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FLEXIBLE AND LOW-CARBON RENEWABLE TECHNOLOGIES IN RESPONSE TO CLIMATE CHANGE

To address climate change and align with the EU's REPowerEU strategy, modern energy systems must become more flexible, low-carbon, and environmentally compliant. Flexibility – the ability to adapt to fluctuations in energy supply, demand, and regulatory constraints – is essential in designing and operating district energy systems, particularly when integrating variable renewable energy sources. This paper investigates how system flexibility can be enhanced through renewable technologies, focusing on large-scale heat pumps. These technologies not only support deep decarbonization but also promote responsive and sustainable operation of district heating networks, in line with environmental policies and emission targets. The study analyzes how thermal system flexibility can be allocated across components and coordinated over time, geography, and energy markets. A detailed performance evaluation of large-scale heat pumps is presented, demonstrating their potential to reduce greenhouse gas emissions while improving overall system resilience and operational efficiency. Findings underscore the critical role of embedding flexibility across all levels of energy infrastructure to meet climate obligations, support the energy transition, and ensure regulatory compliance. By leveraging technologies like heat pumps, energy systems can better adapt to climate-related challenges and contribute meaningfully to a sustainable, low-carbon future.

1. INTRODUCTION

The transition towards sustainable energy systems plays a fundamental role in the global effort to mitigate climate change, reduce environmental degradation, and ensure long-term energy security. Modern energy systems are expected not only to meet growing demand but also to align with the principles of environmental responsibility and

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climate resilience. In this context, integrated and intelligent energy infrastructures – capable of utilizing renewable energy sources (RES), enhancing energy efficiency, and ensuring operational flexibility – are becoming essential components of future-proof, low-emission economies.

One of the key roles of such systems is to decarbonize heating and cooling sectors, which still heavily rely on fossil fuels and are responsible for a significant share of global CO_2 emissions. The deployment of renewable energy technologies, such as solar thermal, geothermal, bioenergy, and heat pump systems, offers viable pathways to reduce the environmental footprint of thermal energy supply. Among these technologies, heat pumps stand out as a highly efficient solution for converting low-grade ambient or waste heat into usable heat, contributing to both reduced greenhouse gas emissions and improved energy efficiency in buildings, industrial processes, and urban heating networks.

In particular, large-scale and group-operated heat pump systems integrated with smart district heating (DH) networks offer a compelling model for the future of sustainable urban energy. As part of clean technologies, heat pumps exemplify how modern energy systems can leverage renewable sources while enabling sector coupling, grid balancing, and demand-side flexibility.

The European Union has the ambitious goal of becoming the world's first climate-neutral continent. Achieving this goal by 2050 is a challenge for many sectors of the economy. For the energy sector, this means increasing the share of renewable energy to 40% by 2030 and an overall reduction of 36–39% in terms of final and primary energy consumption as an objective of delivering the European Green Deal [1].

One of the main options to achieve this goal is to apply large-scale and group heat pumps for intelligent and flexible district heating. District heating (DH) networks are an attractive energy system solution because they permit the integration of different renewable energy technologies and local excess of hot sources. Smart district heating networks are advanced heating systems that use advanced technology to improve efficiency, reduce environmental impact, and provide a better experience for users. Key features of smart district heating networks include: integration of renewable energy sources, use of advanced control systems, energy storage solutions, monitoring and diagnostics components [2]. The most important factors for smart DH are intelligence, efficiency, sustainability, and flexibility in heat production and consumption. The heat pumps in DH are linking the thermal and the electrical sectors, and for that, they are seen as part of a flexible coupler to match the thermal and electrical demand. Heat pump technologies can be used to decarbonize buildings and industrial processes irrespective of the specific design or layout of a heat pump-based solution [3].

Flexibility is a widely used term, in general, defined as the ability to change, to suit new conditions or situations. This definition can be transferred to the flexibility definition in the context of demand-side energy management (DSM) [4]. It is the ability to modify the energy generation or consumption of a system in response to external signals specified by markets or market members.

Flexibility can be defined as the ability of a system to adapt its operation to both predictable and unpredictable load fluctuating conditions, either on the demand or generation side, at different time scales, within economical boundaries, or as the ability of a system to cope with the short-term un-certainty of energy system variables, or to deploy the systems' resources to respond to unexpected load changes in supply and demand sides [5].

Another possible definition of flexibility is the ability to accelerate or delay the injection or extraction of energy into or out of a (DH) system. Speeding up or slowing down requires a comparison with a reference energy consumption profile [6]. The researchers identified different types of flexibility, and they suggest ways in which the large flexibility potential can be unlocked.

This article discusses the issue of large-scale heat pumps as a part of intelligent, flexible, and sustainable DH networks. The development of DH networks combined with heat pump technologies demonstrates that the heat pump technology can meet the needs of DH and it can feed DH effectively, by using both conventional and renewable energy sources (RESs), energy storage as support elements for driving energy, on both of supply and demand sides. So the role of large-scale heat pump systems will effectively contribute future smart energy system processes and will accommodate higher flexibility for DH networks.

2. DISTRICT HEATING NETWORKS IN EUROPE

In 2022, the amount of heat produced in DH networks worldwide was around 17 EJ of which more than 90% of global DH production is accounted for by China, Russia, and Europe [7]. The IEA report states that although DH networks offer significant potential for cost-effective, efficient, and flexible use of low-carbon energy for large-scale heating [7]. Currently, almost 4% of global CO_2 emissions come from district heating systems. In 2022, CO_2 emissions were 1.5% higher than in 2021 and thus 25% higher than in 2010. To meet the requirements of net zero emissions by 2050, it is necessary to integrate DH networks with renewable heat sources (such as bioenergy, solar energy, large-scale heat pumps, and geothermal energy). Europe is a leader in the integration of renewable energy sources in DH, where renewable sources account for approximately 25% of the heating supply. However, there are countries where more than 50% of the heat produced for DH comes from renewable sources: Denmark, Sweden, Estonia, Austria, Latvia, Lithuania, or Iceland [7].

Flexibility in DH systems is essential for managing the intermittent generation of heat and electricity as the share of renewable energy sources increases. Key sources of flexibility in DH include the thermal energy storage units, the thermal inertia of the buildings, and the thermal networks themselves. To unlock this flexibility in the thermal network effectively, a suitable automation and control strategy and efficient technologies are needed to quantify the flexibility requirements [6].

A substantial portion of commercially available large-scale heat pumps operate using high-temperature vapor compression, utilizing the thermodynamic cycle. This confirms that these heat pumps specifically use the vapor compression process to achieve high temperatures. A number of studies proposed that large-scale electric heat pumps can provide an integration between the heating and power sectors, improving their operational flexibility and increasing the use of (RESs) [8].

The future energy systems, based on decentralized production and various RES technologies, need effective management systems and information communication technologies (ICT) to function more efficiently [9].

The DH networks can be a flexible system that can be adapted in the short, medium, and long term [10]. Short-term adaptation means adapting energy supply and demand situations to different sizes of storage systems, DSM, and peak thermal load supplied by Heating Only Boilers (HOBs), all of which need to be integrated into the smart energy system. Medium-term adaptation means adjusting the temperature level in existing networks. In the long term, the adaptation is achieved by aligning the network development with urban planning. Smart thermal systems should also be flexible in size, meaning they must offer possible wide-scale solutions for neighborhood-level or city-level systems, depending on their heating and cooling requirements and environmental targets.

3. ENHANCING OPERATIONAL FLEXIBILITY IN DISTRICT HEATING

There are no direct policies for flexibility in the DH systems in European countries, which means that flexibility is mainly provided by market incentives and frugally by Energy Polygeneration. There is no one-size-fits-all solution for flexibility, which concerns DH–electricity interface [11].

Presently, the power market reflects what is best for flexibility needs, but it does not itself provide a sufficiently attractive business case to invest in combined heat and power (CHP) and power to heat. Some solutions, like subsidies for CHP and power to heat, might be necessary. All countries with DH networks display potential for changes in other regulatory framework conditions with which different solutions or subsidies should be compared, in addition to socio-economically and from an energy system perspective.

It is necessary to mention that since the DH markets differ between the European countries concerning the energy technology mix and fuel distribution, the presence of certain regulatory framework conditions has greater importance in some countries than in others. The observations show a large variation in regulation, but at the same time, some similarities and patterns have emerged. General characteristics of DH flexibility are concerns with the current and future role of DH networks, particularly the infrastructure and regulations of the DH elements. The flexibility resources related to DH–electricity interface are: heat storage, CHP plants, electric boilers in DH, large heat pumps HOBs in DH (as a substitute to CHP), large field of solar PV panels, flexible operation of DH network, consumers of DH as flexibility providers, individual HOB generation (as a substitute to DH), feed-in to the DH network from industry, etc. [12].

Reducing the primary energy demand in DH systems has to be undergone in three main sectors: heat generation (conversion process efficiency, renewable heat, and integrated energy), heat distribution (better distribution thermal efficiency), and the consumers of the thermal demand sector (thermal loads reduction, smoothing the requirement profiles).

From a historical perspective, traditional DH distribution technologies went through five generations. Figure 1 shows the details of the technologies [13, 14]:

– 1st generation: steam-based systems (> 120–150 °C),
– 2nd generation: pressurized high-temperature water systems (> 100 °C),
– 3rd generation: pressurized medium-temperature water systems (< 100 °C),
– 4th generation: low-temperatureswater systems (30–70 °C),
– 5th generation: ultra low-temperature water systems for heating and cooling (< 30°C).

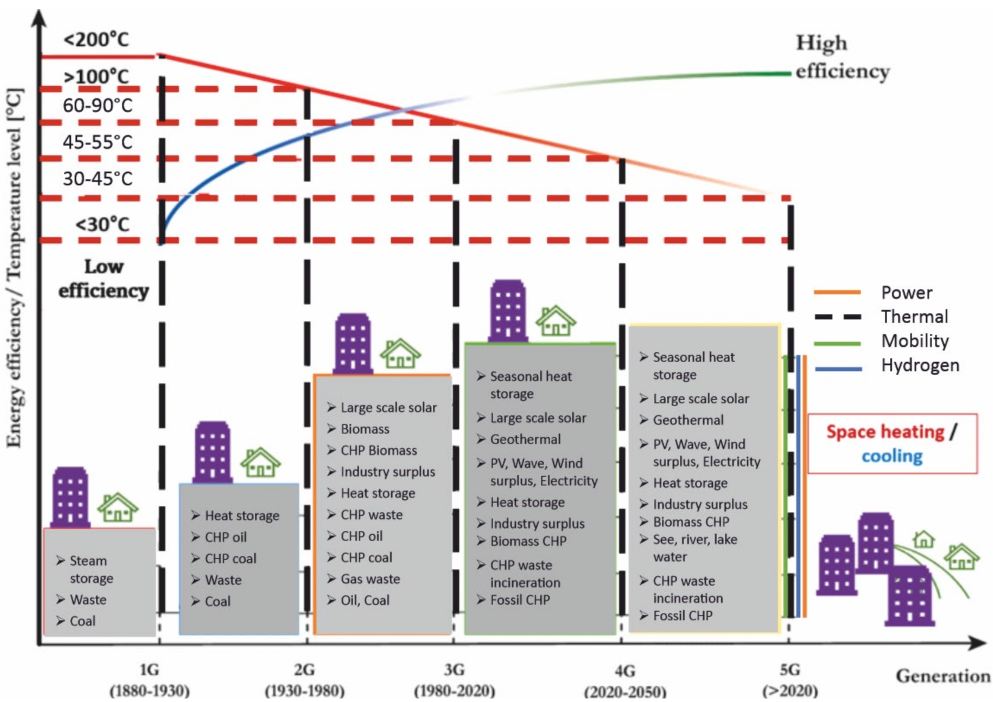

Fig. 1. From traditional DH to 5GDH technologies (adopted from [13])

Fourth-generation DH (4GDH) network with lower temperature levels and an increasing number of small-scale generation plants, yielding both a higher level of decentralization and demand for more flexibility, and further a higher level of complexity as an author's own composition as a flexibility paradigm of heat pump-based district networks. These challenges can be addressed by the concept of smart DH networks. 5th generation DH (5GDH) provides both heating and cooling for various buildings.

With the development of thermal networks, it is necessary to incorporate more renewable energy and responsive demand. Regulators and system operators are recognizing that flexibility across all elements of the thermal systems must be addressed by ensuring:

- Flexibility of heat generation. Plants that can quickly and efficiently ramp up and down and run at low output levels (i.e., deep turn-downs) [15].
- Flexibility of heat distribution. In heat transmission networks with limited bottlenecks and sufficient capacity to access a broad range of balancing resources, including sharing between neighboring systems (backup or auxiliary), and with smart network technologies that better optimize the heat distribution usage.
- Flexibility of demand-side resources. Incorporation of smart grids to enable demand response, thermal storage, responsive distributed generation, and other means for the demand side or customers to respond to the market signals or direct thermal load or requirement control.

The share of heat pump technology in the residential heating sector is increasing, and this trend is expected to continue. The structure of CHP energy production in EU members determines the proportion of DH consumers with CHP and heat pump units. This advantage will facilitate and encourage the integration of renewable power generation. As it is known, managing heat and electricity demand is a core requirement when dealing with fluctuating energy generation sources, especially when linking RESs and thermal energy stores. In cogeneration or CHP plants, heat pumps will facilitate primary energy savings and enhance energy efficiency compared to other heat and power generation technologies, leading to a reduction in greenhouse gas emissions.

The advancement of DH networks and heat pump technologies shows that heat pumps can effectively meet the requirements of DH. On the other hand, heat pump technology can feed DH effectively by using both conventional and RESs as driving energy, which needs to be analyzed and modeled to enhance and accommodate greater flexibility on both the supply and demand sides. So the role of heat pumps and their contribution to the future smart energy system processes will be more essential and effective.

4. FLEXIBILITY OF HEAT PUMPS IN DH NETWORKS

Heating substations and heat pumps are essential components of modern district heating systems, playing complementary roles in optimizing heat distribution, enhancing energy efficiency, and promoting the use of RESs for heating purposes. Heating substations are intermediate points in a DH network where heat from the primary distribution network is transferred to the secondary distribution system within individual buildings or properties. They act as interfaces between the centralized DH system and the internal heating systems of buildings. The connection modes of heating substations and heat pumps in DH systems differ based on their specific design, configuration, and requirements.

Every DH system is unique and varies in several ways, including the size of heat production, temperature level, and the network structure. The investments in heat pumps under consideration also vary largely, depending on factors such as the characteristics of the DH system, the feasibility and scale of the heat source to be used, and the location of the heat source relative to the DH network. These are the reasons why it is not possible to give any universal guidance for a heat pump's profitability or its role in a DH or cooling system.

The energy flexibility of a building refers to its capacity to manage both demand and generation in response to local climate conditions, occupancy levels, and the needs of consumers and the power grid. Flexibility can be seen as the range within which a building can operate while meeting its functional requirements. This flexibility enables demand-side management, load control, and demand response based on the needs of the surrounding grids.

Flexibility in buildings' energy use is needed to accommodate the further integration of varying renewable heat and power energy generation. The degree of flexibility is highly influenced by the thermal characteristics of the building; greater thermal mass and higher insulation levels positively impact the switch-off times [16].

Concerning low-energy building support flexibility, the same is true for thermal energy storage, so the buildings have the ability to become energy flexible and energy efficient. Heat pumps can be used successfully to provide demand response, regarding the level of flexibility in relation to the different thermal characteristics of the building stocks. Energy flexibility is represented as one of the main pillars governing the smartness of a building since the European Community study defines a smart building as a building that can manage itself, interact with its users, and take part in demand response.

Thereby, buildings are introduced as an important potential source of energy flexibility in future smart energy systems. Three general properties return when communicating energy flexibility:

- Energy capacity, the amount of energy that can be shifted per time unit, including the rebound effect.
- Time aspects like starting time and duration.
- Cost, potential cost for saving or energy use associated with activating the available flexibility.

In present energy systems, the flexibility of the heating requirement load associated with residential buildings with the use of heat pumps can be defined as the ability to shift the heat pump electric load from peak hours to off-peak hours in terms of electricity prices.

Figure 2 presents the heat source location characteristic of heat pumps powered by electricity in the DH network; the location choice is as a main central heat source in addition to RESs for heat pump or local heat sources, or an optional location as an individual heat pump, for example, river heat source heat pumps. Due to the connection and operational modes, it can be defined as the operational role of the heat pump technology integration in the district heating network. So, due to the technical triangles and the case of heat pump application in the district heating network, the flexibility can be provided to the power system. The technical and economic performance of the heat pump is closely related to the characteristics of the heat source. Research indicates that heat pump-district heating systems will play a pivotal role in the energy infrastructure in the future, thanks to their ability to adjust electric demand for specific periods, thereby providing flexibility to the power system.

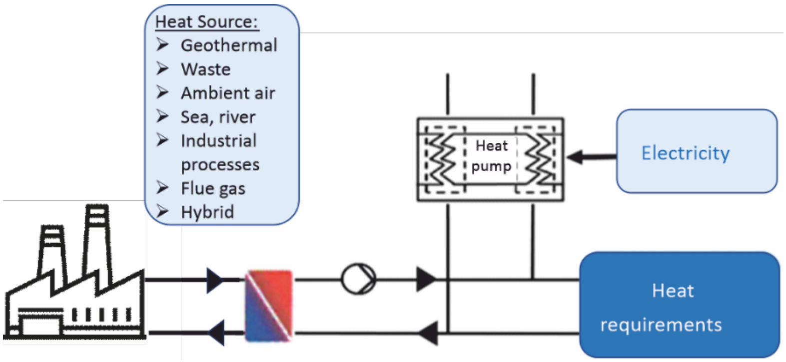

Fig. 2. Heat source location characteristic of heat pumps powered by electricity in the DH network

Heat pump systems not only provide sustainable heating and cooling solutions for buildings but also serve as a linking and enabling technology in future energy systems. The focus on consumer flexibility is a central point of demand response (DR) and demand-side energy management (DSM) [17] as well as decentralized energy management approaches. In the context of a smart grid, heat pumps are viewed as a demand-side resource that can be actively managed to support the development of a smart grid [18]. The need for flexibility in the power system is frequently motivated by an increase in RES [19] and the resulting need for an ability to react or plan for safe and efficient power system operation.

Generally, in the case of heat pump system intended for residential purposes can be characterized by the type of heat source and heat sink. In all application cases, it should be noticed that the level of controls has a certain minimum autonomy to guarantee that the heat pump unit is operated within the allowed range and user thermal comfort is not sacrificed, and the heat pump provides flexibility to the power system while providing efficient heating and cooling solutions to residential buildings.

Currently, large heat pumps combined with heating and cooling networks allow the harvesting of untapped renewable heating resources (geothermal, solar thermal) and recovered heat from urban environments (sewage, metros), the tertiary sector (data centres, supermarkets), and public buildings (hospitals). The integration of thermal storage, electric boilers, and large heat pumps supports system flexibility and security by delivering flexibility on daily, weekly, and seasonal timescales..

5. LARGE-SCALE HEAT PUMPS IN DISTRICT HEATING

The term high-temperature heat pump or large-scale heat pumps is frequently used in connection with industrial heat pumps, mainly for waste heat recovery in process heat supply. There are high-temperature heat pumps with heat sink temperatures ranging between 100 and 140 °C, and even more than this range for industrial purposes. Figure 3 shows the extent of temperature levels of the heat source and heat sink for conventional and industrial or high-temperature heat pumps, as well as the temperature range scope for various conventional utilities and industrial sectors [20].

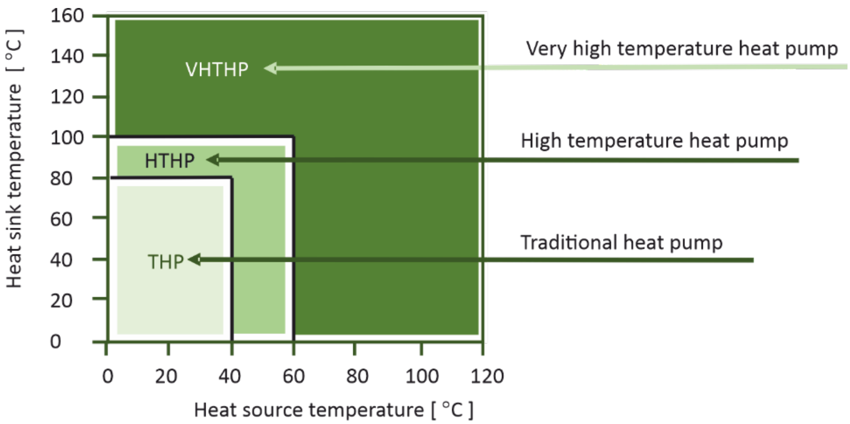

Fig. 3. High-temperature heat pump temperature range

Starting with a few 100 kW of power, they can reach capacities of several megawatts, which is sufficient to provide heat for different European countries, e.g., in Helsinki, Stockholm, or Oslo, for heating and cooling purposes. Figure 4 illustrates the thermal production and the capacity of large heat pumps in district heating and cooling (DHC) for different European countries [21]. Table 1 shows the typical role for different-scale DH and cooling networks [22]. The largest potential for heat pumps is in small

DH systems, where they reduce the use of fossil fuels. In medium and large DH systems with economical CHP production, the potential of heat pumps is smaller [22].

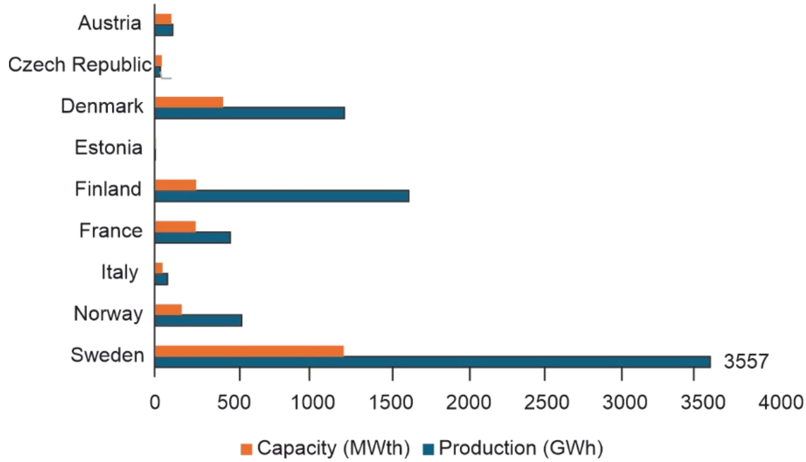

Fig. 4. Large-scale heat pumps LLSHP
in district heating and cooling (DHC) networks

Lund et al. [23] predicted that the role of large heat pumps will increase in future energy systems, reaching 25–30% of the total DH heat production. Werner [24] claims that factors such as lower temperature levels in the DH network and more variable electricity production in energy systems will make excess heat from large heat pumps a more favourable source for DH. Large heat pumps are expected to play a prominent role in all markets. Large heat pumps will be an effective tool for decarbonising heat markets in Europe in line with Green Deal objectives.

Table 1

Typical role of heat pumps in DH and cooling networks of different scales

System size	Types of production	Target of a heat pump	Role of a heat pump
Small	heat-only boilers	minimizing heat production with fossil fuels	continuous base load
Medium	CHP plant (heat accumulators)	maximizing CHP production or CHP full load hours	supporting CHP production
Large	CHP plant, energy storage (heating and cooling storages)	optimizing the whole system, optimizing the system according to varying electricity prices	continuous or periodical depending on the situation

The analysis showed that there were several ways in which large-scale heat pumps (LSHP) could increase the total profitability of existing DH systems. Heat pumps were regarded as devices bringing flexibility to a DH system, especially together with CHP production. Heat pumps start up quite quickly (usually in less than an hour), and starting-up costs are small, which brings flexibility in cases where some other units are unavailable. The profitability is highly influenced by the energy performance of the system, which mainly results from the sizing of the heat pump, load conditions, and achievable COP.

Further recent developments have been that many heat pumps have been installed in order to recover heat from local cooling devices and data centers to DH systems. Future operation of large heat pumps in DH systems will probably be based on variable power generation with short-term availability [25].

6. CONCLUSIONS

Modern energy systems, characterized by flexibility and the integration of multiple energy carriers and renewable sources, are essential for sustainable development and climate change mitigation. They enable the transition from fossil fuels to resilient, low-carbon networks. Within this context, heat pumps are a key technology in district heating systems, offering a promising solution for decarbonization and improved environmental and economic performance. Future flexible district heating networks with environmentally sustainable thermal solutions can provide cost-effective operation by increasing the share of renewable energy and diverse energy carriers. However, the deployment of large-scale and grouped heat pumps in buildings connected to these networks requires further study, especially considering different future power generation scenarios.

The lack of direct policies for flexibility in the DH systems in European countries means that flexibility is mainly provided by market incentives and frugally by Energy Polygeneration. There is no one-size-fits-all solution to achieving flexibility, which concerns the DH–electricity interface. All in all, it could be seen that the technology of HPs is available, sufficient heat source capacities exist, but the current regulatory framework does not allow sufficiently large shares of HPs in the DH sectors. However, due to the goals of making energy systems more sustainable, measures must be taken to accelerate the penetration of HPs on the market.

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