Review

Enabling Technologies for Sector Coupling: A Review on the Role of Heat Pumps and Thermal Energy Storage

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Abstract: In order to reduce greenhouse gas emissions, current and future energy systems need to be made more efficient and sustainable. This change can be accomplished by increasing the penetration of renewable energy sources and using efficient technologies in energy generation systems. One way to improve the operation of the whole energy system is through the generation and end-use sector coupling. Power-to-heat energy conversion and storage technologies, in this view, are enabling technologies that can help in balancing and improving the efficiency of both thermal and electric grids. In the present paper, a comprehensive analysis of the role of heat pumps and thermal energy storage for sector coupling is presented. The main features of the analyzed technologies are presented in the context of smart electric grid, district heating and cooling and multi-carrier energy systems, and recent findings and developments are highlighted. Finally, the technical, social, and economic challenges in the adoption of investigated technologies are discussed.

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1. Introduction

Globally, electricity is mainly produced by fossil fuels, which lead to greenhouse gas emissions (GHG) [1]. To reduce the GHG emissions in the energy sector, high shares of renewable energy sources (RES) penetration are required in existing and future energy production systems. Upcoming energy infrastructures should make full use of RES available locally as it will help energy systems in bringing a sustainable green transition of the economy [2]. Moreover, it will also help in reducing the environmental impacts caused by the use of fossil fuels in energy production. Solar, wind, and hydro power are the main RES through which electric power can be generated. Nevertheless, CO₂ emissions do not only come from electricity generation. Indeed, sectors including heating and cooling, transport, industry, and agriculture also cause relevant CO₂ emissions. For instance, according to the International Energy Agency (IEA), the heating sector accounts for almost 50% of global energy use [3]. Therefore, a sustainable energy system requires the use of RES also for heating and cooling and, since the main output from RES generation is electricity, electricity, and heating sector coupling is of paramount importance [4]. Decarbonization strategies bring new challenges in terms of planning and operational activities but also provide opportunities for optimization across different energy sectors [5]. In a worldwide existing scenario, efficient heating and cooling technologies are needed to reduce greenhouse gas emissions, while some sort of storage mechanism is needed to reduce the supply and demand gap in the heating and electricity sectors. Both these sectors (heating/cooling and storage) can be electrified to achieve low carbon emissions goals. In turn, the sector coupling will also be beneficial for the power sector as it provides improved flexibility, reliability, and adequacy [6]. The transition from current energy systems to future sustainable

systems also requires an approach based on the integration of various energy components and exploitation of synergies by sector integration [7].

Sector coupling, a synonym to sector integration and multi-carrier energy system (MCES), has recently gained increased attention [8]. The benefits of investing in one sector may spread to other sectors as all available energy sectors work in cooperation with each other. High expectations are associated with sector coupling in terms of decarbonization and a smooth green transition, but it is yet to be seen how and to what extent current technologies will be integrated for this purpose. Due to the wide use of current fossil-based technologies and lack of dynamic market-based price signals, the decarbonization of the heating and cooling sector is a bit difficult. Electrification of these sectors would provide low-cost solutions with a possibility to store energy in large-scale thermal energy storage systems [7]. Moreover, sector integration of electricity and heating can provide a cost-effective way for low-carbon energy systems with high penetration levels of RES. Such integration can mainly be achieved through the incorporation in thermal grids for district heating (district heating networks, DHNs) of enabling technologies for high RES deployment, easing the coupling with the smart grid. Two main challenges need to be tackled for a full deployment of RES in DHC: solutions to cover the gap between demand and supply and the use of systems to adjust temperature levels according to the distance between heat source and end-users. Among the various technical solutions available for the sector coupling of electricity and heat, heat pumps (HP), electric boilers, combined heat and power (CHP) plants and thermal energy storage (TES) can be used [9].

The main focus of this paper will be on HP and TES. It first discusses the latest status of HP and TES technologies that are mainly being employed in district heating and cooling (DHC). Moreover, both these technologies can play a significant role in the upcoming fifth generation of DHC. This generation will have ultra-low supply temperatures, which will help in reducing heat losses. HP, as mentioned in the work of [10–12], is among the possible technologies for the transition toward low-temperature and cooling-dominated district networks. In order to reduce the demand and supply gap, TES can be incorporated into DHC systems. It can work as a buffer between heat demand and supply and thus increases the reliability of energy supply. Moreover, it also provides flexibility to DH systems in order to integrate RES with them [13].

So far, the subject of enabling technologies for sector coupling has been analyzed, but it is mostly focused on specific cases and configurations or centered on single technologies, such as heat pumps only [14] or TES only [15]. Accordingly, the novelty of this paper lies in the fact that it extensively reviews the role of heat pumps and thermal energy storage technologies in the context of sector coupling of heating/cooling and electricity.

2. What Is Sector Coupling?

Sector coupling refers to the integration and interconnection of different end-users and supply energy sectors [7]. Until recently, energy networks have been considered separately, and only interventions for the optimization of a single network have been put in place. Sector coupling instead allows all present networks to be integrated into a comprehensive energy system usually defined as a multi-carrier energy system (MCES). An MCES consists of several energy carriers, e.g., heat, electricity, natural gas, hydrogen, etc., as shown in Figure 1 [16]. The benefits of combining various energy vectors are multiple; apart from economic and environmental aspects, sector coupling also allows for increased resilience of the energy system. For instance, a study conducted by Muhammad et al. [17] compared risk-averse and risk-seeking scenarios to evaluate the impact of MCES in the operation of unified gas, electricity, and DH networks. The paper concluded that MCES reduced the operating cost of the integrated system by 1.3%. Moreover, MCES could reduce the influence of uncertainty in wind power production on operating costs by 20%. In the risk-seeking scenario, the MCES technology allows the operator to implement its strategy under lower risk levels. In the risk-averse scenario, the operator can implement a strategy with a reliability 20% higher than in the risk-seeking approach.

Figure 1. Concept of a multi-carrier energy system (MCES).

In MCES, energy carriers are connected and interrelated with the help of energy hubs [18,19]. An energy hub behaves like an interface between transmission setups and clients. It delivers energy to cover consumer needs [20]. In this type of system, thermal energy storage and heat pumps, which can act as energy conversion systems and even carrier-conversion systems, are crucial components, and their role for service provision to prosumers and the grids needs to be evaluated.

Among the different sector coupling combinations, the integration of electricity and heating sectors can assume a major role in decarbonization strategies. A part of this regulatory framework is the EU strategy for energy system integration [21], which advocates, among the measures in the path for climate neutrality by 2050, the transition from networks where different energy carriers were built and operated independently to a system where interconnected networks (gas, electricity, heat) are operated in strong synergy. This sector coupling is mainly made possible by technological advancements in the different networks, among which the wide deployment of combined heat and power, power-to-heat and distributed energy storage technologies, as well as smart management algorithms are included [22].

Within hybrid grids, the CHP concept is especially interesting since it already provides both energy carriers needed. A number of previous studies discuss the possibility of the power-to-heat concept, with some discussing combining heat pumps and CHP to balance renewable production [23–25]. Levihn [23] studied the combination of CHP and heat pumps via modeling. The research was performed based on a DH network in Stockholm, which has over 12 TWh annual heat demand. This study provided insights into the empirics and practical knowledge of CHP and HP operation. It was mentioned that heating and cooling demands serve as boundary conditions for HP operation. Moreover, it was observed that higher COP of HP reduces the sensitivity to electricity prices. Grohnheit [24] discussed the feasibility of modeling existing CHP powerplants to provide heat as well. The study explains that previously, only electricity was considered as an output of CHP in modeling approaches performed at the national level. This modeling was mainly carried out by commercial utilities and companies that were supposed to provide energy to consumers. The paper discusses short-term modeling based on days and weeks and long-term modeling based on a year. Another study found that the incremental cost to build a CHP compared to a single-purpose plant is usually minimal and lies in the range of 100–200 EUR/kW [26]. Moreover, the combined production of heat and power leads to the overall efficiency of the plant as compared to the sole production of electricity only [25].

In the last decade, energy production from RES has seen a sharp rise. The energy supply from RES is often intermittent because it is weather dependent. So, the energy production from solar and wind power plants partly matches the electricity demand. Nevertheless, the generation of energy exceeds the demand during certain time durations in a day because of high input from RES [27,28]. This surplus energy should be used through a power-to-heat approach. The power-to-heat concept refers to the conversion of electricity to heat through heating resistors, electrode boilers, and heat pumps. Power-to-heat applications can better use the existing RES and can also make better use of the expanding renewable network. Temporary renewable surplus generation can be fed to power-to-heat, especially at the district level [29]. For instance, a study made in Denmark suggested that large-scale installation of heat pumps is the most important strategy for increasing the share of wind power in Danish primary energy consumption [30]. If active or passive thermal energy storage is available, the use of renewable overflows can even be used better [31–33].

Power-to-heat strategies can be applied at the centralized or decentralized level. A comparison of centralized and decentralized power-to-heat options in DH networks is shown in Figure 2. The DH approach is an example of centralized power to heat. Heat is produced centrally either with electric boilers [34] alone or in combination with large-scale heat pumps (ground sourced, waste heat, brine, etc.) [35]. In a centralized approach, energy is withdrawn from the grid for the generation of heat. Decentralized heat production accounts for the generation of heat at the residential level and does not involve the use of a heating network. Most of the power-to-heat options, both at centralized and decentralized levels, are associated with an energy storage mechanism.

Figure 2. Linkage of power-to-heat options with DH networks and electricity [34].

3. Thermal Grids: General Aspects

Both HP and TES are currently being used extensively in DHC. So, before explaining their current status of employment in DHC and how they can be used in future scenarios for sector coupling, a brief discussion on main aspects related to existing and proposed DHC architectures has been presented below.

A thermal grid for district heating (DH) is a system used for providing heat to consumers [36]. Heat is moved from production sources (boilers, combined heat and power (CHP), industrial waste heat, etc.) to sinks (consumers) through distribution networks. A typical DH system is shown in Figure 3. District heating and cooling (DHC) systems date back to several years, but they were not widely implemented in all countries. USA, Germany, and Russia were among those countries who developed DH systems initially [37,38].

Figure 3. A traditional DH system supply line is red, while the return line is blue.

DH systems have evolved over time, changing from the first generation to the fifth generation, which has been recently proposed [14]. Initial DH generations used steam as a heat carrier in concrete pipes and temperatures above 200 °C. The second-generation DH systems used pressurized hot water as a heat carrier with supply temperatures above 100 °C. Large shell-tube heat exchangers were used along with material-intensive heavy valves. Second-generation DH systems prevailed till 1970, and then the third generation took on. In the third generation, pressurized water was used as a heat carrier, but supply temperatures fell below 100 °C. Pre-insulated fabricated pipes and substations with plate stainless steel heat exchangers were used underground to transport heat [39]. The new generation of DH, i.e., the fourth generation DH, supplied water at low temperatures (45–60 °C) [40]. One of the main peculiarities that marked the evolution of DHC, which allows the sector coupling, is the radical change in the number and type of heat generation technologies used, passing from the first/second generation (steam boilers running on coal and CHP plants) to the third generation, which included the heat production from biomass, waste, fossil fuel boilers, along with large-scale and distributed CHP plants. Solar energy was also harnessed at a large scale to meet heating demands. Renewable sources were integrated into the fourth generation to a greater extent, and low-temperature heat recycling was also made available [39]. Solar photovoltaic (PV) and wind energy were brought in parallel with CHP plants for power production by connecting them with the electricity grid. Junca [41] found out that a grid-connected system needs lower initial-investment costs as storage (battery banks, e.g.) is not required. Such a system can result in a 50% reduction in the total life cycle cost of installation. Seasonal TES using sensible heat technology was also incorporated in the fourth generation DH systems.

The latest and upcoming generation, i.e., the fifth generation, has ‘prosumers’ as end-users who will both consume and produce energy. The concept of the fifth generation is shown in Figure 4. Buffa et al. analyzed 40 different DHC network projects of the fifth generation, which are currently operational in Europe [14]. These are mainly pilot projects that will help to understand the economic and technical aspects of the fifth generation in real operation. These projects are being carried out in Italy, Switzerland, Netherlands, Belgium, England, and Norway. The fifth generation thermal grids for DHC also include some additional and unique features that require a paradigmatic shift in the technologies employed, especially at the building and neighborhood level. In particular, the temperature level of water in the supply lines is close to ground temperature, and therefore it is paramount to use efficient technologies such as heat pumps that can work as temperature boosters/adjusters. Finally, due to the massive introduction of different heat generation sources, among which several are renewables, it will be necessary to incorporate energy storage systems.

Figure 4. Fifth-generation DH system supply line is red while return line is blue. Arrows represent energy exchange. HP represents heat pumps.

A comparison of all generations of DH systems is given in Table 1, which allows identifying the main peculiarities of new generation DHC and their main differences from the previous cases.

Table 1. Features of DH generations [39,42].

Features	1st Generation	2nd Generation	3rd Generation	4th Generation	5th Generation
Temperature	>200 °C [11]	>100 °C [11]	<100 °C [11]	45–60 °C [11]	Region dependent, close to ambient temperature (10–30 °C)
Energy sources	Coal-fired boilers, CHP [39]	Coal- and oil-based CHP [39]	Biomass, waste or fossil fuel boilers, CHP [39]	Solar PV, wind energy, low-temperature recycling [39]	High penetration of RES, heat pumps, industrial surplus heat [39]
Renewable energy sources	No	No	Yes	Yes	Yes
Simultaneous provision of heating and cooling	No	No	No	No	Yes
Centralized/Decentralized	Centralized	Centralized	Centralized	Partially decentralized	Highly decentralized
Heat carrier	Steam [11]	Pressurized water [11]	Pressurized water [11]	Low-temperature water [11]	Ultra-low-temperature water
Prosumers	No	No	No	Yes	Yes
Period of available technology	1880–1930 [39]	1930–1980 [39]	1980–2020 [39]	2020–2050 [39]	In research phase
Thermal losses	High	High	Medium	Low	Very low
Exergy losses	High	High	Medium	Low	Very low
Thermal storage	No	No	No	Yes	Yes

4. The Heat Pumps for Power-Thermal End-Use Sector Coupling

4.1. Generalities

Heat pumps, when used in a controlled and appropriate way, can help ease the transition toward decentralized energy systems. Heat pumps are considered to be a low CO₂ emission technology in the residential heating sector. Generally, electricity is used to drive low-exergy heat through a vapor compression cycle toward high temperature and high level of exergy [43].

In recent years, heat pumps have gained interest as an enabling technology for smart electric grids, becoming an enabling technology for sector coupling, converting renewable electricity into heating and cooling. Working fluid, which is a refrigerant, is used for delivering heating or cooling via a vapor compression cycle. Depending on the operation, useful effects can be extracted in the form of heat on the condenser side (i.e., space heating, domestic hot water) and cooling on the evaporator side (i.e., space cooling, refrigeration). On this topic, vast literature exists, and the most recent relevant studies are summarized in Table 2, mainly focusing on the benefits garnered by smart grids when HP are integrated. These can mainly be divided into the following domains:

- **Supplying ancillary services for the grid (grid-driven);** Heat pumps are employed in a grid to ensure that voltage remains within allowed limits [44]. Excessive load causes a decrease in voltage and vice versa. The voltage level often increases during daytime when electricity is being injected into the grid through solar PV. During times of over-voltage, the active power demand of heat pumps can be increased to keep the voltage within the allowed range while decreasing it during the low-voltage time period. Heat pumps also help in congestion management by reducing grid reinforcement, keeping the transformer load in pre-determined tolerance ranges [45,46] through a switch on/off of heat pumps pools. Finally, HPs act as demand-side management units and can be used for responsive loads during times of imbalances in the grid [47,48]. For such reserves, a mechanism has been developed in the electricity market, which helps in deciding which units to use. In most countries, a minimum limit has been set to participate in the reserve market (e.g., 5 MW in Germany and 10 MW in northern European countries). So, a pool of heat pumps is needed in order to take part in a reserve market. Such projects have been mentioned in the references [49–51]; however, on-field examples are limited and need deeper understanding [44,52];
- **Enabling integration of power through RES at building, grid, or power system level (renewable energy-driven);** As far as wind power is concerned, it was shown that it can be integrated with variable speed heat pumps at the building level and the required electricity from the grid can be reduced up to 95% [53,54]. At grid level, as wind power plants are installed with a capacity of over 1 MW, a large number of HP would be needed to use the generated electricity. It has been shown that such a pool of HP, being controlled in an optimal way, helps in absorbing the electricity generated from wind power and thus assists in reducing the need for peak capacity [43]. Hedegaard and Münster studied the influence of heat pumps in reducing the need for peak capacity investments of 300–600 MW, corresponding to the size of a large powerplant [30]. They concluded that the integration of HP in large wind power systems can facilitate in reducing system costs, fuel consumption, and carbon emissions. They also mentioned that HP, along with individual heat storage, contributes significantly to peak load shaving. For optimal operation of heat pumps, an external signal is required containing electricity prices or real-time wind power production, which helps in adjusting the operation of heat pumps. Another effect of a wide deployment of heat pumps is linked to the fact that, for the last few years, locally generated PV electricity has become cheaper, thus going toward decentralized generation. In this view, the main advantage of heat pumps is the possibility to fully adapt to a demand-response approach if combined with real-time information. For instance, PV generation, upon exceeding a threshold, can switch on the heat pump's operation, thus increasing the use ratio of locally produced electricity from 30% to over 65% [55]. Finally, with the help of heat pumps, reduction in feed-in peaks in the grid are reported in the range of 30–55% [56,57];
- **Operating under fluctuating electricity prices (price-driven);** One of the features that make the electrification of the heating and cooling sector interesting from an economic point of view is that energy costs can be saved by taking advantage of low prices in the day-ahead market and additional revenues can be earned in the balancing market [58]. Indeed, electricity prices keep fluctuating on day to day basis

(day-ahead pricing) or even throughout a day (real-time pricing). A predictive model or a scheduling algorithm is needed that considers the load profile and electricity prices in order to guarantee a smooth and cost-efficient operation of heat pumps. Different price schemes were applied in studies that included prices of electricity that remain static for a long time [59–62] or fluctuate after short intervals [31,63–65]. The aim is to minimize the annual cost of energy. Most studies focused on decentralized control and reported significant load shifting using price signals. Moreover, savings were reported ranging from 7% up to around 35% [66,67]. Studies were carried out on how to control the working of HP when electricity prices are known ahead of time. Having such a schedule of electricity prices leads toward the operation of HP during night time, since prices are low at that period of time. It should be noted that the operation of an HP at variable times based on ‘reducing cost of energy’ may cause a decrease in its efficiency. The reduction in efficiency can be mainly because of higher storage temperature, lower external temperatures during operation, and enhanced part-load ratios [43].

Table 2. Summary of the role of heat pumps in smart electricity grids.

Application	Aim	Findings	References
Ancillary services for grid	Voltage control	Voltage problems can be reduced with the appropriate controlling strategies of HP.	[44–52,59,68–71]
	Congestion management	Grid reinforcement can be reduced. Control strategies can reduce peaks but not in all cases. HP operation shows strong seasonal dependency for grid services.	
	Balancing generation demand and frequency regulation	Pools of HP can be used. On-field examples are limited.	
Integration of RES	PV	Self-consumption increases with the use of variable speed HP. Seasonal inconsistency affects self-consumption. Feed-in peaks at noon can be reduced.	[30,53–57]
	Wind	Wind integration reduces carbon emissions. It also helps in reducing fluctuations and peaks. Use of grid electricity can be reduced with local wind turbines.	
Price-driven operation	Fluctuating electricity prices	More focus on decentralized control. Significant load shifting reported using price signals. Negative effect on efficiency reported.	[31,43,58,61–67]

4.2. Application of Heat Pumps in DHC

As already stated, the latest studies are focusing on fifth generation DHC networks, which, compared to the previous ones, can be considered neutral from the perspective of thermal losses since the temperature of supplied water is close to the ground one. In this case, to reach the temperature levels needed by the users (i.e., for heating/cooling and domestic hot water (DHW)), the water at lower temperatures (in the range of 0 to 30 °C) is supplied to “local adjustors”, which operate according to the demand. Reversible heat pumps can be a beneficial technology in the context of local adjustors as they have the capability to work in both heating and cooling modes [72]. Localized heat generation via

heat pumps can then greatly reduce the thermal losses in the grid. Different uses of heat pumps in a DH network for coupling of different sources and sinks are shown in Figure 5.

Figure 5. Operation of heat pumps with typical heat sources and sinks of DHC.

Having heat pumps in DH networks will also help in the decarbonization of the energy system. According to Chen et al. [73], significant emissions reduction, in the range of 30–40%, were noticed in Beijing based on a scenario when heat pumps partially replaced coal boilers. Similarly, a study carried out in New York City by Waite and Modi concluded that 10% CO₂ emissions reduction were noted when heat pumps replaced 20% of gas-fired boilers [74]. Heat pumps along with thermal energy storage are considered to be a valuable combination as they will help in further combating greenhouse gas emissions. An analysis carried out in Finland considering future (2035) and present scenarios regarding fulfilling the heating demand of users indicated that 30% emissions reduction can be achieved in future scenarios with the use of heat pumps, thermal energy storage, and electrical boilers [33].

The technical characteristics of heat pumps used at the district level (up to now mainly for heating purposes) are shown in Figure 6 [75].

4.3. Heat Pumps as Enabling Technology for Sector Coupling

In the previous sections, the main benefits and features for the application of HPs within the smart electric grid and the new generation DHC were discussed. However, sector coupling requires a true integration between the two types of grids through synergistic actions. This section discusses the barriers still existing in incorporating HP as connectors of the electric and thermal grid, along with policy measures that need to be taken to boost the use of HP.

From the technical point of view, one of the main challenges is the placement of heat pumps in existing networks (second or third generation DHC) [75], due to the high temperature levels of the network and the lack of suitable sources (geothermal, solar). A common solution can be to place heat pumps either at the existing central heat source (CHP or electrical boilers) or at a local heat source [75]. Heat pumps will work alongside the existing heat source in a multi-source mode. This connection can be made either parallel or series, and both sources will work with different shares of thermal capacity. CHP or boiler can be made to work at lower part-load ratios, and load can be adjusted with HP. In order to investigate such working performance of HP and CHPs, modeling of energy systems is needed. Felten presented an integrated model for sector coupling of heat and electricity for

large-scale energy systems [76]. The technologies considered for modeling sector coupling include CHP, electric boilers, HP, heat-only boilers, and thermal energy storage. It was concluded that such modeling techniques help a lot to take future measures related to energy policies, curbing greenhouse gas emissions, supporting RES schemes while also lending a great help in analyzing power systems and assessing investment valuation.

Figure 6. Technical characteristics of heat pumps in district heating [75].

Existing thermal grids are operating at high temperatures, which makes the integration of HP difficult and unfeasible. In upcoming thermal grids, it is possible to define the temperature level that suits the range where HP is more efficient [77]. Moreover, through suitable exergo-economic models [78–80] or dynamic simulations [81,82], it is possible to define the main parameters for the selection of heat pumps features within hybrid thermal-electric grids, mentioned below and also shown in Figure 7 [83]:

- Heat source;
- Heat pump technology, i.e., the connection, sizing, and operating mode of the heat pump;
- Heating demand, which is linked to the need for a demand-response approach.

Ground source HP, which has a suitable potential as a low-exergy heating system, gained considerable attention from researchers because of its highly effective use of electricity and suitable use of low-temperature sources [78]. Meesenburg et al. [79] made an exergo-economic analysis of a heat pump in an integrated energy system. The focus of the study was to integrate a heating and power system with a ground source heat pump. It was mentioned that coupling of the above-mentioned sectors provides feasibility to decouple the electricity demand and supply. Moreover, it also provides a balancing service to the power grid. The used operation strategy takes into account the heat demand and power regulations. It was concluded that providing demand flexibility leads to higher exergy destruction. Barone et al. [82] made a dynamic simulation for thermo-economic analysis as

well as optimization of DH systems containing heat pumps/ chillers. The developed simulation tool assesses and optimizes the energy, environment, and economic performance of a DH system. Optimization of system design and operating parameters is also achieved through dynamic modeling. Another aspect to be taken into account is the presence of adequate infrastructure for sector coupling, which is currently hindering the wide adoption of HP [84]. For instance, decentralized heat generation may result in frequent run-and-stop times, which should instead be avoided through suitable control logic [55]. Furthermore, there is a need for the digitalization of such a hybrid thermal-electric network in order to optimize the interaction and transaction processes at the local level where heat pumps have been employed. Indeed, whereas in the past, the inter-communication between the supply and end-use sections was complex, the use of advanced controlling techniques through artificial intelligence for appropriate use of HP technology [85] has strongly reduced such an issue. It is worth considering that in the majority of available studies, the heat pump has been treated as a black box, with no specific consideration for the particular operating conditions within the thermal and electric grids. On the contrary, the design of the whole heat pump should be investigated according to the requirements for specific grid applications.

Figure 7. Technical triangle featuring key features for integrating heat pumps in DH [75].

Apart from the technical considerations, the economic aspects are still the major barrier to be considered when discussing sector coupling. In principle, the price-driven operation of HP should be advantageous since electric boilers can be used when the price is very low, while HPs can operate over a broader spectrum of electricity prices because of their high efficiencies. However, current heating technologies, such as oil, gas, or biomass heat-only boilers, are cost-competitive against HP, which hampers the inclusion of HP in current DHC systems [2]. The use of fossil fuels-based techniques should be disincentivized to encourage low-carbon heating systems. HP integration can be encouraged by adjusting investments, operation subsidies, taxation [86], and electricity grid tariffs [87].

Another aspect of being considered is the acceptance rate of new heating technologies by the different stakeholders. For instance, the adoption of heat pumps at the industrial level has increased in recent years, but it still can be improved. In certain industries, the use of such technologies is considered a risk to the production and quality of products.

However, heat pumps are being used in food, pulp, and paper industries but in a limited way [88]. The common objection is that new technologies may disturb the rhythm of production because of longer start-up times and different heat transfer mechanisms [7]. In the residential sector, there is a lack of willingness to adopt new technologies because of a lack of clarity on available information and behavioral barriers [7]. In order to boost the confidence of consumers and investors, demonstration projects should be promoted, and their benefits should be highlighted. To facilitate the investment in sector coupling and low-carbon heating technologies such as heat pumps, it is important to develop a future policy with financial incentives for end-users as well as energy communities. In recent years, the concept of 'energy communities', in the wake of efforts owing to the Paris agreement [89], has received attention from researchers and policy makers [90]. EU overhauled its energy policies in 2019 and initiated a 'Clean energy for all Europeans package' in which energy communities have been added to the legislation [91]. These communities contribute to increasing the awareness about the usage of renewable energy projects and also help in enhancing the public acceptance rate. Such communities organize citizen-driven energy actions, which help in paving the way for the energy transition. Demos, pilot projects, sandboxes, and energy communities can be used to show that smart integration of sectors can be achieved using appropriate technologies [92], systems, and devices. Lessons learned through these pilot projects can then be communicated to scientific communities and industries, which can then suggest optimization and modification in techniques. An open exchange of data and results can accelerate the efforts in achieving sector coupling. In the context of energy communities, such technologies are required that are not too complex and have a higher acceptance and reliability rate. HP is one such technology that can play an important role here. Another significant thing is to increase self-consumption at the residential level. In a study made by Rinaldi et al. [93], it was concluded that HP provides increased local PV self-consumption. If a building has the possibility to install solar PV, wind turbine, HP, or a micro CHP, self-consumption can be increased by consuming a major portion of renewable energy being produced locally. In case of lack or excess energy production, it can be exchanged with the neighboring residential buildings, the main concept of energy communities, thus increasing the energy utility. This exchange of energy can be measured by smart meters [94]. Martorana et al. [95] analyzed the solar-assisted HP for supplying domestic hot water in energy communities of southern Italy. Three different solar technologies, namely PV, solar thermal, and photovoltaic thermal, were analyzed. It was concluded that PV-assisted HP is most suitable for the desired operation. Moreover, it was also recommended that a storage mechanism should also be present to serve the sudden change in demand since HP coupled with solar systems are not suitable for demand-response programs. In another study by Jambagi et al. [4], sector coupling of heat and electricity at the domestic level is analyzed. Two houses are considered, with one having micro CHP with electrical and thermal storage and the second house with a PV-assisted heat pump. Results show that having both electrical and thermal energy storage help CHP by maximizing its use. Moreover, the use of PV increased and reduced the cost of energy for households. The prospects of HP in sector integration of electricity and heat are quite bright, and a huge increment in the installation of HP is expected with the advent of projects aiming for electrification of the heating sector [96].

5. Thermal Energy Storage for Power-Thermal End-Use Sector Coupling

5.1. Application of TES in DHC

Thermal energy storage (TES) is the technology by means of which it is possible to store thermal energy, which can be used later in order to cover the mismatch between energy generation and its use. Implementing TES in an energy system results in better economics and more efficient use of energy while lowering CO₂ emissions and increasing the system's reliability [97,98]. TES technologies can exploit sensible, latent, and thermochemical heat. A detailed classification of TES is given in Figure 8.

Figure 8. Classification of thermal energy storage.

Several reasons lie beyond the wide adoption of TES in DHC systems. The benefits, ranging from technical to economic to environmental, associated with TES in district heating are discussed in detail elsewhere [13]:

- **Coping up with heat load variations due to demand side:** DHC systems often face heat load variations that result in increased cost for heat/cold generation and an increase in greenhouse gas emissions because of use of fossil fuel use associated with the use of boilers as generators for peak load. In order to cope with heat load variations, thermal energy storage can smooth the peak heat loads;
- **Coping up with variations in the generation side:** which are mainly due to variable renewable energy sources, such as solar. As the penetration of renewables in the heating sector has increased in the past decade, the incorporation of thermal storage with the heating sector is crucial [99]. Moreover, different RESs have different time scales for variation (i.e., seasonal or daily) and therefore require different types of TES;
- **Increasing flexibility of system:** Integration of thermal energy storage with district heating increases the flexibility of the system. Flexibility in terms of district heating can be defined as the capacity to shift the energy supply in terms of time, temperature levels, and power levels [100];
- **Less infrastructure for DHC:** Connecting TES to DHC networks allows for the use of a shorter pipe size for the distribution network [101]. When TES is installed on the primary line, it helps in overcoming the issues related to mass flow circulation. Water can be circulated at lower flow rates, which allow for smaller pipe size, thus reducing the associated pumping costs;
- **Energy savings and reduction in greenhouse gases:** the application of TES systems in buildings, industry, and DHC systems not only provide an annual energy saving but also helps in reducing CO₂ emissions [102].

5.2. TES Technologies for DHC

Before making an analysis on how TES can play an important role in sector integration, a description of its different types and latest status is presented below. Currently, TES is extensively used in district heating and cooling. Storage in thermal or hybrid grids can either be short or long term. Short-term storage (STS) includes the use of heat storage tanks, the thermal inertia of buildings, and the network pipeline of district heating and cooling (DHC). Long-term storage (LTS) uses boreholes, tanks, and pits. Short-term storage can be of the order of an hour up to a few days [103], while long-term storage is of the order of weeks up to a season (seasonal TES).

Within DHN, short-term storage can be centralized or decentralized. Having centralized storage tanks results in decreasing the total annual operating cost of a DH system as compared to no storage [103]. The operating cost increases because of heat load variations, and the presence of a storage mechanism helps in coping up with such variations, thus reducing the operating costs. Examples of such a type of storage are sensible storage close to generation plants (such as CHP or a centralized gas or biomass boiler); see Figure 9, which helps in covering peak demand time periods, enabling peak capacity of the plant to be reduced and to operate at full capacity for longer time periods [104,105]. The temper-

ature ranges shown in Figures 9 and 10 are from the third generation [11]. These supply temperatures will drop considerably in upcoming generations.

Figure 9. District heating and cooling with centralized storage (1—generation plant, 2—TES, 3,4—DH users).

Figure 10. District heating and cooling with decentralized heating (1—generation plant, 2,3—DH users).

The presence of TES in a DHN is beneficial in the way that it reduces the imbalance in the supply and demand gap. Dmytro et al. [103] made an analysis of thermal energy storage in district heating systems. Two storage types, i.e., centralized hot water tank (HWT) and building inertia thermal energy storage (BITES), were extensively analyzed in the context of heat load and supply. The study concluded that both storage technologies reduced the imbalance between heating load and supply. For the case considered in the study, hot water tanks proved to store double the amount of heat as compared to the thermal inertia of buildings. Moreover, it was observed that if the purpose is to store heat for more than 48 h, HWT can come in handy. HWT has its full capacity available for charging and discharging, while BITES depends on many factors, including heat transfer between the building core and indoor environment. The results have further shown that both TES technologies are equally efficient in straightening out the daily net load variations. When compared at longer time intervals, HWT showed better performance in smoothening the load variations up to a few weeks because of its high potential to store heat and reduce losses. Relative daily net load variations decreased by 19% and 20%, while weekly net load variations dropped by 10% and 17% for BITES and HWT, respectively, when compared to a scenario in which no thermal energy storage was present. It is then possible to use decentralized storage for DHC, which can be the exploitation of thermal inertia of buildings or realized by storing energy locally at the building level, usually through a sensible or latent heat storage system, as shown in Figure 10 [103].

Another solution for thermal storage inside DHC is the possibility of using the pipelines of the system. Even though this system can be effective in decreasing the daily peaks, it requires the increase in the temperature of the water supply, which increases distribution losses [106]. Furthermore, high return temperatures decrease the efficiency of the energy system [36].

The decentralized storage is usually part of a renewable-based system installed on the end-user section. In this case, the heat stored can be in the form of sensible or latent, or both contributions can be exploited, i.e., through a hybrid system [107] and used for domestic hot water and space heating purposes, as shown in Figure 11.

Figure 11. Meeting heating demands with solar thermal in residential building (1—solar thermal collector, 2—TES tank, 3—pump).

For cold storage purposes, water/ice is used because of its low cost and high latent enthalpy. Chan et al. reported a DC system combined with ice storage [108] and discussed the economics of the use of such a solution. Results indicate that, although considerable savings can be achieved during operation, payback time is estimated to be 22 years due to the higher installation cost and electricity tariffs.

Alongside sensible storage, LTES is also suitable for applications in district cooling systems. He et al. [109] investigated a PCM paraffin wax for cold storage in a district cooling (DC) system with the aim of peak shaving. It was concluded that using PCM storage combined with an absorption chiller not only helps in peak shaving but also reduces the storage size. According to the results, the storage size of PCM was 61.5 m³, while a stratified chilled tank would require a volume of 690 m³. In DC systems, the temperature difference between supply and return temperatures is much lower as compared to DH systems, and therefore, a larger storage volume is needed. Having a latent system results in a reduction in specific volume as compared to a sensible system [36].

In addition to short-term storage, DHC often makes use of seasonal thermal energy storage, which can store heat for longer periods of time, ranging from days to weeks and even months. For applications concerning long storage times, thermochemical and latent seasonal storage technologies are still in the laboratory-scale testing phase, while sensible seasonal storage technologies have been in operation for a long time [110,111]. Some of the widely used seasonal storage techniques are briefly described below. These technologies have been termed promising for sector integration of power and heat [112]. Moreover, such storage techniques also allow a greater share of renewables to be incorporated and can also make use of HP in conjunction.

Aquifer thermal energy storage (ATES) is a method for storing heat underground for long periods of time. Two wells are usually employed, namely cold and warm wells. When charging needs to be performed, water from the cold well is extracted and passed through a heat exchanger. After water absorbs heat, it is injected into the warm well. For cooling purposes, a reverse process is performed. The temperature of the ATES system is limited to 50 °C because temperatures above this limit cause a change in the chemical properties of soil [113]. Figure 12 shows the use of this technology in the summer and winter seasons within DHC. Most often, the storage temperature is not sufficient enough for the whole heating season. So, a supporting equipment, e.g., heat pump, is required to elevate the temperature to the user level [114]. In the case of low-temperature energy storage, heat pumps can be used to raise the temperature needed for domestic hot water and space heating.

Pit thermal energy storage (PTES), another technology adopted in DHC, is shown in Figure 13. It resembles a large pool covered with an insulating roof. Water is pumped into or out of the storage unit to add or extract energy. This technology can be helpful in the successful implementation of energy systems' transformation to renewable-based ones. If higher temperatures are needed, a heat pump may be used to elevate the temperatures. Sorknæs [114] developed a simulation model for integration of PTES with HP and validated it by testing it on Dronninglund DH for the year 2015. Results found were in close proximity to actual ones. One of the biggest examples of PTES storage system is Marstal Fjernvarme on the island of Ærø, Denmark [115], which involves the heat pumps [116].

Borehole thermal energy storage (BTES), shown in Figure 14, is another seasonal storage technology being applied in DHC. This storage system can be used in almost all geological conditions. The higher temperature of storage results in higher COP values of ground source heat pumps, and therefore, less electricity is required [117]. Nam et al. [118] concluded that employing ground source HP coupled with solar thermal energy help in maintaining better ground temperature balance and perform at higher COP values over their lifespan.

TCMS (Thermochemical storage) is also used to store heat seasonally. The working principle of a TCMS can be found elsewhere [119]. One of the main strengths of using TCMS lies in its high energy density, which is about 400 MJ/m³ [120], while the energy

density of water is around 200 MJ/m^3 when a temperature difference of 50°C is considered. Another benefit associated with TCMS is its low thermal losses over time. Indeed, the storage process is related to the thermochemical reaction potential occurring between two components. During charging, the energy is spent to separate the two components. Accordingly, the stored energy is almost unaffected by heat losses since it is guaranteed as long as the two components are kept separate. Once the energy is needed, the recombination of these components releases the stored energy [119]. The concept of TCM seasonal storage installed within a thermal network is shown in Figure 15.

Figure 12. Aquifer thermal energy storage in summer (a) and winter (b). 1—DH users, 2—cold well, 3—warm well.

Figure 13. Seasonal pit storage in summer (left) and winter (right), 1—DH users.

Hui et al. [121] investigated seven different absorption working pairs to find a feasible combination with convenient properties for seasonal storage of solar energy for a house heating system. These couples were $\text{CaCl}_2/\text{H}_2\text{O}$, glycerine/ H_2O , $\text{KOH}/\text{H}_2\text{O}$, $\text{LiBr}/\text{H}_2\text{O}$, $\text{LiCl}/\text{H}_2\text{O}$, $\text{NaOH}/\text{H}_2\text{O}$, and $\text{H}_2\text{O}/\text{NH}_3$. The analysis showed that none of the mentioned

absorption couples turned out to be suitable for DH applications because of not reaching the required temperature threshold.

Figure 14. Borehole thermal storage in summer (a) and winter (b). 1—DH users, 2—borehole, 3—soil underground.

Figure 15. TCM seasonal storage charging phase (a) and discharging phase (b).

In Munich, a large sorption zeolite prototype for two buildings was investigated with the intention of peak shaving in summers and winters [122]. The hot source was provided through a DH network, while the cold source was made available from the returning line of the DH system. Optimal desorption temperature for best performance was investigated. The payback period of this system was found to be in the range of 7–8 years. Results showed that 86% of theoretical maximum efficiency and 81% of theoretical maximum thermal energy density were reached. Moreover, the prototype helped in straightening out the load profiles of both buildings.

5.3. TES as Enabling Technology for Sector Coupling

The main benefits for the application of TES in DHC were discussed in Section 5.1, but its potentialities are even higher when considering the sector coupling with the electric network [110].

Both sensible and latent TES technologies have been termed as promising technologies for sector integration in a report published by IRENA in 2020 [110]. According to the report, sensible technology is suitable for sector coupling because of its high maturity and commercial availability, while latent TES has a very low physical footprint and high energy density. Among seasonal storage technologies for sector integration, all the above-mentioned technologies, namely ATES, PTES, and BTES, have been termed promising, and the development of these technologies has been considered encouraging [114]. Examples at the commercial level are quite low as these technologies have still not reached commercial readiness. Steinmann et al. [123] analyzed the prospects of PTES technology for sector coupling of heat and electricity. It was concluded that PTES has great potential as an enabling technology for sector coupling. IRENA terms TCMS as an interesting and promising technology from a sector coupling point of view, but it is still in the applied research and prototype phase [110]. The examples in literature for TCMS as a service for sector coupling are also limited. Cammarata et al. [124] developed a storage device based on thermochemical materials to store excess generated power. The aim was to develop a storage system for household applications for a temperature range of 50–100 °C. The material used was strontium bromide ($\text{SrBr}_2 \cdot 6\text{H}_2\text{O}$) and graphite as an additive material. It was concluded that the concerned material is a suitable fit for storage applications, which also makes it feasible for sector coupling. Ferruci et al. [125] developed compressor-driven thermochemical storage for cooling applications in households. The mechanical-driven compressor is powered by grid and PV electricity. The thermochemical material being used is pair of $\text{BaCl}_2/\text{NH}_3$. In case of excess electricity and no cooling load, energy will be provided to the compressor to store energy. It was concluded that the proposed system can provide cooling and energy storage in the context of smart grids. Fito et al. [126] studied an ammonia-based refrigeration system consisting of compression refrigeration with thermochemical storage. The configuration of the system consisted of a heat pump, a grid-connected solar PV, and a thermochemical storage reactor. Electricity requirements for meeting the cooling demand are covered by solar PV and the grid. In case of excess RES power generation, it is used to store energy in the form of heat by the desorption phase of the reactor.

TES can play an important role when the integration of electricity or gas grids with DHC is foreseen. Typical energy vector conversion systems are power-to-heat, heat pumps, heat-only boilers, power plants, and cogeneration plants. Energy can be converted to other forms and stored while guaranteeing economic and environmental feasibility. Indeed, as already mentioned, TES allows for better use of RES. Since the majority of renewables produce electricity, TES increases the flexibility of the system because it helps in reducing the variability and uncertainty of RES by storing energy in the form of heat at the time of production and releasing later for use when required; this allows covering the gap between generation and demand [127,128]. Heat pumps can be used for energy storage purposes in this case. When electricity is in excess, it is converted to thermal energy using HP and is stored. Moreover, TES allows for better use of CHP plants in the framework of optimized management of the whole energy system. CHP is often controlled according to the electricity demand needed at a certain time. However, the heat produced at the required part load does not always meet the thermal demand. The presence of TES will help in keeping the desired part load without wasting the produced heat. It was demonstrated that with such a strategy, it is possible to integrate renewable electricity around 20–25% of total demand without hindering the overall efficiency of the CHP system [39]. CHP plants use then results in maximized profits [129,130]. The presence of TES makes it possible also to shift the electricity production to hours when the unit price is higher [131]. Ramm et al. [132] explored the integration of heat pumps and TES with CHP and how this

integration allows stabilizing the electric and thermal grids. The study concluded that it is possible to couple thermal and electricity grids by using heat pumps, TES, and CHP through a controlled strategy, and stability can be provided to a low and medium voltage grid. The application of a suitable management technique to control the operation time of CHP and HP to exploit the opportunities to stabilize the grid was suggested.

Another effect of using TES coupled to power-to-heat systems such as heat pumps is that TES improves the operation of the heat generation system by reducing the temperature fluctuations, thus increasing its efficiency. It is then discussed in some studies that in this way, the burden on the electric grid is reduced [103]. A similar effect is achieved by using TES as a way to support the time of rapid demand; using the stored heat allows reducing the need for oversized boilers or chillers, which consume a high amount of electricity, especially during start-up.

The possibility of using TES for sector coupling opens up also another path, i.e., the replacement of part of the electricity storage with thermal storage. Regarding electricity storage, two techniques have been applied at a large scale, i.e., pumped hydro energy storage (PHES) and compressed air energy storage (CAES) [5]. Compared to them, TES possesses many features, which makes it a valid alternative:

- TES systems are less expensive, with costs at around 0.5–3 €/kW, while costs of CAES and PHES lie around 170 €/kW [133]. Another study carried out by Scapino et al. [134] estimated the cost of TES in the range of 10–50 USD \$/kWh, while CAES had its cost in the range of 2–100 USD \$/kWh;
- CAES and PHES technologies lead to significant losses, and roundtrip efficiencies are 65% and 85%, respectively [5]. TES, on the other hand, minimizes roundtrip conversion losses;
- TES leads to higher efficiencies when RES are integrated as compared to electric storage [5];
- The lifetime and capacity of TES systems are also higher than the other two technologies mentioned [135].

It is worth noticing that the economics of this solution is also profitable. The installation of TES systems is not expensive, especially for the sensible technology, whose cost ranges between 0.1 and 10 €/kW [136]. Currently, sensible TES is the most attractive technology to store energy in an electrical network for a longer period in an economical way [137]. Rech and Lazzaretto [138] discussed the optimization of an energy system operation fed by RES and connected to a grid. It concluded that TES is the best system to optimize the working of energy systems while electrical storage may appear unfavorable. There is another technology for the energy storage process in large electrical applications known as ‘Pumped thermal energy storage’, and it involves both HP and TES [139]. It has been termed as a key technology for sector integration while also providing the possibility to incorporate increased RES penetration [123]. In pumped thermal energy storage, heat from a low-temperature source is converted to high-temperature heat through heat pumps and is stored in a thermal storage unit. Later, heat is discharged, and mechanical work is produced through a thermal cycle. Steinmann et al. [123] studied the possibility of using pumped thermal energy storage as a sector coupling technology with butene as a working fluid. The thermal storage unit is charged with steam at 350 to 400 °C and at a pressure of 100 bar. Roundtrip efficiency of 70% has been achieved. Wang et al. [140] proposed a pumped heat electricity storage based on the Brayton cycle. The behavior of storage units was observed under four different operation modes, namely series, parallel, in sequence, and a novel mode named ‘temperature complementation’. It was claimed that the proposed novel mode requires low TES unit volume and cost. Moreover, it was also mentioned that pumped heat electricity storage has efficiencies and energy densities comparable to CAES. The storage with series-connected reservoirs resulted in a roundtrip efficiency of 64.9%. Under novel mode, the delivery stability of power improved by 13.2%. Moreover, it was mentioned that with the proposed novel mode, the size of the TES reservoir can be reduced by 1.8 times while having roundtrip efficiencies of 63–65%. The novel mode

has been proposed to increase the delivery stability since it was observed that the stability of power delivery was low in other operating modes. It is accomplished by controlling the operating time and flow rate of each reservoir. It is important to mention here that the quality of energy drops in TES because of losses attributed to it. The process of converting heat to electrical energy is quite complicated. There are different methods to do so, and each method has its own requirements and limitations [141].

TES can also be incorporated at the local level in order to support the integration of varying RES. Arteconi et al. [59] conducted a study to analyze the installation of small TES systems and heat pumps in buildings for demand-side management and power balancing. The aim was to flatten the electricity load curve by switching off the heat pumps during peak hours and to assess the thermal comfort of occupants inside the house. The temperature control of the building under consideration was strongly affected by the thermal mass of the system when heat pumps were turned off. For example, thermal comfort was maintained through underfloor heating even when heat pumps were turned off. For heating systems with low thermal mass, such as radiators, TES becomes necessary to be installed to improve temperature control. Results show that electricity bills can be reduced by using the ‘time-of-use’ tariff and by using incentives on renewable heat generation, if available.

Finally, TES has the ability to overcome the limitations of certain technologies associated with DHC and to boost their advantages. TES installation allows CHP to operate at full capacity when electricity prices are high while keeping the stored heat intact. For DH purposes, CHP-DH is the most common and widespread technology. The use of TES has proven to increase in flexibility of CHP operation [5]. Moreover, the size of the installed capacity of power generation units can be reduced if TES is integrated with a CHP, and profits have been observed to be increased. An increment in the capacity of CHP has been proved not to affect the flexibility, while the buffer size has an almost linear effect on it [142]. A TES system tailored according to the needs of a CHP helps the plant to run at optimal conditions. A reduction of almost three times is observed in the greenhouse gas emissions when TES is integrated with CHP-DH combination in a study carried out by Haeseldonckx et al. [143]. Moreover, Al-Qattan et al. [144] discussed the integration of TES in DH with fuel cells and concluded that this combination resulted in an efficiency increase of around 346% while decreasing the carbon emissions by 54% [144]. A study by Verda and Colella [145] about thermal energy storage in district heating networks concluded that total annual costs can be reduced by 5%.

Despite such benefits, different barriers to the implementation of TES technologies can be identified. There is a lack of technology readiness related to some TES technologies. TES is a ‘relatively new’ technology that is competing against technologies with high TRL (technology readiness level), e.g., low-cost fossil-generated heating [110]. Moreover, there is a lack of knowledge and awareness confidence in how TES can prove to be beneficial for the power, heating, and industrial sector. This lack of confidence has been recently demonstrated when research and development’s focus was disproportionately shifted to electrical battery storage despite the proven fact that TES can incorporate high levels of RES. TES projects are generally long-term and large-scale projects. Currently, there is uncertainty on how a future energy system would look like and the way it will develop through the transition phases, which leads to reluctance to invest in long-term projects. Another technical issue to be tackled through dedicated R & D is the design of TES for DHC, which requires the knowledge of network dynamics and the development of ad-hoc tools for planning and selection of the best technology. This is particularly true for seasonal TES; that, however, demands more attention as it is one of the best ways to make full use of heat sources such as solar, geothermal, and waste heat. More case studies are required on selection-procedure of type of seasonal storage to know about different decision criteria that should be taken into account to check the feasibility as each type of seasonal storage has its own requirements and limitations. For example, ATEs needs particular geological conditions with water-saturated sand layers having high permeability without natural

groundwater flow. If these conditions are not met, then clogging effects start to appear, which are difficult to manage. If the geological conditions are not checked carefully before the initiation of the project, irreparable damages take place, and unexpected disadvantages appear. Moreover, the soil formation and composition also need to be checked before drilling holes and bores. High thermal losses are also a serious problem associated with seasonal storage. Moreover, proper insulation is needed to reduce losses and leakage from storage. From the technical point of view, another issue to be considered is the definition of robust monitoring and control models, which can exploit the maximum benefit from all energy resources associated with a system. A vision on the barriers and development path for the various TES technologies toward a higher TRL for various applications, including DHC, is given in the work of [146].

Apart from technical issues, future smart energy systems call for a unified policy as the aim is to develop MCES that carry different energy vectors. Currently, there is siloed thinking for each energy vector, which often leads to conflicting policies and inefficient future planning. The heating sector is yet lacking a solid policy for decarbonization as compared to the power sector [110].

Policy makers and actors from the energy sector can tackle the above-mentioned issues by technology push, market pull, and enabling mechanisms to encourage the wide deployment of TES projects [110]. The focus should be increased on building an integrated energy policy for the heating and cooling sector with the incorporation of TES to achieve benefits. An all-system approach is required to analyze available technologies across all energy vectors to devise the most cost-effective way for the energy transition. Demonstrations related to the research and development of TES should be regularly funded in order to increase market awareness, build consumers' confidence and progress the TRL [110]. In short, more investment is needed in the R&D of TES technology. Policy makers can consider removing or decreasing subsidies on the use of fossil fuels, which would certainly help in increasing the competitiveness of low-carbon heating technologies. A comprehensive market mechanism is required, which should address time-of-use tariffs to help reduce the consumers' bills and furthermore should also provide revenue incentives for owners and operators of TES systems [110].

Up till now, it has been discussed how HP and TES can play a significant role in sector coupling. In the coming paragraphs, the impacts on the power sector as a result of sector coupling will be discussed. Sector coupling helps to improve the flexibility and efficiency of energy systems while also adding to the reliability and adequacy. Moreover, sector coupling can also provide voltage control, congestion management, and balancing supply-demand frequency regulation as additional support. It is also the answer to growing flexibility needs in EU power systems because of increasing RES share. There have been various examples from EU countries when RES provided 100% of the power demand, and the high availability of RES is leading to scenarios related to negative prices in the market [6]. Therefore, several member states with a high share of RES in the energy mix have the challenge of making their power systems flexible in order to match supply and demand at any moment. This challenge can be overcome by the combined use of HP and TES. Although several solutions have been applied, the repeated occurrence of negative prices in the spot market implies that more efforts and options are needed. According to a position paper from DNV [147], the flexibility offered to the electricity sector by sector coupling comes in different forms. Besides traditional fixed demand, two new parameters come into play that are known as responsive and opportunity demand. According to the authors, responsive demand helps in absorbing large fluctuations for a short interval of time. Opportunity demand, on the other hand, gives an additional dimension to the price-forming mechanism as this demand can become price-setting based on the cost of alternative options. A price-setting strategy is a mechanism to set the prices of a product seeing its demand in the market. It is mentioned that heat pumps and electric vehicles have the potential to absorb large amounts of renewable electricity, thus shifting demand toward high renewable production. Moreover, it is also mentioned that with an increase

in renewable electricity, the need for large energy storage mechanisms will also increase. Thus, TES can play an important role here in aiding sector coupling [148].

Sector coupling provides support to the connected sectors in order to exploit synergies while leading to a more energy and cost-efficient power system [149]. It also helps to better use the abundantly available RES as mentioned above. Power-to-heat technologies combined with thermal energy storage help to convert electricity to heat and store it during the abundant and cheap availability of electricity [147]. Stored heat can be used to meet either thermal demand or to produce electricity later. In the same way, electricity can be converted to liquid fuel (methanol, for example) or to hydrogen through electrolyzers [6]. The electrification of the heating and transport sector is very likely in the near future. An increase in electricity demand in these sectors will cause an increase in electricity prices, which may help in positive business cases for RES power generation. After the above discussion, it is quite clear that HP and TES technologies can play a significant role in sector coupling. Moreover, sector integration is beneficial to both the power and heat sectors and is the need of the hour.

6. Conclusions

In this paper, a comprehensive review of the role of heat pumps and thermal energy storage technologies in the context of sector coupling is made. The main emphasis is on sector integration of electricity and heat. The concept and need of sector coupling are explained in the beginning. Before making an analysis on how HP and TES can be helpful in enabling sector coupling, the current status of both technologies is reviewed. Both these technologies are being used in district heating and cooling and will assume a major role in upcoming generations of DHC. HP technology is concluded to have a huge impact on the decarbonization of fifth generation DHC networks.

The role of HP in smart electric grids, in the context of sector coupling, was discussed to understand how this technology would help in supplying ancillary services to the grid and in enabling the integration of renewable energy sources (RES). Moreover, HP technology has the potential to be used in interconnected energy systems and would greatly help in bringing efficient and renewable practices in the future. Several studies found in the literature concluded that HP, while providing supplementary services to the grid, could help in voltage control and congestion management. Furthermore, HP could also help in balancing generation demand and frequency regulation. Solar and wind power could also be integrated with variable speed HP to increase the on-site consumption of energy.

Different TES technologies, namely sensible, latent and thermochemical, were discussed in terms of their applications in DHC and multi-carrier energy systems. Literature shows that TES can contribute to smoothening net load variations and can cause a reduction in CO₂ gases. Seasonal storage techniques are termed equally important and significant, by an IRENA report, for sector integration of power and heat. From the findings of this review, it could be considered that the use of TES in smart grids will increase considerably in the future as it helps in increased renewable penetration. Moreover, the use of TES will help to reach the core objective of the Paris agreement, which is to promote clean energy initiatives and to reduce greenhouse gas emissions. A comparison of TES with compressed air energy storage and pumped hydro energy storage is performed in order to provide a clear view of the financials involved in employing these technologies. TES supersedes both the above-mentioned technologies in economic competitiveness. Moreover, the latest studies on pumped thermal energy storage, which use both HP and TES technologies, are also mentioned. Pumped thermal energy storage is termed a promising technology for large-scale electrical storage.

Apart from technical barriers, the economic, social, and political barriers are also discussed. Both heat pumps and TES have not been in the focus of national incentives, and economic support to their implementation is missing. Moreover, suitable business models need to be defined, which can increase the market penetration of the investigated technologies. A common plan and assessment to incorporate HP and TES for sector

integration are still missing at the policy level, and strong efforts are required to materialize the vision of an integrated energy system. The use of both technologies will help in easing the transition toward energy-efficient ways to reduce carbon footprint. Moreover, both these technologies will be helpful in the decentralization of energy generation and storage. Finally, social aspects are discussed, and it is highlighted that the lack of clarity and low acceptance rate of the technologies is strongly hindering their installation and widespread adoption. Suggestions are provided in order to speed up the extensive adoption of investigated technologies.

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Nomenclature

ATES	Aquifer thermal energy storage
BTES	Borehole thermal energy storage
BITES	Building inertia thermal energy storage
COP	Coefficient of performance
CHP	Combined heat and power
CAES	Compressed air energy storage
DH	District heating
DHC	District heating and cooling
DHN	District heating network
DHW	Domestic hot water
EU	European union
GHG	Greenhouse gases
HP	Heat pumps
HWT	Hot water tank
IEA	International Energy Agency
LTES	Latent thermal energy storage
LTS	Long-term storage
MCES	Multi-carrier energy system
PCM	Phase change materials
PV	Photovoltaic
PTES	Pit thermal energy storage
PHES	Pumped hydro energy storage
RES	Renewable energy resources
STS	Short-term storage

TES	Thermal energy storage
TCMS	Thermochemical storage
TRL	Technology readiness level

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