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Heat Pumps and Their Role in Decarbonising Heating Sector: A Comprehensive Review

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Abstract: Addressing the growing concerns of climate change necessitates the decarbonisation of energy sectors globally. The heating sector is the largest energy end-use, accounting for almost half of the total energy consumption in most countries. This paper presents an extensive review of previous works on several aspects of heat pumps, including their role in the decarbonisation of the heating sector. In addition, we cover themes related to the recent technological advances of heat pumps as well as their roles in terms of adding flexibility to renewable-rich systems and carbon abatement. We also identify challenges and barriers for a significant uptake of heat pumps in various markets. Generally, as the share of renewables in the energy mix increases, heat pumps can play a role in addressing a multitude of problems induced by climate change. However, economic, regulatory, structural and infrastructural barriers exist, which may hinder heat pump integration rate.

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1. Introduction

The Paris Climate Agreement was one of the first global accords that brought together all nations at a common platform to fight climate change. With 197 countries having ratified the agreement, there is a global drive to reduce greenhouse gas (GHG) emissions. Since then, most countries have undertaken new policy measures to promote integration of clean energy sources, and thereby reduce GHG emissions and curb climate change. Such measures, if successful, should eventually lead to a sustainable energy future, with a low or zero carbon footprint. However, the transition to a low carbon energy future will require decarbonisation of energy sectors such as electricity, heating, transport etc. Among these sectors, the heating sector is the most energy and carbon-intensive. In the EU, this sector accounts for nearly 50% of the total energy demand in the Union, of which 75% is contributed by fossil fuels [1]. According to International Energy Agency's 2018 report, only 10% of the global heat demand in 2017 was sourced from renewables [2]. However, current trends indicate that the share of renewable heat is growing in many countries, especially in the EU states. The level of renewable share in the electricity mix is growing dramatically, and therefore a low carbon electricity is a viable solution to decarbonize the heating sector. Hence, a transition from fossil-fuel based heating to electric heating may be imminent via heat pumps or other devices.

Heat pumps are electrical devices which convert energy from external heat sources (air, water, etc.) to useful heat which can then be used for space heating and/or hot water supply in residential and commercial buildings. They are regarded as one of the most energy efficient and environmentally friendly technologies that enhance the utilisation level and effective integration of intermittent renewable energy sources [3].

Heat pumps have been popular for decades but, in recent years they have gained significant importance owing to their potential to reduce emissions. Generally, there has been a growing trend in adopting heat pump technology, albeit at a low penetration level. Policy makers in various countries have recognised the key role such a technology can play in the transition to a sustainable energy future, evidenced by incentives towards its adoption and diffusion. Likewise, stakeholders have also shown renewed interest in this technology. As a result, growth in heat pump installations is anticipated in the years to come, especially in countries where the majority of heat demand is still sourced from fossil fuels. The International Energy Agency [4], still projects vast fossil fuels and conventional electric heating technologies, which are less efficient and more carbon intensive to dominate in the heating sector. However, with supportive policies, the sale of energy efficient and renewable based technologies, such as heat pumps, will increase market share.

The main aim of this paper is to provide readers with a literature review covering several aspects of heat pumps and their possible role in the decarbonisation of the heating sector. We cover themes related to recent technological advances of heat pumps, as well as, their role in adding flexibility to renewable-rich power systems and carbon abatement. We also identify challenges and barriers for a significant uptake of heat pumps in various markets, and set out directions for future research.

The remainder of the paper is structured as follows. Section 2 presents the technological, end-use and economic aspects as well as the environmental impacts of heat pumps. A review of the flexibility potential of heat pumps in renewable-rich systems is covered in Section 3. Issues concerning modeling approaches of heat pumps are presented in Section 4. Barriers in integrating heat pumps are summarized in Section 7. The last section provides a summary.

2. Aspects of Heat Pumps

2.1. Heat pump technologies and end-uses

2.1.1. A summary of heat pump technologies and applications

Heat pumps are electrical devices that extract heat from one place and transfer it to another. This transfer is accomplished by circulating refrigerants. Heat pumps (HP) can convert excess renewable energy to heat, thereby contributing to the decarbonization of the heating sector. An in depth review of heat pumps (technologies, modeling approaches and applications) concludes that the literature sees a central role for heat pumps, be it decentralized or connected to district heating grids [5]. For instance, the deployment of heat pumps has shown significant growth in the U.S. [6]. They enjoy a growing popularity as they can serve as primary heating and cooling systems in mild climates while as secondary heating systems in colder climates [6]. The heating and cooling operations of heat pumps are fully reversible. HPs can essentially provide thermal comfort throughout a year, providing heating during cold seasons and cooling during hot seasons. Heating and cooling systems using heat pumps appear to be popular solutions for new office and residential buildings with a specific mode for domestic hot water production [7].

There is a strong body of evidence that the deployment of heat pumps results in reduced carbon emissions, savings in primary energy consumption and increases the overall efficiency. For example, a study for the Italian energy system clearly shows these benefits [8]. It also highlights more pronounced benefits of HPs with increasing shares of renewable power which significantly helps in decarbonizing the electricity sector [3]. For on-site heating, based on a Swedish case study, heat pumps are considered superior to several alternatives [9]. A case study for California identifies heat pumps as key elements for decarbonising the heating sector, reporting up to 50% emissions reductions [10].

An analysis of the Danish energy system [11] shows that, by 2035 the integration of HPs would reduce system costs by as much as 16% and biomass usage by 70% compared to a system without HPs [11]. Under UK conditions, cost and emissions savings of 37% can be obtained from HP systems when compared with natural gas boiler systems [12]. However, an undersized HP system may incur higher operational costs [12]. For residential heating in Germany, HPs are favored in the case of higher levels of renewable generation penetration, in heat and electricity demand [13].

The electrification of heat involves risks and uncertainties [14]. Heat pump technologies may require vital localised improvements, otherwise their deployment may not lead to the anticipated reduction in the carbon intensity of the heating sector [14]. However, heat pumps are some of the most promising technologies, capable of achieving worldwide endeavours of low carbon heating. For example, an hourly study of heat pumps for space heating in residential buildings finds almost 30% savings in primary energy consumption and similar reductions in emissions compared to an existing natural gas boiler based heat generation system [15]. This is due to the combined effects of the heat pumps' high coefficient of performance (COP)[1] and relatively low primary energy consumption.

Figure 1 shows categories of heat pump technologies currently available in the market. The most common ones are air source, water source and ground source. However, due to technological advances and increasing economic viability, other types of heat pumps are also being deployed in many countries.

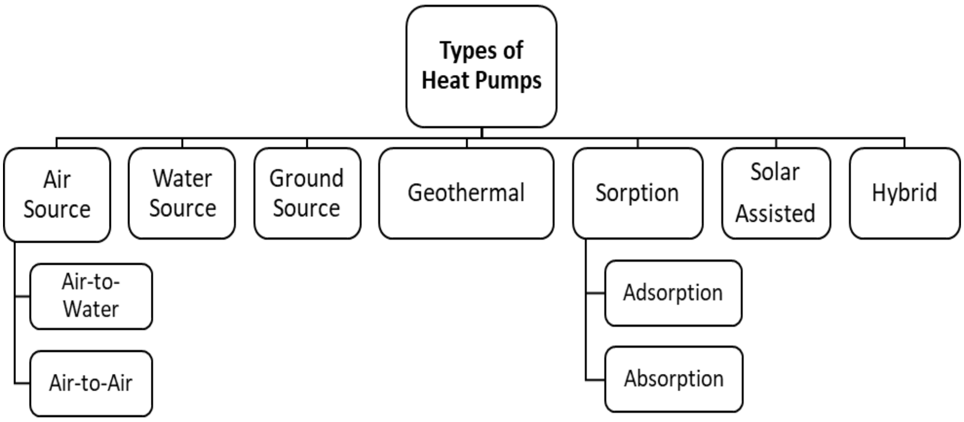

Figure 1: Heat Pump Categories

An air source heat pump (ASHP) takes low grade heat from the air, and boosts it to high grade that can be used for domestic heating or any other purpose. The pump uses less electricity than the heat it produces. The performance of an ASHP is similar to a refrigerator, but works in a reverse mode. ASHPs may also constitute some hybrid heat pump systems such as air-to-water and air-to-air heat pumps. Air-to-water HPs take advantage of wet central heating systems, and distribute heat through it while the air-to-air system produces warm air which is circulated by fans.

ASHPs find applications in domestic space heating and hot water supply. If combined with radiant floor heating system, ASHPs provide the best thermal comfort when compared with cast

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[1] The efficiency of a heat pump is denoted by its COP. It is defined as the ratio of useful heat or cooling provided to the work required. The COP of heat pumps usually exceeds 1.

iron radiator, radiant floor heating and more recent bi-metal radiators [16]. ASHPs integrated for heating and cooling an indoor environment may need more intelligent control mechanisms to meet the thermal comfort requirement of dwellers [17]. However, experimental results show poor levels of satisfaction (29%) in terms of the overall thermal comfort under cooling conditions [17]. Marcic [18] shows that ASHPs with an integrated scroll compressor economizer can provide high grade heat and high capacity hot water even under very low ambient temperatures. A techno-economic feasibility study on air to water heat pump retrofits for a Canadian housing stock shows a 36% decrease in primary energy consumption [19]. However, the COP of such heat pumps is strongly dependent on the season and hence a seasonal performance evaluation is difficult [20].

Water source heat pumps (WSHPs) use water bodies such as lakes, ponds, rivers, etc. as a source of heat. They extract low grade heat from water and convert to useful heat. Compared to air-source heat pumps, WSHPs generate less carbon emissions and result in substantial cost savings. As opposed to ASHPs, ambient temperature conditions do not significantly influence the performances of WSHPs. This is due to the fact that a waterbody possesses enough heat to enable WSHPs to operate even during wintry weather conditions. A Danish study on potential heat pump integration finds the seasonal variation of COP having little or no effect on the results, as COPs of water source heat pumps do not vary much throughout a year [21]. WSHPs are often characterized by high efficiency, but their applications are limited due to the requirement of large waterbodies or storage tanks near dwellings. Moreover, the need to adhere to certain environmental regulations may further result in a low uptake rate of WSHPs.

Both ground source heat pumps (GSHPs) and geothermal HPs use heat energy naturally stored in the ground as a source. Sometimes, the terms ground source and geothermal are used interchangeably. However, there are some key differences between both technologies. GSHPs use heat from relatively shallow ground (often between 1.2m and 200m depth), and are usually used for domestic and small commercial applications. Whereas, geothermal HPs use energy from the earth's core from about 500–2500m deep, and are used for large industrial applications. Both technologies are the most common types of heat pumps deployed worldwide mainly due to their high efficiency and performance under any ambient conditions. A detailed review of GSHPs by Sarbu and Sebarchievici [22] reveals that they can be used in cold and hot climate conditions with significant energy saving potential. For example, Weeratunge et al. [23] find that GSHPs cover 90% of the heat demand for economical operation in Melbourne, while Carvalho et al. [24] draw similar conclusions on the efficiency of GSHPs for space heating in Portugal. Compared to other options designed for green buildings, geothermal HPs have the advantage of being a more reliable energy sources and operating conditions that are subject to fewer interruptions [25]. Alberti et al. [26] report that the integration of geothermal HPs leads to significant reductions in primary energy consumption and operating energy costs compared to traditional heating systems. There are also contrary examples. Renaldi et al. [12] highlight poor performance and high operational costs of underspecified HP systems. Majuri [27] also cite poor performance but a key conclusion highlights the need for ensuring quality HP installations. Bleicher and Gross [28] conclude that geothermal heating is not “ready-made” and needs to be adapted to the specific situation, however, it can be used to cope with unforeseen risks or uncertainties associated with ongoing energy transitions.

Sorption heat pumps make use of thermal energy from low grade heat sources (e.g. waste heat). Adsorption and absorption heat pumps fall into this category, and are often called heat-driven heat pumps. The difference between these two types of heat pumps lies in the thermodynamic cycle. Absorption HPs use liquid refrigerants and hence may face problems such as crystallization of sorbent, corrosion and efficiency loss from circulation. Adsorption heat pumps are used at industrial sites to utilise waste heat and are also combined with solar thermal collectors. Dias and Costa [29] conclude that current research on the interactions among system components and detailed information on experimental studies is not adequately provided in the literature. Notwithstanding, the knowledge gap Demir et al. [30] suggest a key benefit of adsorption heat pump systems is their ability to utilise waste heat and that they have a relatively long life.

Solar assisted heat pumps are efficient and reliable systems which can meet low temperature heat demand such as domestic space heating and hot water requirements. The intermittency of solar may affect the performance of such heat pumps. This problem can be solved by incorporating dual sources of heat. One example in this case is a solar assisted GSHP, which serves to be cost effective as well as environmentally friendly [31]. However, effective control strategies may be required to optimize the performance and efficiency of dual-source HPs. Busato et al. [32] find that multi-source HPs (ground + solar) can be the most cost efficient solution for heat supply.

Some other types of heat pumps are available as well, such as multi temperature HPs, which find application in the refrigeration industry [33]. These heat pumps are uncommon and still at research stage. An optimal design of thermoelectric HPs is discussed by Ramousse et al. [34], which examines how a compact design can decrease power density compared to conventional designs. Johra et al. [35] propose an innovative heat pump based on magnetic regenerator technology integrated with heat storage to improve performance.

Hybrid heat pump systems consist of conventional heating systems such as gas boilers in conjunction with heat pumps. Given the fact that many existing homes already have gas supply, hybrid systems may prove to be ideal solutions to efficiently supply demand for domestic heating and hot water while reducing emissions. But appropriate control strategies need to be integrated along with the hybrid heating system to enable an automatic and cost-effective operation of such systems.

There have been several comparative studies of heat pump technologies across different climatic conditions. Hakkaki-Fard et al. [36] present a comparison of GSHP and ASHP performance in Canada and conclude that GSHPs are better options though technological enhancements to GSHPs may be necessary for economic feasibility. Another Canadian study shows that GSHPs have rather constant performance throughout a year unlike ASHPs whose performances are highly location specific [37]. In Shanghai, China GSHPs had 40% lower annual energy consumption compared to ASHPs [38]. In a comparison of heating tower and ASHP heat pumps in Nanjing, China, the former has marginally higher installation costs but with higher energy efficiency, 10% lower costs across a 10 year period [39]. Mattinen et al. [40] compare GHG emissions across direct electric heating, ASHP and a novel ground-air source heat pumps (GASHPs). Their findings show that GASHPs perform better in colder climates due to higher COP at lower outdoor temperatures. GHG emissions in ASHPs are 40% lower compared to direct electric heating, and 70% lower in the case of GASHPs. From a GHG emissions perspective, this makes GASHPs theoretically the best option; however, the reduction in emissions is only possible if the heat pumps are integrated in low carbon power systems [40]. Otherwise, deploying large quantities of heat pumps in a power system (or country) where there is a low level of decarbonisation of electricity generation merely results in shifting emissions from one sector to another. Heat pumps are also used in cooling applications. A study on cooling of telecommunication data centre using HPs finds that geothermal HPs and hybrid geothermal HPs perform better than ASHPs in colder climates with higher temperature variability [41]. Ground source absorption HPs are 60% more efficient and have 38% lower primary energy consumption than GSHPs since the former have smaller heat exchangers [42].

Table 1 provides a summary of the primary features of the main heat pump technologies. Installation costs are location specific but the range is indicated in the table from lowest installation cost depicted by ‘+’, and multiple ‘+’ signs indicate an increasing cost gradient. The consensus from the literature is that an optimal heat pump technology choice is chiefly based on application type and weather conditions. For instance, GSHPs are well suited for regions with extreme winter conditions while ASHPs are preferred in mild temperatures. Soprtion HPs are the first choice if the aim is to utilise waste heat. HPs combined with solar technologies have higher COPs, provided that the solar radiation is persistent in the area. Generally, HPs will reduce primary energy consumption and operating costs, help in decarbonizaing the heating sector, utilise waste heat and provide a path for sustainable development.

2.1.2. Heat pumps with thermal energy storage systems

Heat pumps along with other components such as storage devices and building thermal mass prove to be more effective than heat pumps alone in reducing GHG emissions and increasing their economic feasibility. A comparative study of different seasonal thermal energy storage (TES) systems using HPs with solar collectors identifies the COP of HP and solar fraction as the main factors that influence the efficiency of the system, with both factors being a function of the collector area and storage volume [43]. Pensini et al. [44] undertake an economic analysis of using excess renewable energy for heating purposes, finding that HPs with centralised thermal storage meet heat demand at lower costs than conventional systems even if there is a charge for producing excess renewable energy. Kapsalis and Karamanis [45] consider solar thermal energy storage and heat pumps with phase change materials (PCMs), and conclude that further investigation and experimental work is necessary to determine the combined effect of PCMs in building components

Table 1: Summary of HP technologies

Technology	Installation cost	Average COP	Environmental Impacts	Pros	Cons
Air Source Heat Pump	+	3	· Highest environmental impact in cold regions · Leakage of refrigerant can cause pollution . Causes noise pollution	· Less or no pollution concerns · Simple operation · Low Maintenance Cost · High COP · Low primary energy consumption	· Frost formation on outer units · COP varies with ambient temperature · Requires more space
Water Source Heat Pump	++	4.3	· Can cause water pollution, stratum settlement and trigger geological disasters	· Highly efficient · Not affected by ambient conditions · Can utilise waste heat from rivers and lakes	· Requires water bodies or storage tanks in vicinity · Needs regulatory permission for installation
Ground Source Heat Pump	+++	3.5	· Unchecked heat transfer fluids are hazardous · Surface water can enter borehole · Can perturb groundwater temperature	· Highly efficient and shows great energy saving potential · Very reliable source of heat · Can operate in regions with extreme winters	· Needs careful assessment of local geology and requirements · COP may decrease over heating season due to saturation of soil temperature
Geothermal Heat Pump	++++	4	· Reduces emissions with low payback period	· High COP · utilises vast source of heat · Most suitable for large industrial applications & district heating	· May need supplemental heat system for better performance
Sorption Heat Pump	++++	1.8	· Working fluids do not cause ozone depletion	· Waste heat utilisation from sewage and brine	· Low COP
Solar Assisted Heat Pump	++ to +++++	Higher than individual HP COP	· Significant environmental benefits · Can reduce emissions by 50%	· Financially and energetically viable solution · Solar helps HPs in achieving higher COP · Lowers grid electricity consumption	· Needs additional control mechanism for optimal operation · Highly location and application specific

and heat pump operation within different climates.

2.1.3. Heat pumps with solar systems

Solar PV roof top systems are gaining momentum in light of climate change and the increasing pursuit of greener economies. These systems are generally considered efficient [46–48], and can be installed quickly with assurance of supplying electricity throughout a year. PV systems help in providing an additional emission reduction potential for heat pumps [49]. The sizing of a PV system has significant impact on self-consumption, and storage forms a part of the optimal system in most scenarios [50]. The research by Beck et al. [50] serves as a guide to manufacturers, installers and end customers on designing cost-effective, self-consumption driven heat pump systems. However, the effectiveness of integrating PV system and geothermal HPs is highly location and application specific. Advanced control strategies and system optimization may be needed to improve the performance of the resulting system [51]. More generally, solar assisted heat pumps are financially and energetically viable solutions to lower grid electricity consumption [52]. For example, in a test facility for heating domestic hot water for a typical family, the annual average COP for a heat pump is close to 3.5, increasing to almost 9 when integrated with PV systems [53]. The life cycle cost of HPs are also reduced when integrated with solar PV panels and domestic hot water systems [23].

Using solar collectors combined with GSHPs generally helps in achieving higher overall COPs, especially in locations where climate is mild and solar radiation is high, such as the mountainous regions of southern Europe [53–55]. Up to a 10% reduction in electricity consumption and HP performance improvement are achieved by integrating solar PV along with heat pumps [55, 56] though the system's COP decreases substantially if ambient temperature is less than 0.3 °C [56].

2.1.4. Heat pumps with other sources

Heat pumps can also be operated using other sources of heat such as industrial waste heat. Modelling and screening of HP options for exploiting low grade waste heat in process sites suggests that adsorption heat transformer is the best option though its performance may be case specific [57]. Examples of energy savings from power generation include [58–61] with exergetic efficiencies of up to 70% [61] and 16% savings achieved in coal-fired power plants [59]. Likewise, considerable reductions in primary energy consumption and emissions, associated deployment of heat pumps for heat recovery in sewage treatment plants, can be obtained [62].

2.1.5. District heating with heat pumps

District heating is a centralised thermal energy network delivering space heating or cooling and hot water supply to residential, commercial and industrial buildings. A review of district heating and cooling systems suggests that district energy systems are more efficient than individual heating and cooling options [63, 64]. They are more environmentally beneficial and economically viable as they utilise surplus heat in the energy system such as heat from power plants, industry and waste incineration [64]. An energetic, ecological and economic assessments show that heat pumps in low temperature district heating networks abate GHG emissions, decrease primary energy consumption and produce low cost heat supply [65, 66]. In Nordic district heating systems, HPs comprise a large share of the power-to-heat technologies especially when electricity prices are high and are also associated with lower wind power curtailment [67, 68]. Overall, deployment of heat pumps can enable a more sustainable development of district heating systems but the placement, connection and operational modes of HPs are region specific, and there is no universal solution in choosing the right HP technology for specific district heating systems [69]. It is also noteworthy that the integration of HPs within district heating systems can contribute additional costs elsewhere in the system [70], and in cases where HP operational hours are limited, it may be more economical to use conventional boilers instead of HPs [71, 72].

2.1.6. Environmental Impacts of Heat Pumps

Heat pumps are proven technologies that can contribute to the overall efforts of reducing GHG emissions and mitigating climate change. They are seen as some of the most promising solutions for decarbonizing the heating and cooling sectors [73]. Latorre-Biel et al. [74] conclude that considerable environmental benefits are feasible when HPs replace electric resistive space heating. Liu et al. [75] argue that, with economies of scale, HPs can be economically employed for heating homes in China realising substantial emission reductions with the displacement of coal-fired boilers. In some examples, greenhouse gas emissions can be reduced by 50% compared to gas based heating systems with a payback period of less than 2.5 years (ironically heating greenhouses) [76]. Other examples include [25, 77–80].

The ecological cost of heat produced by heat pumps is considered low or negligible provided that they are powered by renewable electricity [81]. Among HP technologies, ASHPs have the highest environmental impacts, especially in cold regions which can partly be explained by their low efficiencies, noise levels and space requirements [82, 83]. Depending on the refrigerant type, ASHPs may also be regarded as a source of emissions and pollution due to potential leakage of the refrigerant [83]. Natural refrigerants such as ammonia have a low global warming potential, and result in carbon capture, but their inflammable nature limits their applicability [83, 84]. Social aspects of HPs have been neglected in most studies and need further investigation [83]. Ground heat exchangers may pose some public concerns, as in Finland, where there are serious concerns regarding GSHP installers leaving hazardous heat transfer fluids unchecked, drilling from multiple aquifers and neglecting to seal boreholes preventing ingress of surface water [85].

Freedman et al. [86] conclude that no significant impact by HPs on the thermal balance of river or water bodies has been detected. But Sciacovelli et al. [87] find increased perturbation of the groundwater temperature fields, and suggest that heat pump installations need careful evaluation and assessment to avoid surrounding environmental impacts. Finally, HPs are a potential source of noise pollution and may require abatement measures to avoid neighbourhood disturbance [88, 89] though technological advancs may have diminished this risk.

2.2. Economic Aspects of Heat Pumps

The economic feasibility of heat pumps is of paramount importance for their widespread integration and use. The technologies are generally characterized by high upfront costs, but these costs are counterbalanced by savings in operation and environmental costs as well as other benefits.

Across HP technologies, Paiho et al. [90] find that GSHPs as the most cost-effective option in Finland. The inclusion of solar leads to increases in life cycle costs regardless of the heat pump technology [90]. However, a similar study in Melbourne showa a low rate of return for GSHP systems, which is partly explained by high capital costs and mild weather conditions [91]. Hence, the economic feasibility of a heat pump is generally dependent on the location and application. Variations in humidity have negligible effects in comparison with variations in temperature [92]. Despite the environmental benefits of HPs and low operational costs, payback periods are still high necessitating government supports for more widespread diffusion, e.g. [93].

At a household level, air coupled HP combined with floor heating and active demand response has been identified as the most economical solution in terms of emission abatement as in [79]. At the other end of the economic spectrum, only in a small number of circumstances are air-water HPs considered economically feasible [94].

Integrating HPs within district heating systems entails considerable investment costs but its cost effectiveness has been demonstrated across a number of systems, yielding reduced operating costs of 8–12% [70, 78]. However, large-scale HPs can have big impact on electricity markets, for example, with price increases up to 40% observed [78], the wider distributional effects of which are unknown. However, Schachter et al. [95] find that potential arbitrage opportunities can be exploited with sizeable benefits accruing in the face of highly volatile electricity prices and assuming that domestic HPs are collectively managed.

A study on wastewater source HPs in China finds considerable economic and environmental benefits compared with conventional boiler systems [96]. Zhang et al. [97] has demonstrated the overwhelming economic advantage of hybrid HP-Boiler over heat networks, and ASHPs when applied individually. This is mainly because of the low investment cost of gas boilers. An economic analysis of benefits arising from integrating solar powered HPs into a CHP system demonstrates that, investing in solar powered HPs on the demand side leads to lower operational costs of the CHP systems in both the electric and heating sectors [98]. A comparison of low grade waste heat recovery using HPs and heat engine power cycles demonstrates that the net economic value of heat delivered by HPs is much larger than the value of electricity delivered by power cycles [99]. Hence, heat pumps are cost efficient compared to alternatives but the result varies by circumstance, typically being less economic with higher ambient temperatures.

3. Flexibility Potential of Heat pumps

Heating systems are capable of providing demand response (DR) services to the power system since their electricity consumption is inherently flexible due to the thermal inertia of buildings, e.g. [24, 100–102]. With low cost sensors and control equipment, it is possible to predict and achieve load reductions by exploiting the flexibility of residential heat pumps, up to 40–65% as evidenced in one case study [100]. The level of flexibility is primarily correlated with building characteristics such as floor area, building age, and space heating system, as well as the type and level of building occupancy [101]. HPs combined with building thermal mass can be used as a flexible load to balance demand and supply, achieve higher cost savings with longer preheating periods to avoid morning peak load [24]. For thoroughly insulated buildings, air coupled HPs combined with floor heating can be the most economical solution [79]. And performing active DR on the resulting system shows clear benefits in terms of reduced costs and substantial peak shaving [103, 104]. Simulations by Brennenstuhl et al. [105] further demonstrate that, HPs combined with a thermal buffer storage in residential buildings, have good load shifting potential if minor losses in efficiency and comfort are tolerated. The DR potential is not limited to buildings purpose-built for a HP installation. A DR study of retrofitted HPs in the UK shows reductions in winter peaks and higher night time operations, lowering peak reserve requirements in the power systems [106]. DR is generally considered to lead to immense benefit to power systems. Arteconi et al. [102] show that there are also benefits to individual household participants though the level of benefit declines as participation rates increases since reduced effort from each household is needed. DR flexibility necessitates additional investment, which may not always be economically viable and depend on technical circumstances and economic conditions [94, 107].

Figure 2 depicts a typical system's electricity load and the heat pump load for a typical winter day (24 hours) in Ireland [108]. Electrification of heat will increase the peak demand substantially thereby requiring additional investments in network and generation infrastructures [109, 110]. HPs contribute to peak shaving, load shifting and energy conservation, especially when combined with thermal energy storage devices [111–114]. During periods of low demand and high renewable power production (e.g. wind), excess generation can be converted to heat and stored in TESs. The stored energy is released when demand is high (and renewable power production is low). This not only contributes to the decarbonising of the heating sector but also improves capacity utilisation of renewable power generation infrastructure.

HPs also have the potential to provide several other technical benefits to power systems. For example, effective management of heat pumps using advanced control strategies can reduce the real-time imbalances in the electricity gird [115]. Moreover, a group of controlled heat pumps can provide an opportunity to restore power system frequency and smoothen power fluctuations [116–118].

To summarize, heat pumps offer the potential to shift electrical loads using thermal energy

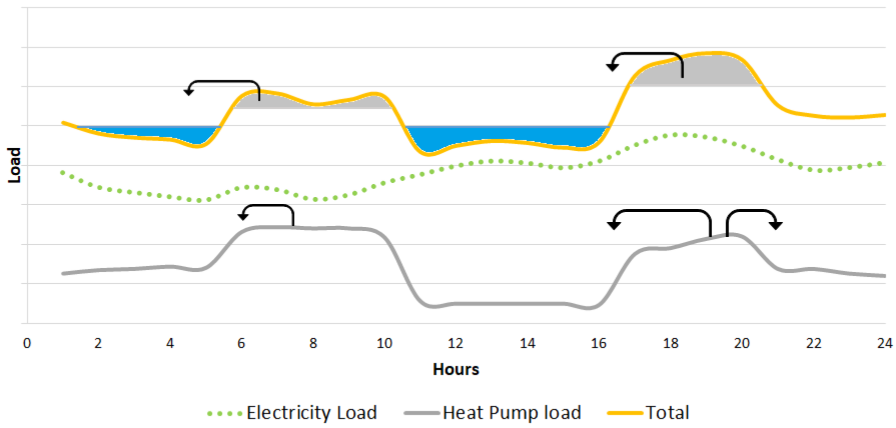

Figure 2: Peak shaving and valley filling potential using TES with HPs [Note that the HP load is scaled up for the sake of illustration]

storage systems, and can be used for demand side management strategies. They can provide demand response which in turn reduces the cost of system operation, allows peak shaving and energy conservation. A flexible operation of HPs also enables a higher renewable generation penetration.

4. Mathematical Modelling of Heat Pumps

Mathematical modelling of heat pumps provides an opportunity to foresee their implications under various scenarios as well as investigate the operational performances of various HP technologies. To this end, the modelling approaches in the extant literature can be broadly classified as static and dynamic. Static HP models are used to perform static analysis such as: cost-benefit analysis, optimal dispatch and planning among others. Whereas, dynamic models of HPs are employed to mainly understand the transient behaviour of heat pumps under normal and contingency situations. Furthermore, dynamic models can be used to assess the impact of heat pumps on the power system in terms of transient stability. Figure 3 provides a graphical illustration of both modelling approaches.

4.1. Static Modelling

Static models are well suited for improving the design of heat pumps [119], and determining their role in reducing renewable electricity generation curtailment, utilizing waste heat and electrifying the heating sector. Static calculations are very fast and satisfactorily precise for a broad range of applications. For example, static models can be used for making standards by comparing various types of heat pumps and their seasonal COPs [119]. Wallace et al. [120] use a static linear model to design an off-set model predictive controller (MPC) for an optimal heat pump operation. Their results show that this design achieves better tracking regulations compared to traditional control approaches. In addition, Halvgaard et al. [121] assume a static model for HP, and use a state space

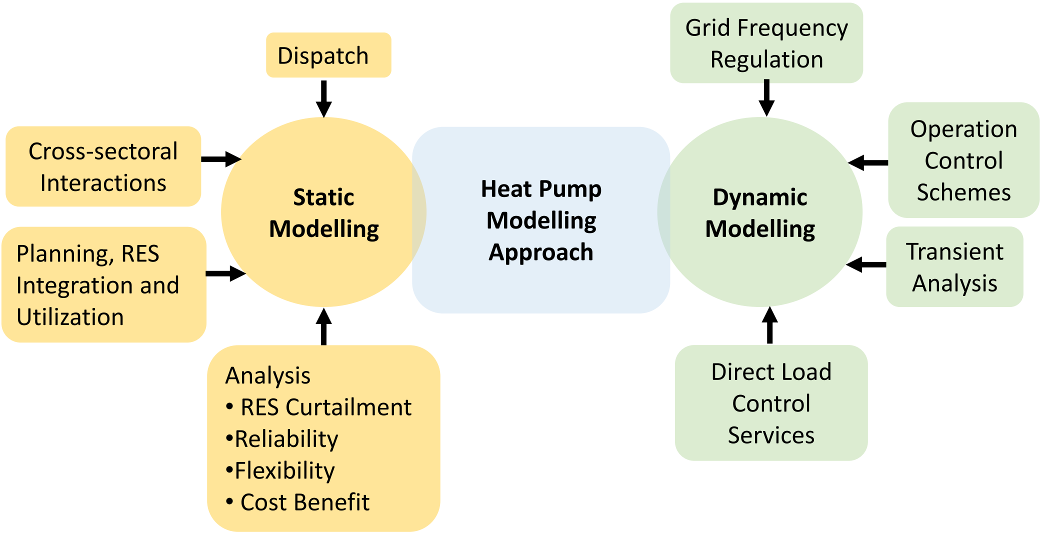

Figure 3: A classification of modelling approachesused for heat pumps

formulation to predict the future outputs of HPs with an economic MPC in an electricity market. Results indicate significant savings in electricity costs with the proposed approach. Further, Staino et al. [122] use the economic MPC to demonstrate that using a cooperative optimization for a building's energy system can result in substantial cost savings. Gustafsson [123] proposes a static method to calculate the most economical size of HPs for residential buildings in Sweden.

Further examples of static modelling analyses, are as follows. Wallerand et al. [124] examine heat pump integrations in industrial processes and demonstrate 5–30% cost savings compared to alternatives (e.g. organic rankine cycles). Jarre et al. [15] examine whether the use of heat pumps can reduce primary energy consumption across the power and heating sectors. Based on hourly simulations, they find primary energy consumption savings between 10–40% compared to natural gas boilers. Bach et al. [21] have integrated heat pump models into Balmorel$^{\text{TM}}$, which is a partial equilibrium model for analysing the electricity and combined heat and power sectors, to determine the optimal dispatch of heat pumps in system, as well as, assess the performance of heat pumps connected to distribution or transmission networks [21]. In a study concerning low carbon heat in industrial processes, Meyers et al. [125] develop a methodology to predict a low carbon heating solution between solar thermal and heat pumps, considering the cost competitiveness of both technologies.

The electrification of the heating sector is expected to have substantial impacts on the electrical system. Hence, possible impacts can be understood by using appropriate mathematical models. In recent years, there has been a growing research developing holistic mathematical approaches i.e. from an integrated energy system (IES) standpoint. Heat pumps, gas boilers, combined heat and power create a link between electricity and gas networks. From this perspective, Liu et al. [126]

show that an integrated approach leads to multi-faceted benefits. These include fewer iterations required to solve the problem, and can be expanded easily to integrate other energy sectors as well [126].

The static approach is best suited for heat pump systems with known components and behaviours, and cannot be reliably used to evaluate new heat pump configurations or extrapolate its application range [127]. Static approaches have a wide range of applications, but they fall short in terms of predicting the performance of heat pumps closer to practical behaviour. Static calculations disregard the effects of dynamically varying COP and heat pump characteristics [123, 128].

4.2. Dynamic Modelling

A dynamic modelling approach is gaining increasing popularity in recent heat pump modelling developments. These models enable modelling of the physical charateristics of heat pumps; hence, the simulated results are in agreement with the measured data [129]. Dynamic models can be used for optimizing heat pump design and operating conditions [124]. These models are usually nonlinear and are used for various applications such as assessing the flexibility potential of residential heat pumps and providing frequency regulation using a variable speed heat pump [130, 131]. Several scenarios can be simulated using dynamic modelling platforms such as Modelica [132–134]. Other modelling platforms for dynamic models include OpenGeoSys, Fluent, TRNSYS [128, 135, 136].

Modelling frameworks considering an optimal operation of heat pumps with other devices such as thermal energy storage and electric boilers conclude that the economic value of HPs increases when integrated with such devices [57, 137–139]. A two-step optimization framework presented in [57] shows that end-users have the potential for providing DR if they use TES and increase RES utilisation. However, another optimization framework based on mixed integer linear programing indicates the importance of accurate modeling of TES to avoid an overestimation of the HP performance [137]. New methodologies to quantify the flexibility potential and economic values of HPs with electric boilers are presented in [138, 139].

In the absence of explicit HP consumption measurements, a non-intrusive methodology for estimating residential HP consumption in a probabilistic manner provides a new dimension to estimating consumption patterns, especially when existing intrusive load monitoring techniques fail due to privacy concerns [140]. The importance of using a coupled heat and moisture transfer model in accurately predicting the seasonal thermal performance of a ground heat exchanger in shallow ground for GSHP systems is highlighted in [141]. A detailed simulation-based analysis for the energy use minimization of hybrid GCHP systems is presented, and carried out considering different controller models and algorithms under various scenarios [142]. Moreover, all control features have been tested on a detailed (finite-volume) emulator model [142]. Detailed modeling of ground water heat pumps can be found in [143], and that of ground source heat pumps in [144].

Patteeuw et al. [145] capture the supply and demand side dynamics of the electricity sector, and its interactions with the heating sector. Their work further shows that only integrated systems can simultaneously consider the technical and comfort constraints of the overall system [145]. A methodology for integrated planning of large-scale HPs and electrical networks is presented in [146]. Numerical results in that show significant cost reductions and better exploitations of the synergy between the heating and power sectors via flexibility service provisions. These benefits are achieved considering the interests of stakeholders in each sector [146]. The work in Wen et al. [147] proposes a novel reliability evaluation method for the electricity-heat IES with heat pumps. Results show that the location, capacity and coefficient of performancesof heat pumps, as well as, the constrains of distribution networks can significantly affect reliability indices [147].

Generally dynamic models permit a deeper insight into the practical operation of heat pumps by considering the physical behaviour of the system. These models allow adequate quantification of demand response that can be obatined from heat pumps, and also their role in demand side management. Dynamic models can also be used to determine appropriate control strategies for heat pumps and maximize their economic feasibility. However, these models require large amounts of physical data and have significant solution times [119].

5. Barriers to Heat Pump Integrations

There is an unanimity on the heat pumps' potential in mitigating GHG emissions, and overall contribution towards the sustainable development of the heating and cooling energy sectors [148, 149]. The market potential for heat pumps is high, and this can create several socio-economic benefits [150]. However, the widespread diffusion of HP technologies faces several challenges, including technological, economic, regulatory, policy and public acceptance issues. Figure 5 graphically illustrates the main barriers that affect the uptake rate of heat pumps.

5.1. Policy

Uncertainty in policy combined with a lack of clear heat decarbonisation pathways and technology uptake are cited as among the main sources of barriers to heat pump uptake [14]. In most countries, either there is no policy instrument put in place or a tendency to have the same policy for all heating options. Such a "one-fits-all" type policy may however render ineffective in achieving desired goals i.e. a roll out of HPs and reduce carbon emissions. It is apparent that an appropriate policy design for a low carbon heating largely depend on the type of end-use as well as on the heating technology [9]. Inadequate funding for research and development in heat pumps can be regarded as another policy barrier that affects the competitive advantages of such technologies, and hence their uptake. Generally, it is suggested that consumers and policy makers be aware of the environmental and economic benefits of HPs in order to increase their deployment [151].

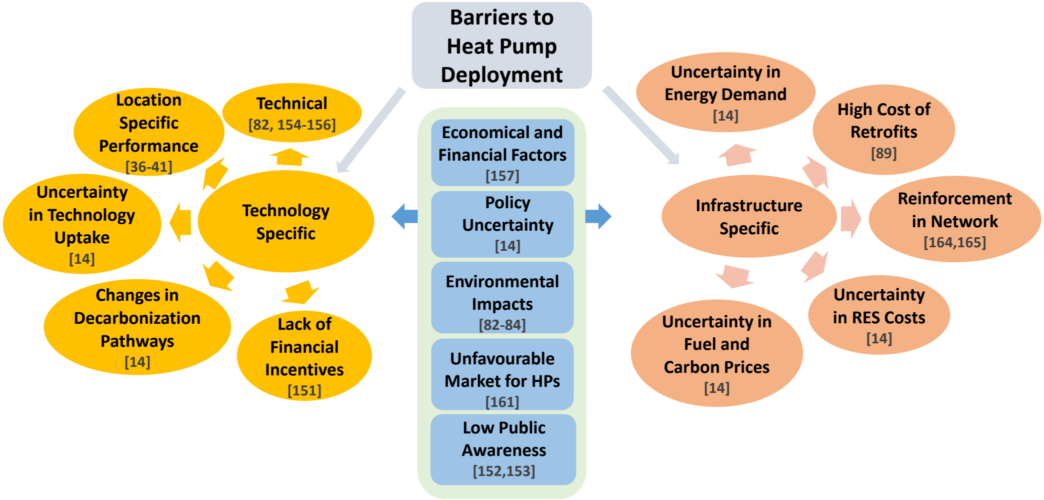

Figure 4: Barriers to heat pump deployment, adopted from [14] (with examples of each barrier cited in bracket)

5.2. Public Acceptance

Public acceptance and awareness issues also pose significant challenges in adopting heat pump technology. These emanate from unwarranted fear, wrong perception, misinformation and/or previous experiences on the reliability of heat pumps i.e. HP technology deficiency. A lack of public understanding on the environmental and cost benefits of heat pumps is not also uncommon, even in advanced societies [152, 153]. For instance, heat pumps can be a potential source of noise, which can potentially create public concerns and lower their acceptance levels. However, their noise levels are often kept in check using enclosing and silencers to avoid noise-related nuisances in a neighbourhood [88, 89]. While the heat pumps' environmental benefits largely outweigh their negative impacts, some research suggests otherwise. For example, Nitkiewicz and Sekret [80] present a comparative analysis between gas boilers and HPs within a power system heavily reliant on fossil fuels. They suggest that gas boilers may cause less damage in terms of public health than heat pumps. However, HPs generally have higher COPs than gas biolers, often 2 or higher compared to gasboilers' theoretical maximum of 1. In a life cycle analysis, Greening and Azapagic [82] suggest that heat pumps have higher environmental impacts than gas boilers but lower carbon dioxide and particulate emissions, as well as, fossil resource depletion.

A study on the initiative launched in USA by Northwest Energy Efficiency Alliance named National Appliance Energy Conservation Act, states that it did not have a significant impact on the sale of heat pump water heater (HPWH) since most salespersons do not recommend HPWH due to lack of knowledge, high initial cost and functioning existing water heater [154–156]. Other environmental concerns suggest that ground-source heat pumps may have some impact on the ecological balance of soils while ground water source heat pumps may cause water pollution, stratum settlement and trigger geological disasters [3]. Concerns of this nature are not widely reflected in the literature [81, 86].

5.3. Economic

Financial factors have been identified as among the largest barriers for heat pump integrations [157]. Studies in the EU identify the price ratio between alternative energy sources and electricity, investment costs as well as installation costs as the major barriers in the European heat pump market [158, 159]. The possible pathways to achieve a high uptake of heat pumps includes overcoming barriers such as cost and access to finance, limited consumer awareness and confidence in heat pumps [160]. It is also important that HPs are not advocated in buildings where they are not suitable, for example, in houses with low energy efficiency [160]. Uncertainties in fuel and carbon prices as well as the costs of renewable technologies also create a significant barrier and influence the heat pumps uptake rate.

Existing market structures combined with public perception can also hinder the penetration of heat pumps. From this perspective, a study in the UK argues that a high market share of gas boilers and cheap natural gas are among the biggest challenges of deploying HPs in the future [161]. Heat pumps work best with low temperature output, hence, they can be installed in well-insulated dwellings with low energy demand [89]. The high upfront costs of heat pumps as well as the need for deep retrofitting of old and thermally inefficient properties are among the economic and structural barriers for large-scale deployment of heat pumps. Other structural barriers are related to the availability of space for hosting heat pumps, particularly in domestic dwellings. When installing heat pumps in such dwellings, space considerations have to be made as standard radiators are replaced by large heat emitters [89].

5.4. Regulatory

Barriers related to lack of standards and mandatory policies can also considerably constrain HP deployments [3]. Getting permission to install ground water HPs is difficult across the EU [89]. Karytsas and Chaldezos [162] recommend improvements and developments in legislative framework involving permission process for the installation of GSHP systems in Greece. Other barriers include difficulty of retrofitting HPs and lack of trained personnel [163].

5.5. Technological

Another barrier to widespread adoption of heat pumps is the limitation of the electrical network. HPs increase the peak demand for electricity and investments in electrical grid infrastructures may be needed to satisfy the demand [164]. Intensive electrification of the heating sector will mainly affect electrical distribution grids, traditionally dimensioned to handle lower electrical loads. Increasing peak winter load may cause significant economic and environmental costs [164]. For example, the deployment of heat pumps into the UK system can increase peak electricity demand by 14% according to [106]. Such an increase in peak demand most likely leads to high network reinforcement needs, negatively influencing the economic viability of HP integrations. The relationship between the penetration level of heat pumps and peak electricity demand needs further analysis. Protopapadaki and Saelens [165] show a higher heat pump penetration could lead to overloading and voltage stability issues. In addition, new ways of reducing the ratio of peak to average demand may be needed [164]. The impact of increased stress on existing electricity grids can, for example, be substantially alleviated by deploying heat pumps along with thermal energy storage.

6. Summary

The paper provides a review of recent works and developments on heat pumps. Heat pumps are classified based on the major technologies currently available in the market and their applications. Global experiences suggest that heat pumps are gaining popularity, particularly in cold regions, to supply space heating and domestic hot water for residential households due to their high COPs, the capability of reducing primary energy consumption and overall system costs. However, we highlight that the type of heat pump to be installed is very location and application specific. Many studies conclude that ground source heat pumps are better options than air source heat pumps in colder regions. This is due to the concern that ASHPs may not be able to meet the thermal comfort conditions when ambient temperatures are extremely low which again affects their efficiency. Water source heat pumps are the most efficient in comparison to ASHPs and GSHPs. However, the requirement of a waterbody or storage tank and other environmental concerns limit their widespread uptake rate. Solar assisted heat pumps have higher COPs, and are proven to be financially as well as energetically viable solutions for places with mild climates and high solar radiations. Integrating heat pumps with conventional heating systems such as gas boilers can be regarded as a very efficient and economical solution. Hence, it is recommended to retrofit homes with pre-existing centralized heating systems with a hybrid HP system.

Heat pumps in conjunction with thermal energy storage provide system wide flexibility services such as load shifting, peak shaving, and demand side management, thereby ensuring increased utilisation of excess renewable energy during off-peak periods. Heat pumps can also utilise waste heat from data centres, sewage, and industrial processes, etc. District heating systems with heat pumps have lower primary energy consumption, abate GHG emissions and are able to supply low -cost heat. Heat pumps are environmentally friendly since they mitigate emissions and reduce energy consumption. They do not have any major environmental impact, but the ecological cost of heat produced by heat pumps is low only if the renewable penetration in the considered system is significant. Hence, heat pump installations needs careful assessment of the surrounding environment and the risks such installations may pose.

The widespread adoption of heat pumps, however, faces several technical and socio-economic challenges. The addition of heat pumps to the existing network leads to an increase in peak demand for electricity, causing network congestion and calling for investments in electric grid infrastructure. Heat pumps can replace conventional heating systems in the old dwellings only if they are well-insulated, thereby increasing the overall cost of retrofitting. Fuel and carbon prices, as well as the cost of renewable energy sources, are subject to uncertainties, which may hinder the rollout of HPs. The technology of HP to be installed islocation and application specific, which may lead to minimal savings in energy and costs, and subsequently high payback periods. There are some gaps in the literature with regards to the economic and financial aspects of heat pumps which makes the market sentiment towards HPs unfavourable. Also, the lack of financial incentives in the form of tax exemptions, high installation costs, and regulatory permissions make it difficult to install heat pumps.

Low public awareness, lack of understanding of costs and environmental benefits arising from HPs may also influence the uptake rate of heat pumps. Lack of adequately trained professionals and knowledge in the science of heat pumps are other forms of barriers that need to be overcome. Uncertainty in policy measures regarding decarbonisation of the heating sector, lack of standards and mandates for heat pump deployments and regulatory interventions are among other reasons which restrain the deployment of heat pumps. There are genuine concerns that WSHPs may cause water pollution and other geological deformities in the soil. However, the environmental impact of each HP technology may differ with local climatic conditions, and this needs further exploration. Although heat pump deployment needs to overcome many barriers, the overall study reveals a future for the heat pump market.

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