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Heat transition in the European building sector: Overview of the heat decarbonisation practices through heat pump technology

Heat transition in the European building sector: Overview of the heat decarbonisation practices through heat pump technology

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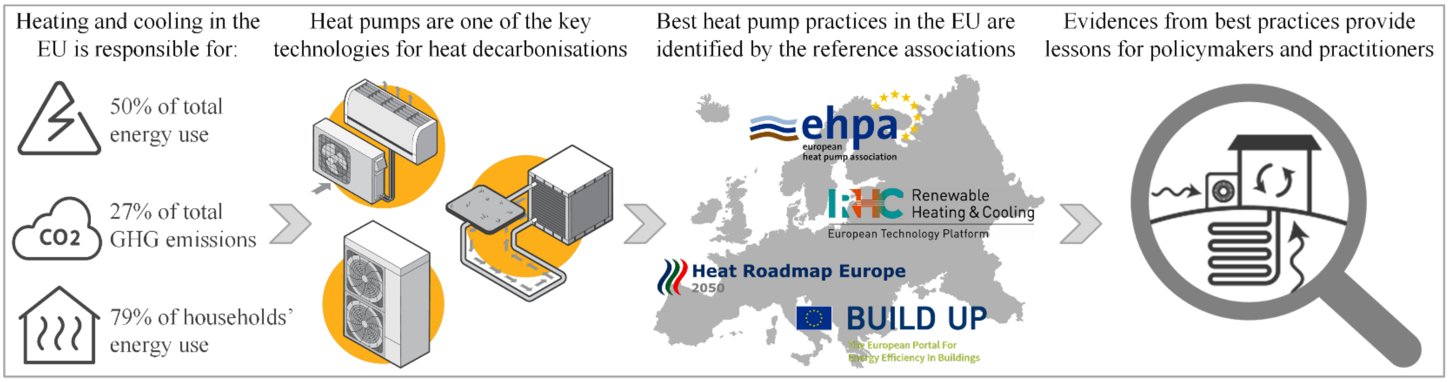
Abstract

Decarbonisation of heating and cooling in the built environment has been recognised as a necessity to achieve any energy and climate change targets. Heat pumps (HP) are one of the technologies that are extremely validated and utilised in the European heat decarbonisation pathways. However, many challenges and uncertainties still lie ahead of HPs in research, practices and policymaking. Practical evidence from real-world case studies could mitigate some of these uncertainties and accelerate the rollout of HPs. Hence, this research aims to present an overview of the key issues and challenges which emerge from the heat decarbonisation practices through HP technologies across the EU. Adopting the evidence-based approach, experiences from the best practices are synthesised, as well as addressing the state-of-the-art and trends of HPs in the EU. Finally, the key factors and insights which are needed to be considered over the design, implementation and operation of HPs are identified and discussed. The conclusions highlight the significant potential of HPs in consolidated solutions such as hybrid HPs, local heat synergies and heat networks. Heat pumps combined with complementary technologies are ready to serve the first wave of heat transition across Europe. However, regulatory provisions, building upgrades and development of other complementary components must be accelerated to keep pace with the HP initiatives.

Graphical abstract



Keywords

Residential heating, decarbonisation, heat pump, electrification, evidence-based approach

Abbreviations

GHG: Greenhouse gases; HP: Heat pump; ASHP: Air source heat pump; WSHP: Water source heat pump; GSHP: Ground source heat pump; COP: Coefficient of performance; SPF: Seasonal performance factor; SHHP: Smart hybrid heat pump; DH: District heating; CHP: Combined heating and power; CCHP: Combined cooling, heating, and power; ICE: Internal combustion engine; CAPEX: Capital expenditure; OPEX: operating expenditure; CFC: Chlorofluorocarbon; HCFC: Hydrochlorofluorocarbon; HFC: Hydrofluorocarbon; GWP: Global warming potential; ODP: Ozone-depleting potential

1. Introduction

Importance of transition towards a low-carbon and climate-resilient economy is now well understood by all countries. However, the current efforts need to be sharply stepped up to meet greenhouse gas (GHG) emission targets of international agreements [1, 2]. In this context, the heating and cooling (H&C) sector has a key role to play in decarbonisation process [3, 4]. According to the figures from Eurostat [5], the total production of derived heat in the EU28 increased from 2000 levels at 568 TWh to its highest in 2010 at 717 TWh, before decreasing to 622 TWh in 2019. The challenge though is that despite the increasing share of renewables, the sector still highly relies on fossil fuels. Natural gas and manufactured gases are the most used primary fuels, accounting for 37.7 % of the total heat generation in 2019 (234 TWh). The share of solid fossil fuels has decreased during the period from 211 TWh in 2000 to 135 TWh in 2019, still contributing 21.8 % of total derived heat. In contrast, renewables and biofuels more than tripled over the period from 52

TWh in 2000 to 187 TWh in 2019, making them the second largest source of heat generation in the EU (30%). Development of total gross heat supply in the EU by fuel sources are shown in Fig 1. On the consumption side, however, heating and cooling are accounted as the biggest energy consumer (nearly 50% of final energy demand) and a large source of GHG (27% of total GHG emissions) in the EU [6, 7]. Space heating is the biggest consumer of this section (53%), followed by process heating (32%) and hot water supply (9%) [6]. From the end-user perspective, households hold the largest share of overall heating consumption with almost 45%, followed by industry with 34% share [5]. Fig 2 breaks down the consumption side of the heat in the EU by end-users.

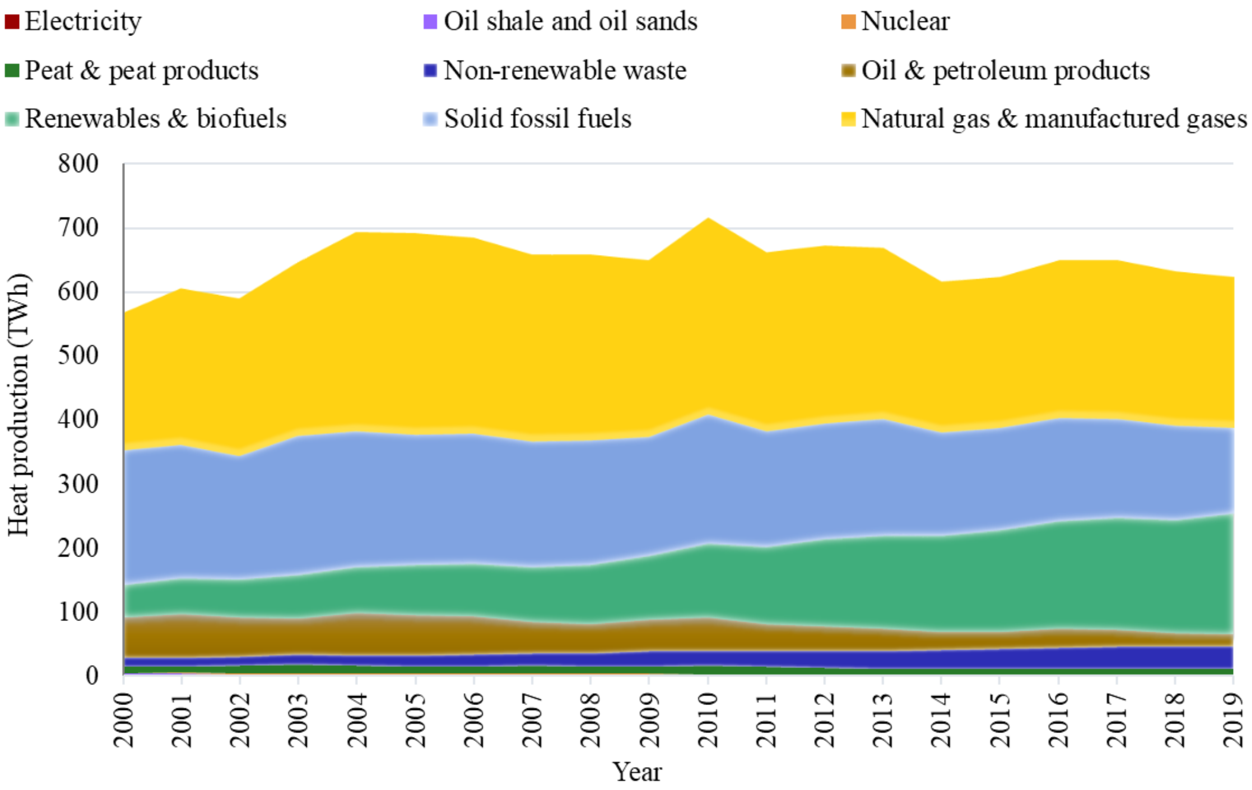
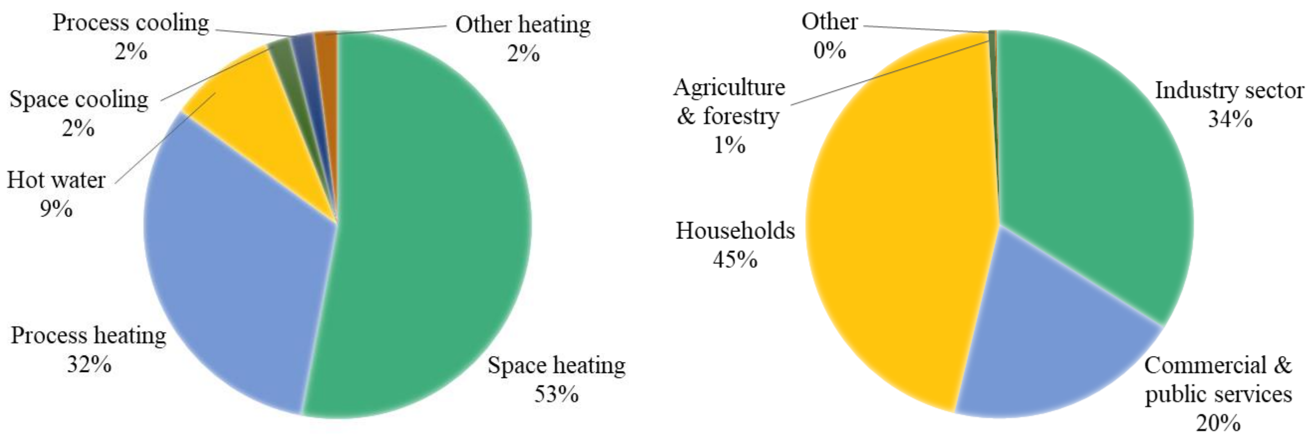


Fig 1: Gross derived heat production by fuel sources, EU28, 2000-2019 [5]



(a) **(b)**

Fig. 2: Heating and cooling energy consumption, EU28; **(a)** Share of end-use applications, 2015 [6, 8], **(b)** Share of end-user sectors, 2019 [5]

Figures clearly show the necessity of deep reforms in the heating sector, particularly in the building industry, in order to achieve an 80-95% reduction in GHG emissions below 1990 levels by 2050, set by European Commission [9]. Therefore, sustainable heat transition has become an increasingly important concern for energy governance in recent years.

In Europe, the number of international institutional architectures and projects to speed up the heat transition is on the rise. One coherent European step was made in 2016 when the European Commission proposed its first energy package, "An EU strategy on H&C", including a dedicated strategy for removing barriers to heat decarbonisation in buildings [10]. Furthermore, the EU 2020, 2030 and 2050 frameworks for climate and energy policies have determined the general binding targets for the H&C sector [11]. Addressing the building sector in particular, the European Commission has established two legislative frameworks, Energy Performance of Buildings Directive (EPBD) in 2002 and Energy Efficiency Directive (EED) in 2012 [12, 13]. The 2009 Renewable Energy Sources Directive (RED) also provides general guidelines for the promotion of energy from renewable sources in H&C [14]. For instance, the RED set the target of 32% renewables by 2030 in the whole EU energy sector, about 40% of which to be contributed by the H&C sector [15].

The issue is better addressed at national or regional levels, where some ambitious commitments are made, surpassing the EU's respective targets. For instance, the UK is targeted to fully decarbonise the building heating systems by 2050, under the Climate Change Act 2008 [16]. This process is emphasised in the 'Future

Homes Standard' revealed in 2019, mandating the end of fossil-fuel heating systems in new houses from 2025 [17]. Similarly, the Dutch government has set to end gas production by 2030, along with plans to completely phase out gas in heating by 2050. The main target is to reduce CO_2 emissions from the built environment by 80% in 2050 [18]. The Scandinavian model is one of the pioneers in targeting zero-carbon configuration, based on high levels of district heating along with maximum use of renewables in heat production [19]. Denmark for instance has put renewable heat from biomass at the corner of its efforts, along with the heat network covering 64% of Danish homes [20]. Danish government banned oil boilers in all new constructions in 2017, pursuing to achieve 100% independence from fossil fuel in the national energy mix by 2050 [21].

However, the EU heat policies and practices are not immune from uncertain decisions and un-evidenced judgements. Some stakeholders perceive heat decarbonisation as particularly problematic and disruptive, highlighting the need for more evidence-based research and analysis and technological trials [22]. Evidence from demonstration projects could reduce uncertainty around the variety of low-carbon options.

This paper seeks to address the above issue by providing an evidence-based overview of the heat decarbonisation practices through heat pump (HP) technology across the EU. HPs are the focus of this paper as they are known as the prominent option for delivering low-carbon electric heat to the residential sector [23-25]. Hence, evidence from HP practices will be discussed in this paper by focusing on the number of distinguished deployments of this technology across the EU. It presents an overview of the state of the art, trends, and influential factors of HP development through a comprehensive synthesis of existing evidence from the field trials and policies. The paper is aligned with the aims and scope of the journal as it assesses the state and the impacting factors of sustainable heat generation through HP technology. As a study, it investigates practical evidence to answer the main research question: what are the strategically important issues, constraints, and benefits associated with HPs that should be considered in policymaking and project planning? It is also tried to go beyond the technical aspects and draw attention to contextual factors such as social implications and regulatory obstacles.

The paper starts with the introductory part, providing essential background about heating in the EU and the context of the paper. It is followed by describing the motivation, rationale, and scope of the study in section 2. Section 3 elaborates the methodology employed in this study. Section 4 presents an overview of the HP technologies and their state-of-the-art in the EU, as well as addressing the best demonstration practices. The experiences and evidence are synthesised in section 5 and the lessons from the study are drawn. Section 6 represents the derived conclusions and proposes the potential further work.

2. Motivation and Context

The role of 'evidence' in developing policy and practices is highly regarded in the energy sector. The use of more and better evidence could provide unique insights and greater certainty for decision-makers, leading to better policy-making [22]. The role of empirical evidence is more critical in heat decarbonisation strategies, due to the strong interconnections between heating systems and social factors such as consumer experience, transition disruptions, and fuel poverty. However, it is frequently reported in the literature that the available evidence from real-world practices is not effectively reflected in heat roadmaps, projects and future plans [26]. One possible reason for this is the lack of experimental evidence and project reports. The outcomes from real-world practices are not always well documented and extensively published to be considered by policymakers [27]. The second reason is that the available evidence is not often effectively synthesised and analysed, making it difficult for practitioners and policymakers to reach a collective understanding. This often leads to wide-ranging propositions and sometimes conflicting conclusions regarding the same issue [28]. Subsequently, the third reason can be the traditional divide between practitioners, academicians, and policymakers. Policy-makers' decisions and perceptions are not necessarily based on the evidenced judgements and technical knowledge [22].

To tackle the above criticisms, the evidence-based approach is highly endorsed in the literature. The evidence-based approach gives greater weight to practical experience by integrating evidence, judgement, and expertise with the research outcomes to set out the key issues in the development of policies and practices [28]. However, despite the growing popularity of the evidence-based approach, this concept is still emerging within the context of energy over the last decade [26, 29, 30]. This research adopts the evidence-based approach to synthesise evidence on heat decarbonisation through HP technology, gathered from best practices across the EU. Ideally, the overview will provide transferable lessons for policymakers and practitioners about the enablers and barriers to promote the uptake of HPs in decarbonisation plans.

There are several reviews articles dealing with HP technologies and their applications in various fields. Predominantly, these review articles are focussed on design and technical factors of a specific technology [31-36]; along with fewer papers on policy and regulatory aspects of HPs and decarbonisation strategies [3, 37-39]. However, giving greater weight to real-world projects, the novelty of the paper lies in presenting a review of practical evidence, experiences, and professional judgements related to HP practices. The paper contributes to the existing literature by providing a synthesis of evidence-based and critical issues and insights that are needed to be considered for successfully designing, implementing, and operating HP systems.

3. Methodology

According to the scope of the research, qualitative evidence from the distinguished HP projects in Europe is explored and discussed in this paper. To do so, we first started searching for academic papers, institutional documents, and project reports which contain any qualitative evidence on the practical application of HP technologies. Qualitative evidence in this context includes any post-implementation analysis, documentary assessments, critical discussions, and professional judgements. Academic papers are found through English indexed articles in databases such as ScienceDirect, MDPI, Taylor and Francis, ProQuest, and Google Scholar over the past Twenty-two years (2000-2021). Regarding the non-academic articles, reports from the international associations such as EHPA (European Heat Pump Association), RHC (European Platform on Renewable Heating and Cooling), BUILD UP (European portal for energy efficiency in buildings), EHI (European Heating Industry), HPA (UK's Heat Pump Association) and GSHPA (UK's Ground Source Heat Pump Association) are been searched. Then, among the found resources, those addressing HP projects with the following criteria were selected for in-depth review.

- Best-practice projects which are validated or awarded by one of the reference associations such as EHPA, BUILD UP, HPCY (Heat Pump City of the Year), Euroheat & Power, or HRE (Heat Roadmap Europe).
- Projects which are analysed and studied in a peer-reviewed journal or an article that is peer-reviewed via a conference, an academic committee, or an institution.

Eventually, 34 articles evaluating 15 projects as the best practices are selected and closely reviewed in section 4.4. The researchers have looked for and analysed the qualitative evidence and issues with generality and magnitude of the impact in the practices. Following that, strategic lessons which necessarily should be considered in the European HP policies and practices are discussed. The research flow chart considered for the present study is shown in Fig 3.

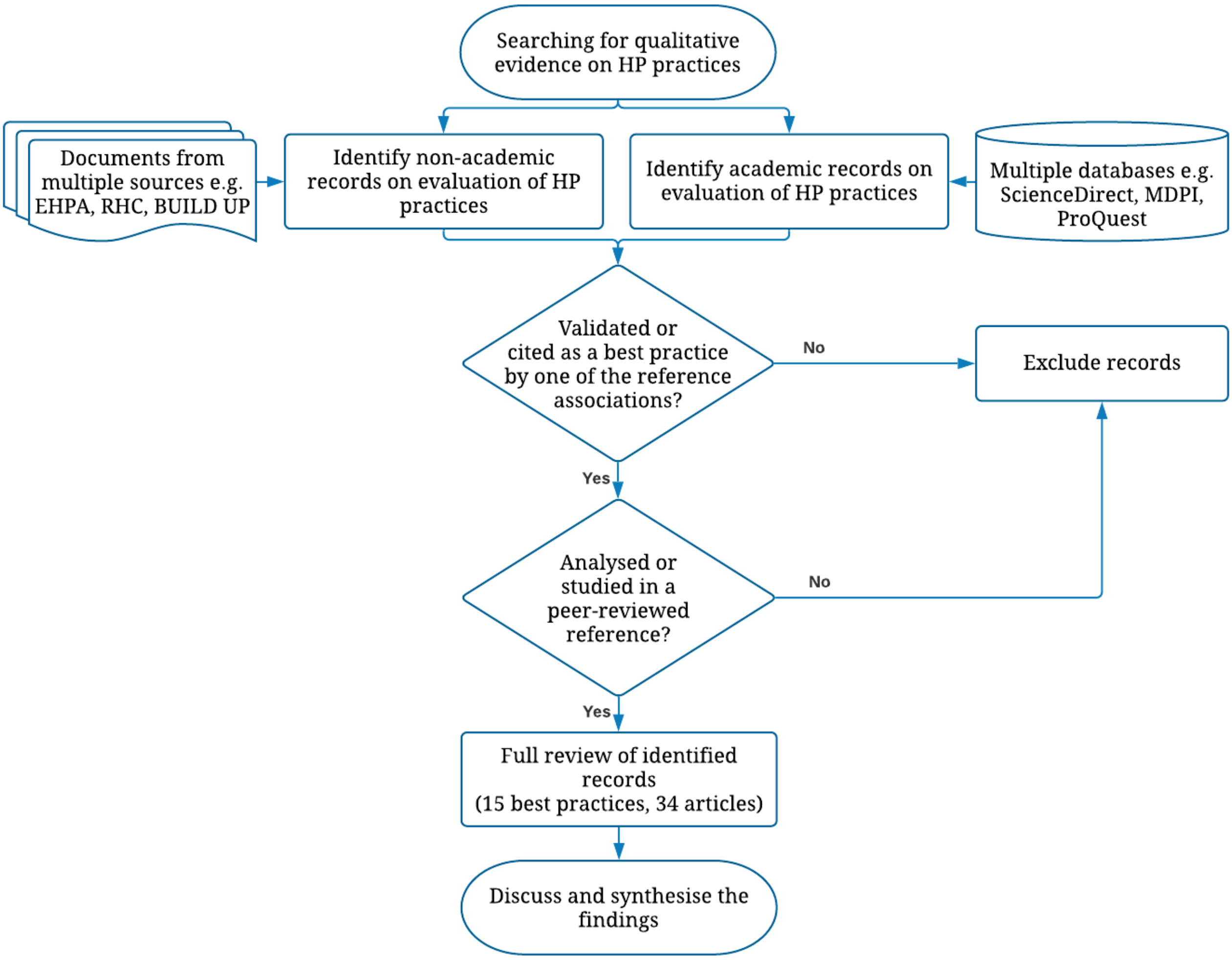


Fig. 3: Research methodology flow chart

4. HPs in Policies and Practices

4.1. Heat Decarbonisation Pathways

Mitigation of carbon emissions in the supply side of the building heating sector can be sought through various technologies that can be categorised as follows.

- Electrification

- Decarbonisation of heat networks
- Decarbonisation of gas supply
- Complementary technologies

None of these pathways can separately suffice on its own and a range of programmes and technologies are needed in parallel to form an effective heat transition. In Fig 4, the most common low carbon heating options under this categorisation framework are listed. The first three categories are the key vectors of heat transition, complemented by the fourth category's technologies which are usually used as the secondary systems.

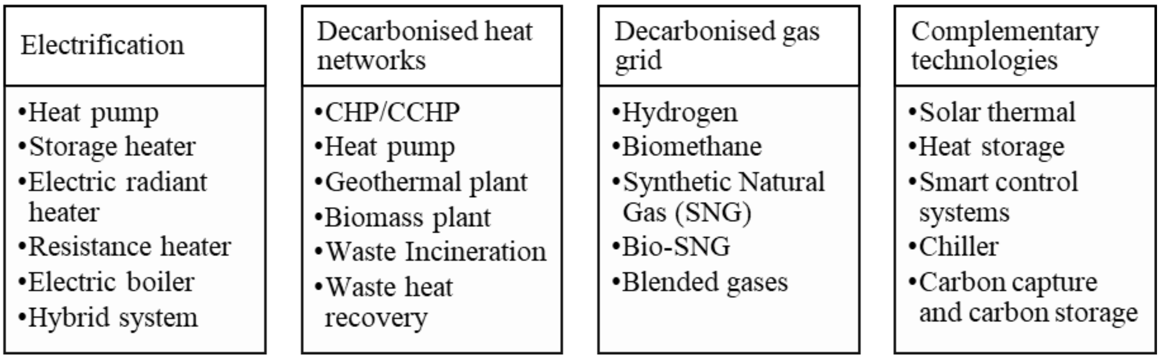


Fig 4: Heat decarbonisation categories and the main technologies

The concept of electrification or power-to-heat refers to converting electricity into heat to meet the energy demand for heating, cooling, and transport. The European Commission has recognised in Energy Roadmap 2050 that electric heating can reach a share of 36-39 percent contribution to heat decarbonisation in 2050 [40]. Several technologies of space heating by electricity are commercially available. However, HPs are the most appealing technology due to their higher efficiency and profitability, as the other ones can reach a maximum of 100%. A review of technologies, modelling approaches, and potentials of power-to-heat technologies can be found in [24, 41, 42].

Heat networks or District Heating (DH) systems play a key role in achieving the European energy objectives. According to the HRE the contribution of DH for space heating and domestic hot water supply in the EU accounts for 12%, 70% of which is driven by fossil fuels in 2017 [43]. The key issue concerning DH systems is how to decarbonise the existing heat networks and expand the new installations most sustainably, using a wide variety of compatible renewables such as biomass, solar, geothermal, and heat pumps [44]. The Heat

Roadmap Europe (HRE) studies estimate expanding the capacity of DH systems to supply around 50% of EU heat demands by 2050 [45]. Recent advances in DH systems, integration of renewables and design innovations are reviewed in [43, 46-50].

Decarbonisation of gas supplies with the aid of low carbon gases is another vital pathway towards net-zero emission targets. In 2018, gas supplied around 45% of households' heating demand in the EU [51]. Many European countries have already robust gas infrastructure and national network linked up to most homes and industries. Clean gases such as hydrogen, SNG and biogas can be blended with natural gas or replace it in the grid and transported through pipes to end-users. However, hydrogen, known as the missing link in the energy transition, is the only choice for at-scale decarbonisation of the gas supply [52]. Projections estimate a potential of €820 billion market size for hydrogen industry and equipment, representing approximately 24% of the EU's total energy demand in 2050 [53]. A review and evaluation of recent developments of power-to-gas projects can be found in [54-56].

The complementary technologies mostly are being used as auxiliary systems. For instance, heat storage is an inseparable component of low-carbon heating, though it always needs to be fed by a primary heat generation system. The complementary systems guarantee that the heat demand could be met all over the year by managing, covering, or shifting the peak periods when insufficient heat is supplied by the original equipment. Integration of heat storages, solar systems, and smart controllers into primary heating systems are among the most prevalent complementary measures that are thoroughly reviewed in [46, 57, 58], [32, 35, 59, 60], and [61-63], respectively.

This paper focuses on HPs as the most trusted solution to electrify space heating in Europe. The following sections shed a light on HPs and their implementation status in the EU heating sector.

4.2. Heat Pump Technologies

Heat pumps convert free or waste energy to a higher temperature heat through a closed and high-efficiency process. Functioning in a reversed Carnot cycle, they run with a low-temperature heat, convert it to a higher temperature and pump it into the building. There are several types of heat pumps available in the market which can be differentiated by their operational principle, heat source, application, or scale. However, typically, HPs have been classified based on their heat source as follows:

i) Air Source HP (ASHP): Use ambient air as the heat source and supply heat locally through the air (air-to-air) or hydraulic (air-to-water) distribution systems.

ii) Water Source HP (WSHP): Use water as the heat source; local water resources such as wells, streams, lakes, and ponds are used through open- or closed-loop systems.

iii) Ground Source HP (GSHP): Use ground as the heat source; take heat from geothermal resources using ground heat exchangers or borehole heat exchangers.

iv) Other Sources: Use other thermal sources or a combination of them such as waste-water, industrial exhaust heat, flue gas, or district cooling as the heat source.

ASHPs are currently the most widespread HPs in the world. Although ASHPs still have the limitation of reduced efficiency during the heating season, they have made significant advances in recent years that are reviewed in [31, 64-66]. For the large-scale applications, WSHPs with sewage water as the heat source are the most installed systems, representing 56% of the total capacity of large HPs across the EU [45]. Nevertheless, WSHPs also lose efficiency as the temperature goes down and this is apart from some other constraints that are explored in the previous publications [67-69]. In turn, GSHPs take advantage of a heat source with a much lower variation of the temperature. However, they have higher installation costs in comparison with other types of HPs. Utilising GSHPs in residential and commercial buildings is experiencing increasing interest and advances over the last decades which are reflected in few studies [33, 70, 71]. Heat pump technologies with other heat sources are very promising as they can integrate renewables or recover waste heat to enhance the overall energy efficiency. Considerable efforts have been done so far to make the most of these technologies and more innovations and advancements are being created that can be reviewed in [34, 35, 72, 73].

Heat pumps, like all other types of electric heating systems, more or less, will impact on the total and peak electricity demand. Electric resistive heating has the worst effect because they operate when the heat is desired, meaning the maximum rise during peak times. Storage heaters, however, use the same amount of electricity but can shift a proportion of their usage away from peak times and store heat when demand is lower. HPs also will increase the peak demand, but in a lower extent, due to their higher coefficient of performance (COP). Results of a study show that in the UK for instance, replacement of all gas heaters with HPs would result in a 25% increase in national electricity demand and a 65% rise in peak demand [74].

Integration heat storages [57], solar systems [32, 35], and smart grids [61] are among measures that are evolving to deduct the risk of grid overloading.

Hybrid HPs, meanwhile, could potentially go further in tackling grid overloading. Hybrid HPs use another energy source such as a boiler or solar collector as backup heat generation during cold spells [75]. The householders can tune using either fuel or both via a control system to achieve the best fit of thermal comfort, energy security and money-saving. Coupling smart control systems with hybrid HPs enables the system to automatically find the most cost-effective heating pattern considering parameters such as external temperature, flow temperature, and tariffs. New generations of smart controllers go beyond the simple switching based on energy tariffs. They iteratively aggregate and analyse data from the thermal comfort, occupancy pattern, and weather forecast to predict the loads and refine the heating management algorithm [76].

4.3. State of the HPs in the EU

Within the Eurozone, HP is recognised as a renewable energy technology in legislative frameworks and is one of the key players of 2030 and 2050 European energy and climate strategies [77]. By 2018, HP stock amounted to a total number of 11.8 million units, heating almost 10% of all buildings across 21 European countries [78]. Nevertheless, the EU heat roadmap 2050 suggests a significantly larger share of HPs in both individual and large-scale applications mostly based on waste heat and renewable resources [79]. According to EHPA, HPs have still vast untapped potential to be unleashed and are expected to have a rising market share in the coming decades [80].

The EHPA annual report reveals that HPs contribute 163 TWh to energy savings and 32.8 Mt to CO_2 saving, responding to over 3.2 TWh of heating/cooling demand [78]. HP market in Europe has undergone four consecutive years of double-digit growth (+12%) in 2018. Around 3.2 million units in France produce 19,300 GWh energy, making this country the first European market for HPs, followed by Italy and Spain [81]. The EHPA also disseminates information of collective examples of HP deployment in the European market. For instance, two volumes of the report “Large scale heat pumps in Europe” provide 32 real-life examples of successful large heat pump applications in commerce and industry [82, 83]. The SEPEMO-Build, GROUND-MED, and GROUND-REACH are some other international projects with a total of 113 case studies in 18 European countries, aimed to help plan, implement and monitor HP projects [84, 85]. For instance, GROUND-MED projects specifically focused on advanced GSHPs in 8 demonstration sites to discover and improve the key parameters of these systems [86]. A great deal of information about reliability, seasonal efficiency, site management, installation guidance, design tips, etc. can be obtained through the project reports.

Heat pumps have also shown great compatibility with new generations of DHs. Implementation of small or micro scale DHs combining with renewables such as HPs are strongly encouraged in the EU's 2030 and 2050 energy directives [77]. The HRE appraisals estimate that by 2050, approximately 25–30% of European DH systems will be powered by HPs [45]. Applications and examples of HP integration in the European DH infrastructure are particularly discussed in [77] and [45].

In the academic field, numerous research works have been carried out to assess the uptake of heat pumps in the building sector in recent decades. For instance, Staffell et al. [87] presented an overview of the various domestic HP technologies and their corresponding operational, commercial, and installation considerations. As a conclusion, the influence of some non-operational factors such as design and installation on carbon emission and efficiency of HPs is highlighted. This conclusion is derived by comparing efficiency figures from real-world trials and their field measurements from German and UK practices. In another research, the compatibility of European DH infrastructure for HP integration and deployment is evaluated by Sayegh et al. [77]. Frequently observed in similar works, the authors have affirmed that it is not possible to prescribe a general solution for all regions and transitions need to be analysed case by case. Similarly, David et al. [45] assessed large-scale HPs, greater than or equal to 1 MW thermal output, by focusing on their heat source, refrigerant, operating temperature, and operation configuration. The authors assert that HPs has reached a level of technological maturity to be further deployed across Europe, provided they use appropriate refrigerant and integrate renewable electricity. Fawcett et al. [74] studied the potential contribution of HPs to supplying space heating in domestic sector from the global and UK market perspectives. They surveyed different UK scenarios and policies to encourage a transition to HPs and compared them with global practices. They have eventually come up with the conclusion that the main challenges of mass adoption of HPs are the increase in the peak electricity demand and the HPs' efficiency drop at lower temperatures.

4.4. Best Practices of HP Deployments

Today, numerous HP projects are either operating or under development in various applications across the EU. This section reviews a number of successful deployments of HPs with diverse configurations and highlighted, followed by practices highlights in table 1.

Sweden is a leading country in utilising large scale ground and water energy resources for heating, typically with HPs [88]. Numerous HPs with an accumulated heat capacity of more than 1500 MW have been installed in Sweden since the 1980s (approx. 80% is still in operation)[89]. A similar trend for using large HPs in DH systems in the early 1980s can be traced in some other countries e.g. Germany [90] and Norway [91]. The Hammarbyverket heat plant, in Sweden, is the largest plant in the world which provides 100% of the heating demand in the area from waste incineration and wastewater treatment [92]. Averfalk et al. [89] have summarised gained experiences from this project and other Swedish large-scale HP plants. Acknowledging the dominance of HPs in heating system developments during the 1980s and 1990s, it is demonstrated that after 2001, the competitiveness of HPs has been influenced by the increase of national electricity prices and taxes. Furthermore, environmental concerns with refrigerants and mechanical wear on components have decelerated the HPs' development. In their study, transition to natural refrigerants has been accounted as a serious challenge for the future of HPs.

Many of these large-scale HPs are integrated with a CHP plant, enabling the use of site-generated CHP electricity by HPs. One good example is the Brista 2 plant in Stockholm where two large industrial HPs are implemented to recycle heat from 240,000 tonnes of combustible municipal and industrial waste and pre-heat the CHP boiler feed. By studying Brista 2 and a number of similar projects in Stockholm, Levihn [93] has published practical insights into the operation of DH systems with a combination of HPs and CHPs. The author demonstrates that the combination of CHP and HP increases the system efficiency and CHP running hours, as well as helping to balance the intermittence of renewables.

Similarly, Freiburg in Germany with about 220,000 inhabitants entitled as "The Most Sustainable Large City of Germany" in 2013, beholden to wide implementation of CHP+HP systems [94]. Almost 36.4% of heat demand was supplied by newly built or refurbished DHs by this year [95]. Meanwhile, new standards for buildings were imposed in parallel to increase demand-side efficiency. However, a row of actors posed challenges to the desired energy transition goals. Späth and Rohracher [96] analysed the contradictory decisions which erupted in the Vauban residential district. In the case of Vauban, the DH strategy which was set at the municipal level was not aligned with the up-scaled passive house strategy at the council level. Eventually settled by revising the energy policies, the Vauban case revealed that local strategies can become problematic and ineffective if are not compatible with other in-place regulations like energy tariffs and assistance programmes.

In contrast, the Brædstrup district in Copenhagen showed a successful local planning demonstration. Brædstrup is a consumer-owned district heating project in which all consumers have a vote in decision makings. This local assembly, in co-operation with the local municipality, is set to convert this DH network to 100% renewable. By 2011, the heating was fully supplied by a combination of biogas CHPs, solar thermal plants, excess heat from industries, large-scale HPs and heat storages. The project is also a frontrunner on how to provide heat at a highly competitive price for the end-users. This is done through a set of activities pursued in parallel, e.g. smart metering, stricter standards than the national building code for buildings, and enhancing renewable electricity [97]. This Danish model has been able to reduce costs on both supply and demand sides, as well as achieving aspiring environmental targets. Today, more than 98% of the heat demand in Copenhagen is covered by DH [98]. Aiming to become the world's first carbon-neutral capital city by 2025, 100% of fossil fuels burned in cogeneration plants shall be replaced by renewable resources [95].

Heat pumps are also highly flexible and compatible to enable waste heat recovery. Bergheim I and II DH systems can be picked up as top practices of this application. In these projects, HPs use sump water extracted from open-pit mining as a heat source to supply heat to nearby areas through DH networks. Plants in Bergheim I and II contain several HP and CHP modules to produce a maximum of 586 kW and 865 kW thermal power, respectively. Both Bergheim projects are known as two best practices of waste heat recovery and their technical considerations are aggregated and discussed in [99] and [100].

The new Mäntsälä project in Finland is another novel application of HPs which reuses waste heat from the cooling process of a data centre. A couple of data centre projects equipped with waste heat recovery facilities such as HPs are surveyed in a paper by Wahlroos et al [101]. In this paper recycling waste heat using HP and reusing it in DH networks are proposed as the most economically viable solution among the heat recovery options. Waste heat recovery can be combined with other decentralized heat sources to deliver a more efficient production. The Mijnwater DH system in Heerlen, Netherlands is technologically one of the most advanced practices of this application. In this project, residual heat from industrial processes and warm returns from space cooling and supermarket refrigerators are integrated with heat from water stored in abandoned coal mines to deliver a good practice of the 5th generation DH system [102]. However, the new development plans of this project are decreasingly using the mines as a geothermal source, while more relying on surplus heat of customers. Buffa et al [103] argue that the holistic design approach used in this project allows the exploitation of local energy synergies to reach a net-zero energy balance at different time scales.

Heat from higher-level underground reservoirs (shallow geothermal resources) with lower temperatures can be well utilized by HPs in medium-sized DHs due to their low running cost, small plant area, long lifetime, and low sound emissions. A few numbers of such practices are carried out in the Croydon district in outer London. Among them is one of the UK's largest GSHP projects which can supply 225 kW heating and 285 kW cooling for an area of about 3000 m^2 of commercial facilities. Witte et al. [104] conducted a post-construction survey on this project. Despite some minor technical problems, the project achieved a remarkable satisfaction level of consumers because of the low operating costs and long life-expectancy. Similar results have been reported in other GSHP projects. For instance, high levels of comfort and 50-100 years lifetime have been highlighted as the most important achievements of the Schoenmakershoek project in the southwest Netherlands. In this project, 1400 houses are served by individual GSHPs as a step towards their all-electric energy-neutral vision. Witte et al. [105] have studied this project and have drawn some practical guidelines for future GSHP implementations including determining the optimum range of COP, noise emission, and borehole number.

The world's largest groundwater HP powered system and the second-largest geothermal system is under development in Milan. The contractor has designed five DH plants in the greater Milan that use groundwater heat pumps to serve a total area of 5,500,000 m^2 with almost 250,000 inhabitants. The Canavese GeoDH system is a part of this project which is comprised of CHP system, HPs, gas boilers and heat storage tanks to maximise the economic performance and operating flexibility [106]. In a study by Sparacino et al. [107], it is estimated that the project could result in a reduction in primary energy consumption and CO_2 emissions by 35% and 45%, respectively. Authors expect that widespread use of HPs coupled with heat storages could extremely help the electric demand to be equilibrated by shifting a major proportion of the energy use to night time.

The Customer-Led Network Revolution project (CLNR) is one of the best UK smart grid projects. As part of this project, electricity usage of 380 domestic units which were equipped with ASHPs is systematically monitored. Trials are carried out with different scenarios, including HPs without interventions, HPs with smart controls, and HPs with restricted operation hours to find the best scenarios for network management and customer engagement. The project evidence shows that the HPs add an average of 82% of the load to the annual household consumption [108]. Yi et al. have assessed the project from the network perspective and concluded that electrical energy storage and demand-side response systems can be utilised collaboratively to cover the peak demand [62].

Hybrid HPs, however, enable switching between the electric and gas load, avoiding the need to further increase the power generation capacity. Hybrid HPs are proven and well tested solutions for countries with a sophisticated gas grid. For instance, in the UK, the FREEDOM project was carried out to better understand the technical capabilities and costs of hybrid heating systems. In this project, 75 diverse properties in South Wales were equipped with exterior ASHPs and interior gas boilers, controlled by hybrid control panels [109]. A study based on the field data identified that responsive hybrid HPs could save at least £0.9 bn/year more than the saving that can be achieved through the pure ASHP strategy. Another important outcome of the project was demonstrating the efficiency of hybrid HPs in a broad range of housings without major modification in the building and heating system [109]. Sun et al. [76] based on the data from this project showed that the average COP values of installed ASHPs were between 2.6 at 0 °C and 4.0 at 10 °C. Authors also concluded that assuming a COP increase of 5-10%, adding smart control to hybrid HPs will result in the whole-system benefits between 2.1 and 5.3 £ bn/year.

The key specifications of the discussed projects are summarised in Table 1 as the best practices of HP developments within Europe.

Table 1: Key information of the best deployment practices of HPs across the Eurozone

Project	Location	Development / Commissioning Year	Key Figures	Heat Sources	Budget	Source
Hammarby verket Plant	Stockholm, Sweden	1998	o World's largest HP waste-water treatment plant o Contains 7 heat pumps, 2 bio-oil boilers, and 2 electric boilers o Seven HP with a total of 248 MW heat capacity o COP of 3.5 o Heated up to 95000 m^2 apartments	Waste incineration wastewater-WSHP	-	[92, 110, 111]
Brista 2	Stockholm, Sweden	2012-2014	o The waste to energy CHP/HP plant o Output capacity of 6.8 MW of heating, 5.8 MW of cooling, and 20 MW of electricity o Generate 490 GWh heat and 120 GWh electricity annually o Efficiency of over 95% by combining booster HPs o Handles 240,000 tonnes of household and industry waste o Supplying demand of 50,000 apartments	Waste incineration plant exhaust gas-ASHP	-	[45, 93, 112]
Vauban DH	Freiburg, Germany	2010-2011	o The greenest area of the Freiburg city with around 5,700 inhabitants o Twelve units of gas/woodchip-fuelled CHPs coupled with an HP with a capacity of 140 kW_{th} o Overall electrical power of 850 kW and thermal power of 1,150 kW o Overall efficiency of more than 96% o Low-energy building standards are obligatory	Biomass CHP+ waste ASHP	-	[96, 113, 114]

Brædstrup DH	Jutland, Denmark	2005-2008	○ Almost 100 % renewable energy DH ○ 8.2 MW_{th} of biogas CHP ○ 1.3 MW_{th} heat pump ○ 18,600 m^2 solar collectors ○ 13.5 MW_{th} biogas boiler ○ 10 MW_{th} electric boiler ○ 48 borehole seasonal storage and 7,500 m^3 tank storage ○ Supplying 1,500 households demand	Thermal storage+ CHP+ waste-WSHP	-	[97, 98, 115]
Bergheim District Heating I & II	Bergheim, Germany	2011-2015	○ Using sump water from open-pit mining as the heat source ○ Combined with gas engine powered CHP, gas boiler and heat storage ○ Provide heating and hot water for an industrial and commercial region ○ Heat capacity: 2x293 kW for Bergheim I and 865 kW for Bergheim II ○ COP: 4.4 for Bergheim I and 3.01 for Bergheim II	Sump water-WSHP	-	[82, 99, 100]
Mäntsälä combined data and heat	Mäntsälä, Finland	2015-2018	○ Awarded the Heat Pump City of the Year 2015 by the EHPA ○ Recycling the waste heat generated from the cooling of Yandex data centre ○ Heat capacity of 3.6 MW ○ COP of the system is 3.7	Cooling system waste-ASHP	€2.5 million	[101, 116]
Mijnwater 1.0, 2.0, & 3.0	Heerlen, Netherlands	2008-2017	○ Won the European Geothermal Innovation Award in 2015 ○ Using a flooded coal mine a geothermal source and multiple waste heat sources ○ backbone on the surface ○ Operates 100 HPs of 200 kW and 100 booster HP for hot water ○ Provides H&C services to 250,000 m2	Underground mine water+ waste heat/cold – WSHP & GSHP	€35 million	[102, 103, 117]
Croydon Kensa GSHP Pilot	Croydon, UK	2018-2020	○ Trial fifth-generation GSHP system ○ Installation of HP at a 44-flat, 10-storey block in New Addington ○ Coincide with a £3.2 million refurbishment to the block	GSHP	£700,000	[104, 118, 119]

Schoenmakershoek project	Etten-Leur, Netherlands	2002-2011	○ Awarded the Heat Pump City of the Year 2012 by the EHPA ○ Individual closed-loop GSHPs with 4-8 kW heat capacity ○ In an off-grid neighbourhood ○ Comprises about 40 hectares with 1400 dwellings equipped with HPs ○ The total installed HP capacity is approximately 7 MW_{th} ○ HPs with COP between 4 and 4.5	GSHP	-	[105, 120]
Canavese GeoDH	Milan, Italy	2010-2015	○ Awarded project by the IEA and Euroheat and Power in 2011 ○ Integration of a GSHP within the DH system ○ Part of the world's second-largest geothermal DH project which is under development ○ Installation of HP unit with 15 MW heating and 11 MW cooling capacity ○ HPs with nominal COP of 3 ○ Coupled with 15.1 MW_e gas engines, 45 MW_{th} of boilers, and 3,000 m^3 storage tanks	GSHP	-	[106, 107, 121, 122]
Customer-Led Network Revolution (CLNR)	North East, UK	2010-2014	○ A major smart grid demonstration ○ UK's largest heat pump trials ○ Involved 11,000 domestic, 380 of which equipped with HPs ○ Trial domestic customers with different tariffs and control scenarios	ASHP	£31 million	[62, 108, 123]
FREEDOM	Bridgen, Wales	2016-2019	○ World's first sizable trial of smart hybrid heat pumps ○ Installation of 75 hybrid systems in a mixture of private and social housing ○ The 5-8 kW_{th} hybrid HPs from different manufacturers ○ Investigating consumer and network implications of domestic smart controlled hybrid systems	Hybrid-ASHP	£5.2 million	[76, 109, 124]

Electrification of Heat Demonstration Project	Three locations in UK	2019-2022	○ Ongoing project ○ Installation of HPs in 750 dwellings with wide range of archetypes ○ Demonstration and monitoring gas-electric hybrid HPs connected to gas grid	Hybrid-ASHP	£14.6 million	[125]
TESSe2b	Austria, Cyprus and Spain	2015-2019	○ Residential hybrid system combining thermal storage, GSHPs, solar collectors and PCM heat exchangers ○ Collaboration of academia and industries from 8 EU countries ○ Different configurations and sizes (15-40 kW_{th}) are demonstrated in the three sites	PCM storage-solar collector-GSHPs	€4.3 million	[126-128]
IDEAS Project	Ferrara, Italy	2019-2022	○ Ongoing project ○ Trial of integrating PVTs, PCM storage, HPs, and intelligent control systems ○ Collaboration of 14 academic and industrial partners from 6 countries ○ Trial of 5 kW_{th} water-to-water HPs and a 10 kW_{th} air-source heat exchangers	PCM storage-PVT panels-WSHP	€4 million	[129-131]

5. Discussion

Project reports, post-construction surveys and research on the selected practices in the previous section are thoroughly reviewed. Analysing these outcomes and experiences, lessons with a good level of generalisability and applicability that should be considered in the EU perspective are identified. The most important of these considerations are highlighted as follows:

5.1.The Key Lessons from Practices

- **Technology perspective:** Heat transition is crucial for achieving the EU climate targets. Nevertheless, there is a broad consensus that none of the available technologies will dominate in the coming decades as much as the gas boilers do today [132]. Thus, there is a need to develop a range of reliable technologies to be able to cater sufficiently for a wide range of building types, consumers, climatic conditions, local potentials, and constraints. Unlike the power sector where main decarbonised technologies are commercially available at a large scale, decarbonisation pathways in the residential heat sector requires a breakthrough in some of the existing technologies, namely dramatic improvements in the application of HPs [9]. Some research suggests that the current market, technology and power system have the capacity to accommodate further uptake of HPs, sufficient to cover up to 32% of space-heating demand of EU buildings [133]. However, it is estimated that electrification of the residential heating, mostly through air and ground source HPs, could potentially cover up to 90% of the heat demand in buildings (after energy efficiency improvements). Achieving this goal would require the deployment of around 100 million HPs for buildings or city districts across Europe [9]. Some countries e.g. UK, Germany and Sweden, have already started relying on HPs in their heat roadmaps. However, the accomplishment of the HPs' mission requires fundamental developments in the power and construction sectors in parallel [134].

- **Multi-disciplinary approach:** Unlike the relative clearness of long-term objectives of decarbonising electricity in Europe, there is still much uncertainty on how this will be achieved in the H&C sector [6]. Future heating scenarios are tightly interlinked with multiple technical, economic, environmental and social aspects of the energy system and society. Regarding the HPs, there is a lack of studies which comprehensively include all the factors of energy, environment, economic and society. Furthermore, there are still no consistent boundaries or clear approaches for studying HPs and their lifecycle performance and impacts. Every design guide and standard establishes its own methodology and system boundaries, making comparisons between system solutions difficult [32, 135]. Additionally, the uncertainty of the gas network in the future further aggravates the problem, as HP's roll-out ultimately depends on the trade-offs between gas and electricity. This highlights the importance of strategic planning in a broad and multidisciplinary context.

- **Impact on the power sector:** Replacing gas boilers with different types of electric heating systems on large scales will result in substantially increasing the amount of electricity consumption and peak demand. HPs can potentially double the household annual consumption [108]. Adding the impact of increasing uptake of air conditioners in the residential sector, peak electricity demand could also reach two times today's peak figures [136]. Another study estimates that shifting 90% of the building H&C demand to HPs would result in a 10 to 15% increase in peak demand [9]. However, a recent study concluded that the current power system capacity would be inadequate for above 32% of average electrification rates across the EU (replacing around 60% of fossil-fuelled systems) [8]. Beyond that point, the role of grid reinforcement and flexibility of energy systems will be more critical. HPs equipped with storage and smart control systems can provide more stability and flexibility to the power grid by enabling load shifting and load shaping [42]. This will allow higher incorporation of fluctuating renewable power, e.g. wind power [77]. It is therefore essential to understand the interactions between electricity and heating sectors to make an efficient power-to-heat conversion while maintaining a secure and resilient power supply [42].

- **Financial barriers:** The economics of HPs is greatly reliant on the investments and operating costs that form the total cost of ownership. Despite the decreasing trend of capital expenditure (CAPEX) with technology developments, the capacity factor (CAPEX per kW of energy generation) is still substantial compared to the market competitors. On the other hand, operating expenditure (OPEX) highly depends on electricity pricing and taxing. Therefore, financial triggers are needed to facilitate the uptake of HPs, as well as the availability of surplus, low-cost and low-carbon electricity. The previous practices argue that further financial triggers and support programmes e.g. electricity tariff revision and tax incentives are required to increase HP's viability [75].

- **Market facilitation:** Market framework and support schemes should be designed to reward long-term cost-efficient options and avoid market distortion. For instance, flat-rate grants which are common across Europe are not often effective enough to incentivise the adoption of GSHP or WSHP-based CCHP systems, due to their typically higher CAPEX rates and despite their higher effectiveness [70]. In this case, some argue that capital allowances that could be varied by type and size of the HP may be better suited to the HP market and lead the market towards the systems with higher lifetime benefits [137]. Others argue that subsidies and penalties have failed to fairly distribute households with different socio-economic backgrounds, especially those with lower income [138]. Therefore, effectivity of supportive schemes should be further investigated in the practices, as well as examining innovative business models e.g. heat as a service and leasing the heating appliance.

- **Building upgrades:** The evidence demonstrates that HPs will cost more to run and release higher carbon emissions in less-insulated properties. Therefore, the building stock needs to be upgraded in terms of physical characteristics and geometrics to unleash the full potential of HPs. Furthermore, some changes in heating systems' configuration are required e.g. fitting larger radiators, setting lower flow set points, and using smart controllers, each of which imposes considerable up-front costs [139]. This causes difficulties to people without enough capital or renters who do not have the required authority. In addition to the building improvements, the development of new high-temperature HPs for buildings without upgrading capability is required to serve the market needs [70].

- **Consumer experience:** Any policies for the promotion of HPs need to carefully consider the impact on consumers, their awareness and wellbeing. Switching to HPs requires changes in buildings, gas appliances, and heating distribution systems in most cases. In addition to these disruptions over the transition process, noise levels and interrupted supply of hot water cause disruptions over the operation phase [140]. On the other hand, HPs make a different heating experience by delivering more sustained ambient heat compared to the immediate response of gas boilers at very high temperatures. Surveys suggest that utilising advanced control systems and increasing awareness of the consumers could enhance the level of customer satisfaction. Moreover, holistic planning and management are required to pass the transitional phase with minimum financial shock and disruption to consumers [26].

- **Regulatory barriers:** It is frequently seen in the literature that transition practices have been adversely affected by regulatory gaps and constraints, such as conflicts over strategies, complexity of ownership, conflict of interests, logistical constraints, and lack of standardisation. Most of these frictions emerge when distinct plans are being designed and organised independently and at different levels. For instance, some of the electrification programmes which were planned at the level of the city council have been conflicted with national refurbishment schemes [96, 141]. Any long-term decision making requires involving the right actors including technology manufacturers, housebuilders, energy suppliers and households through a detailed consideration of local circumstances

- **Complementary solutions:** Rollout of HPs could be facilitated by using complementary technologies such as heat storage, solar collectors, advanced control systems and hybrid HPs. While using smart controllers, heat storages and solar systems are highly regarded by practitioners and researchers, hybrid HPs have been less extensively investigated. Hybrid HPs could potentially represent a low-regret solution for initiating the transition process. Evidence from trials demonstrates that hybrid HPs can maintain thermal comfort for a broad range of housing types with no major changes to the existing heating system nor thermal improvements of buildings [109]. Coupling with intelligent control systems, hybrid systems can also prevent excessive peaks in electricity. Hybrid systems can go further and deliver near zero-carbon heat when combined with hydrogen/biogas boilers and renewable power network.

- **International collaboration:** The role of international cooperation in support of a global transition to low carbon heat is widely acknowledged. There are already several cross-border partnerships funded by the European Commission to support research and innovation in the H&C sector. The HRE, Hotmaps, WEDISTRICT, CoolHeating, KeepWarm, THERMOS, I-ThERM, HYRREG, SEPEMO-Build, GROUND-MED, GROUND-REACH and TASIO are some of these successful projects that contribute considerably to the market uptake of sustainable heating technologies. However, there is still room to develop international collaborations on HP promotion and joint investment plans [142].

- **District heating potential:** Large scale HPs have already proved their potential for providing low carbon H&C in DH systems. Higher energy efficiency, integration of renewables, sector coupling, and flexibility in the energy source are the main attractive points of the HP+DH systems. Recently, a shift from large scale units in the MW range towards smaller units in the range of hundred kW can be tracked in the European Union priorities [77]. In practice though, this trend is opposite in some countries where the application of HPs tends to large districts and complexes rather than small and medium-sized buildings [135, 143]. Different HP technologies and configurations can be fitted into DH systems. However, selecting the best technology and optimal configuration are still the key challenges in designing HP powered/supported heat networks. Utilising large-scale ASHPs, integrating renewables resources, utilising site-generated electricity, and using waste heat resources are on the cutting edge of research in this area today.

- **Heat synergy and waste heat:** Mid-level measures such as heat synergy collaborations and heat recovery have a huge decarbonisation potential at lower total costs [144]. This is more stressed in Europe where 23.8 EJ heat is lost in energy transformations, corresponding to 29% of all primary energy supply that is roughly equal to the EU's final net heat demand [145]. Heat pumps have a huge potential for synergies with surplus heat/cold providers. Recently developed thermal maps such as "Peta" [146] and "Hotmaps" [147] can facilitate the development of these plants in positive-heat-balance regions. Results from thermal maps demonstrate that a major fraction of demand in the high heat-density regions can be balanced with the excess heat resources in their neighbourhood [148].

- **Fuel poverty:** Social factors associated with heat decarbonisation, e.g. fuel poverty, employment, and public acceptance are often overlooked or superficially covered when the cost and carbon implications are studied [149-153]. Some trials also have resulted in worsening fuel poverty in vulnerable households[138]. On the other hand, HPs need to be accompanied by some changes in the electricity market to be able to deliver affordable heat [139]. Hence, enforcing the installation of HPs without modifications in energy tariffs, financing models, and supportive schemes will expose more households to the risk of energy poverty and social inequality. Therefore, understanding and coordinating the linkages between transition schemes and social factors and constraints are of vital importance.

- **Variations in performance:** Heat pumps normally operate at reduced capacity due to a couple of reasons like poor system design, faulty installations and seasonal fluctuations of the temperature [154]. The efficiency of the HP decreases as the temperature of the heat source decreases. Therefore, the performance of HPs is rated with the Seasonal Performance Factor (SPF). SPF represents the average COP over a full heating or cooling season to reflect how HPs work at both low and high temperatures. A multidisciplinary and holistic approach in design is needed to find out what type of HP, what configuration and what setup would lead to the optimum SPF rates.

- **Mechanical wear**: Wear of mechanical components, such as heat exchangers, compressor rotors, piping, and gearboxes, is a matter of concern, especially in large HPs [89]. The ageing problem makes the service lifespan of these components shorter than the unit's lifetime. This discrepancy sometimes leads to necessary variations in the system or even major overhauls, prematurely to their design life. Regularly scheduled tests, vibration damping, and using upgraded materials such as stainless steel and titanium tubes are some of the most endorsed recommendations to prolong the lifespan of the components [155].

- **Refrigerant**: Emission of refrigerants is worrying to note about HPs. Unavoidable refrigerant leakages during operation, maintenance, and breakdowns can be harmful to surrounding air and hydronic system. Ozone-depleting potential (ODP) of conventional substances such as chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC) has been warned in several Protocols. The other alternative, hydrofluorocarbons (HFC), are restricted to use by the Montreal Protocol due to their high global warming potential (GWP) [156]. After a global agreement on the phase-down of HFCs in 2016 [157], finding a sustainable alternative refrigerant with lower GWP and ODP factors has become a big challenge. Apart from the environmental factors, other specifications e.g. toxicity, flammability, stability, solubility, lubricity, and vapour pressure and temperature must be considered when replacing refrigerants. Substituting substances can also impact the HPs' efficiency and heating capacity. Natural refrigerants with zero ODP and negligible GWP have a large potential for small to large HPs. Ammonia (NH_3), carbon dioxide (CO_2), and hydrocarbons (propane, propene, isobutane) are viable natural refrigerants which already being developed in the industry [89]. However, all these options come with drawbacks that require some amendments in HPs design to maximise the performance.

5.2. Challenges, Advantages, and Recommendations

Then the main barriers and advantages of HPs over development, implementation, and operation phases of the selected projects are summarised in table 2. Also, judgments and recommendations made by researchers and professionals, drawn based upon these practices, are presented.

Table 2: Overview of the heat pump challenges, advantages and development priorities

Challenges	Upfront costs, cost of equipment, installation and building upgrades are rather high	Impact on the amount of electricity consumption and peak demand	Efficiency and viability vary with local geology, climate, and electricity	Are not suitable for buildings with poorer insulation and require building upgrades	Environmental concerns regarding the refrigerant fluid used in the pipe system	Professional competence and knowledge are required for design, installation, and services	End-user challenges due to the lower temperature, transition disruptions, and noise pollution	Could increase the risk of fuel poverty without regulating the energy market	Technology constraints like components' erosion and relatively large size
Advantages	Can provide cooling through the reverse operation of the cycle	Main energy is provided from renewable sources; Also enables using renewable electricity	Can reduce operating cost and emissions because of highest energy efficiency over other solutions	Require little servicing and maintenance	Enable heat synergy collaboration: waste-to-energy and waste heat recovery	Sector coupling which provides flexibility and stability to the electricity system	More safety by eliminating the need for gas pipes or oil tanks	Great capacity to fit into new generations of DHs and coupling with other technologies	Hybrid HPs could efficiently operate in a broad range of housings
Action priorities	Accelerating development in technology and fill the supply chain gaps	Increase the share of renewables in power generation, a step towards fully decarbonisation	Prepare market mechanism and regulate respective energy market parameters	Provide supportive schemes to reward long-term cost-efficient types and configurations	Implement higher levels of insulation and airtightness in buildings, fitted for low-temperature heating	Triggering development of complementary solutions such as smart control systems, heat storage, and hybrid HPs	Removing regulatory and administrative barriers and clarifying legal obscurities	Promoting knowledge and experience exchange and international collaborations	Promoting natural refrigerants; restricting high-ODP and high-GWP refrigerants

5.3.Trends and Projections

Long-term planning for heat decarbonisation helps to direct actions, investments and installations in line with the strategic targets. Some studies in the level of EU have been conducted so far to project the future structure of the heating sector. Reviewing the projections of the ‘Heat Roadmap Europe 4’ and ‘Hotmaps’ projects discloses some similarities [158, 159]. These studies agree upon the 25-40% reduction in the total heat demand in residential and commercial buildings by 2050 through the improvements in the thermal efficiency of the buildings, offset by the rise in the number of buildings. Despite a significant reduction in the contribution of natural gas, it will still cover the largest proportion of heat demand until 2050. Share of renewables, made up mainly of biomass boilers, HPs and solar thermal systems, will rise to 30-37% based on the baseline scenario of both models. HPs and electric heaters are projected to supply 200-300 and 400-500 TWh/year, respectively. On the other hand, some considerable inconsistencies can be found in the speculations. For instance, in the simulation carried out in the Hotmaps project, the demand for natural gas in 2050, based on the business-as-usual scenario, would be around 819 TWh. While the baseline scenario of the Heat Roadmap predicts 54% more gas demand (1268 TWh) in the same year [159, 160]. Fig 5 illustrates how these two projects estimate the composition of H&C supply by 2050.

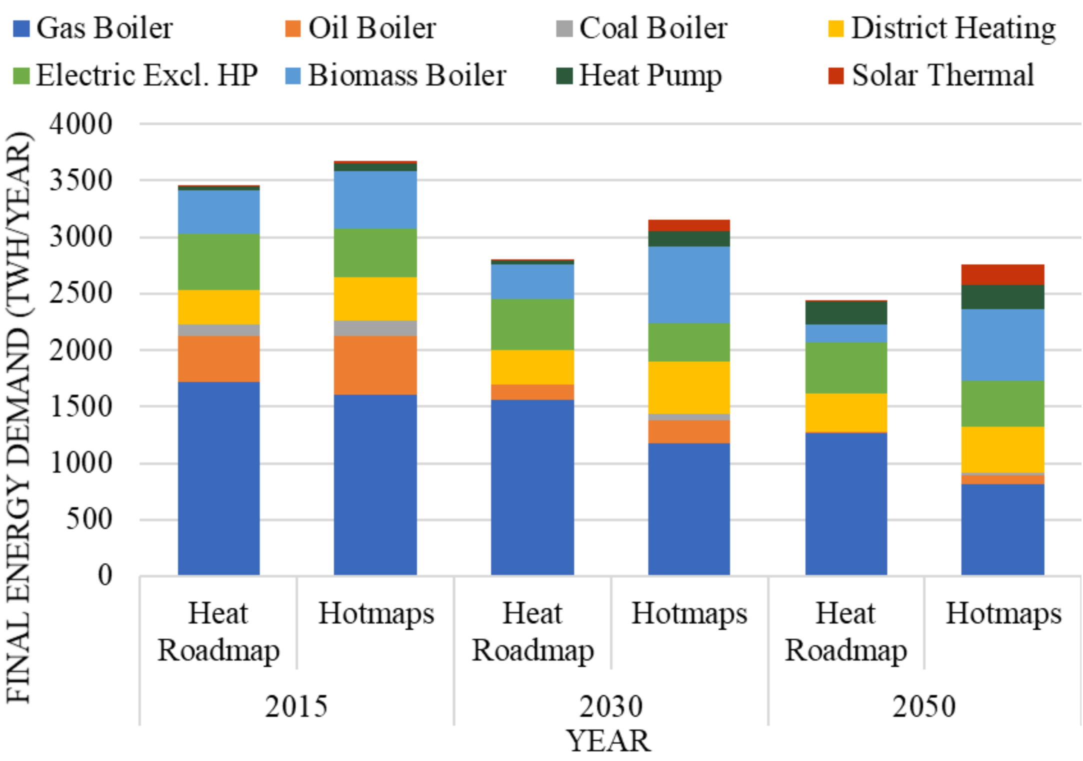


Fig 5: Total heating, cooling, and hot water demand estimations of EU buildings by technology based on the business-as-usual scenario, conducted by 'Heat Roadmap Europe 4' and 'Hotmaps' projects, 2015-2050 [159, 160].

In the scientific field, academic trends are good indicators, representing the level of maturity of each technology and their market perspective. Fig 6 illustrates the number of academic articles published between 2000 and 2020 on the main technologies of low carbon heating. The data is extracted from the Scopus database and includes all the articles, books and conference papers published in this period. Industrial, governmental, and institutional reports are not included in these figures. Overall, a clear upward trend in the academic interest in low carbon heating systems can be seen over the period. Among the heat generation technologies, HPs have received the most attention from researchers, followed by DH and hydrogen systems. Publications associated with heat storages have hit the peak number of 1465, due to their wide applications and adaptability with various heating systems.

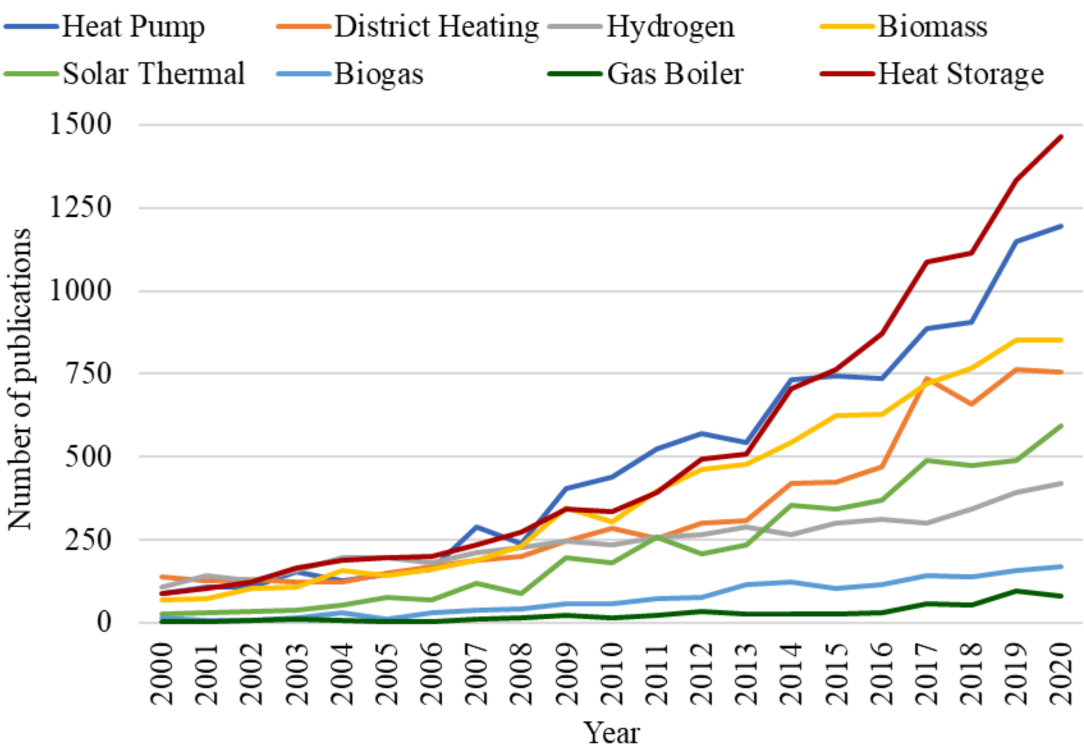


Fig 6: The number of indexed documents in the Scopus database, 2000 to 2020

6. Conclusion

Heat transition is not a simple replacement of a technology. The complexity and variety of involved parameters require extensive knowledge to formulate an appropriate transition framework. Furthermore, a limited number of real-world trials and lack of extensive reporting have resulted in the inefficacy of some policies and demonstrations. This review paper has highlighted the most prominent issues which have to be considered in delivering heat through HPs. Adopting the evidence-based approach, it is sought to provide an analysis of the evidence from HP demonstration practices across Europe. A wide range of academic, industrial, and institutional reports are reviewed to aggregate the challenges and implications of real-world projects. The following key conclusions and insights are derived from the study.

Within the many regions of Europe, HPs have been widely acknowledged as one of the prevailing heat transitionary solutions due to their remarkable economic, environmental, and energy benefits. However, it is strongly agreed that HPs cannot be promoted as a stand-alone substitute for gas boilers. A mix of primary heating systems such as hydrogen and DH, along with complementary technologies such as solar thermal and heat storages, are required to be developed to fulfil the market. Heat pumps can present a practical low-regret solution for a wide range of scales and applications. However, in more present times, a trend towards decentralised systems and individual HPs can be tracked in policies, followed by research and practices.

However, many challenges still lie ahead of HP technologies during their development, implementation, and operation phase. The effect of HPs on electricity consumption and peak demand is frequently discussed as the key technical challenge of electrification. Widespread deployment of this technology requires a significant enhancement in the capacity of electricity production and distribution, as well as increasing the share of renewables in the power sector. Besides, new homes and retrofits should be fitted for low-temperature heating to benefit from HPs in terms of thermal comfort and energy consumption. Making these infrastructural upgrades in buildings and electricity network is considered as the major barrier and cost factor to roll out HPs. Additionally, the end-users must pay more upfront fees to purchase and install an HP rather than a fossil fuel-based equivalent. Therefore, both developers and end-users need to be supported by appropriate legislation and economic mechanisms to move towards the HPs. These mechanisms should be able to regulate the market so that the non-economic benefits of the technologies could be reflected in their price.

Most HP demonstrations are coupled with one or more heating technology to promote system resilience and supply security. Large-scale HPs are often accompanied by auxiliary systems such as thermal storage, boiler, or CHP. While, in small scales using a secondary boiler is more common, known as hybrid HPs. Hybrid HP is a reliable solution that is often recommended as a no-regret shortcut towards low-carbon domestic heating.

Coupling with smart control systems and storages, hybrid HPs can deliver large amounts of carbon saving as a result of load shifting and load shaping activation. Furthermore, with the advancements in gas network decarbonisation and renewable power generation, hybrid HPs could potentially deliver fully decarbonised domestic heat.

Lastly, heating systems -unlike power generation- directly influence the consumers' experience, health and comfort. This means that apart from the technical, economic, environmental considerations, it is much more important than in the electricity sector to evaluate the wellbeing and social consequences of the various options in the studies and decision-making. Performing multi-criteria sustainability assessments, incorporating factors such as thermal comfort, health impacts, fuel poverty, employment, and public acceptance can improve the quality and reliability of future research.

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