production from thermal plants) and much greater use of excess heat from existing and new industries.

The Danish District Heating Association made a very interesting analysis [21] which concludes showing that district heating production towards 2040 will be dominated by heat pumps and excess heat (see Diagram 6).

This includes air source heat pumps, seawater heat pumps, heat pumps supplying geothermal heat and heat pumps that utilise excess heat from PtX plants, such as:

PtX Type	Meaning	Output product
Power-to-Heat (PtH)	Electricity → Heat	District heating, industrial heat
Power-to-Hydrogen (PtH_2)	Electricity → Hydrogen	Green hydrogen
Power-to-Gas (PtG)	Electricity → Synthetic gas	Methane, syngas
Power-to-Liquid (PtL)	Electricity → Liquid fuels	E-fuels, methanol, ammonia
Power-to-Chemicals (PtC)	Electricity → Chemicals	Fertilisers, plastics, feedstocks

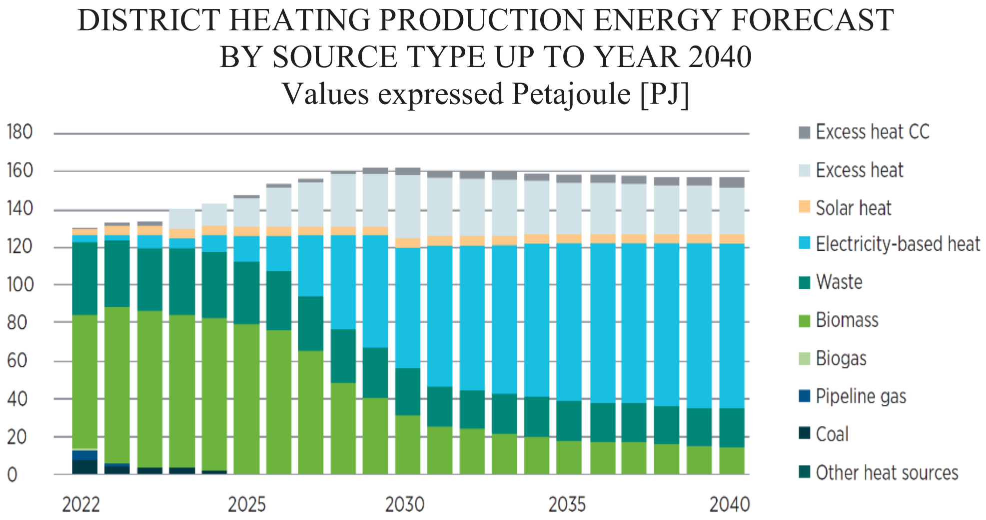

Diagram 6. According to the Danish District Heating Association estimations Heat Pumps are foreseen to taking over large parts of district heating production.

According to the simulation model realized by ECCO [22] by 2040 it will be advisable an economic advantage in the full electrification of heat processes. This is driven by:

a) the progressive decoupling of electricity prices from gas prices;
b) gas cost projections, which are expected to rise progressively due to the increasing impact of ETS2;
c) the reduction in capital costs of technologies for process electrification.

Conclusions

The deployment of Large Heat Pumps (LHPs) integrated with waste heat recovery and powered by renewable green electricity within Fourth-Generation District Heating (4GDH) systems has, over the past decade, evolved from a conceptual vision into a robust and operational reality. A prominent and visionary example is the Esbjerg Harbour [4] installation in Denmark, which hosts the world's largest seawater-based heat pump system. Seawater is classified as a Renewable Energy Source according to the EU Renewable Energy Directive (RED) [2]. This project represents a benchmark for the sustainable transformation of district heating systems and offers a valuable reference model for stakeholders involved in the evolution of district heating infrastructures, from example from District Heating generation 1-2-3 to generation 4.

In this context, Fourth-Generation District Heating (4GDH) introduces new technological perspectives and operational opportunities. While High-Temperature Heat Pumps (HTHP) and Very High-Temperature Heat Pumps (HTHP), capable of delivering supply temperatures in the range of 100–160 °C (and more), enable direct integration into existing high-temperature district heating networks, their deployment remains constrained by technological maturity, frequent prototype-level development and the need for customized system configurations. These aspects often result in elevated capital expenditures (CAPEX) and extended payback periods, particularly when coupled with the additional investments required for renewable electricity generation.

Conversely, 4GDH systems, encompass a broad family of network configurations characterized by reduced supply temperatures, typically up to 70 °C. Such operating conditions unlock significant opportunities for the integration of commercially mature, modular HP technologies, efficiently producing hot water at 75-90 °C.

These systems are more widely available, compared to HTHP and VHTHP, technically reliable and capable of achieving nominal heating capacities ranging from 2 to 10 MW per unit combination in cascade, with straightforward scalability through additional modular replication. Furthermore, the combination in 2 stage systems and the adoption of low–Global Warming Potential (GWP) refrigerants like R1234ze (for example) or natural refrigerants, combined with renewable electricity generation, enables environmentally sustainable and economically optimized 4GDH solutions.

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