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Review

Heat pump placement, connection and operational modes in European district heating

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ABSTRACT

The use of heat pumps in district heating is one of the most promising technologies for enhancing the efficiency of systems and for meeting the 2030 and 2050 European energy and climate targets. It is essential to assess the available data, the practice and experience of planners and engineers to determine heat pump placement, connection and operational modes in district heating networks, as the systems ought to be capable of covering residential heat requirements for all year around operation. The main selection criteria for the appropriate heat pump system are the heat source, the heat pump technology and the heat requirements. These parameters form a technical triangle, which should be used as a comprehensive instrument to enable heat pump integration into residential district heating. The triangle allows the definition of the bidirectional interdependences and the design of a high efficiency, sustainable heat pump based system. This paper presents the solution to scenarios of how to integrate heat pumps into district heating, in terms of heat pump placement, connection and operational modes based on available heat sources and heat requirement profiles and their environmental impact.

1. Background of district heating in the EU

The following sections of the article will present the energy and technology backgrounds of European district heating systems in order to give an overview of the scenarios for heat pump integration into district heating in terms of placement, connection and operational modes. Before assessing the potential for heat pump technology, it is necessary to gain an overview of the state of the art in European residential district heat technologies, European Union (EU) energy and climate polices and, further, the district heating infrastructure, components, parts and temperature ranges for covering the required heating loads.

District heating is a wide spread and known technology in Europe. Europe is one of the world leaders regarding district heating technology, as more than 6000 different systems are installed all over Europe [1]. District heating systems have the potential of replacing several conventional heat sources and offer key advantages such as the enhancement of total energy efficiency, the reduction of the overall maintenance demands, the reduction of greenhouse gas emissions and an increase in the contribution of renewable energy sources [2]. In district heating the huge energy demands and large number of consumers provide a unique opportunity for energy savings [3]. Every improvement in the central energy source, such as integration with advanced technologies e.g. heat pumps or using low carbon technologies, will generate positive effects for all consumers simultaneously [4]. Thus, district heating systems could enable the EU to achieve its energy and climate targets and to meet its challenges towards a more sustainable energy future and climate policy [5–9].

District heating systems in Europe are not uniform in size of thermal capacity, technology and network length. The networks are built according to a large variety of specifications and local design parameters such as demand temperature, pressure levels, direct or indirect installations etc. Historically in Europe, three primary forms of district heating have been established: Nordic, Central and Eastern Europe. These pose challenges and have advantages and disadvantages as well and they differ in energy supply and heat sources, temperature ranges, efficiencies, and technologies provided such as insulation, substations and control systems [10,11]. District heating can also integrate renewable energy through heat pumps, geothermal and solar thermal energy, waste heat, energy from municipal waste and thermal energy storage, all of which increase the flexibility of the systems [5,12,13]. To increase the heat supply security for heating sectors, the district heating heat source

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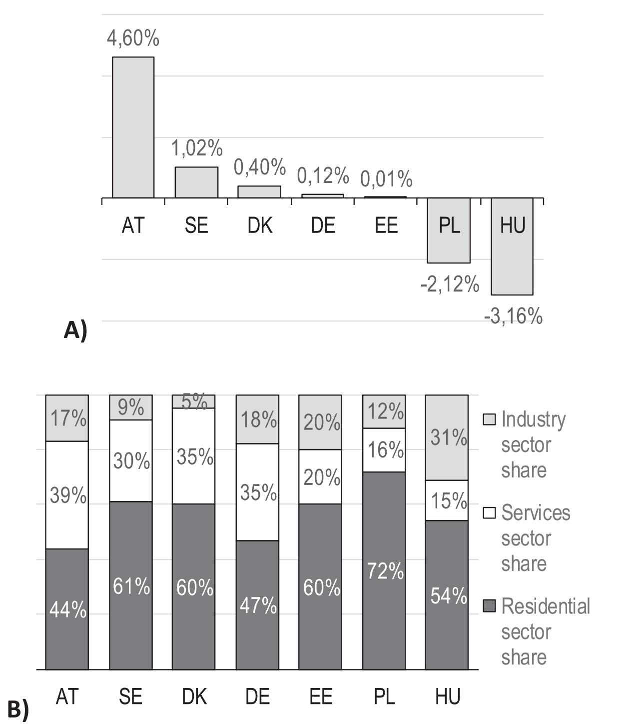

Fig. 1. (A) average annual growth rate of district heating consumption for some EU countries 2005–2015, (B) district heating percentages for residential, service and industry sectors.

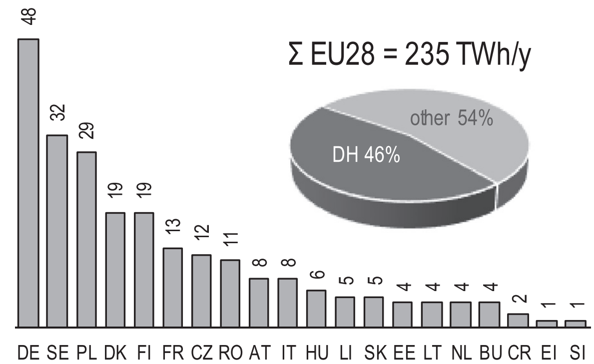

Fig. 2. Total final district heating heat consumption in the residential sector in TWh/year.

can be changed from one fuel to another, or to a fuel mix or to hybrid sources. However, where the network is already constructed, then a boiler or combined heat and power (CHP) plant using any fuel could be used to supply the required heat. Alternatively, surplus industrial heat, heat pumps, electric boilers, geothermal, solar and waste incineration could be used. In general, the overall security of the heat supply is dramatically improved with the introduction of district heating innovations [14–17].

District heating is an important option for supplying heat to numerous consumers, especially in urban areas with a high density of heat demand. The significant percentage of heat supply and the large consumption of district heating in EU residential heating makes district heating an important sector in EU energy and climate policy. Additionally, district heating is a suitable platform for integrating low carbon technologies like heat pumps on a large scale, renewable energy sources and thermal energy storage to improve the general efficiency and to minimise greenhouse gas emissions. Currently, heat pumps are still not a particularly common technology in European district heating systems. In existing district heating systems any changes in the heat supply technology would require huge investments that would need justification. Developments in district heating will help to increase energy efficiency and to decarbonise the European district heating sector. Current systems have become part of a district energy system, which links different fuels, energy carriers, innovative technologies and renewables to create a more flexible and sustainable energy mix in the EU [4,18–20].

1.1. Heat consumption in European district heating

District heating and cooling are consumed in main three sectors, namely residential, service and industry. From Eurostat and Euroheat statistics, Fig. 1A shows the average annual growth rate of district heating consumption in a 10 year period (2005–2015) for some individual member states of the EU, which is characterised by a great diversity. It is evident that district heating is increasing in some EU countries, it is stable in others, but in some countries the rate is decreasing. Fig. 1B shows the split in district heating between residential, service and industry sectors for the same countries; the percentage for the residential sector rate is the highest in each case [21].

Around 73% of the EU population live in urban areas, according to the United Nations World Urbanization Prospects, indicating that a major part of the EU's buildings are in high heat density areas. People living in these buildings are the main consumers of district heating and cooling. Requirements for heating and cooling in buildings depend on the building type (e.g. single family houses, multi-apartment buildings), building energy standards and the climate zone etc. In the EU there are about 240 M homes, of which 40% were built before 1960, that is, before any building regulations. According to Buildings Performance Institute Europe currently 97% of the existing buildings in the EU need major renovation to be upgraded. Hence a significant disparity in heating requirements for residential buildings exists among EU countries, which vary from 60–90 kWh/m^2 in southern European countries (Malta, Spain, Bulgaria, Greece and Croatia) to 175–235 kWh/m^2 in colder countries such as Estonia, Latvia and Finland [2,3]. This results in large differences in the heat demand density delivered by district heating in different European cities, which specifies the requirements of heat sources and heat distribution networks. It can be seen from Fig. 2, that the heat supplied to residential consumers via district heating is 46% of the total final heat consumed in the residential sector (excluding countries which do not have district heating or for which data were not available) [5,10,13].

The majority of the heating requirement for district heating is 52% for space heating, 30% for process heating and 10%for domestic hot water. Space cooling is currently limited to less than 3%. Space heating accounts for more than 80% of district heating in colder climates, on the other hand, in warmer climates space cooling is the most important and this sector is growing fast [22–25]. Heating requirements for space heating depend on the climate zone and the season, which requires constant adaptation of the heat supply. This imposes additional requirements for heat pump technology and the type of heat sources for heat pump integration into district heating.

1.2. Residential district heating in Europe

There are three main heat loads in buildings: space heating, space cooling and domestic hot water, which represent approximately 50% of the global energy consumption for buildings [26–28]. Fig. 3 shows the percentages of residential district heating in EU countries; the countries are divided into five groups accord-

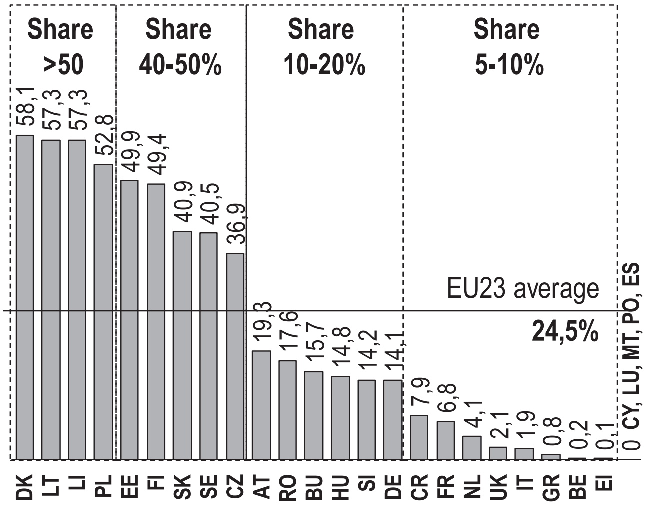

Fig. 3. Percentages of residential heat supply from district heating in EU countries.

ing to the percentages of district heating, which varies from more than 50% to zero. The average percentage for the 23 EU countries which have district heating systems is 24.5% [5,13].

District heating systems represent a large proportion of the residential heating sector in EU countries and a significant annual growth rate in heat consumption [1,2,29–31]. It is a strong argument for utilising district heating in Europe, but, as outlined in Fig. 3, the average market share for residential district heating in EU member states is just 24.5%. The European countries with a cold climate tend to have a much higher percentage of district heating (between 40 and 60%) than the rest of the EU. These member states are all either Scandinavian, Baltic or Eastern European countries [2,3,29,30]. As mentioned above, thousands of district heating systems can be found all over Europe today [1]. They have various sizes and technologies, were built in different years and vary in levels of refurbishment. District heating systems in Central and Eastern Europe are a sinkhole for investment. They require urgent improvements, which should lead to increasing energy efficiency and decarbonisation through, for example, heat pump technology, renewable energy sources and thermal energy storage.

1.3. European district heating strategies and energy policies

The EU defined three energy policy targets in order to address the challenges related to climate change, security of supply and competitiveness with objectives for 2020, 2030 and 2050. The 2020 Energy Strategy defines the EU's energy priorities between 2010 and 2020. It aims to reduce greenhouse gases by at least 20%, to increase the proportion of renewable energy in the EU's energy mix to at least 20% and to improve energy efficiency by at least 20%. The EU 2030 targets are to reduce greenhouse gas emissions by at least 40%, to increase the use of renewables by at least 27%, to improve energy efficiency by at least 27% when compared with 1990, and to complete the internal energy market by reaching an electricity interconnection target of 15% between EU countries. Finally, The EU aims to achieve an 80% to 95% reduction in greenhouse gases by 2050 when compared with 1990 levels [2,5,31–35]. None of the 2030 and 2050 scenarios involve implementation of district heating on a large scale. They focus on small or micro scale district heating, electrification of the heating sector, primarily by using heat pump technology [36,37].

One of main consumers of primary energy and the biggest energy sector in the EU is the residential heating and cooling of buildings. Currently this heating and cooling consumes half of the EU's energy. Therefore, the building sector assumes an important energy role, not only in the achievement of the EU sustainability targets, but also in the decreasing of energy consumption and greenhouse gas emissions [36]. Developing a strategy to make heating and cooling more efficient and sustainable is a priority for Europe. It should help to reduce energy imports and dependency, to cut costs for households and businesses, and to deliver the EU's reduction in emissions. To achieve the above mentioned objectives, the energy system must be decarbonised [5,10,22,24,38,39].

Different strategies have been proposed for EU district heating with heat savings to decarbonise the EU energy system. Some of these strategies are to develop new networks and/or refurbish old networks for the deployment of renewable energy sources, the recovery of waste heat for residential space heating and building renovation. The rate and the extent of improvements vary from country to country; it depends on potential and capabilities. This differentiation slows down the decarbonisation of the district heating sector, but it also gives enough time for evaluating the different solutions and scenarios for a central power supply aided by low carbon technologies. In order to achieve higher energy efficiency and meet the heating requirements of buildings, all EU directives encourage member countries to use more sustainable heating options. The integration of heat pumps into district heating is considered an implementation of renewable technology, which would enable the EU to achieve its energy and climate targets [30,40,41].

2. Infrastructure, parts and components of district heating

2.1. Infrastructure of district heating

Traditional district heating is a system where a large number of buildings or dwellings are heated by a central heat source. Warm water passes through a double pipe network (supply and return) and is distributed to the buildings to be used for different applications, such as space heating, domestic hot water and process heating. Often, district heating systems cover large areas and are very complex plants involving many substations and thousands of consumers. A district heating system may consist of more than one heat source including fossil fuels, renewable energy sources, thermal energy storage, heat pumps, a combined heat and power (CHP) plant with a mixed fuel or hybrid sources. District heating systems which enable the use of a flexible energy mix provide an infrastructure for easy transition to renewable energy sources, with higher energy efficiency, faster decarbonisation and enhanced heat recovery alongside building refurbishment and a smart grid [16,17,24,42–44].

The objective for realising the deployment of district heating practically differs widely between individual member states of the EU, which has a major impact on the set of measures that result in optimal improvements. Furthermore, it has been experienced that the proportion of district heating as well as the potential for new expanded networks differs between urban and rural areas [22,23,26], although district heating systems enable a highly flexible energy mix. New fuels and energy sources can be integrated when there is a need for restructuring district heating systems. For customers, no adaptation measures at all are required when a switch of energy source is made. District heating and cooling provides an essential infrastructure to ensure large scale integration of renewable energy sources. District heating and cooling as a technological concept has a significant presence in many countries and it is implemented in many different forms and it seems that district heating and cooling will increasingly move away from fossil fuels [18,45]. All these possibilities require the use of dedicated technological solutions, the integration of different energy systems and advanced management for energy production and consump-

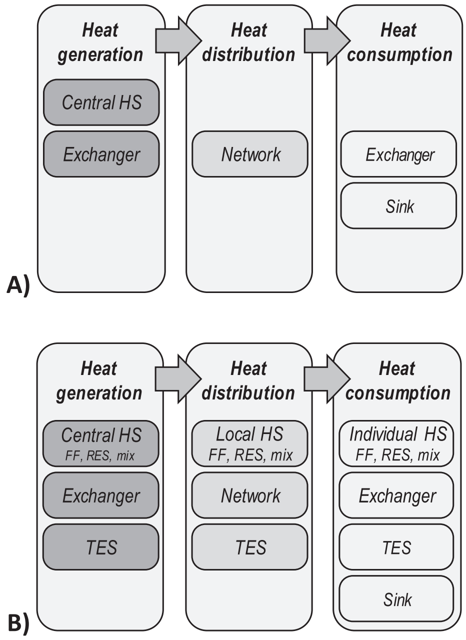

Fig. 4. Main components of district heating system: (A) standard, (B) advanced. (FF—fossil fuels, HS—heat source, RES—renewable energy sources, TES—thermal energy storage system).

tion in the system. This requires the definition of all dependencies, improving and evaluating scenarios and the conscious choice of preferred solutions which take into account local conditions, requirements and capabilities.

Some contemporary district heating systems include many innovative and renewable thermal technologies concerning fuel, energy carriers or heat generation. A suitable layout enables their connection and collaboration in an integrated energy system and smart grid, which gives flexibility for collaboration for both energy systems and fuels [4,18,20,46,47]. District heating infrastructures have an important role to play in the task of increasing energy efficiency and thus making scarce sources meet future demands. District energy systems and smart grids are the most promising ways for integrating a larger contribution from renewable energy sources and thermal energy storage into contemporary systems. However, district energy systems and smart grids are not widely used yet in European district heating systems due to numerous technical and economic issues.

2.2. Parts and components of district heating

In general, a traditional district heating system has three main parts: heat generation, distribution and consumption. Fig. 4A shows the main components, which consist of the central heat source and heat exchanger (HX) for generation, a pipeline network for distribution and in consumption a heat exchanger as a main part of a consumer substation and a heat sink for space heating and domestic hot water etc. Within the evolution of district heating systems, additional advanced components have been added to satisfy the heating requirement for space heating, domestic hot water and process heating for buildings and industries to meet environmental and climate challenges and energy efficiency legislative requirements. Fig. 4B shows an advanced district heating system with possible additional components fitted in the three main parts. For generation there are a central fossil fuel heat source, renewable energy sources including heat pumps, a heat exchanger and thermal energy storage. In the distribution network there are local heat sources, renewable energy sources including heat pumps, heat exchangers and thermal energy storage. In the consumption section there are individual fossil fuel heat sources, renewable energy sources including heat pumps, heat exchangers, thermal energy storage and of course heat sinks. It is noted from Fig. 4B that renewable energy sources and thermal energy storage can be installed in the district heating system at generation, distribution or even consumption [23,48,49,50]. The advanced scheme gives more flexibility for better performance and environmental effects, energy security and fuel independence; it is more open to the inclusion of future new technologies, both in micro and macro scale. This scheme also indicates the current direction of changes in district heating [51,52]. This flexibility increases the number of possible solutions and improvement scenarios. This is a good feature, but it increases the scope of the analysis and hinders the choice of a preferred solution. This means there is an opportunity for implementing other solutions whenever and wherever possible and the impossibility of introducing universal changes in all district heating systems. It is important to mention that an overly complex system consists of many different components, which hampers its operation and increases the costs.

2.3. Scales of district heating systems

As it was mentioned, traditional district heating is a system where the heat is produced centrally and distributed by a network. Systems can be differentiated due to scale as small or large. Small scale systems supply heat to a small number of consumers within a short pipeline distance of a few kilometres, in rural areas using biogas or woody fuel often in combination with CHP plants [43]. Large scale systems supply heat to many consumers, for instance in city districts, where the underground pipeline length may be up to a hundred kilometres [37]. These distances can be extended by installing additional heat sources along the way.

Nowadays in the EU it is common to build small or micro scale district heating where all components would be designed to maximise the use of heat pumps. The main barrier for small and micro scale district heating is the accessibility to a stable heat source, if a heat pump is to be used.

2.4. Temperature ranges and heat generation technologies

In general, traditional European district heating systems depend on fossil fuels, they are large, high temperature systems for distributing heat which is generated in centralised units [53]. Among the disadvantages of high temperature district heating are the high capital cost of the pipe network for heat distribution, significant heat losses from the water in the network and large fuel deliveries; high temperature district heating systems can also preclude some technologies [54]. The incentive for establishing a district heat supply is the possibility of obtaining a higher efficiency, and thereby lower operating costs, when converting thermal energy in a few large plants rather than using small individual units with the same total thermal capacity. From a historical perspective, traditional district heating distribution technologies went through four generations with the following temperature ranges [55]:

- 1st: steam-based systems (>120–150 °C).
- 2nd: pressurised high-temperature water systems (>100 °C).
- 3rd: pressurised medium-temperature water systems (<100 °C).
- 4th: low-temperature water systems (~30–70 °C).

The development trends in working temperatures focus on the 4th generation technologies, which is appropriate to heat pump technology. Network technologies are different with the progress of district heating in Europe; some are 2nd generation, others are 3rd generation, while others are between 2nd and 3rd generations and they are different in different EU countries.

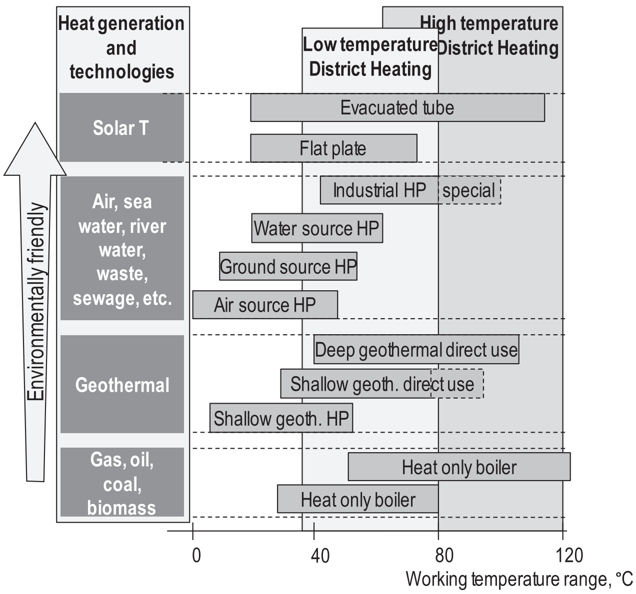

Fig. 5. Overview of district heating temperature range due to heat generation technologies and sources.

Heat pump technology and the corresponding design solutions can be easily integrated into 4th generation district heating. With the 3rd generation specific technologies are required due to the higher operating temperatures needed or due to the use of conventional heat sources. Then the heat pump unit will supply only part of the required heat for the system. In 2nd generation systems the heat pump can support only the central conventional heat source, for example, they can provide the heat for domestic hot water during the summer. In order to increase the contribution from heat pumps to cover the heating requirement, a considerable refurbishment of networks, substations and management is needed.

Currently in EU countries it is clear that district heating supply-return line temperature ranges are characterised by a great diversity due to the technologies applied at the national level. It is also evident currently that low temperature district heating is a practical trend and feasible option. Low temperature systems increase the possibility of using low grade and renewable energy sources widely with, for example, heat pump technology [37].

Low temperature district heating can operate with supply line water temperatures between 50–55 °C or 60–70 °C with return line water temperatures of 25 °C to 40 °C and meet heating requirements for space heating and domestic hot water in residential or public buildings. This low temperature definition is pushing the temperatures to the limit and so it is suitable only for new, low energy buildings or refurbished buildings. Lower temperatures in district heating networks lead to lower distribution losses, higher integration possibilities for heat pumps, a lower electricity supply and an improvement in heat storage possibilities [56,57].

Fig. 5 shows an overview of water temperature ranges from the heat generation technologies used for high and low temperature district heating. It is obvious that heat pump technology does not cover the entire working temperature range in European district heating systems. Thermodynamic constraints do not allow the achievement of the parameters needed for high temperature district heating. The comparison with conventional and renewable heat sources defines the ability of heat pump units to be used with them. If they can reach a similar temperature range, they can work in parallel simultaneously. Alternatively, if the heat pump does not reach the required temperature, it requires support from another heat source and then it can work only during periods of low heating requirement, it cannot be used generally in the district heating system. The type of the heat source for a heat pump determines the water supply temperature. Water, ground or air source heat pumps can provide heat for low temperature district heating from air, sea water, river water, waste, sewage, shallow geothermal etc. Supplying high temperature district heating requires special solutions like industrial waste heat or deep geothermal sources, which limits their use.

Low temperature district heating enables the use of low grade heat sources and the absorption of more thermal energy from these sources by using different heat pump technologies [37,58]. From Fig. 5 it is clear that low temperature district heating has several advantages. First of all, it ensures energy efficient supply and increases the utilisation of renewable energy and heat pumps. Low temperature district heating networks allow access to different heat sources to increase the flexibility in matching heating requirements with locally available low temperature sources. Pipeline thermal stress is also reduced. In addition, lower temperatures mean lower investment costs in heat generation, lower operating costs, improvements in the efficiency of heat production, a higher potential for using renewable energy, etc. From an economic and environmental point of view low temperature district heating systems with heat pump technologies are fully competitive, but for high temperature district heating systems the heat generation technologies (mainly fossil fuel) are very limiting for heat pumps [48,59]. Trends in district heating development however appear to show a preference for the application of heat pumps because they allow the use of so far unnoticeable waste heat sources or inaccessible heat sources for district heating. Heat pumps contribute to a reduction in greenhouse gas emissions and they integrate renewable energy sources and decarbonise district heating [60].

3. Heat production technologies in district heating

3.1. Energy carriers

The maximum percentage of natural gas use for heating purposes is 68% in the UK, with 66% in the Netherlands and 59% in Hungary. In Finland, Sweden, Norway, Iceland, Malta and Cyprus the percentage is lower than 5%. The highest percentage for the use of coal is 38% in Poland, followed by 20% in Slovakia and 17% in Czech Republic [32]. In 24 EU countries the proportion of coal heating is below 10%. The percentage for electricity use for district heating and cooling in Norway is 45%, in Iceland it is 28% and in Mediterranean countries the figure is 20% (due to a high space cooling demand) [24]. The proportion of biomass used in district heating and cooling is high in the Baltic countries, Sweden and Finland (more than 28%) [29]. Cyprus has the highest percentage of solar energy (14%), followed by Malta (4%). It is obvious that for the energy carrier mix in 2012 the dominant fuel for heating and cooling in buildings in EU countries for the main three sectors, residential, industry and service is natural gas as shown for example in Fig. 6. The overall percentage in the residential sector is 43% for gas and this is followed by oil products and electricity with 13% and 11% respectively [61]. The percentage for coal and coal products is 4%, which raises concerns about pollution and consequent negative health effects especially in urban areas. Biomass represents 17%, while solar is 1% and geothermal is around 0.1%. District heating is supplying 9% of Europe's heat demands, meanwhile district cooling is supplying 2% of the cooling demand but in both cases the distributions are highly uneven at an EU national level [5].

As shown in Fig. 6, district heating systems provided 9% of the EU's heating load in 2012, where 40% of this came from gas, 29% from coal, 16% from biomass and the rest from other fuel sources. From Fig. 6 it is clear that around 70% of the heat generation for

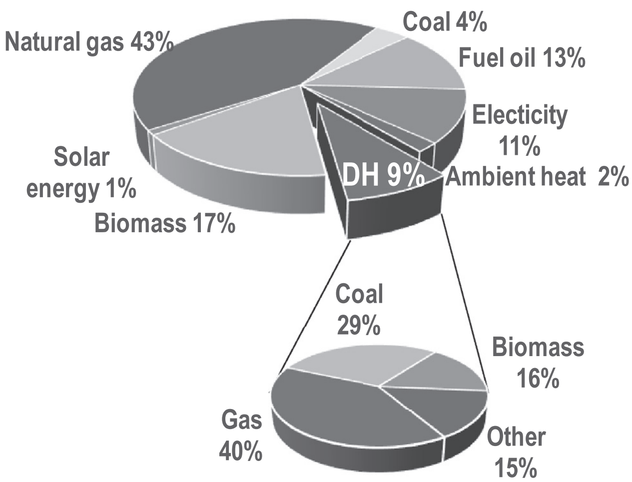

Fig. 6. Energy carriers mix for heating/cooling in residential sector in EU, 2012.

district heating came from fossil fuels. Hence, the large proportions from fossil fuels stimulate an interest in the use of new, energy efficient solutions, for example, heat pumps and renewable energy sources [10,27].

Simultaneous district heating and cooling systems can be useful and technically flexible for applying multiple types of energy sources and technologies. They can deploy new, innovative low-carbon and renewable energy technologies at a more rapid pace, while in parallel offering the potential of achieving primary energy savings through the increased transformative efficiencies of larger generation units and reduced air pollution. District heating and cooling systems can apply recycling technologies to recover waste heat from industrial and other processes or to harvest thermal energy from natural sources, such as geothermal heat or cold from low-grade sources like seas, lakes and rivers etc [15–17,20,62].

3.2. Heat sources in district heating and cooling

It is noticeable that district heating systems are open to high efficiency and low carbon heat generation and heat delivery technologies such as combined heat and power (CHP), renewable energy sources, etc [60,63]. There are a number of different heat sources that can be used, including industrial waste heat, geothermal, biomass and biogas, fuel cells, nuclear, solar and heat pumps, in addition to conventional boilers and cogeneration. The integration of diverse heat sources reduces the dependency on a single fuel and technology. This is a significant factor for achieving high levels of system reliability, service continuity and future-proofing [4,11,54,64–66].

The proportions and types of fuels used and the heat source technologies vary greatly in European district heating systems. Conventional technologies, fuels and energy carriers are well known and analysed more deeply in many references, which consider their environmental impacts too. The next stages of this paper will concentrate in detail on heat pump integration into residential district heating systems.

Fig. 7 shows an overview of general heat sources and technologies in European district heating systems. It is obvious that it is possible to use different heat source technologies from fossil fuels, such as renewable energy sources or hybrid sources. In the case of hybrid combinations, there is a need to balance their advantages and limitations, e.g. hybrid combinations of fuels and sources enable the use of renewable energy sources, where these alone are not able to supply the district heating system, thus increasing the

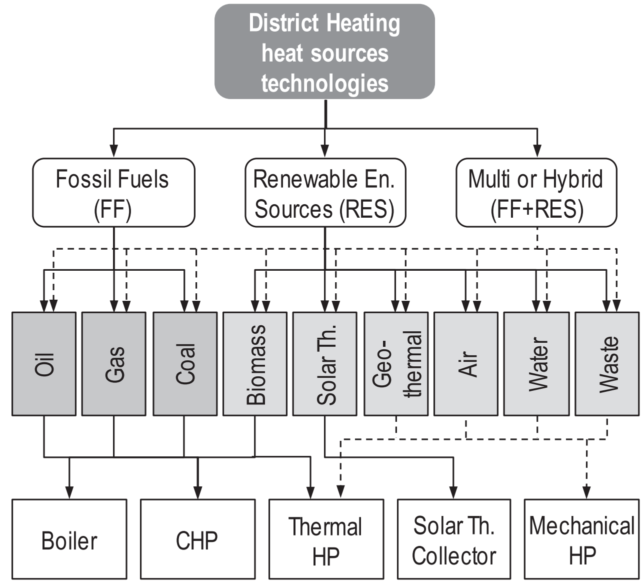

Fig. 7. Overview of heat sources and technologies used in European district heating systems.

use of renewable energy and reducing the consumption and emissions from fossil fuels. It should be noted that the integration of too many different heat and fuel sources hampers the design, construction, operation and management of such systems: problems and increased costs can outweigh any benefits.

System flexibility allows the integration of different technologies and heat sources in order to meet sustainability targets. The inclusion of district heating in sustainable cities of the future allows for the wide use of combined heat and power together with the utilization of heat from waste-to-energy and various industrial surplus heat sources as well as the inclusion of geothermal and solar thermal heat [15–17,60,67,68]. In the future, such industrial processes may involve various processes of converting solid biomass fractions into bio(syn)gas and/or different sorts of liquid biofuels for transportation fuel purposes, among others [55,60,69,70].

3.3. Combined heat and power technologies in European district heating

The EU encourages combined heat and power (CHP) as an efficient energy production technology. CHP offers a high performance in heat and electricity generation with lower emissions than with separate processes. There are certain clusters amongst the EU countries with an interest in the relationship between renewable energy sources and CHP based heat generation for district heating schemes. High proportions of renewable energy and CHP heat generation in district heating are characteristic for those countries with high levels of district heating penetration [21].

Most new EU member states managed to more than double their renewable energy heat generation in the last decades with CHP based heat generation being the motor of the growth [32]. Renewable energy heat generation gained a significant market share in the last decade within the EU countries both in non-CHP and CHP based heat generation categories [30,71].

The structure of CHP energy production in a given member state of the EU determines the proportion of district heating consumers with CHP and heat pump units. In a CHP plant, electricity and heat are produced simultaneously. If the heat pump is powered by electricity from the CHP plant, the excess heat generated from CHP must be consumed to ensure high energy system efficiency, otherwise the heat will have to be dissipated and lost.

Currently there is not a simple way for completely changing the supply to all European district heating systems; if a system is to be supplied by a heat pump powered by electricity, it is not easy additionally to accommodate heat from a CHP plant. Considering the scale of additional electricity required to electrify future heating and cooling demands, heat pumps should be prioritised over electric heating and other alternatives, such as fossil fuel district heating and cooling; they will be required to minimise the strain on the electricity grid in the future [72]. Heat pumps link thermal and electricity sectors, which can play a pivotal role in the energy infrastructure due to the ability to balance heat and electricity demands and thereby provide flexibility to the district power system. This advantage will facilitate and encourage the integration of renewable power generation. As it is known, managing heat and electricity demand is a core requirement when dealing with fluctuating energy generation sources, especially when linking renewable energy sources and thermal energy storage [73].

Fuel cells are the next most promising environmentally friendly technology of combined heat and power generation. Fuel cells operating as CHP plants could supply power and heat to smart district heating systems including heat pump advanced technology. The fuel cell offers environmental benefits of low emissions, but at the present, fuel cell technology is still under development [1,60,74].

3.4. Renewable energy sources and thermal energy storage

Heat pumps and thermal energy storage can be integrated in various ways and such a combination can be beneficial for heating and/or cooling applications. The storage can be accomplished by using ground based storage, combined with latent thermal energy storage, or the use of renewable energy sources for various storage modes [75]. Almost all EU Member States prefer the application of low energy building technologies and encourage available on-site and local applications of renewable energy. The technologies used are photo-voltaic (PV), PV with thermal energy recovery, solar thermal, heat pumps, geothermal, passive solar, passive cooling, wind power, biomass, biofuel, micro combined (CHP) and heat recovery [76,77,64,65,78].

Heat pump technology in district heating gives an opportunity of using heat and electricity from waste and a wide variety of renewable energy sources. Renewable energy sources are environmentally friendly and essential to cover the current energy demand but mainly they are highly variable and have an intermittent nature, uncontrollable and to some extent unpredictable characteristics, which cause large fluctuations in their power production. This aspect coupled to the need of flexibility with district heating networks gives emphasis to the necessity of installing short, long or seasonal thermal energy storage systems, which are able to store large quantities of energy [79,80].

Thermal storage technologies in district heating play a very important role for achieving the European targets for renewable energy heat generation and energy efficiency. Thermal energy storage enables a higher proportion of renewables to be utilised and better efficiencies to be achieved by balancing the supply of renewable energy sources and the energy demand for an extended range of energy conversion technologies [27]. Combining heat pumps with seasonal thermal energy storage has many advantages for both large and small applications [81,82]. Thermal energy storage can enlarge the proportion of renewable energy and heat pumps in the energy supply of district heating and cooling [83]. Thermal energy storage allows the use of long term hot or cold storage for seasonal accumulation or short-term storage for periodic excess energy accumulation for supplying district heating and cooling networks in energy deficit periods. More investigations to reduce the thermal energy storage losses, innovative storage materials and plant management strategies are essential to enlarge the role of thermal energy storage applications in heat pump based district heating.

There are many thermal energy storage technologies for district heating. Seasonal storage is more complex and expensive compared to short term storage [82]. In heat pump based district heating systems thermal energy storage has a buffer function too, which allows the integration and management of different continuous and discontinuous heat sources, in order to store excess energy and to cut off or shift peak energy demands [5,22,55]. It is possible to combine two or more seasonal storage systems with heat pumps to achieve the optimum in terms of cost and efficiency. The most cost-effective storage systems are aquifers, or ducts with high heat capacity storage or hot water tanks [81]. Thermal storage improves heat pump flexibility for smart grids in residential heating; at the same time heat pump units offer a huge potential for flexibility on a smart grid [84].

4. Heat pump deployment in European district heating

In order to meet building energy efficiency and heating requirements, national legislation in all EU countries encourages the use of more sustainable heating and cooling options. One of the best candidate technologies is the heat pump with mechanical and thermal heat pump technologies becoming widespread. The heat pump converts the low temperature of the heat source (heat of extraction) to the higher temperature of the heat sink (heat of rejection) by consuming energy, either for mechanical heat pumps (e.g. using electricity) or for thermal heat pumps (e.g. absorption heat pumps) [85]. Heat pump systems are able to use both low grade renewable energy sources in the environment (such as air, water, ground) and waste heat sources in order to reduce the demand for fossil fuels and hence reduce greenhouse gas emissions, to provide a stable, affordable energy supply, to create new employment in Europe and to contribute to a sustainable energy future [85–89]. As the driving energy for mechanical heat pumps, units can use non-renewable electricity (from a power plant, CHP etc.) or renewable electricity (such as PV, hydro, wind power etc.) [22,26,90]. For absorption heat pumps the driving energy can be heat from various sources: heat from burning fossil fuels (coal, gas, oil and derivatives), heat from renewable energy sources (geothermal, solar, biofuel) and waste heat (solid waste, industrial wastes etc.) [85,91].

In the EU, the Renewable Energy Directive has recognised this fact by identifying the ambient energy from air, water and ground as renewable [85,91]. Heat pumps are considered as a renewable energy technology in the EU, where they are expected to account for between 5% and 20% of the EU's renewable energy targets [24,30,92]. The Renewable Energy Directive also states that renewable energy produced by a heat pump has to be calculated from the final energy. This has the positive effect of increasing the impact of the renewable contribution from heat pump units in the EU energy mix. Heat pumps use renewable energy for heating and cooling and to integrate a larger proportion of electricity from renewable sources. The integration of heat pumps into district heating is considered as an implementation of renewable technology, which would enable the EU to achieve its future energy and climate policy targets [30].

Heat pumps have a unique role in the future urban energy system as an integrated design concept with dimensioning and control as a part of a holistic approach towards future smart energy systems. The energy system integration capabilities of heat pumps are obvious, especially for bridging the electric power and heating and cooling sector for an enhanced overall energy efficiency, which increases the network flexibility as an asset in future energy systems [93,94].

Connection of a heat pump into district heating allows for easy integration with automatic systems, so that the heat pump identifies the boundary conditions aiming for optimal system specifications. Heat pumps are a key technology for realising cost effective and flexible energy systems as the future standard for a sustainable built environment. Heat pumps offer a management potential with huge possibilities for interaction with novel technologies. Heat pumps provide a holistic view on their role in the context of smart grids and future urban energy systems [27].

The European heat pump market is one of few relatively mature heat pump markets in the world. The economics and market penetration of heat pumps have significantly improved in the last decades. The use of heat pumps in various applications, including their integration into district heating, is steadily increasing in Europe. Heat pump advantages offer on a national and European scale a wide field of renewable energy applications, which needs to be analysed more deeply. Therefore, a specific policy platform in the field of heat pump integration into district heating systems needs to be applied [30,92].

4.1. Technical characteristics of heat pumps in district heating

The heat pump is an efficient technology based on thermodynamic refrigeration cycles, that achieves high energy efficiency by using low grade heat from air, water, geothermal, waste, etc. Heat pump units can generate three to six units of useful thermal energy for each unit of driving energy consumed, giving the system a coefficient of performance (COP) of 3 to 6. Using heat pump technology within district heating increases the proportion of heat from renewable energy sources and integrates the electricity produced from renewable energy in the generation of a stable and affordable energy supply. In so doing it contributes to a sustainable energy future, by reducing fossil fuel combustion and greenhouse gas emissions [16,17,95–97].

Heat pump technology includes heating, air conditioning, refrigeration; it covers many applications in residential and commercial buildings and industry. The full potential of heat pumps still needs to be quantified. Heat pumps driven by renewable sources are proposed as a step to replace fossil fuel boilers. From Fig. 8 the mechanically driven HP units can be powered by non-renewable electricity (e.g. from power plants) or by renewable electricity (e.g. PV, hydro, wind power etc.) [22,26]. For absorption heat pump units the driving energy can be supplied by various sources: combustion of fossil fuels (coal, gas, oil and derivatives), the use of renewable energy sources (geothermal, solar, biofuel) and waste heat (solid waste, industrial wastes etc.).

Heat pump units can be installed in individual dwellings or as heat production units in district heating networks, they can be placed as a central, local or individual heat source and can be connected to the district heating network in serial or parallel connection modes [48,98–102]. The integration of heat pump technology into district heating considers at least placement, connection mode and operational mode of the heat pump unit. Fig. 8 shows details of the technical characteristics of heat pump technology which can be used in district heating networks. The details include the design framework of heat pump unit technology such as heat sources, driving energy, heat sink, connection and operational mode. The evaluation of the technical design parameters of the heat pump should take into consideration different technical aspects, connection and operational modes.

It is clear that the use of heat pumps is one of the solutions to provide a stable and affordable energy supply, to create employment and contribute to a sustainable energy future [16,17,103]. Heat pumps can play an important role in the necessary conversion of European heating markets. It has been estimated that widespread use of heat pumps for space heating and cooling and domestic hot water in the commercial sector could reduce greenhouse gas emissions by 1.25 billion tonnes by 2050.

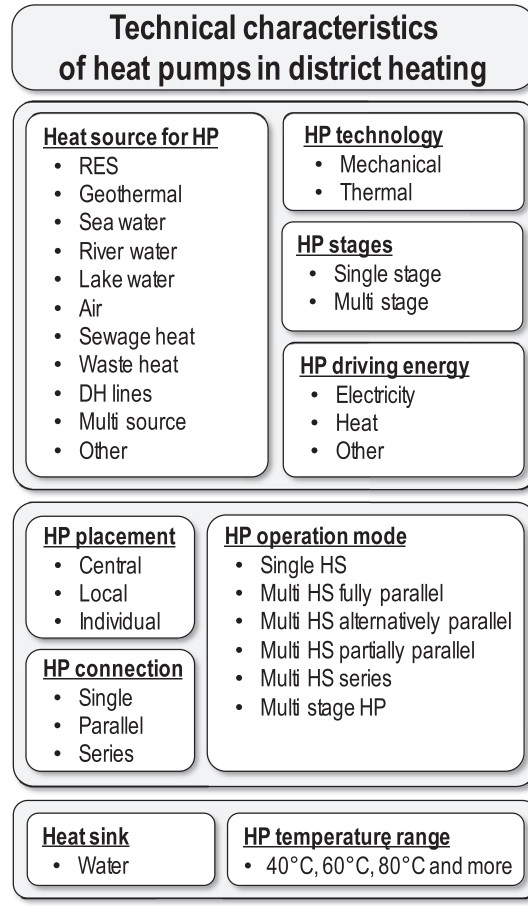

Fig. 8. Technical background of heat pumps in district heating.

4.2. Heat pump deployment phases in European district heating

There has been active deployment of heat pump technology in the EU since 1970 in Austria, Denmark, Germany, etc. The heat pump market has experienced both rates of growth and decline over the last decades [71]. The findings from a literature review suggest that the deployment of heat pump technology in the EU can be divided into two separate phases of growth, which can be summarised as follows [28]:

In the first phase—1970s to 1990s—the technology was mainly used for domestic hot water with small thermal capacity units not exceeding 100 kW, rarely connected to district heating networks and usually deployed in dual systems with supplementary conventional heat sources. Initially the deployment of heat pumps was driven by high oil prices. This was followed by support for heat pumps in the form of tax breaks for those installing new systems. When oil prices fell in the mid 1980s and 1990s, however, the annual deployment of heat pumps decreased from the highs of the early 1980s. Additionally it is also understood that many of the first installations were of poor quality and therefore confidence in the technology was initially relatively low.

In the second phase—2000s to the present day—the deployment of heat pumps began to grow at higher rates. Large capacity bespoke units (1 MW and more) were manufactured and some industrial heat pump designs were suitable for district heating and cooling. The change in growth was due to a number of reasons: financial support, education and training, preferential tariffs for the operation of heat pumps, EU energy efficiency regulations for buildings, RES directive, etc. It is apparent that stability, in respect of legislative, energy and climate policy drivers is a critical factor. More important lessons can be learnt from EU trends and policies for renewable energy sources and energy efficiency to enable EU targets to be met. For all EU countries, underlying and wider market conditions, in particular, changes in the costs of fossil fuels and moves towards a green environment have been observed to have a key impact upon the growth in the deployment of heat pumps in district heating in general [10,27,30].

The use of heat pump applications and the integration of heat pump technology into district heating systems are increasing in EU countries. However, the advantages of such actions on the national priorities for each EU country in the renewable energy field needs to be analysed further. Therefore, a specific policy platform in the field of heat pump integration into district heating systems needed to be applied. However, a holistic evaluation of the environmental performance of heat pump deployment in European district heating systems is advisable during the planning and design stage and a life cycle assessment is needed too in order to assess the potential contribution and environmental sustainability of heat pump deployment. In particular, the contributions of renewable energy sources and thermal energy storage for heating and cooling should be evaluated within an "eco" design approach [66,104–107].

4.3. Future vision of heat pump development potential in EU28 district heating

Heating and cooling consume half of the EU's energy and much of it is wasted [5]. Currently the biggest share of heating and cooling in EU's energy is still generated from fossil fuels, while only 17% was generated from renewable energy in 2016. In order to fulfil the EU's climate and energy goals, the heating and cooling sector must therefore sharply reduce its energy consumption and cut its use of fossil fuels. The European Commission's heating and cooling strategy makes clearly the case that demand reduction and the deployment of renewable energy and other sustainable sources have a great potential to reduce fossil fuel consumption and ensure energy supply security, while ensuring affordable provision of energy for the end consumer [108]. Heat pumps are one of the most common solutions for the future heating sector in Europe and they were mentioned as a one of the smart energy technologies for future smart energy systems [109,110].

The future electricity system, with a high proportion of variable power generation from wind and solar power, will create both new opportunities and conditions for heat pump integration. First, excess power generation can be absorbed in district heating systems through heat pumps and electric boilers, these possibilities have been explored in district heating systems [111,112]. Second, CHP plants need to be more flexible in order to compensate for variable power generation [113,114], so that supply and demand become more flexible [5]. Third, some of the integration between electricity and district heating systems can be managed by heat pumps and large heat storage, since heat storage has much lower installation costs than electricity storage [115,116].

Many projects funded by the energy programmes of the EU deal with low temperature networks or energy systems and they are used both for heating and cooling networks; connection to those networks may be more effective through heat pump technology. Heat pumps will be used to exchange heat with the district heating and cooling networks on the demand side. Drivers for heat pump support policies will include improvements in energy efficiency of district heating and cooling networks, increased effective, smarter and more flexible use of variable renewables and reductions in local air pollution. Transformation to efficient buildings supports the application of renewable energy, especially heat pumps, solar or geothermal heating and waste heat technologies. With the technological development of heat pumps, more advanced applications for low and medium temperature heat (up to 200 °C) will become market feasible. The heat pump advanced technology allows the integration of renewable electricity into district heating, simultaneously offering flexibility to district energy systems by transforming and storing thermal energy [5,111–116].

5. Heat pump integration into district heating

At least four basic scenarios can be distinguished for heat pump integration into district heating networks:

(i) Heat pump placement into the existing network without major changes,
(ii) Heat pump placement in an expanded network,
(iii) Deep refurbishment of the existing district heating,
(iv) The design of a new district heating system supplied by a heat pump.

Each of these scenarios allows operation in various ranges with different technical parameters and design solutions [90].

In the first scenario the placement of the heat pump in the existing network depends mainly on the technical parameters of the network and the available heat sources for the heat pump. There are two critical barriers in existing district heating systems which are: the high temperatures for the district heating and the lack of appropriate heat sources for heat pumps in urbanised areas. The common solution is the placement of the heat pump at the existing central heat source (conventional CHP or heating only boiler) or at a local heat source. The heat pump unit thus placed cooperates with the existing heat source in multi-source mode, in serial or parallel connection, with different shares of the thermal capacity. The advantage of such a placement is to increase district heating efficiency, to increase the use of renewable energy sources and to reduce greenhouse gas emissions. This solution enables the provision of a cleaner and more renewable energy based district heating through the existing network to the already connected consumers without considerable modification from their side.

For the second scenario, where the heat pump is placed in an expanded network, such integration of heat pumps increases the thermal capacity to meet the heating requirements of new consumers.

The third scenario depends on a deep refurbishment of the existing system so that the technical parameters of the network and the profile of the heating requirement can be redesigned in order to maximise the input from the heat pump. These changes involve enormous costs and need a long time for the changes in the district heating components (such as heat sources, the pipeline network, substations and heating installations) and even refurbishment of the consumers' buildings. The refurbishment costs depend on the technical conditions of the existing system, on the scale of changes in the supply and demand side and specially the necessity to add new heat sources for the heat pump.

The last scenario is the design of a new district heating system supplied by heat pump units or so called heat pump based district heating. For such a scenario, all technical parameters and technologies will be prepared for heat supply from a heat pump, including generation, transmission and heat sink. High efficiency and near zero emissions can be achieved for such systems.

The integration of heat pump units into district heating networks needs the connection and the operational mode of the heat pump units to be defined.

The connection mode refers to the pipeline connection of heat pumps and the network, the geographical location and specification of the heat sources, the type of heat pump technology, the required supplementary heat sources to cover peak heating requirements, etc. In other words, it depends on the physical configuration of the required heat sources in the district heating system.

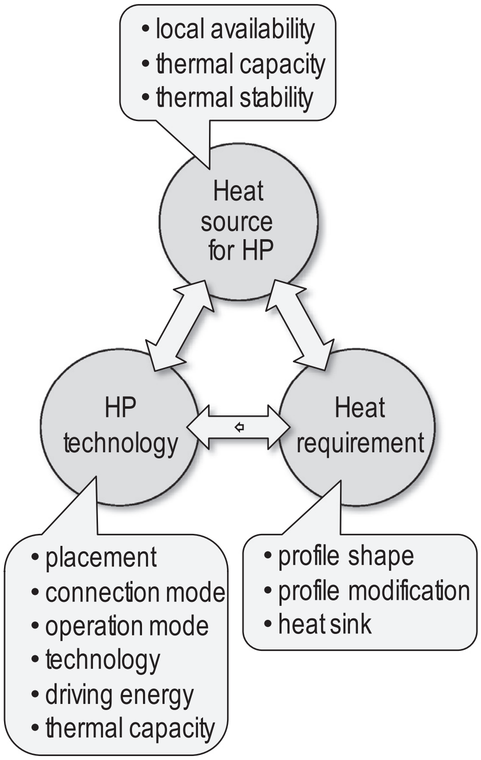

Fig. 9. Technical triangle for heat pump integration into district heating.

The operational mode is associated with the profile for seasonal heating requirement, the seasonal behaviour of the heat sources and their flexibility regarding heat generation. The combination of the connection and operational modes defines the role of the heat pump technology integration in the district heating system.

6. Technical triangle of heat pump based district heating

Attaining the full potential of heat pump technology in district heating applications is a complex engineering task, which requires a multi-criterial technical analysis taking into account both heat generation and heat demand, in addition to national energy policies, legislation and economics in each EU country. The selection of a suitable heat pump arrangement for a given district heating system depends on three main technical features: the heat source for the heat pump, the technology of the heat pump to be applied and the profile of the heating requirement [1,55,68]. The heat sources available for the heat pump (local availability, estimated thermal capacity, thermal stability, etc.), heat pump technology (placement, connection and operational mode, driving energy, thermal capacity, etc.) and the heating requirement of the application (thermal capacity and profile, possible modifications, thermal characteristics of the heat sink, district heating network design parameters, etc.) are key points to be considered in heat pump integration into a district heating system. Fig. 9 illustrates the relationship between all these parameters and a triangle is formed to show their interdependencies. This technical triangle is an efficient instrument for identifying all essential interdependencies for selecting the heat pump technology for renewable energy based district heating [1,55,60].

So far, there is no comprehensive approach for linking the three main parameters of heat sources, heating requirements and heat pump technology, although there are some specific examples for individual solutions for heat pumps in district heating. In EU countries there is not a consistent way for designing a suitable heat pump placement, connection or operational mode in district heating networks. The technical triangle approach is a universal framework giving guidance for designing heat pump based district heating. It is a key approach for avoiding unnecessary investments or new investment strategies and plans for network expansions. It helps to create technical measures for energy choices or to suggest specific thermal measures for reducing expensive peak heating requirements in the buildings which are always beneficial; such a long-term vision is critical to implementing successful urban planning decisions. It is also helpful for involving different building renovation measures and new technological investment choices in the long term in cities or urbanised areas, which are adopting heat pump based district heating and sustainable urban energy strategies.

According to the technical triangle in Fig. 9, the available heat sources for heat pumps have a great influence on the selection of the appropriate heat pump technology, the placement of the heat pump unit, satisfactory fulfilment of the heating requirement, adequate heat pump connection and operational modes, a convenient thermal capacity of the heat pump and the corresponding range of operational temperatures for the system. The profile of the heating requirement determines the required heat pump thermal capacity and the necessity for any supplementary heat source to cover the peak heating requirement. The heat pump technology and operational mode should be designed to ensure high efficiency thermal performance in order to cover the needed heating requirement with the available heat sources. All considerations mentioned, heat sources, heating requirements and heat pump technology have bidirectional based dependencies.

6.1. The characteristics of the technical triangle

The technical triangle allows the definition of the concept and approach of heat pump based district heating. Its framework deals with the placement and connection of heat pump units, the modifications of heating requirements and the multiple heat sources needed to cover the heating requirement over the year. During the heat pump design process it is essential to signify which components of the technical triangle can be adjusted and what are the suitable arrangements for efficient functionality of the district heating. It is important to underline the fact that the components in the technical triangle can be redefined depending on the choice of heat pump technology for the given system. In some cases, it is necessary to modify components of the future system. According to the technical triangle there are many options such as a reduction in heating requirement (e.g. through thermal modernization or refurbishment of the buildings), connection of heat pump units with other heat sources (e.g. conventional energy sources for maximum load, renewable energy sources, etc.) and feeding the heat pump by renewable energy sources (e.g. PV, hydro, wind). The heat source can be enlarged (e.g. additional geothermal boreholes) or diversified (two or more heat sources), etc. The proper choice for some of above mentioned options is a major and complex engineering challenge which requires a special thermal approach and financial investigation.

6.2. Technical triangle framework functionality

Fig. 10 shows four chosen cases to illustrate the use of the technical triangle for analysing different scenarios of heat pump integration into district heating. These scenarios can be discussed as solutions for more relevant and more efficient choices. Fig. 10A illustrates the scenario where the main issue is the limited capacity of the available heat source for the heat pump. Consequently, the heat pump is unable to cover the heating requirement for the network. The solution in this case is to add a supplementary heat

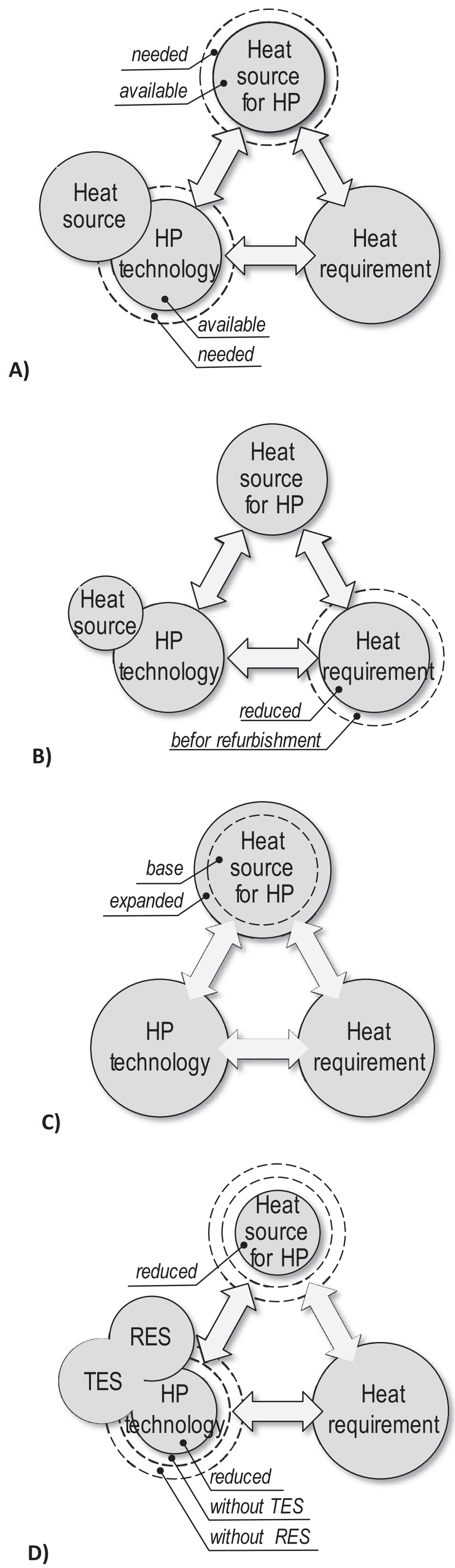

Fig. 10. Technical triangle framework cases.

source to support the heat pump to fulfil peak heating requirements. Fig. 10B shows the next scenario where the heating requirements are decreased by refurbishment and modernization of the buildings, so that the supplementary heat source became smaller or completely unnecessary. Fig. 10C includes an enhanced heat source for the heat pump to cover the heating requirement, by expanding the existing heat sources or adding a new one. Fig. 10D shows the technical triangle for heat pump based district heating, which is supported by thermal renewable energy and thermal energy storage. Using the latter two components, the heating requirement is covered by heat pump units of lower thermal capacity. Thermal energy stored from heat pumps and renewable sources is used during periods when heat production is in deficit.

6.3. Heat requirement profiles in district heating

The first component of the technical triangle analysed is the profile for heating requirement as shown in Fig. 11. This curve presents the annual thermal load and determines the relationship between the required thermal capacity and the contribution from each of the heat sources (e.g. fossil fuels, renewable energy sources, heat pump, etc.). It illustrates the heat requirements needed and possible heat source connection and operational modes. According to the technical triangle it is necessary to acknowledge the heating profile needed and the possible modifications to reduce it [26]. The variation of the heating requirement profile directly determines the thermal capacity needed and the required operating mode of the heat sources.

Fig. 11A shows a heating requirement profile for a residential building supplied by a district heating network. It is assumed that the demand for domestic hot water is approximately stable all over the year, the requirement for space heating occurs only in the heating season and this varies according to the external temperature. The peak requirement for such district heating occurs for a short period at the design condition. For longer periods during the heating season the heating requirement is at an average level. At the end of the heating season the heating requirement decreases rapidly. The end of the heating season depends on the thermal characteristics of the building and the control system [26,27]. In this case the district heating network is supplied by two heat sources in parallel connection and operational mode. The heat pump unit is the major heat source of the district heating network, supported by a fossil fuel as a supplementary heat source. According to the technical triangle, the fractions of the energy provided by the heat pump unit and fossil fuel depend on the heating requirement profile, the unit's technology, the thermal capacities and the availability of the heat source for the heat pump. It should be mentioned that in this case the heat pump can operate with both stable and variable thermal capacities depending on the local heat source and its thermal characteristics.

Fig. 11B shows the reduced and shortened heating requirement profile due to energy-efficient, refurbished or modernised buildings in the district heating network [10,61]. The reduction in the heating requirement allows the heating season to be shortened and the temperature of the district heating to be reduced. It gives a longer period of stable heating requirement and reduces its volatility during the heating season. As with the previous case (Fig. 11A) the district heating network is powered by multiple heat sources connected in a parallel operating mode. The reduced and shortened heating requirement is preferred when heat is supplied from heat pumps; increasing heat pump energy production in district heating systems decreases primary energy consumption and emissions. According to the technical triangle, the stable heating requirement for long periods of the year needs a stable thermal capacity of heat pump units, which requires an appropriate heat source for the heat pump [10,61].

The next case is shown in Fig. 11C, where further reduced and shortened heating requirement profiles are achieved by using more thermal renewable energy sources (e.g. large scale solar thermal plants), in addition to energy-efficient, refurbished or modernised consumer buildings. The summer heating requirement will be both reduced and shortened, when compared with that in Fig. 11B [53].

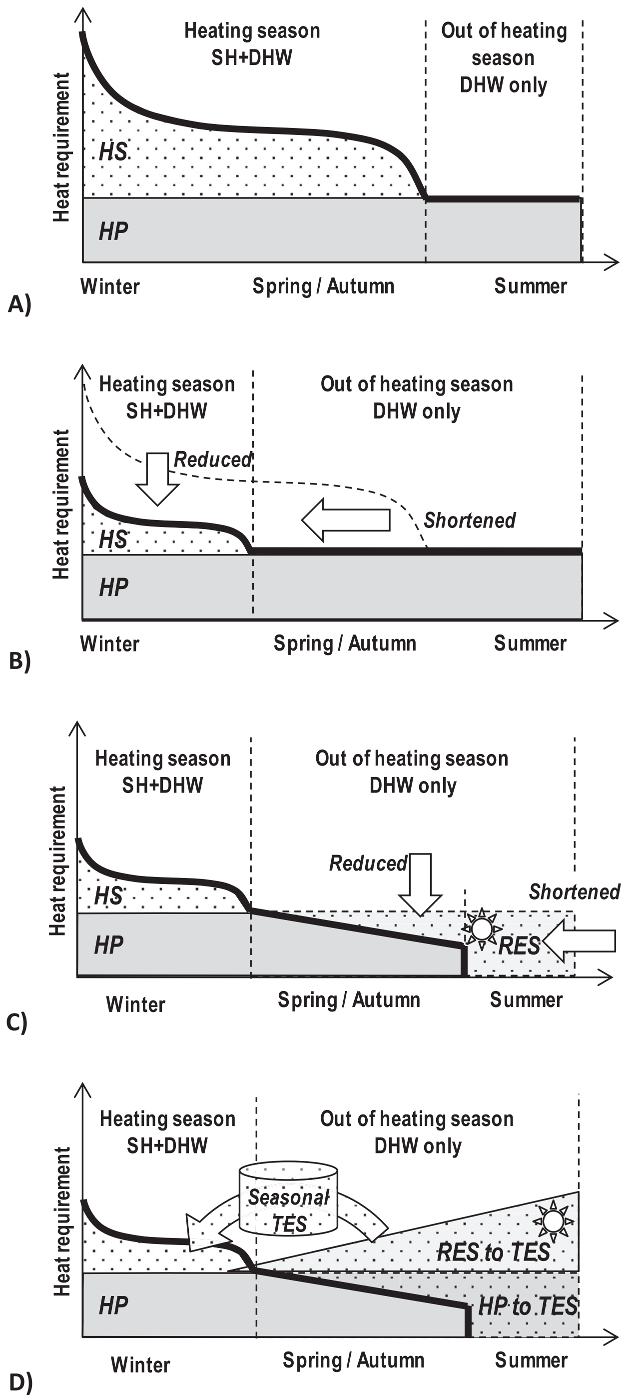

Fig. 11. Examples of heating requirement profiles for heat pump connection and operational modes in district heating
(DHW—domestic hot water, HP—heat pump, HS—heat source, RES—renewable energy source, SH—space heating, TES—thermal energy storage).

In summer, the water supply line temperature is the lowest in the year and this favours the use of solar collectors for supplying the district heating network. Solar based district heating can use large fields of solar collectors or distributed solar collectors on the roofs of buildings and may include solar thermal energy storage too. This solution increases the proportion of renewable energy and reduces greenhouse gas emissions [68]. The heat pump unit in this case operates in a multiple heat source connection mode and in a parallel operational mode with renewable energy sources and a small proportion of fossil fuel based supplementary heat.

Finally, Fig. 11D shows the heating requirement for district heating supplied by a heat pump and thermal renewable sources in parallel, with seasonal thermal energy storage. The heat pump unit in this case operates in a multiple heat source connection mode in a parallel operational mode with thermal renewable energy sources without the use of any fossil fuels. In this case the heat pump and the thermal renewable energy source can charge in parallel the thermal energy storage in summer, in order to use the stored heat during the heating season. Seasonal thermal energy storage allows the heat pump to operate with full thermal capacity over the whole year with a high seasonal performance factor. Based on the technical triangle the participation of thermal energy storage and renewable energy sources should take stable or variable heat pump thermal capacity into account in order to meet the heating requirement needed throughout the year. It is clear that thermal energy storage can deliver substantial benefits in stabilising district heating network operations, but this option is characterised by a high cost, due to the large storage capacity needed and the efficiency required for heat accumulation.

The cases presented illustrate the functionality of the technical triangle approach as an instrument to define the interdependence of various heat sources for heat pump units, the heat pump technologies and the heating requirements in district heating systems. This paper explains the significance of heat pump placement, connection and operational modes. This approach needs to be investigated further in order to improve the performance of district heating networks with different heat pump technologies and placements, as will be illustrated next.

6.4. Heat pump placement in district heating

The heat pump placement strongly depends on the location and availability of its heat source. In district heating networks there are three main placement options as shown in Fig. 12B: a central heat pump, a local heat pump and an individual heat pump. The central heat pump unit has a high thermal capacity and it is a part of a main power plant as shown in Fig. 12B-1. The local heat pump can have a high or medium thermal capacity and it is placed near to a locally available heat source, far from the main power plants (as in Fig. 12B-2). Finally, the individual—or so called distributed—heat pump units have a medium to low thermal capacity, they are installed in the consumers' buildings and are connected directly or indirectly with the district heating network. The direct connection involves pipelines between the heat pump unit and the district heating network, as shown in Fig. 12B-3. With an indirect connection mode, the heat pump units are powered by electricity generated from CHP as shown in Fig. 12B-4. All individual heat pump units are a part of the district energy system with central management of heat and electricity for both supply and demand.

The centrally placed heat pump units have to have a high thermal capacity and so they require a high thermal input from the heat source in order to cover the heating requirement. They can operate with single or multiple heat source connection modes and in single, multi stage, multi parallel or multi series operational modes. In a single heat source mode, the heat pump unit alone supplies heat to the district heating network. In multiple heat source systems the heat pump is the major heat source and the other source or sources (e.g. fossil fuels or renewable energy sources) are used to cover the peak heating requirements.

One or more locally placed heat pumps can be integrated into the district heating network, supplying high or medium, stable or variable thermal capacity. The local placement of heat pumps depends on the locally available heat sources. Locally placed heat pump units operate with multiple heat sources and parallel or se-

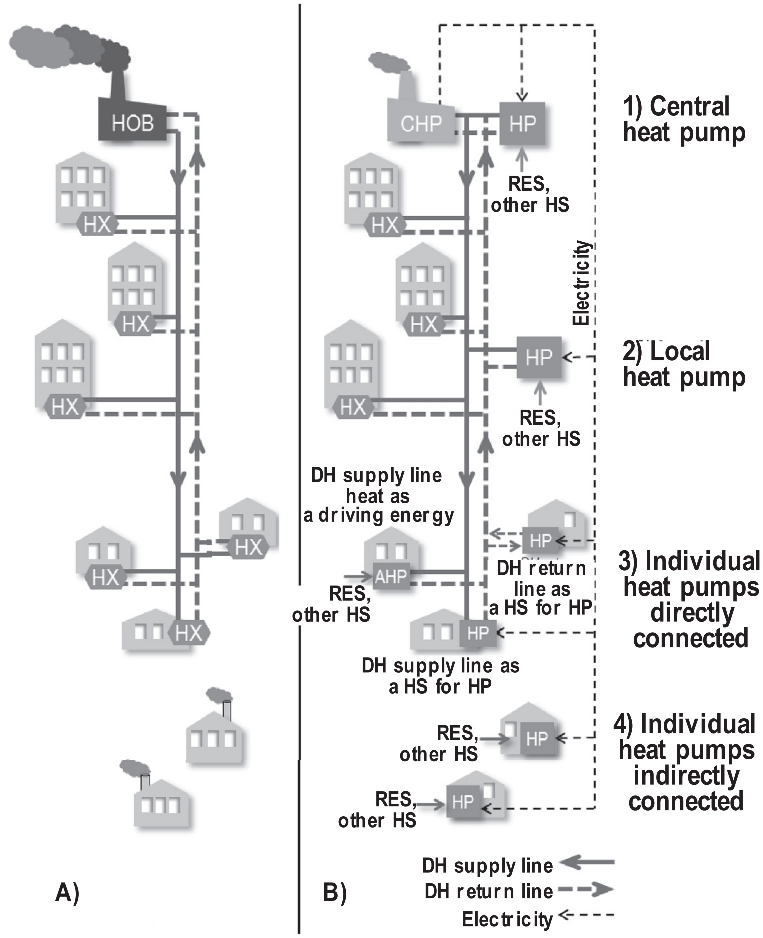

Fig. 12. The schemes for: (A) traditional fossil fuel based DH and (B) heat pump placement options in advanced DH (DH—district heating, HOB—heat only boiler, HX—heat exchanger, HP—heat pump, HS—heat source, RES—renewable energy source).

ries connection modes. The use of locally placed units can increase the district heating network's thermal capacity as they use the various local heat sources to cover the heating requirement. Moreover, they can increase the flexibility of the system by using different technologies, various heat sources and driving energies.

The individually placed heat pumps connected directly to the network supply heat to separate buildings in a single or multiple heat source connection and operational mode. Small scale heat pumps can use local renewable energy sources and district heating supply or return water lines as heat sources as shown in Fig. 12B-3. Absorption heat pump can use the district heating water supply line as a source for driving energy. The use of various individual heat pumps is the next available option (after a locally placed heat pump) to increase the thermal capacity of district heating networks by using small thermal capacity renewable sources.

Individual heat pumps indirectly connected to district heating networks use local renewable energy sources to supply the separate buildings with heat and they are powered by CHP plant electricity. The CHP plant can increase the heat generation to meet rising heating requirement in the district heating network, so that the cogenerated electricity will be consumed by individual heat pump units and can be stored as heat in domestic hot water tanks, space heating installations, etc. Hence a large number of individual heat pump units can increase the CHP efficiency and utilise extra renewable electricity (e.g. wind power).

6.5. Connection and operational modes of heat pumps in district heating

There are two basic aspects of heat pump integration into district heating, its connection mode and its operational mode as explained above. The type of heat source for heat pumps defines the variability of their thermal capacity over the year. The thermal capacity may be stable year-round or they can increase or decrease in winter. Heat sources such as geothermal, industrial waste and deep sea water can ensure stable heat pump thermal capacity for the whole year. Heat sources from air, lakes, river water and shallow sea water decrease heat pump capacity in winter [62,97,98]. When district heating can be used as the heat source for the heat pump units, their thermal capacity increases during the heating season with the operational temperature of the district heating.

Fig. 13 shows the possible combination of operational and connection modes for different heat pump placements in a district heating network. There are two basic connection modes for the heat generation: single heat source and multiple heat source. The single heat source connection mode means one central heat source for supplying the entire heating requirement of the district heating, which can supply heat only in single operational mode. Multiple heat source connection modes mean two or more heat sources for supplying heat in parallel or series. In this connection mode there are two operational modes (single and multiple) with three placement possibilities for the heat pump units (central, local and individual).

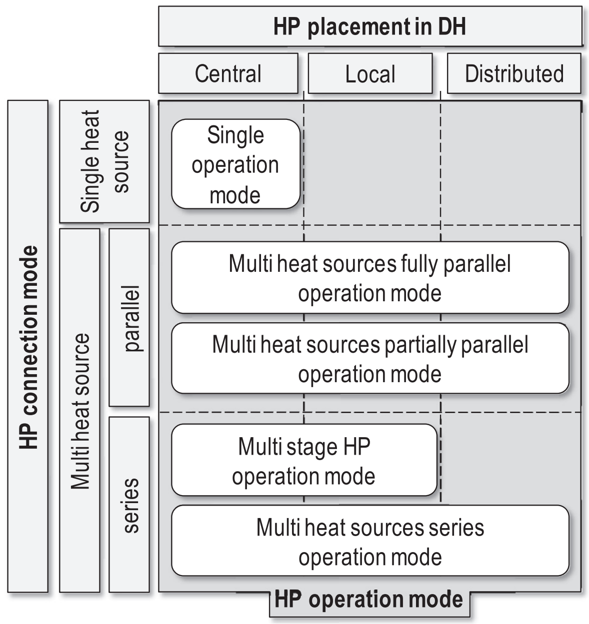

Fig. 13. The possibilities of operational and connection modes due to heat pump placements in district heating.

Multiple heat sources with fully parallel operation mean cooperation of all heat sources for district heating supply for the whole year, and the heat pump can be placed centrally, locally and individually. In the partial parallel operation the heat sources cooperate only for a part of heating season, for the rest of the season a lone heat source supplies the network, normally the heat pump (placed centrally, locally or individually). In multiple heat source series connection there are two operational modes with two or three possibilities for heat pump placements. In multi stage operation each stage of the heat pump units contributes to the supply for the district heating and they are dependent. The heat pump units in multi stage operation can be placed as central or local heat sources. In multiple source series operation two or more heat sources are connected in series to operate together all year round and the heat pump unit can be placed centrally or locally.

7. Case studies of heat pump connection and operation in district heating

Heat pump applications in district heating can be summarised in the layout of heat sources, driving energy and connection modes presented in Fig. 14, which illustrates the general range of technically possible scenarios. There are three main types of heat pump technologies using different driving energies: a mechanical heat pump driven by electricity (from both of the grid and the renewable power); a thermal heat pump (i.e. an absorption heat pump) driven by a high temperature conventional, renewable, waste or multi heat sources; a thermal heat pump driven by high temperature heat from the district heating supply line.

The driving energy needed dictates whether the heat sources are suitable for heat pump units. Electrically driven mechanical heat pumps can use a wide range of heat sources. Thermal heat pumps driven by high temperature renewable energy sources or waste heat can extract heat from another renewable source or the district heating return line. A thermal heat pump using heat from the district heating supply line as the driving energy can use a renewable source as the heat source. The heat sink is the next important component for heat pump integration into district heating: the heat supplied by the heat pump can go to the supply line, the return line or directly to the buildings for space heating and domestic hot water requirements. Every heat sink needs a specified temperature range and thermal capacity. The choice of heat pump technology is strictly connected to the available heat sources, the driving energy needed and the technical characteristics of the heat sink. The operation and connection scenarios presented below show the flexible range of possible solutions for integrating heat pump technology into district heating.

7.1. Heat pump with single heat source

With this arrangement the heat pump is placed centrally as shown in Fig. 15. From the technical triangle the heat pump as a single heat source should have a sufficient and flexible thermal capacity to fulfil completely the heating requirement throughout the year. The challenge here is to ensure that the thermal capacity of heat source is adequate for covering the peak heating requirement. The design condition heating requirement occurs rarely and even for very short periods and so such an operational mode is not cost effective and decreases the use of the installed heat pump thermal capacity.

7.2. Heat pump as single heat source with thermal energy storage

Providing seasonal thermal energy storage to the previous single heat pump based district heating will decrease the thermal capacity of the heat pump needed to less than the maximum heating requirement. Thermal energy storage plays a buffer role for stabilising network operations. Such an operational mode allows the single heat pump to operate at full capacity over the whole year, for cases of both stable and variable capacity (as shown in Fig. 16B and 16C, respectively), according to the heat source characteristics. In the case of stable heat pump thermal capacity there are three scopes in this operational mode. In scope I the heating requirement is supplied by the heat pump and thermal energy storage and the stored energy is being discharged. In scope II the heat pump alone supplies the district heating. In scope III the heat pump supplies the district heating and charges the energy store. In the case of variable heat pump thermal capacity there are only two scopes of operation. In scope I the heating requirement is supplied by the heat pump and thermal energy storage and the thermal energy store is discharging. In scope II the heat pump supplies the district heating and charges the thermal energy store. The second case requires a larger storage capacity due to the variable thermal capacity of the heat pump. According to the technical triangle, using thermal energy storage in heat pump based district heating allows the use of a heat source with a lower thermal capacity, either stable or variable and using seasonal thermal storage expands the range of suitable heat sources. Thermal energy storage increases the seasonal performance factor of the heat pump and increases the thermal capacity of the system to meet excess heating requirements. The design of the thermal capacities for heat pump and thermal energy storage can in such an operational mode fulfil the yearly heating requirement as shown in Fig. 16. It should be mentioned that using a seasonal thermal energy storage tank in the network is favoured but it is a costly option due to the large storage capacity needed; the heat storage efficiency of such an installation should be taken into account too.

7.3. Heat pump with single heat source and multi stage operation

For the best fulfilment of the heating requirement it is possible to use multi stage connection for the heat pump units. In this operational mode, the heat pumps could have similar or different technologies and thermal capacities [117,118]. The heat pump

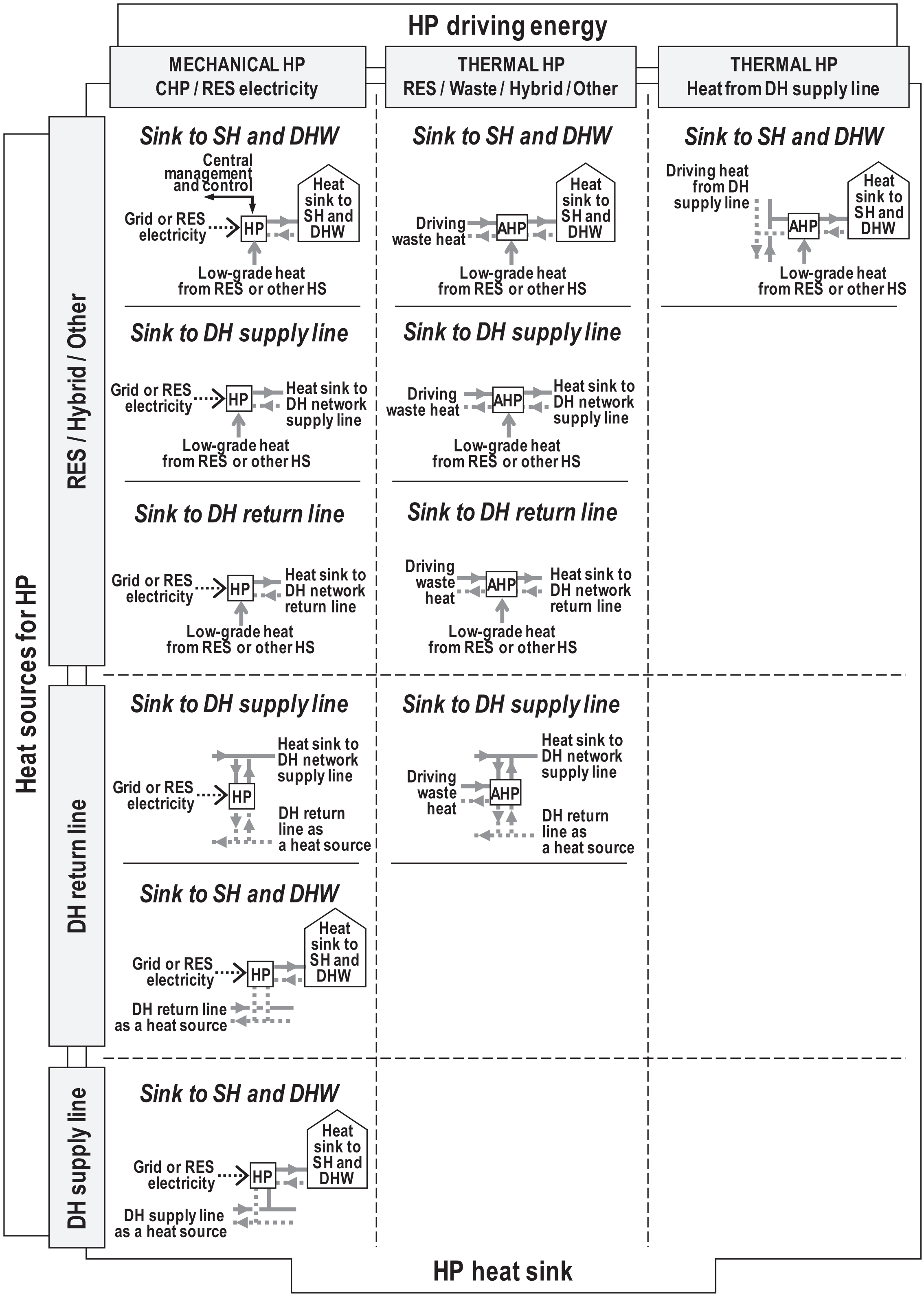

Fig. 14. Layout of heat sources, driving energy and connection modes for heat pump integration into district heating (AHP—absorption HP, DH—district heating, DHW—domestic hot water, HP—heat pump, HS—heat source, RES—renewable heat source, SH—space heating).

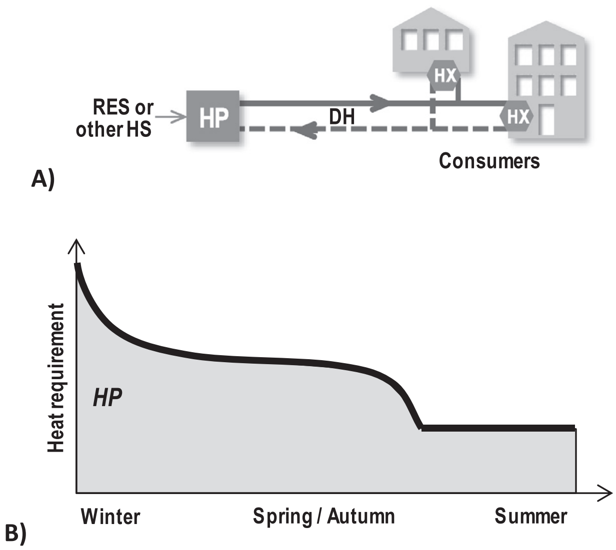

Fig. 15. Heat pump in single heat source option: (A) heat pump placement and connection mode, (B) heat requirements profile and operation mode.
(DH—district heating, HP—heat pump, HS—heat source, HX—heat exchanger, RES—renewable energy source).

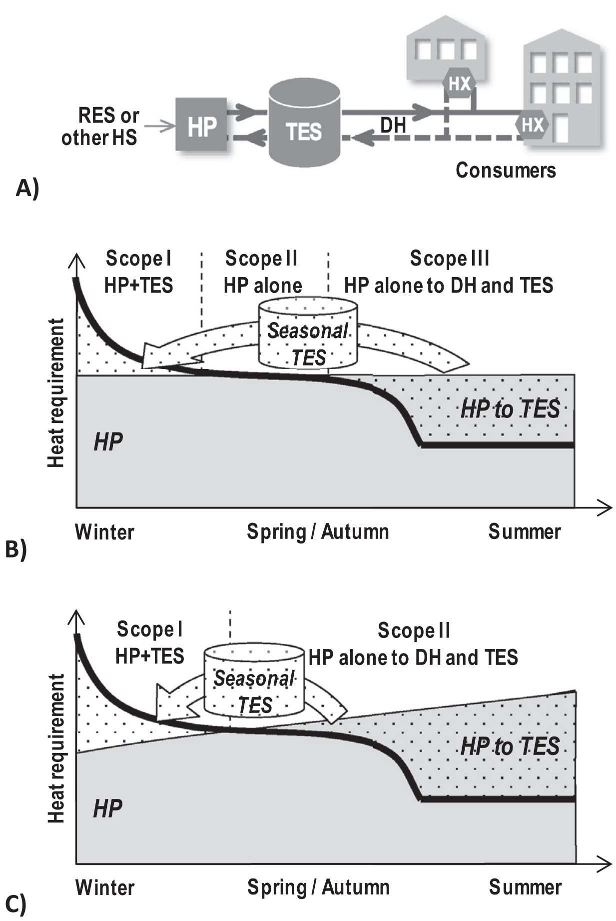

Fig. 16. Heat pump in single heat source option with TES: (A) heat pump placement and connection mode, (B) heat requirement profile and operational mode for stable thermal capacity of heat pump, (C) heat requirement profile and operational mode for variable thermal capacity of heat pump.
(DH—district heating, HP—heat pump, HS—heat source, HX—heat exchanger, RES—renewable energy source, TES—thermal energy storage).

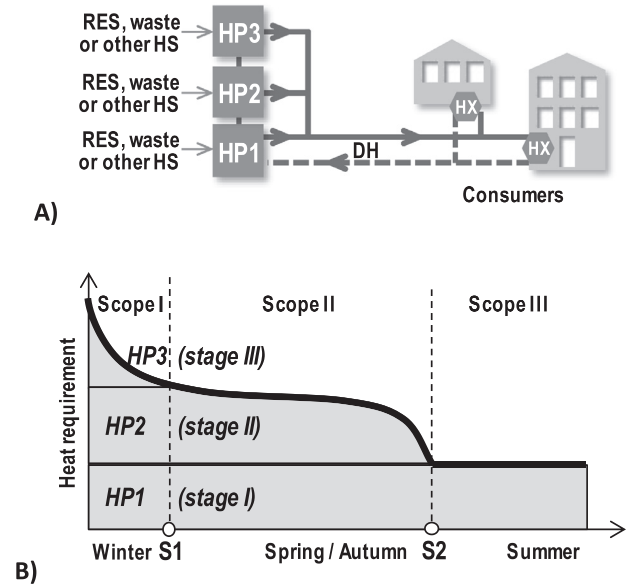

Fig. 17. Heat pump in single heat source with multi stage option: (A) heat pump placement and connection mode, (B) heat requirement profile and operational mode.
(DH—district heating, HP—heat pump, HS—heat source, HX—heat exchanger, RES—renewable energy source).

units contribute sequentially to the district heating supply line water temperature. Fig. 17A shows an example of three stage connection. Each stage is designed to operate only in a defined temperature range which leads to an increase in the seasonal performance factor, but they are not universal for operating in different technical parameters. The operating stages are dependent and cannot be changed. As shown in Fig. 17B, for scope I all three heat pumps stages are operating together (HP1 + HP2 + HP3) to fulfil the heating requirement up to point S1. In scope II the HP3 unit is switched off, leaving units HP2 and HP1 to fulfil the reduced heating requirement up to point S2. In scope III the HP1 unit continues alone to fulfil the reduced heating requirement out of the heating season. The design of multi stage heat pumps can match the heat supply to the profile of heating requirement throughout the year as shown in Fig. 17B. It should be mentioned that with multi stage heat pumps different kinds of heat sources can be used for each stage, but all heat pump units and their heat sources should be placed together. According to the technical triangle the multi stage option enlarges the possible range of heat sources for pumps, but only for those which are available locally. It allows the combination of different heat pump technologies for district heating, depending on the required thermal capacity and network temperatures during the year.

7.4. Heat pumps with multiple heat sources connected in parallel

Multiple heat source district heating means a system which is supplied by two or more conventional or renewable heat sources. These heat sources can be connected in parallel or series and they can work fully or partially in parallel. In the case of the cooperation of heat pumps with fossil fuel heat sources, the heat pump always has priority for supplying heat to the network. In the case of heat pump cooperation with renewable energy sources, the supply priority depends on costs, emissions and technical requirements. With this option the heat pump generally operates as the major heat source with its full thermal capacity for as long as possible. Such an operational mode provides a higher seasonal performance factor, better use of the installed heat pump thermal capacity, which is cost effective and environmentally friendly. In a dis-

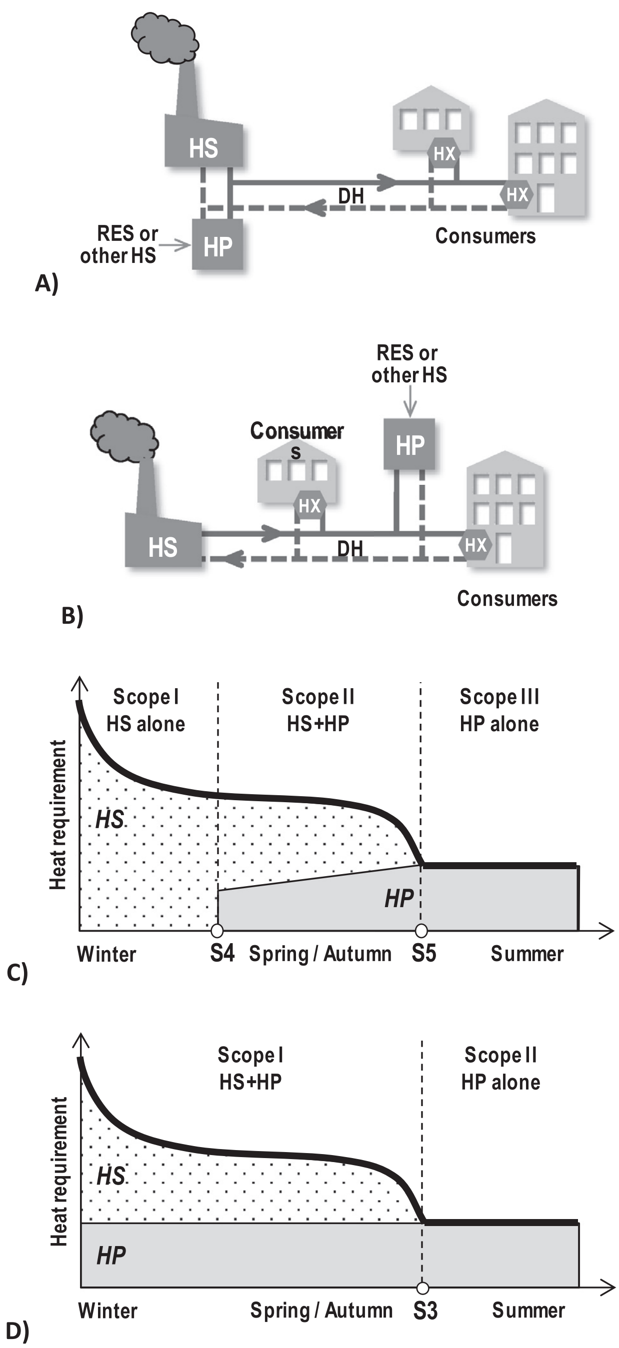

Fig. 18. Heat pump with multiple heat sources connected in parallel: (A) centrally placed heat pump connection, (B) locally placed heat pump connection, (C) heat requirement profile for fully parallel operational mode (stable thermal capacity of heat pump), (D) heat requirement profile with partially parallel operational mode (variable thermal capacity of heat pump).
(DH—district heating, HP—heat pump, HS—heat source, HX—heat exchanger, RES—renewable energy source).

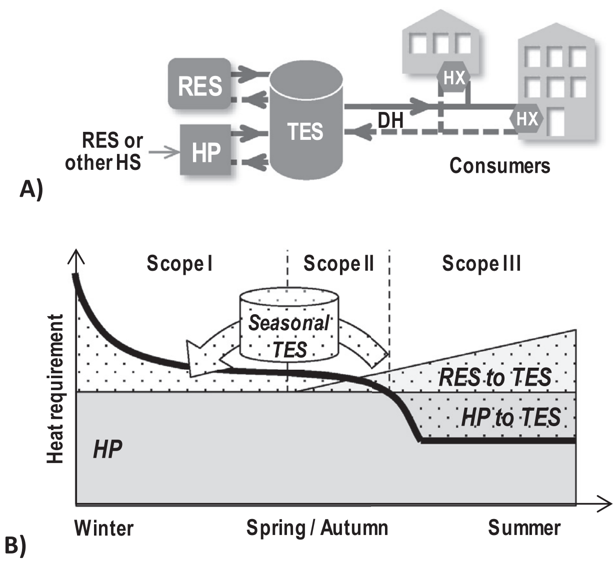

Fig. 19. Heat pump with multiple heat sources connected in parallel with renewable energy sources and thermal energy storage: (A) heat pump placement and connection mode, (B) heat requirement profile and operational mode.
(DH—district heating, HP—heat pump, HS—heat source, HX—heat exchanger, RES—renewable energy source, TES—thermal energy storage).

trict heating system supplied by a heat pump connected in parallel with a conventional heat source there are two possible connection modes: both heat sources are centrally placed as in Fig. 18A, or the heat sources are far from each other e.g. a central conventional heat source cooperating with a local heat pump placed close to a local heat source (such as a river or lake) as in Fig. 18B. In both connections the heat pump can operate with constant or variable thermal capacity. The constant thermal capacity unit can operate in fully parallel operation as shown in Fig. 18C, where in scope I both the heat pump and the conventional heat source supply the district heating up to point S3. In scope II the conventional heat source is switched off and the heat pump alone continues to supply the reduced heating requirement out of the heating season. It is noticeable that the heat pump operates with its full thermal capacity over the whole year. In Fig. 18D the variable capacity heat pump operates in a partially parallel operation mode. In scope I the conventional heat source alone supplies the heating requirement needed in the heating season up to point S4, after which in scope II, where the heat pump operation becomes profitable and effective, the heat pump supplements the heat source to meet the heating requirement up to point S5. In scope III the supplementary heat source is switched off and the heat pump alone continues to fulfil the reduced summer heating requirement. In this mode, the heat pump and conventional heat source should not be placed together; this allows a low grade local heat source to be provided for the heat pump, even if it is located far from the conventional heat source. It is possible to link more than one heat pump unit with different locations, different thermal capacities and heat pump technologies. This helps to increase the thermal capacity supplied by renewable energy and to save the consumption of fossil fuels.

7.5. Heat pump with multiple heat sources connected in parallel, with seasonal thermal energy storage

The unfavourable variability of renewable sources for supplying district heating can be eliminated using multiple heat sources connected in parallel (e.g. a heat pump with solar thermal collectors) using a seasonal thermal energy storage tank. As shown in Fig. 19 the tank stores heat from both sources, from the heat pump and the renewable energy source. It needs mentioning that the heat pump, renewable energy source and storage tank should be located together. There are many possible operational modes and the main modes are described in three scopes: scope I where heat pump and thermal energy storage tank supply the district heating, in scope II the heat pump, thermal energy storage and the renewable energy source all play a role in the district heating, while in scope III the heat pump supplies the district heating and with the renewable

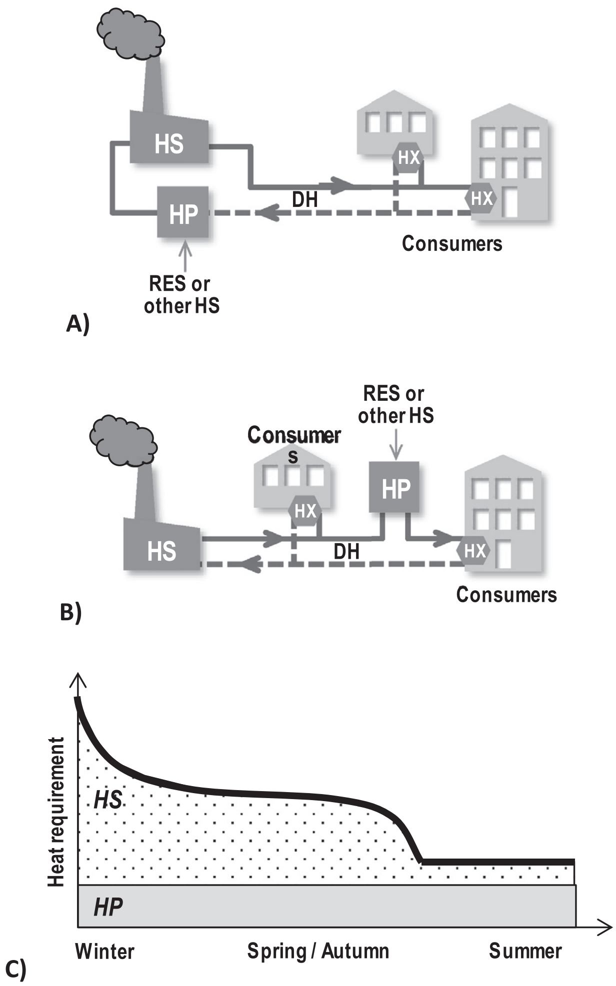

Fig. 20. Heat pump with multiple heat sources connected in series: (A) heat pump central placement in series connection, (B) series connection for central heat source and local heat pump, (C) heat requirement profile and operational mode.
(DH—district heating, HP—heat pump, HS—heat source, HX—heat exchanger, RES—renewable energy source).

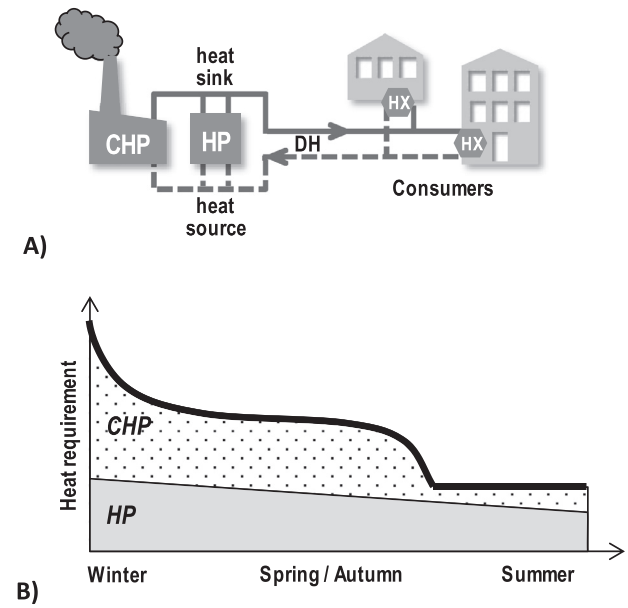

Fig. 21. Heat pump with multiple heat sources connected in series (heat pump in return to supply operational mode):
(A) heat pump placement and connection mode, (B) heat requirement profile and operational mode.
(CHP—combined heat and power, DH—district heating, HP—heat pump, HX—heat exchanger, RES—renewable energy source).

source simultaneously charges the thermal storage energy tank. It is obvious that in scope III the heat pump charges excess heat to storage and this heat accumulation allows the heat pump unit to operate with full thermal capacity over the whole year, ensuring a high seasonal performance factor and effective use of the heat pump's thermal capacity. This connection mode allows renewable energy sources to supply the district heating and a better use of the heat pump's thermal capacity, but using seasonal thermal energy storage is a costly option. The seasonal heat storage efficiency should also be taken into account.

7.6. Heat pumps with multiple heat sources connected in series

In this mode heat pumps and conventional heat sources are connected in series to operate together over the whole year, consecutively increasing the water supply temperature in the district heating. With this option a heat pump can be placed centrally or locally. It is noted that the heat pump operates with its full thermal capacity over the whole year. Fig. 20A shows the unit as a part of a central heat source. The heat pump increases the water temperature of the district heating return line and then the conventional heat source raises the temperature to the level required to meet the heating requirement. It is underlined that such a connection allows the heat pump to co-supply higher temperature district heating than would be possible with the heat pump alone. Fig. 20B shows a central heat source connected in series with a heat pump placed locally, close to a locally available heat source (e.g. river or lake, etc.). In this connection mode, the heat pump increases the water temperature of the district heating supply line which means increasing the overall thermal capacity of the district heating system. It allows new consumers to be linked without increasing the thermal capacity of the central heat source. Such a connection mode allows the installation of more than one heat pump unit in the network at different locations, with different thermal capacities, but such an option will only be convenient for low temperature district heating.

7.7. Heat pump with multiple heat sources connected in series using return line

In this case the heat pump utilises the district heating return line as a heat source and the supply line as a heat sink. The unit is placed with the central heat source and connected in series with CHP plant as shown in Fig. 21. Traditionally in the case of an increased heating requirement in the district heating, the CHP generates the heat needed and excess power simultaneously. The heat pump unit will partly replace the heat generation in the CHP plant to avoid excess power generation or the extra electricity can be consumed as energy to drive the heat pump. It is noted that the heat pump unit powered by its own CHP plant will increase its efficiency and improve the energy management in the district energy system [12,43].

7.8. Individual heat pumps in district heating

Fig. 22 shows five examples of connection modes for integrating individual heat pump units into district heating:

A) individual heat pumps in place of heat exchangers in selected buildings,
B) individual heat pumps using the return line of the district heating as a heat source,

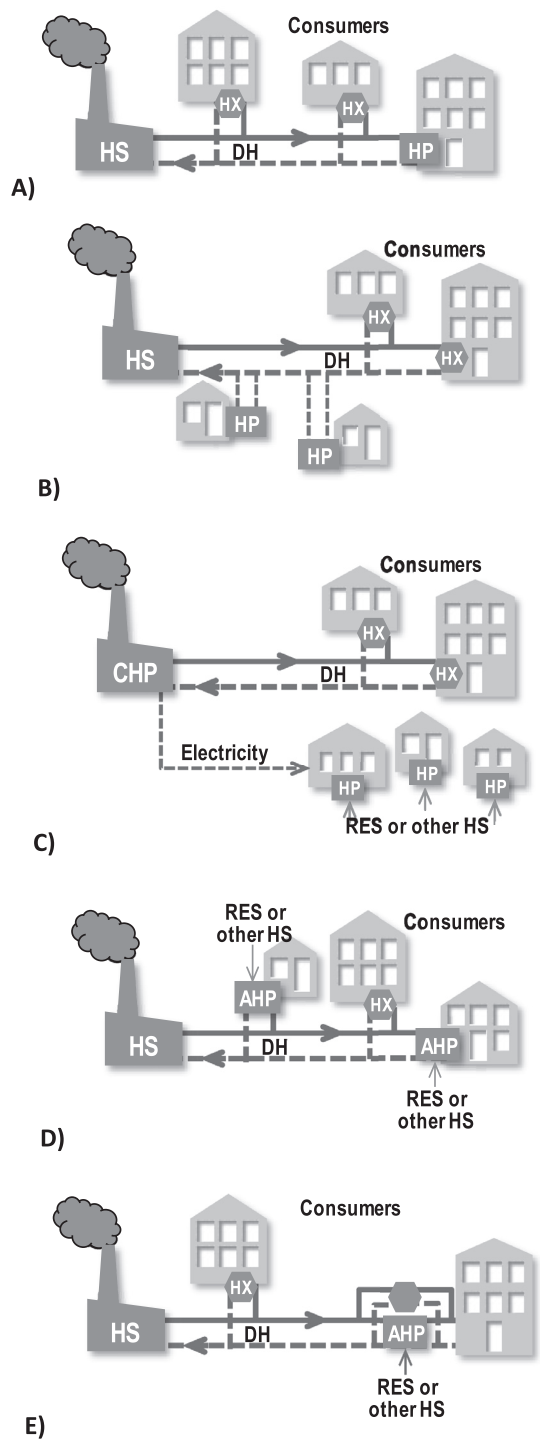

Fig. 22. Placement and connection modes for individual heat pump units: (A) heat pump in place of heat exchanger, (B) heat pumps using the district heating return line as a heat source, (C) heat pumps powered by CHP and not connected to district heating network, (D) absorption heat pumps in place of heat exchangers in buildings, (E) absorption heat pumps connected in parallel with heat exchangers in building.
(AHP—absorption HP, CHP—combined heat and power, DH—district heating, HP—heat pump, HS—heat source, HX—heat exchanger, RES—renewable energy source).

C) individual heat pumps units connected indirectly with the district heating network and powered by a CHP plant,
D) individual absorption heat pumps as single heat sources in buildings,
E) individual absorption heat pumps connected in parallel with heat exchangers in buildings.

As shown in Fig. 22A, using an individual heat pump in place of a heat exchanger in the building allows a decrease in the temperature of whole network and so the network becomes low temperature district heating. The heat pump uses the district heating supply line as a heat source, and supplies domestic hot water and space heating at a higher temperature. Fig. 22B shows individual heat pumps using heat from the return line of the district heating as a heat source and so it decreases the return line temperature. This connection and operational mode improves energy efficiency and the thermal capacity of the system. In Fig. 22C individual heat pumps are not connected to the district heating network, but they are powered by CHP. All heat pump units can be managed centrally and controlled as a part of a smart grid or district energy system. The CHP plant can increase the heat generation because the additional electricity generated can be consumed as driven energy in the individual heat pumps and stored in the form of heat in domestic hot water tanks, space heating, etc. In Fig. 22D individual absorption heat pumps operate in place of heat exchangers in selected buildings and use the heat from the supply line at high temperature as the driving energy, similarly renewable energy sources or other heat sources can be used to feed the absorption heat pumps [119]. As shown in Fig. 22E, the individual absorption heat pumps which are connected in parallel with heat exchangers are used in selected buildings. The heat exchangers will support the heat supply for the heating requirement when the absorption heat pumps generate insufficient thermal capacity or are switched off. Heat exchanger integration can improve the applicability of absorption heat pumps in district heating networks with a higher operational temperature range [120,121].

8. Emissions from heat pump based district heating

Emissions are associated with heat and electricity generation from fossil fuels and they can be reduced by using more efficient generation technologies. In EU countries that generate electricity and heat from different technologies such as nuclear, renewable sources as well as fossil fuels, the emissions from each source must be carefully examined to determine the mass of emissions per unit energy generated [75]. Heat pump integration into district heating systems is one of the most promising technologies for mitigating or reducing emissions from that sector. In EU member countries that generate electricity for heat pumps from various sources, it is necessary to evaluate the emissions from the heat pump technology applied because the environmental impact of heat pump integration depends mainly on its driving energy source.

Fig. 23 shows the three main considerations when determining emissions from heat pump based district heating systems: the driving energy, heat pump technologies and the heat sink characteristics. Heat pumps powered by fossil fuels cause emissions appropriate to the driving energy generation and transmission grid and storage losses. The measure of emissions can be determined from the coefficient of performance and seasonal performance factor of the unit. The heat pump unit can be powered by energy generated in a mix of fuel sources, e.g. partially from conventional fossil fuels and renewable sources [74]. Using renewable energy allows zero or near-zero emissions for the heat pump operation. In multiple heat source systems the emissions depend on both the heat pump driving energy and the technology needed to cover the peak heating requirement, such as fossil fuels, renewable energy or its mix.

According to Fig. 23 the emissions from the heat pump driving energy are provided by generation technology (e.g. fossil fuel based, cogeneration, fuel mix, hybrid, renewable sources etc.). The driving energy can be generated on-site by different technologies or off-site and transmitted by the electricity grid. Energy transmission and storage losses increase the environmental impact of

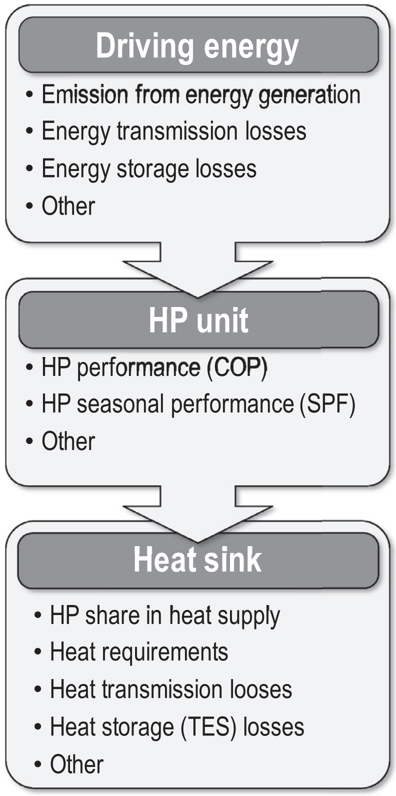

Fig. 23. Emission considerations for heat pump based district heating.

heat pump applications. At the heat sink a large heating requirement has the worst influence on emissions. Heat transmission and thermal storage losses need additional driving energy production which contributes to more emissions. Increasing the contribution from heat pumps with multiple heat sources allows a decrease in emissions due to the high efficiency of heat pumps compared with conventional heat sources. Heat pumps in district heating systems have a great potential for contributing to a significant reduction in emissions [123]. It is clear that reducing the environmental impact of heat pump based district heating is achievable through using low emission heat pump driving energy, increasing the contribution of high-efficiency heat pump technology, by limiting energy and heat losses and by adjusting energy generation and heat sinks [60,122,124].

To illustrate the influence of the above-mentioned considerations on emissions from heat pump based district heating systems, emission calculations were conducted as an example for district heating systems for Poland and Sweden. The calculations conducted considered the power generation technologies and emissions in both countries from the national power grid. The calculations were based on allocations of emission to the electricity and heat according to the fixed-heat-efficiency approach methodology [125–127]. The selection of the two countries among the EU countries was on the basis of the renewable proportion in national power generation. The renewable contribution is a maximum in Sweden and a minimum in Poland. The proportion of electricity generated from renewable energy sources is 57,2% in Sweden and only 15,5% in Poland, the rest of the electricity required comes from fossil fuel based technologies and has similar emission factors for heat generation technologies [128].

Fig. 24 shows the relative emission changes in district heating due to the contribution of electrically driven heat pumps in the heat supply. From Fig. 24A where the SPF = 3.0, for case of Polish

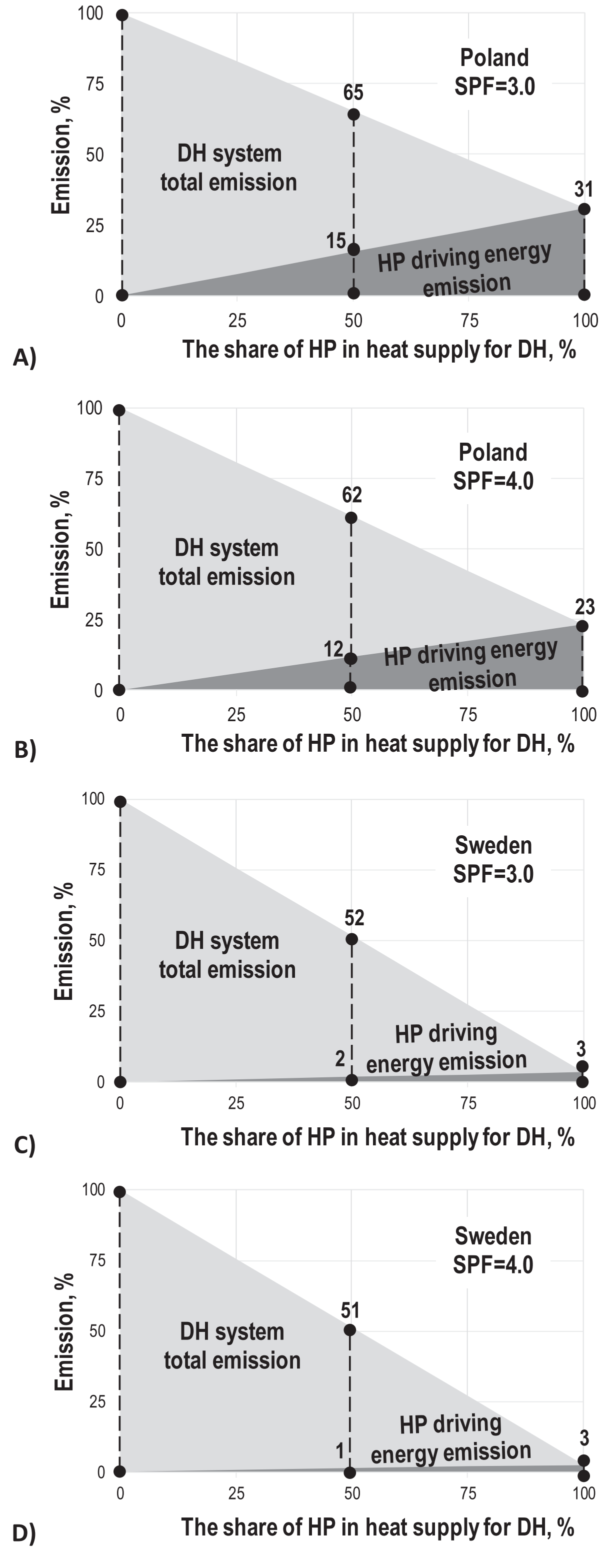

Fig. 24. The relative emission from DH system versus HP share in heat supply for Poland and Sweden.

conditions the total relative emission decreases to 65% with the heat pump contribution of 50%, in which 15% comes from generation of the driving energy consumed by the heat pump. Even a 100% contribution of heat pumps in district heating reduces emissions only to 31%. For Sweden, a 50% contribution from heat pumps will reduce the emissions to 52%, and the contribution of

100% reduces the emissions to 3%, due to the large share of renewables in the Swedish power system. It is clear from Fig. 24B, even if we assume that SPF = 4.0, the emission for Poland will be reduced by only 8% and still 23% of the emission will remain due to fossil fuel based power technology. Meanwhile for Sweden with SPF = 4.0 the emissions will be still 3%. The disproportion of emission between Poland and Sweden indicates the crucial role of the electricity origin needed for the heat pumps as a driving energy. It is advisable to focus on the promotion of the cogeneration power plants' electricity generation, to use renewable based and low-carbon power technologies for heat pump applications.

These results confirm that it is not possible to create a universal heat pump integration into district heating for all EU members. Each EU country should be analysed individually, taking into account all technical and emission considerations mentioned above in the article.

9. Conclusions

Despite the efforts made towards achieving energy efficiency, contemporary district heating in the EU remains extremely dependent upon fossil fuels and their related environmental constraints. Heat pumps are performing well to fulfil nearly all the requirements for a sustainable heat source, but there is still a tremendous potential to use heat pump technology in district heating systems, although this is increasing in EU countries. Heat pump technology is recognised as a renewable resource in most EU legislation, but it will require a heating and cooling strategy that makes heat pumps a cornerstone.

The widespread popularity of district heating networks in Europe is an appropriate platform for integrating environmentally friendly heat pump technology. Furthermore, the contribution of district heating as well as the potential for new expanded networks differs between urban and rural areas. With an effective integration of heat pumps into district heating, the district heating system will become cost effective and ecologically justified.

Heat pump integration into district heating networks brings an increase in efficiency and flexibility, the decarbonisation of the sector and it could help achieve EU sustainability targets. Heat pumps link thermal and electricity sectors, which can play a pivotal role in the energy infrastructure due to the ability to balance heat and electricity demand, thereby providing flexibility in the district power system. This advantage will facilitate and encourage the integration of renewable power generation. Future EU targets for energy and climate focus on small or micro scale district heating and electrification of the heating sector, primarily by using heat pump technology. Low temperature district heating is now a feasible option and a practical application for current district heating networks. It is noticeable that neither of the 2030 and 2050 scenarios involves the large-scale implementation of district heating.

The choice of heat pump technology for integration in district heating networks is complex and multicriterial. There is no consistent way to create heat pump based district heating in EU countries. The approach presented includes the heat pump placement, connection and operational modes and the heat sources available for heat pumps. A large number of possible scenarios and technological solutions from the technical triangle are presented in this paper, which give a very wide spectrum of heat pump based district heating applications and possibilities. The technical triangle is an instrument capable of defining the bidirectional interdependences of heat pump technology, heat sources for heat pump units and the profiles of heat requirement. The technical triangle enables a technology rich, bottom up analysis of the systems with heat pumps, renewable energy sources and thermal energy storage. The functionality and usability of the technical triangle was summarised by typical cases, which are investigated in this article.

Scenarios of heat pump placement, connection and operational modes in district heating and their emissions confirm that it is not possible to create a universal solution for all EU members of heat pump integration into district heating. Each EU country should be analysed individually, taking into account all technical characteristics and emission considerations.

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