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OPERATIONAL FLEXIBILITY OF HEAT PUMPS IN SMART DISTRICT HEATING

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Marderos Ara Sayegh

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PREFACE

The purpose of this book is to investigate the integration potential of heat pumps into district heating (DH) networks and of the measures to remove barriers hindering their widespread implementation, to assess developed technologies and solutions, policies and trends and, to discuss the environmental consequences resulting therefrom especially for future smart thermal networks.

In many countries, both DH and heat pump design and installation are still regarded as areas of specialist expertise and technology of heat pumps is often not considered as a conventional option amongst the design alternatives for various residential buildings' heating and cooling systems. There is a knowledge gap regarding the heat requirements for space heating and domestic hot water preparation amongst professionals that are responsible for the design of heat pump use in DH technology, the flexible operation of heat pumps in DH, etc.

It is evident that the most important factors for smart thermal networks are intelligence, efficiency, flexibility in heat production and consumption, integration with other energy systems, reliability and customer involvement, and the provision of a heat-electricity interface in the thermal networks. Hence, there is "no one size fits all" solution for DH heat pump options for flexible operation, which concerns the district heating-electricity interface.

It is necessary to mention that the DH markets differ between the European countries with regard to the energy-technology mix and fuel distribution and so the presence of certain regulatory framework conditions has greater importance in some countries than in others. However, the flexible technologies in energy markets are still developing, and this provides an indication of possible requirements and prospects in the future market structures, where the potential of heat pumps technologies to provide flexibility to the power system depends on the application and the characteristics of the heat pump system.

This book consists of four chapters. The first chapter addresses general concepts, fundamental principles, and basic aspects of district energy systems

(DESs). DESs represent adequate opportunities to implement efficient polygeneration conversion technologies, and due to their higher efficiencies, polygeneration systems are likely to play a major role, especially in the context of energy efficiency and decreasing CO_2 emissions. This chapter covers the centralised and decentralised polygeneration, multi-energy systems, inputs, and outputs of polygeneration. Hence, prime movers or energy conversion devices are required for power generation in a polygeneration types, polygeneration based DES, conversion technologies and fuels in DES energy systems, the DES elements and specially the future role of efficient DES in energy hub, solar hybrid polygeneration systems, etc. All these systems play an important role in decision support on the size and capacity of future energy systems. In future smart networks, the role of DES is likely to become even more important considering the potential of electrification of other sectors, such as heating, cooling, and transport, and as the future sustainable option, specifically for different energy applications.

Chapter two focuses mainly on district heating infrastructure, technologies, and trends. There is a considerable diversity of DH technologies and their components in the EU countries, their interaction with fossil fuels, renewable energy sources, the energy efficiency of the systems and their impact on the environment and human health. The key conclusion obtained from this chapter is that the DH development requires more flexible energy systems with building automation, more significant contribution in-situ RE sources, more dynamic prosumers' participation and third-party access, smooth integration with mix fuel energy systems as part of smart energy sustainable systems in smart cities. These are the main issues that Europe has to address in order to establish an efficient transition to the 4th generation of DH and toward smart DH systems across European countries.

The third chapter deals with the use of heat pumps in DH. Heat pumps are one of the most promising technologies for enhancing the efficiency of thermal 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 DH networks as the systems ought to be capable of covering residential heat requirements for the all-year-round operation. The main 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 DH. The triangle allows for the definition of the bidirectional interdependences and the design of high efficiency, sustainable heat-pump-based system. This chapter presents various scenarios of how to integrate heat pumps into DH in terms of heat pump placement, connection and operational modes based on available heat sources and heat requirement profiles and their environmental impact.

The major objective of the fourth chapter is to study the special characteristics of thermal requirement profile flexibility in heating networks concerned with the flexibility of technologies in DH based on heat pumps for heat production and consumption, integrated with fluctuating energy from RES, thermal storage, CHP plants, heat pumps in the infrastructure of smart energy systems and how DH networks are adapting to them.

As stated above, smart energy systems have been studied widely so far, but nowadays, a wider perspective is needed to link electricity with heat in a smooth manner. Increased flexibility in supply and demand is required to allow for flexible generation plans with higher shares of distributed renewable energy and variable generation sources. It is essential to note that deployment of flexibility technologies and systems will be important to support decarbonisation of electricity generation. The DH is treated as a practical framework of flexibility, DH carries through a large share of heat supply and storage, and as an intermediary between the heat generation, distribution and demand side, so it has a large potential for providing the flexibility that is far from being exploited today. Power to heat technologies such as electric boilers and heat pumps possess a large potential for supplying flexibility that is largely unexploited.

Heat pumps can be used successfully to provide demand response, regarding the level of flexibility about the different thermal characteristics of the building stocks. On the other hand the heat pumps in DH are linking the thermal and the electrical sectors, and for that, they are seen as part of a flexible coupler to match the thermal and electrical demand in smart systems, where the DH and cooling networks are argued to be important tools for reaching European energy and environmental targets.

The topics mentioned above are covered broadly in the four chapters, supported by obvious illustrations, schemes, and descriptive figures to furnish the reader with the background information and updated knowledge and necessary details for subsequent chapters.

April 2019 *Marderos Ara Sayegh*

ABBREVIATIONS

CCGT – combined cycle gas turbine
CCHP – combined cooling heating and power
DES – district energy system
DC – district cooling
DH – district heating
DSM – demand side management
GHG – greenhouse gas
GWP – global warming potential
HX – heat Exchanger
HOB – heat only boiler
ICT – information communication technology
RES – renewable Energy source
CHP – combined heat and power
DHW – domestic hot water
4GDH – the 4th generation of district heating
EV – electrical vehicles
MES – multi energy system
TES – thermal energy storage
ORC – organic Rankine cycle
PV – photo-voltaic
SF – solar Fraction
TEWI – total equivalent warming impact
VRE – variable Renewable Energy

CHAPTER 1.
DISTRICT ENERGY SYSTEMS

1.1. Background

District energy system (DES) first came into operation in Europe in mid of the 1950s, but only recently their potential has been recognised in the activities of conserving energy and reducing the carbon footprint. Currently, almost all European and North American countries and Japan are leading countries where heating and/or cooling services are provided through centralised district energy networks. A typical DES consists of several energy consumers who are connected to the energy plant through the network. Mainly DES consists of two subsystems or networks, district heating and/or district cooling networks.

DES is a set of interacting or interdependent resources, infrastructures, and individuals organized specifically for the production, delivery or consumption of energy.

DESs are categorized according to different aspects. Some groups can be distinguished due to the heat transport environment or based on the thermal energy transported: heating, cooling, as well as cooling and heating. A further categorization can be based on the type of heat resources: using a separate source of energy for heat or using recycled energy/heat [1]. One of the practical examples of thermal networks is the use of combined heat and power (CHP) as cogenerated heat from generating electricity can then be utilized for heating nearby district buildings.

Traditional DES produces the heating and/or cooling services centrally and distributes them through a network to the various types of consumers, such as residential, commercial, and industrial.

DES and combined heat and power (CHP) plants in general, are complementary technologies. If the thermal energy outputs of a cogeneration plant are needed at a distance from the cogeneration plant (tens of meters to tens of kilometres away), rather than onsite, then DES has a useful addition. DES supplies the consumers with electricity and thermal energy in the form of heating or cooling [2]. DESs are a proven energy solution that has been deployed for many years in a growing number of cities worldwide; they are increasingly identified as potentially beneficial in many applications.

The advantages of DES over conventional heating and cooling systems include improved efficiency, reliability and safety, reduced environmental impact, and provide better economics for many situations.

DES has benefits of easier operation controls of thermal loads and other ecological parameters. Although the number of the applied polygeneration and multi-energy systems and/or DESs is relatively small at present, compared to the potential number of energy systems applications, the role of such systems is growing day by day.

1.2. Polygeneration

There is not a standard definition for the polygeneration term, but it is usually used to identify an energy supply system which delivers several forms of energy utilities to the final consumers simultaneously.

Polygeneration is a possible sustainable energy solution that may use multiple fuels with simultaneous delivery of several utilities. Polygeneration is the process of system integration for delivering multiple utilities from a single unit to obtain an efficient multiutility system. The concept and general approach of polygeneration are illustrated schematically in Fig. 1.1, which presents the multiple outputs or integrated services that DES can provide.

There are several advantages of polygeneration. Properly designed polygeneration enhances energy efficiency and conserves the resource as well as the type of fuel used, reduces the waste and the environmental impact, and increases the economic benefit [2, 3]. The overall efficiency increases significantly if the system design and integration of sub-systems are performed efficiently.

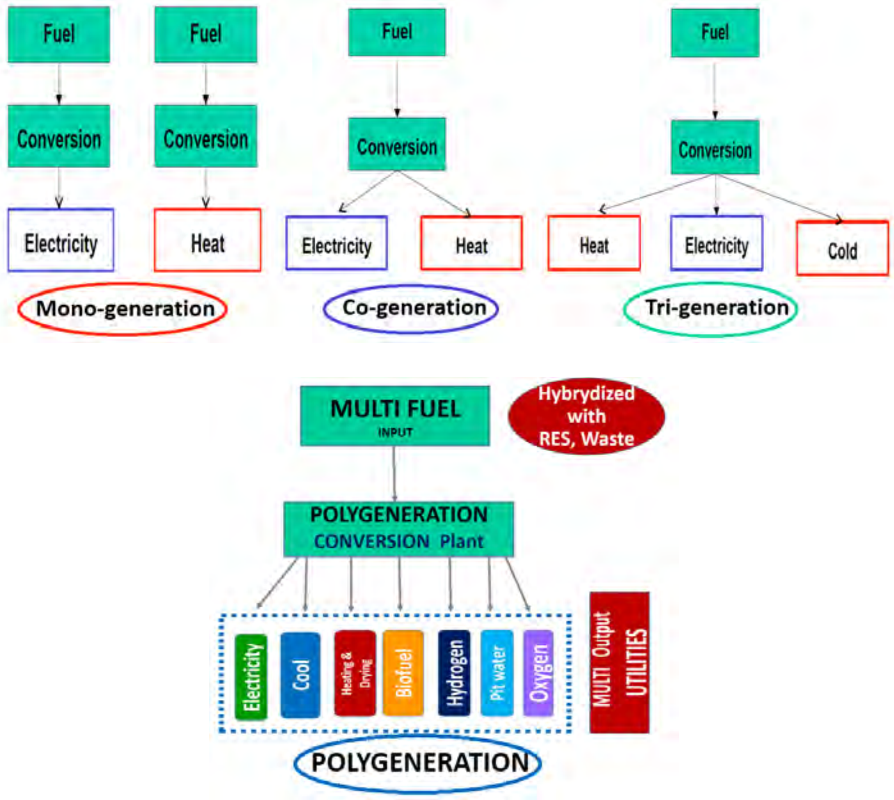

Fig. 1.1. Polygeneration general approach

Moreover, several alternative fuels may be used to improve resource utilization through proper fuel switching or mixing with conventional fuels. Depending on the desired utility outputs and optimum use of the available resources, hybrid systems integrate both renewable and non-renewable resources with an optimum capacity, which may also be efficient and sustainable.

1.2.1. Inputs to polygeneration

Fuel inputs to a polygeneration conversion plant vary widely. For decentralized plant, most of the input energy sources are locally available. However, centralized polygeneration plants are mainly coal-based (biomass-based and biomass hybrid polygeneration), and their capacity is higher than renewable energy based polygeneration. In some cases, inputs of the polygeneration are selected according to the desired outputs (e.g., for liquid fuel production, biomass or coal should be used as input). There may be multiple inputs, too [4, 5]. However, for pre-determined input resources (e.g., for utilization of local resources), outputs are selected according to the configurations of the polygeneration.

In Figure 1.2, different possible inputs are shown, and these inputs may be fossil fuels (coal, oil, natural gas), the renewable energy sources or hybrid and mix of the different sources.

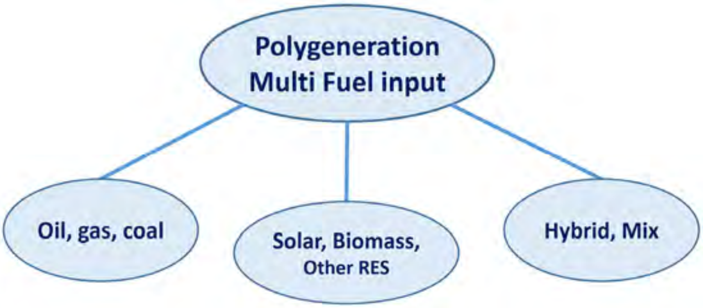

Fig. 1.2. Inputs to polygeneration

1.2.2. Outputs of polygeneration

Polygeneration is designed to deliver multiple utilities. From literature, it is observed that polygeneration can deliver different types of outputs (e.g., energy services, materials, drinking water). Possible types of utilities produced according to the literature are shown in Fig. 1.3. However, these output utilities are selected according to the inputs and utility demands.

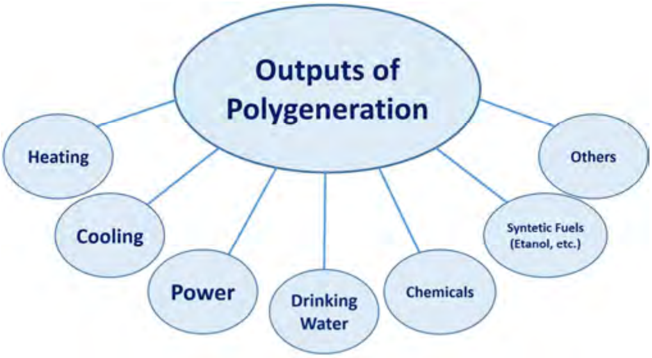

Fig. 1.3. Outputs of polygeneration

1.2.3. Conversion technologies in polygeneration

Power is generally a major output of polygeneration. Hence, prime movers or energy conversion devices are required for power generation in the polygeneration. These devices are selected according to the input fuels, their capacity, economy, availability, market, etc. In Figure 1.4, various types of prime movers of polygeneration are shown.

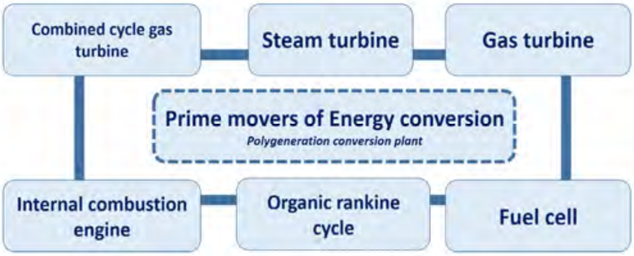

Fig. 1.4. Prime movers of polygeneration

Cost-benefit analyses of polygeneration play an important role in prime mover selection. The gas turbine is used to generate power for gaseous fuels (natural gas or syngas derived through gasification). However, impurities in the syngas should be within the permissible limit. In combined cycle gas turbine (CCGT), gas turbine cycle is used as topping cycle, and steam turbine cycle may be used as bottoming cycle to increase the overall thermodynamic efficiency [2, 3, 5, 6]. Micro-gas turbine is selected as a prime mover for small scale and standalone polygeneration. The steam turbine is useful for direct combustion of solid fuel (coal/biomass combustion). Where available heat is at relatively low temperature (geothermal heat, solar thermal heat), organic Rankine cycle (ORC) is suitable. For ORC, the selection of working fluid is crucial. Supercritical and transcritical CO_2 cycle is another option for low-temperature heat recovery and power generation. In Figure 1.5, schematics of the gas turbine cycle, the Rankine cycle, and CCGT are shown. The fuel cell has the potential to be used for electricity generation if its efficiency is high. Although novel material is required, the fuel cell is highly sensitive to chemical impurities, thus the input of fuels should have a high level of purity.

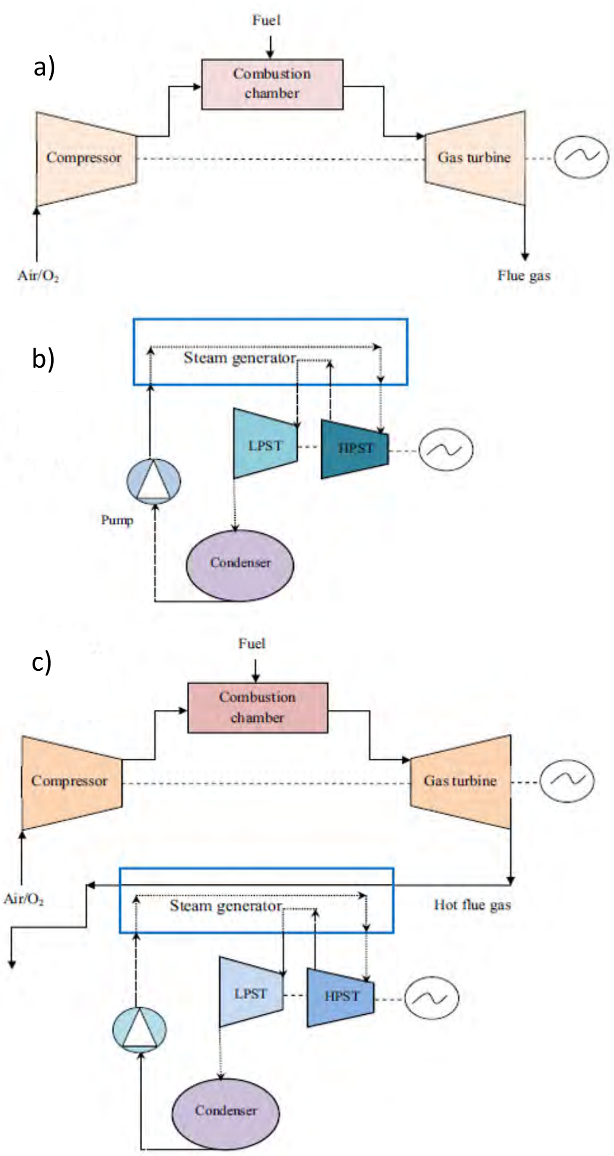

Fig. 1.5. Schematic of: a) gas turbine cycle, b) the Rankine cycle, c) combined cycle gas turbine

In general, the design of polygeneration energy system concerns mainly the energy conversion technologies and distribution networks layout and size. Energy conversion technologies vary according to the type of power plant, size, and location, centralised or decentralised generation of heat, and the fuel source, i.e., conventional fossil fuels, RES or a hybrid fuel. In the case of RES, the essential issue is the feasibility of the local resources inventories like rivers, groundwater, solar, biomass, waste, etc. [5, 7]. On the end users or consumers side, essential are the thermal characteristics of the buildings, the consumers demand and thermal requirement profile, energy services and the building's connection modes to the distribution network [6–8]. The above should be considered in the context of economic analysis and environmental impacts.

1.3. Polygeneration energy systems

Different choices of energy resources can be integrated for the provision of multiple services in the DES or multi-energy systems framework, ranging from classical electricity and heat to hydrogen as well as transport. In particular, the integration possibility of the production with multiple services opens the way to improving the system performance from the energy, techno-economic, and environmental perspectives, for instance owing to the possibility of recovering otherwise wasted heat from CHP to supply local heating or cooling demand (through absorption chillers).

Polygeneration technologies can provide intermittent electricity, balancing both daily and seasonal changes in RES electricity production (from solar and wind) and thermal loads of the boilers, increasing plant availability, peak load duration, and economy [9, 10]. It is evident that without advancements in cross-cutting technologies, decarbonising the heating, cooling, and other energy sectors are likely to be more costly in the future smart networks. They will involve a decentralised energy network with an intelligent central control system integrating data from the energy centre, DES network with intelligent heat meters, heat interface units, customer heating, and cooling systems and external sources to maximize the value of the produced heat and power.

As presented above, the polygeneration energy system refers to multi-energy systems, integrated energy systems, and whole-energy systems [7, 9, 10]. In fact, there are many choices both in how energy is efficiently used and in how it is converted into a usable form, considering that the purpose of any final energy use is eventually to provide a utility, be it a certain temperature in buildings, lighting, cool, power for computers or hydrogen, etc. [4, 7, 11]. In the context of energy systems integration, the question, therefore, arises as to what is the optimal combination of natural resources, technologies, and infrastructure to provide the final multiple end user services and utilities.

1.4. Centralised and decentralised polygeneration

Depending on the scale and capacity of polygeneration, it can be categorised as a centralised or decentralised (i.e., distributed by RES). Figure 1.6 shows the general, main types of polygeneration plants. The types can be classified depending on the energy source~~s~~ location, their potential, and their energy density [12]. As shown in Fig. 1.6, centralised plants require energy sources with high energy density. Generally, centralised plants are fossil fuel based plants because of their high energy density.

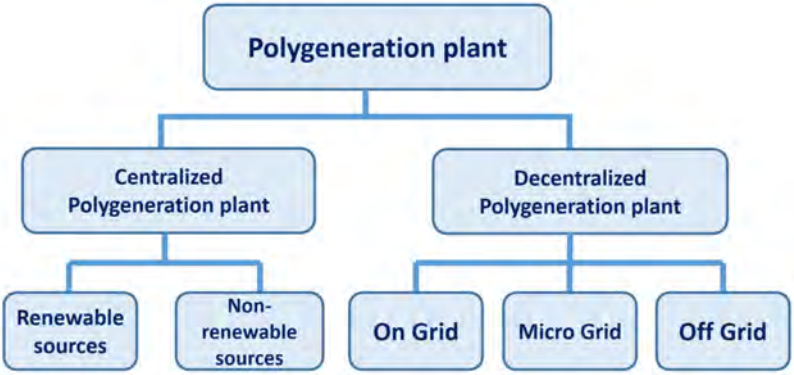

Fig. 1.6. Type of polygeneration plants

Renewable energy based polygeneration may be centralised or decentralised. When the energy resources are available in a scattered way, and there is lower energy density, the distributed generation is preferred. The distributed plants may be on-grid (i.e., connected with national power grid), or it may be the micro-grid system for small villages or towns or the off-grid system for single houses or communities. For the distributed polygeneration plants, supply and demand should be matched, accordingly. It means, in this case, that utilities should be consumed locally because their long-route transmission and transportation is not economically feasible [6, 8, 11, 12]. Hence, the socio-economic conditions of the energy sources locality play an important role in designing an efficient distributed polygeneration. However, energy capacity and investment scale are higher in case of centralized plants than distributed plants [13]. For the centralized plants, utilities can be transported or transmitted over long distances, even across the international boundaries. Other factors like population density, land requirement, socio-economic condition, etc., play an important role regarding decision support on the size and capacity of a polygeneration plant.

1.5. Polygeneration based DES

DES is a system comprising one or more integrated polygeneration energy conversion units connected with the required distribution network(s), fulfilling the task of providing energy services (heating, hot water, cooling and/or electricity) for a group of buildings.

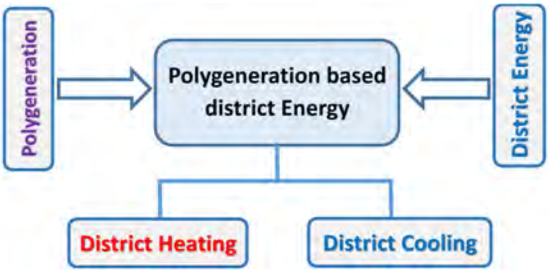

Fig. 1.7. Integration of cogeneration and district energy

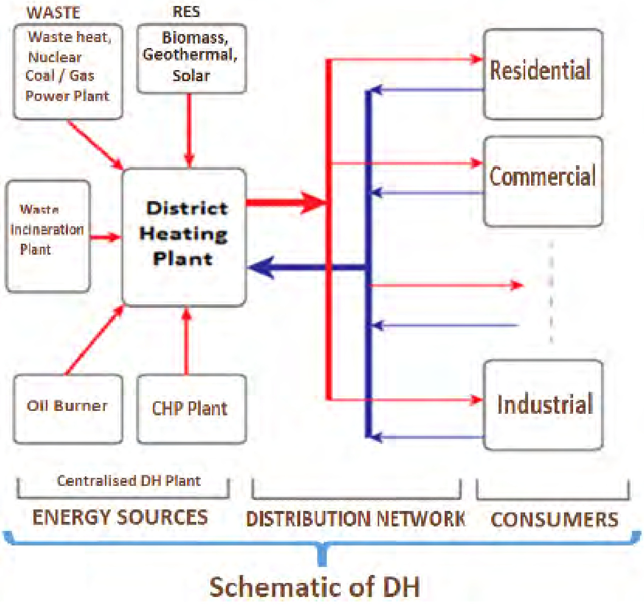

Fig. 1.8. General schematic of district heating in case of centralized DHC plant

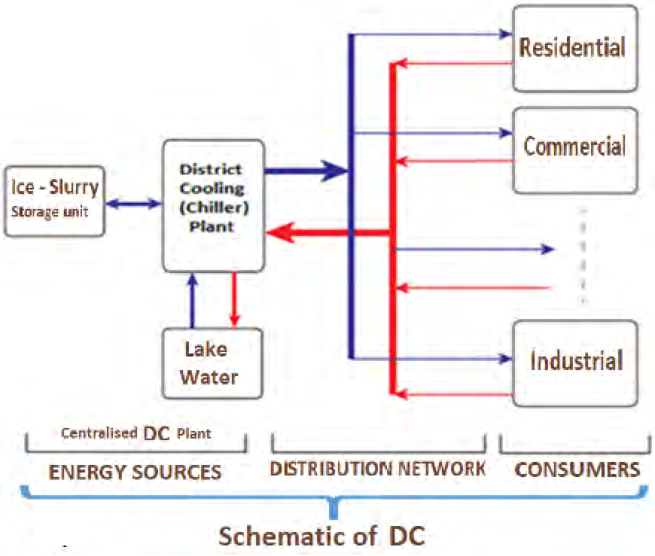

Fig. 1.9. General schematic of district cooling networks in case of centralized DHC plant

DESs can be particularly beneficial when they are integrated with polygeneration plants for electricity, heat, and cool [6, 12–14]. A simple approach of pairing DES technologies is illustrated in Fig. 1.7 as a conceptual illustration of polygeneration technologies integration with district energy. They are complementary technologies to form polygeneration-based DES when the thermal energy outputs of polygeneration are needed at a distance from the polygeneration site [4, 7, 14].

DESs are categorized based on different aspects. A general DES consists of three main subsystems, which are energy sources, transmission and distribution networks, and the consumers or end users [15]. Figures 1.8 and 1.9 show in detail the subsystems of a general schematic for DH and DC networks in case of centralized DH/DC plants.

1.6. DH and polygeneration

DH which is produced by the polygeneration plant is costly if compared to the DH recent prices. Furthermore, it can be noticed that the advantage of polygeneration is the greatest when electricity prices are volatile, and the DH price is high. The district heating prices are particularly important for the polygeneration system. The prices significantly increase when the district heating is operating in electricity mode [16–20]. However, the techno-economic analysis revealed that the district heating product might be important for the economic feasibility of the polygeneration plant. This system may offer solutions for a smart energy system integrating electrofuel, heat, and power production, toward a 100% renewable system.

The polygeneration system achieves positive net present value when bio-synthetic natural gas (SNG) prices are high except when operating at high electricity prices. The polygeneration system achieves a higher net present value (NPV) than single-mode systems, particularly when electricity prices are volatile, and the DH price is high [20].

1.7. Conversion technologies and fuels in DES

DES essentially comprises two parts: the energy sources with the plant of polygeneration energy conversion technologies, and the distribution networks (heating and cooling) [18]. When designing the energy system for a district thermal requirements, it is necessary, therefore, to define which type of polygeneration conversion technologies are best suited for the district. Further, the buildings connection manner to the system should be determined (for instance, if they are located too far away from other buildings or the scale of their thermal requirements to shape the connection from the plant). Moreover, the operation strategy needs to be defined too.

DES represents adequate opportunities to implement efficient polygeneration conversion technologies, and due to their higher efficiencies polygeneration systems, they are likely to play a major role, especially in the context of decreasing CO_2 emissions. Advanced DESs meet the heating, hot water, cooling, and electricity requirements of the district buildings [4, 6, 14–20].

Polygeneration systems feature better overall efficiencies when they are converting primary or distributed energies to the final requested energy services than if the same energy services are provided by a series of single, individual or centralized, energy conversion technologies. One of the main general considerations of polygeneration or multi-energy systems is the scale and dimension issue of such systems. DES can integrate a variety of conventional fuels, RES, and TES to take advantage of commercial or market conditions and use local energy resources as it is shown in Fig. 1.9.

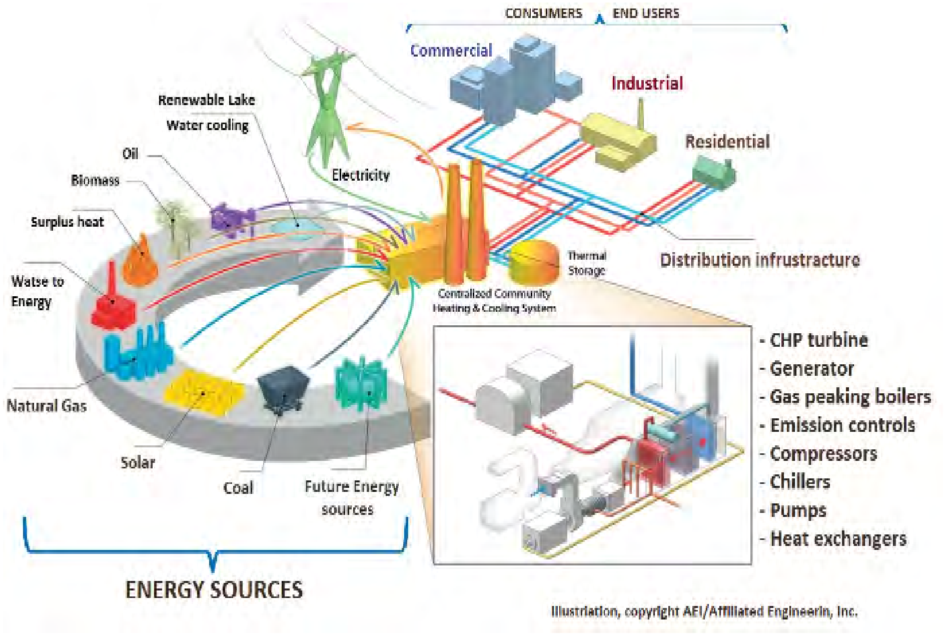

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Fig. 1.9. The infrastructure of fuels and energy sources in DES

TES is interpreted as a bridge to close the gap between the energy demand and energy supply to the DES. TES can be integrated with the DES through the different scales and forms of sensible and latent heat storage.

1.8. Implementation of polygeneration based DES

However, to ensure the possible operation of polygeneration systems at or near their optimal demand load, they should be implemented to meet or fulfill the energy requirements of the district buildings.

By doing so, it is possible to take flexibility advantage of the various demand load profiles of the buildings by balancing the requirements [4, 7, 16–20]. Besides, since these polygeneration systems are complex and de facto difficult to operate, they are usually not justified in an individual building where no continuous professional control can be guaranteed [12, 17, 21]. It is much more advantageous to implement them in a small plant that serves few or several buildings or in an energy managed district (for instance, by an energy service company). However, defining the number of buildings that shall have their energy services provided by polygeneration as energy conversion technology unit is not a trivial task [14, 22–25]. For example, implementing polygeneration energy systems for a whole country, results in too large heat losses and pressure drops, not to mention the security issue of supply in case of failure. Polygeneration energy systems are therefore appropriate for particular districts or small cities, where they can help wipe out the disadvantages of both individual and centralised energy conversion technologies, besides contributing to decreasing the CO_2 emissions.

DES implementation in urban networks offers significant benefits, including an affordable energy provision system and an increased share of RES and TES in the energy mix. Especially the combination of DES and CHP systems enhances the economic benefits of the CHP technology, and the environmental impact since CHP systems provide the ability to recycle waste heat.

1.9. Elements and future role of efficient DES

Polygeneration energy conversion technologies provide different energy services simultaneously, helping to decrease the CO_2 intensity compared to energy conversion technologies that render only one energy service [4, 13, 16, 18–23]. Figure 1.11 shows some of the main elements of the advanced DES, which contains future extended aspects. Moreover, when providing energy to a whole district, polygeneration energy conversion technologies can take advantage of the various requirements or load profiles of the buildings by compensating the fluctuations and having, therefore, a smoother operation.

It is necessary to remember that districts are considered an optimal scale for combining efficient energy activities with promising energy strategies implementation, for example with the advanced district energy systems, and efficient utilisation of the local combined RES and TES possibilities, etc. [7, 14, 15].

Polygeneration energy conversion technologies shall indeed play a major role in the future to mitigate CO_2 emissions linked with the expectations of the different energy services. No other tool beside polygeneration systems addresses the following questions: which type and size of energy conversion technologies shall be implemented in the district, where exactly should these technologies be implemented, how should the distribution network look like, which operating strategy is to be followed, etc.

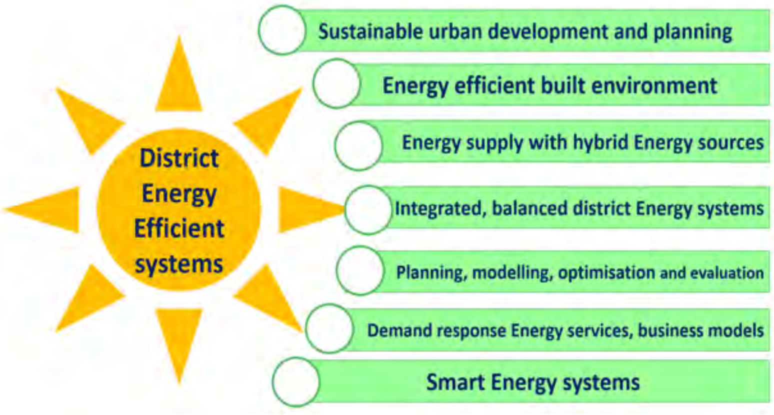


Fig. 1.11. Main elements of efficient DESs [18]

1.10. Multi-energy systems

MES concept is capable of assessing interactions between different energy sectors the multi-energy systems are concerned with, to bring out the benefits and potential unforeseen or undesired drawbacks arising from energy systems integration.

This integration increases requirements for flexibility, smart technologies emerging in the market (from batteries and EVs to smart appliances and pervasive ICT infrastructure), concerns about power system resilience to extreme events, possibly driven by climate change. It can be argued that MES integration provides a useful approach to deal with these power system challenges.

MES concept is gaining increasing momentum to identify how energy systems that have been traditionally operated, planned and regulated in an individual manner can be brought together or integrated to improve their collective technical, economic, and environmental performance [24]. It is known that the power systems are large, complex, and dynamic systems for which intuition alone cannot provide confident predictions of responses to the disturbances. The conceptual vision of a modern power system integration with other energy systems (RES, conventional), sectors, and markets for high, medium, and low voltage power transmission to satisfy the consumer demand is shown in Fig. 1.12.

Converting energy from one form to another requires the possibility of storing it more easily, for example by employing power-to-gas or power-to-heat or, in general, power to X devices so that a surplus of RES production does not have to be curtailed. Furthermore, couplings between the energy networks, that allow for increased deployment of CHP units improving overall efficiency by utilizing waste heat, to serve the load and decarbonisation of the whole DES (not only electricity), can be successfully and most effectively achieved.

It is evident that the need for decarbonisation of the whole energy system is one of the key drivers for energy systems integration. While electrical energy already plays a key role today, this role is likely to become even more important in the future considering potential electrification of other sectors, such as heating, cooling and transport [12, 16, 22, 24, 25]. However, when looking at the whole MES challenge, several options can be identified in terms of energy systems integration rather than electrification, especially in the light of GHG emission reduction. Lastly, renewable electricity-fed heat pumps have the potential to replace other more inefficient types of heating devices, so that emphasizing the link between the power grid and the thermal requirements that can lead to improved efficiency in terms of CO_2 emissions. The literature review demonstrates that the research and engineering projects about MES and integrated demand response have been widely investigated in the past decades. Most of the existing studies are focused on the optimal operation of MES, considering demand response [26, 27].

In Europe, many countries are promoting the integration of multi-energy systems in the demand side. The core concept of multi-energy systems brings new insights about demand response. With the expansion of multi-energy systems towards the demand side, the barriers between electricity and other forms of energy will break down, thereby achieving the deep integration of multiple energy and information streams in the demand side. From the power system perspective, the energy users reduce electricity demand in peak periods [26–28].

Finally, challenges, opportunities, and recommendations are summarised in literature for the engagement of modelers in developing a new range of analytical capabilities that are needed to deal with the complexity of MES [5–7, 16–20] as shown in Fig. 1.12. However, more key issues and potential research subjects remain to be addressed [27].

Therefore, this should also be taken into account that the key underlying challenge in MES is its inter-disciplinary dimension (ranging from power system operation and thermal networks to economics, energy externality, etc.). Consequently, this should be reflected in the development of a new platform of, possibly open-source and data-transparent, flexible tools rather than a “big tool”, for which standards of interactions and compatibility as well as "big data" management become critical too [5, 6].

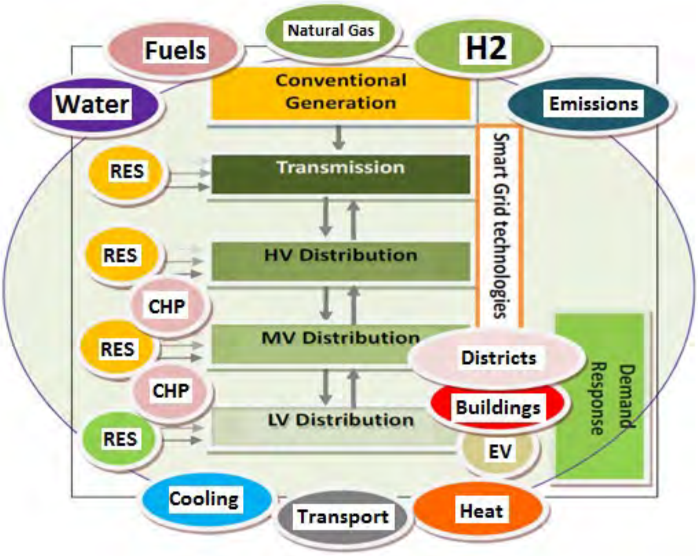


Fig. 1.12. A conceptual vision of power system integration with other energy systems

1.11. Energy HUB

The close concept to MES, which integrated clusters of RES, power systems and energy demand, is the energy hub as illustrated in Fig. 1.13. Energy hub is a node in an overall urban energy system with multiple input and output energy vectors and typically consists of a more elaborate and complex internal arrangement of components. The benefits of this close integration include increased reliability, load flexibility, and efficiency gains through synergistic effects, which suits well in building cluster. Energy hub serves as a practical way to offer more services by sharing and interconnecting household devices in order to reduce the carbon impact of new energy systems. Thus, energy hub is not a single entity containing all necessary systems for transformation, conversion, and storing of energy, but an amalgam of individual energy consumers and producers distributed over an area. This allows taking into account variable loads, systems, and energy sources of multiple buildings in diverse alternative paths [28].

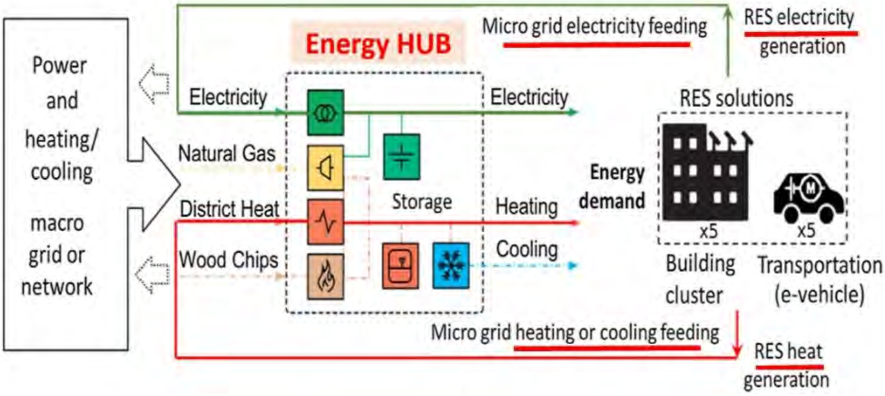


Fig. 1.13. Energy hub concept at building cluster level [28]

By integrating electricity, thermal energy, natural gas, and other forms of energy, the smart energy hub makes it possible for energy users to switch the source of consumed energy flexibly. The integration of electricity, thermal energy, natural gas and other forms of energy enables all the energy users to convert various forms of energy to electricity in peak periods, instead of purchasing electricity from the power system.

The energy landscape is experiencing accelerated changes, centralised energy systems are being decarbonised and transitioned towards distributed energy systems. The transition is facilitated by advances in power system management and information and communication technologies. This includes modern concepts such as smart grid, microgrid, virtual power plant and multi-energy system, and the relationships between them, as well as the trends towards distributed intelligence and interoperability [28, 29].

1.12. Solar hybrid polygeneration system

Polygeneration is a process to build a new energy system through efficient process integration. The integration process increases the efficiency of the system. The better integration process will result in a better output of the polygeneration system.

With the increasing energy demand and the threat of climate change due to existing fossil fuel-based energy systems, development of an efficient renewable energy system is a present imperative need and significantly contributes to achieving the goals of EU’s energy policy in perspective of 2050 [1, 2, 21–30]. With the abundant availability of solar radiation, solar energy systems are considered effective regarding various energy needs in a sustainable way.

However, non-availability at night and unpredictability of availability of solar power over the year demands hybridisation of solar energy systems. The emerging new solar systems should provide a reliable continuous power supply.

Solar energy can be hybridised with some other RESs to get an uninterrupted power supply [7, 17]. The possible hybridisation options for solar energy utilization shows Fig. 1.14.

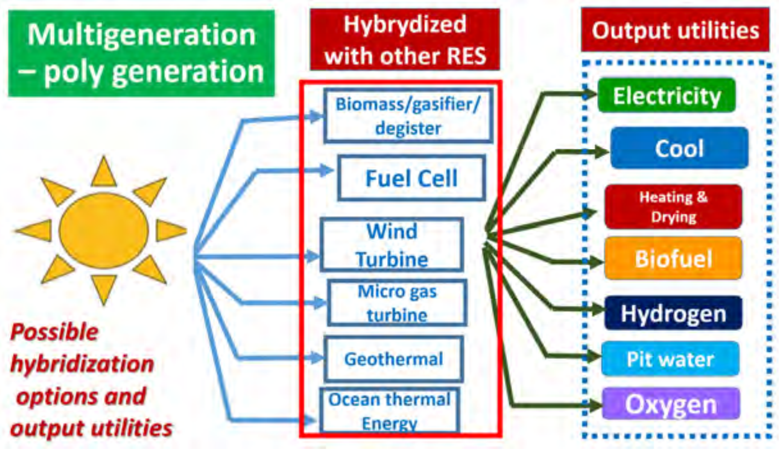


Fig. 1.14. Hybridisation options of solar energy utilization

Generally, solar energy alone (thermal or photovoltaic) cannot be used for polygeneration. Biomass is abundantly available so that the solar energy can be hybridised with biomass. In polygeneration, for example, with solar and biomass inputs, solar biomass hybrid system may be the option. When the solar radiation is high, a part of the total syngas generated by the biomass gasifier system may be used to produce ethanol. During the night, with no solar radiation, the entire syngas is used to generate electricity. Thus, both ethanol and electricity are obtained [21, 26–32]. In polygeneration, solar thermal energy integrates better than solar photovoltaic applications. The generic output utilities of solar-based polygeneration hybridised with RESs are electricity production, potable water, heating, cooling, desalination, ethanol, etc., which can be a future sustainable option, specifically for different energy applications [4, 19, 33].

However, the application depends on the location and the type of devices used for fabricating the system. The costs of the generation of the same utility outputs are lower than those generated by the stand-alone units. This is the purpose of developing integrated polygenerations.

References

[1] European Commission, *An EU strategy on heating and cooling. 2016*, 13, https://ec.europa.eu /energy/sites/ener/files/documents/1_EN_ACT_part1_v14

[2] European Commission, Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: an EU strategy on heating and cooling (COM(2016) 51/F1), COM(2016)51/F1. 2016, p. 13, https:// ec.europa.eu/energy/sites/ener/files/documents/1_EN_ACT_part1_v14.pdf [accessed 13.05.2016].

[3] Murugan S., Horák B., *Tri- and polygeneration systems. A review*, Ren. Sust. Energy Rev., 2016, 60, 1032–1051.

[4] Jana K., Ray A., Majoumerd M.M., Assadi M., De S., *Polygeneration as a future sustainable energy solution: A comprehensive review*, Appl. Energy, 2017, 202, 88–111.

[5] Mancarella P., *MES (multi-energy systems): An overview of concepts and evaluation models*, Energy, 2014, 65, 1–17.

[6] Mancarella P., Andersson G., Peças-Lopes J.A., Bell K.R.W., *Modelling of integrated multi-energy systems: drivers, requirements, and opportunities*, Power Systems Computation Conference (PSCC), Genoa 2016.

[7] Weber C.I., *Multi-objective design and optimization of district energy systems including polygeneration energy conversion technologies*, PhD thesis, L'Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne 2008.

[8] Hawkes A.D., Leach M.A., *Solid oxide fuel cell systems for residential micro-combined heat and power in the UK: Key economic drivers*, J. Power Sources, 2005, 149, 72–83.

[9] UNDP, United Nations Development Programme, *Human development report*, 2016, http:// hdr.undp.org/en/composite/hdi [last accessed on 16.02.2016].

[10] *World energy outlook*, International Energy Agency, Paris 2015.

[11] IEA/OECD, *Energy and climate change, world energy outlook special report*, International Energy Agency, Paris 2015.

[12] IPCC, *Climate change 2014. Synthesis report (AR5)*, Cambridge University Press, 2015.

[13] Lior N. *Energy resources and use: the present situation and possible paths to the future*, Energy, 2008, 33, 842–857.

[14] Serra L.A., Lozano M.A., Ramos J., Ensinas A.V., Nebra S.A., *Polygeneration and efficient use of natural resources*, Energy, 2009, 34, 575–86.

[15] Chicco G., Mancarella P., *Distributed multi-generation: a comprehensive view*, Renew. Sust. Energy Rev., 2009, 13, 535–551.

[16] Hu L., Hongguang J., Lin G., Wei H., *Techno-economic evaluation of coal-based polygeneration systems of synthetic fuel and power with CO_2 recovery*, Energy Conv. Manage., 2011, 52, 274–283.

[17] Sachan A.K., *Study of the Integration of District Heating and Cooling with an Electro-Thermal Energy Storage System*, PhD thesis, L'Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne 2012.

[18] Hukkalainen M., *Low emission energy systems in energy efficient districts*, PhD thesis, Aalto University, 2018.

[19] Rosen M.A., Koohi-Fayegh S., *Cogeneration and District Energy Systems, Modeling, Analysis and Optimization*, The Institution of Engineering and Technology, Stevenage Herts, UK, 2016.

[20] Sigurjonsson H.Æ., Clausen L.R., *Solution for the future smart energy system: A polygeneration plant based on reversible solid oxide cells and biomass gasification producing either electrofuel or power*, Appl. Energy, 2018, 216, 323–337.

[21] Mata-Torres C., Escobar R.A., Cardemil J.M., Simsek Y., Matute J.A., *Solar polygeneration for electricity production and desalination: Case studies in Venezuela and northern Chile*, Ren. Energy, 2017, 101, 387–398.

[22] Tyagi H., Agarwal A.K., Chakraborty P.R., Powar S., *Applications of Solar Energy: Energy, Environment, and Sustainability*, Springer Nature, Singapore 2018.

[23] Beccuti G., *Power Transmission and Distribution*, *Systems System Efficiency*, International Energy Agency (IEA), 2018.

[24] IEA, *CO_2 emissions from fuel combustion highlights*, International Energy Agency, 2014, 1–136.

[25] Beith R., *Small and micro combined heat and power (CHP) systems, advanced design, performance, materials and applications*, Woodhead Publishing, Oxford 2011.

[26] Yang H., Xiong T., Qiu J., Dong Z.Y., *Optimal operation of DES/CCHP based regional multi-energy prosumer with demand response*, Appl. Energy, 2016, 167, 353–365.

[27] Wang J., Zhong H., Ma Z., Xia Q., Kang C., *Review and prospect of integrated demand response in the multi-energy system*, Appl. Energy, 2017, 202, 772–782.

[28] Zhanga X., Lovatib M., Vignab I., Widénc J., Hana M., Gala C., Fengd T., *A review of urban energy systems at building cluster level incorporating renewable-energy-source (RES) envelope solutions*, Appl. Energy, 2018, 230, 1034–1056.

[29] Howell S., Rezgui Y., Hippolyte J.-L., Jayan B., Li H., *Towards the next generation of smart grids: Semantic and holonic multiagent management of distributed energy resources*, Ren. Sust. Energy Rev., 2017, 77, 193–214.

[30] Taher N., Faranak G., Reza M.A., *Probabilistic model of polymer exchange fuel cell power plants for hydrogen, thermal and electrical energy management*, J. Power Sources, 2013, 229, 285–298.

[31] Chen Y., Yang., Wang X., Zhang S., Chen H., *Biomass-based pyrolytic polygeneration system on cotton stalk pyrolysis: Influence of temperature*, Bioresour. Techn., 2012, 107, 411–418.

[32] Jradi M., Riffat S., *Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies*, Ren. Sust. Energy Rev., 2014, 32, 396–415.

[33] Nolting L., Kies A., Schönegge M., Robinius M., Praktiknjo A., *Locating experts and carving out the state of the art: A systematic review on Industry 4.0 and energy system analysis*, Int. J. Energy Res., 2019, 1–22.

CHAPTER 2.
DISTRICT HEATING. INFRASTRUCTURE, TECHNOLOGIES AND TRENDS

2.1. Introduction to the DH network

Heating and cooling contributed to about 50% of the final energy consumption in the EU 28 countries. DH systems are considered to be valuable assets of the energy supply networks which enable efficient resource utilization. Currently, DH networks are well-established in many countries and possess an important part of DES. The operational principle of the system is to produce heat centrally and later distribute it to consumers through pipes buried in the ground, in order to cover their space heating (SH) and domestic hot water (DHW) demands.

DH networks come in a variety of scheme sizes, able to cover the needs of a small group of buildings in the same neighbourhood or city-wide schemes comprising thousands of connected buildings. DH systems are characterized by a diversity of technologies that seek to develop synergies between the power, heat production, supply heat, cooling and DHW applications of the users. The flexibility of DES allows their integration with thermal renewable technologies such as biomass, solar thermal, heat pumps, deep geothermal, etc., this fact can be significant by reducing the overall GHG emissions.

One of the most promising technologies towards the development of sustainable DES is CHP and combined cooling heating and power (CCHP) systems or polygeneration systems. CHP systems are usually located near commercial or residential buildings, where the waste heat produced by the system is readily recovered and used to heat the buildings. This is typically done by the means of heating technology and piping technology for hot fluid (hot water, steam, etc.) while district cooling is made up of cooling technology to generate cooling in the form of chilled water (cold brine, cold water slurry, etc.) and piping technology for cool fluids. Then these fluids are used to transport the heat/cool to buildings' network. In CCHP systems besides a DH loop, a district cooling loop can be used to provide cooling to the buildings.

The potentials of these sustainable DES can be realized if one considers the fact that the largest amount of energy in Europe is consumed for space heating and hot water preparation for buildings, reaching the 43% of total Europe's final energy consumption. Sustainable DES can efficiently cover these consumers' needs. However, the energy demand profile of the consumers must be taken into account, as the demand characteristics are constantly changing. In order to regulate the relationship between the energy demands, the energy production and the energy distribution, advanced and complex control, forecast and energy management systems are required. A variety of software and models for DH supply systems are used to overcome the different heat demand purposes, always considering the supply reliability of the system.

Nowadays, energy sustainability is an important and common goal for all EU countries. However, the implementation of fully sustainable DH system which will satisfy all the above aims meets various obstacles, due to the limited availability of local energy sources and fuels, energy policies, innovation, economic conditions, environment and health protection, etc. The only feasible solution to overcome these problems is the development of a common EU energy legislation regarding DH networks and their technologies.

Currently, in Europe, more than 6000 medium and large DH systems exist. Many of them require modifications of modernization (i.e., retrofitting) to bring them to a reliable standard. DH enables the use of a variety of heat sources that are often wasted, as well as renewable heat. Many researchers have focused their field of studies to investigate methods and advantages of reusing the waste energy, RE utilization, modelling of DH systems and components. DH systems can significantly contribute to achieving the goals of EU's energy policy in perspective of 2050.

The main advantages of DH systems are that they can be incorporated into existing heating facilities at a reasonable cost, using a mixture of RESs and conventional fuels. The combination of conventional and RES technologies with TES creates hybrid systems, which are capable to achieve better system's performance. Energy savings in buildings is a key point towards a more sustainable energy future with the most feasible action first to renovate buildings that are planned to be connected into DH networks. Therefore, energy planning and area mapping are necessary in order to define zones where building renovation and DH development is promoted. The energy savings obtained from DH network extensions seem an attractive solution from an energy and environmental point of view. However, the economic viability of DH systems still needs to be evaluated. Actually, the current key challenge is to find an optimized economic and energy solution combining both the future development of DH systems and the energy savings.

Existing technologies of DH systems in EU countries are characterized by a great diversity of applied technologies and the use of RE sources. The degree of modifications that should be made in the existing DH systems in EU, in respect to the EU goals of 2020 and 2050, differs for each country but are directed towards sustainable development in all EU countries. It is believed that DH systems are capable of achieving all sustainable goals at a lower cost compared to every other technology by 15%.

It should be noted that the DH size and location does not only depend on the climatic conditions. Its utilisation is highly dependent on national energy policies that play a significant role in its adoption on national levels.

All technologies in DH systems are constantly upgrading and improving. The aim is to improve the efficiency of heat generation and transmission, to increase RE uses and to reduce the impact on the environment and human health. Contemporary technologies enable the sustainable development of small and medium scale DH by using large scale energy sources technologies, i.e., CHP, gas turbine, fuel cells, heat pumps, RES, etc. It is preferable to use contemporary technologies with energy storage. The DH development requires more flexible energy systems with building automation, RES and increasing the role of prosumers participation, integration with mix fuel energy systems as part of smart energy sustainable systems in smart cities.

2.1.1. The extent of district heating in Europe

District heating is a widespread 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 it [11]. 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 [12]. In district heating, huge energy demands and a large number of consumers provide a unique opportunity for energy savings [13]. 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 [14]. 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 [15–19].

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 [20, 21]. 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 [15, 22, 23]. To increase the heat supply security for heating sectors, the district heating heat source 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 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 [24–27].

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 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 minimize 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 a 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 [14, 28–30].

2.1.2. Scale of heat consumption in European district heating

District heating and cooling are consumed in the main three sectors, namely residential, service and industry. Figure 1a shows the average annual growth rate of district heating in a 10 year period (2005–2015) for some individual member states of the EU which is characterized by 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. Figure 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 [31].

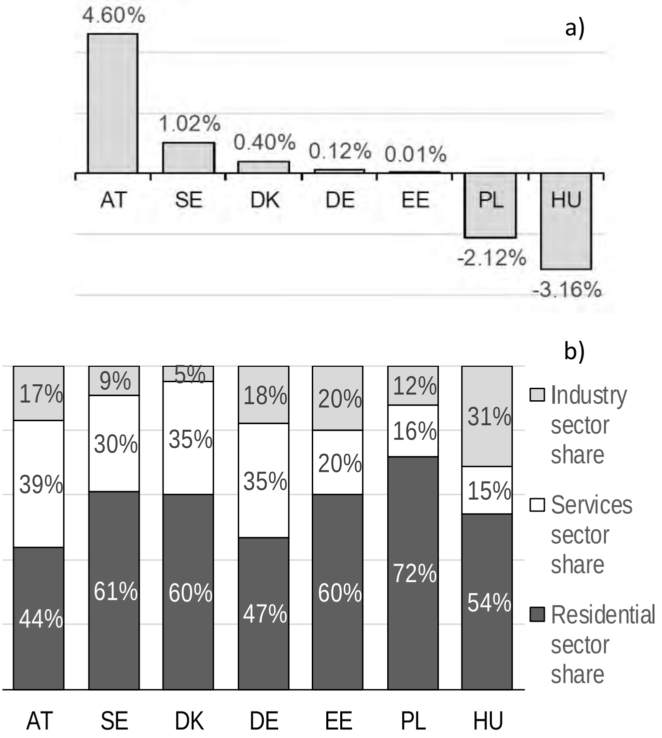


Fig. 2.1. Growth in district heating for some EU countries in 2005–2015 (a), and district heating percentages for residential, service and industry sectors (b) [8]

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 is 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 house, 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 the 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 varies from 60–90 kWh/m^2 in southern European countries (Malta, Spain, Bulgaria, Greece and Croatia) to 175–235 kWh/m^2 in countries with colder climate such as Estonia, Latvia and Finland [12, 13]. 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. 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) (Fig. 2.2) [28, 32, 33].

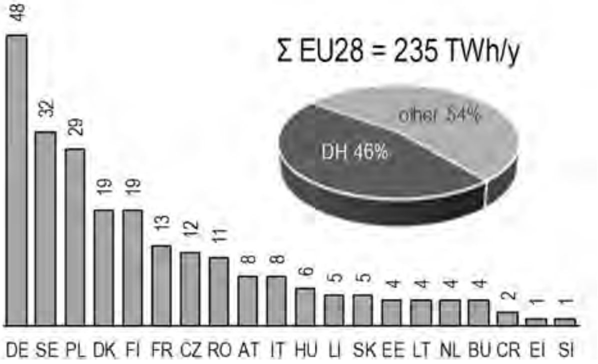


Fig. 2.2. Total final district heating heat consumption in the residential sector in TWh/year [8]

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 [34–37]. 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.

2.1.3. Share of 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 [38–40]. Figure 3 shows the percentages of residential district heating in EU countries; the countries are divided into five groups according 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% [15, 21].

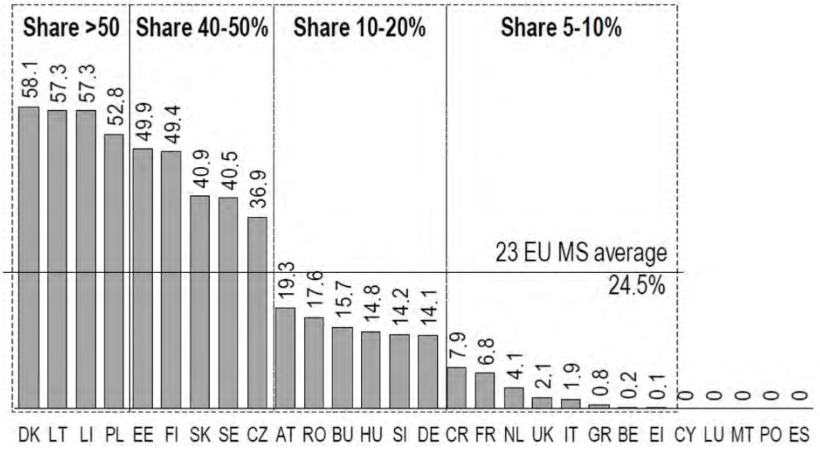


Fig. 2.3. Percentages of residential heat supply from district heating in EU countries [8]

District heating systems represent a large proportion of the residential heating sector in EU countries and a significant annual growth rate in heat consumption [21, 41–44]. It is a strong argument for utilising district heating in Europe, but, as outlined in Fig. 2.3, 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 [41–43, 45]. As mentioned above, thousands district heating systems can be found all over Europe today [46]. 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 increased energy efficiency and decarbonisation through, for example, heat pump technology, renewable energy sources and thermal energy storage.

2.1.4. Strategies, energy policies and trends of European district heating

The European Union defined three energy policy targets in order to address the challenges related to climate change, the 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 80–95% reduction in greenhouse gases by 2050 when compared with 1990 levels [25, 41, 44, 47–50]. None of the 2030 and 2050 scenarios involves 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 [51, 52].

One of the 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 consume 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 [51]. 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 decarbonized [15, 20, 34,36, 53, 54].

Different strategies have been proposed for EU district heating with heat savings to decarbonize 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 depending on potential and capabilities. This differentiation slows down the decarbonisation of the district heating sector but it gives also 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 [43, 55, 56].

2.2. Infrastructure, parts and components of DH

2.2.1. Infrastructure of DH

Traditional DH 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 SH, DHW and process heating. Often, DH systems cover large areas and are very complex plants involving many substations and thousands of consumers. A DH system may consist of more than one heat source including FF, renewable energy sources, thermal energy storage, heat pumps, CHP plant with a mixed fuel or hybrid sources [1, 3, 7–9]. DH systems enable us the use of a flexible energy mix, provide an infrastructure for an easy transition to RESs, with higher energy efficiency, faster decarbonisation and enhanced heat recovery alongside building refurbishment and a smart grid.

Figure 2.4 shows the author’s own composition of the general infrastructure of the DH system, which illustrates the main components of fuel and energy sources switched to the conventional or hybrid sources. Energy conversion technologies with the CHP, heat or chiller plants, DH network and distribution section with the distribution stations and heat transmission, distribution to the residential commercial and industrial consumers [40, 42, 44].

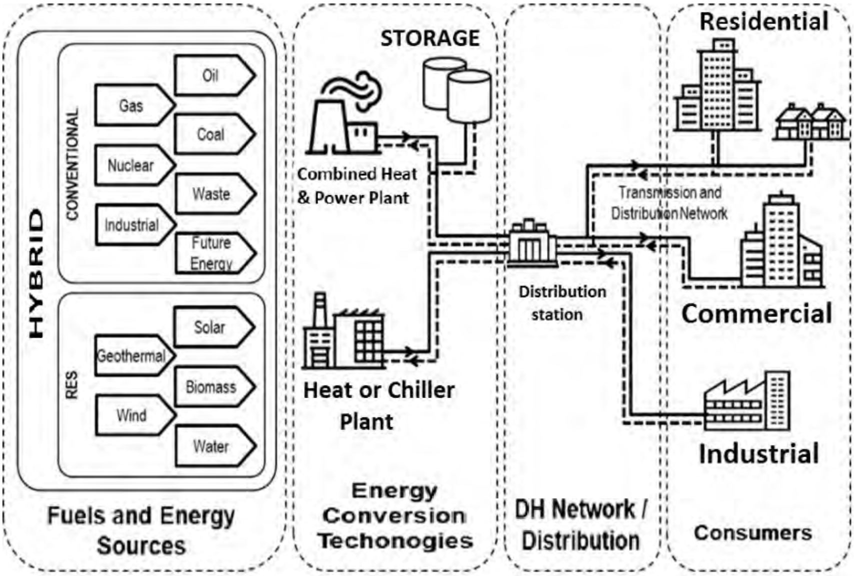


Fig. 2.4. General infrastructure of DH system components and technologies

The objective for realizing the deployment of DH 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 [57]. Furthermore, it has been experienced that the proportion of DH, as well as the potential for newly expanded networks, differs between urban and rural areas, although DH systems enable a highly flexible energy mix. New fuels and energy sources can be integrated when there is a need for restructuring DH systems. For customers, no adaptation measures at all are required when a switch of energy source is made. DH and cooling provide essential infrastructure to ensure large scale integration of renewable energy sources [58]. DH and cooling as a technological concept have a significant presence in many countries and it is implemented in many different forms and it seems that DH and cooling will increasingly move away from FF. All these possibilities require the use of dedicated technological solutions, the integration of different energy systems and advanced management for energy production and consumption in the system. This requires the definition of all dependencies, improving collaboration and evaluating operational scenarios and the conscious choice of preferred connections which take into account local conditions, requirements and capabilities [59].

Some contemporary DH systems include many individual 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. DH infrastructures have an important role to play in the task of increasing energy efficiency and thus making scarce sources meet future thermal demands. DESs and smart grids are the most promising trends for integrating a larger contribution from RESs and TES into contemporary systems [57–59]. However, district energy systems and smart grids are not widely used yet in European DH systems due to numerous technical and economic issues.

2.2.2. Parts and components of DH

DH networks have a long and proven track record in EU and Nordic countries [1, 2, 10]. A traditional DH system has three main parts: heat generation, distribution and consumption. Figure 2.5a shows the main components of DH network, which consist of the central heat source and heat exchanger (HX) for generation, a pipeline network for distribution and in consumption, an HX as the main part of a consumer substation, and a heat sink for SH and DHW, etc. Within the evolution of DH systems, additional advanced components have been added to satisfy the heating requirement for SH, DHW and process heating for residential buildings and industrial purposes to meet environmental and climate challenges and energy efficiency legislative requirements [7, 8, 56–59]. Figure 2.5b shows an advanced DH system with possible additional components fitted in the three main parts. For a generation, there is a central FF heat source, RESs including heat pumps, an HX and thermal energy storage. In the distribution network, there are local heat sources, RESs including heat pumps, HXs and TES. In the consumption section, there are individual fossil fuel heat sources, RESs including heat pumps, HXs, TES, and of course heat sinks as an end consumer. It is noted from Fig. 2.5b that RESs and TES can be installed in the DH system at generation, distribution or even consumption parts. The advanced scheme gives more flexibility for better performance and environmental effects, energy security and fuel independence; advanced scheme of DH 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 DH. 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 preferred DH network connection choices [7, 8, 59]. This means there is an opportunity for implementing other solutions whenever and wherever possible and the impossibility of introducing universal changes in all DH systems. It is important to mention that an overly complex system consists of many different components, which hampers its operation and increases the costs.

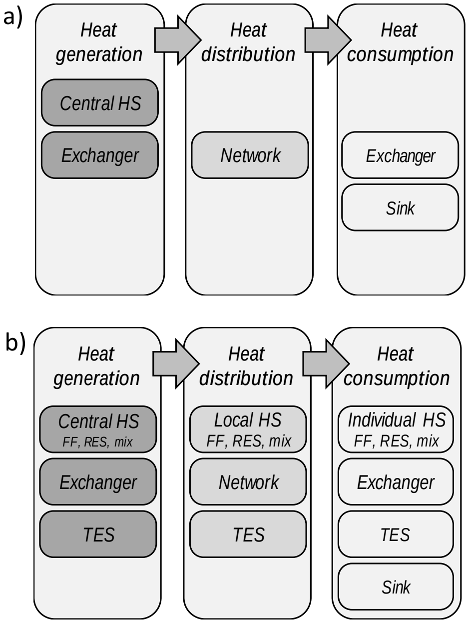


Fig. 2.5. Main parts and components of the DH system:
a) standard, b) advanced [8]

2.2.3. Substation in DH

The substation is an important part of ensuring the lowest possible return temperature in the DH thermal network. There exist several advanced substation designs with high theoretical performance, but the experience shows that more effort should be put in dimensioning and designing well-functioning substations and secondary networks than inventing advanced connection schemes [7, 8, 60]. For apartment buildings, individual substations in each flat (flat stations) have been a popular solution for low-temperature DH networks, due to reduced legionella risk. For very low-temperature DH systems, concepts with local temperature boosters for DHW have been studied in the literature. The most effective solution is found to be instantaneous electric heating. However, this gives very high thermal peak requirements and should be evaluated against the use of a storage tank with the accompanying heat losses.

2.2.4. Technical management of DH

The management term in DH systems refers to the technical operations, the maintenance, the energy and economic management, the continuous development and the modernization of the system as shown in Fig. 2.6a. An optimal DH operation means to meet the consumers, environmental, economic and technical requirements. An accurate forecast of heat consumption offers the possibility of increasing thermal efficiency and minimizing fuel consumption and emissions. Initial designs of DH systems provide heat to the consumers, based on the ambient temperature [12].

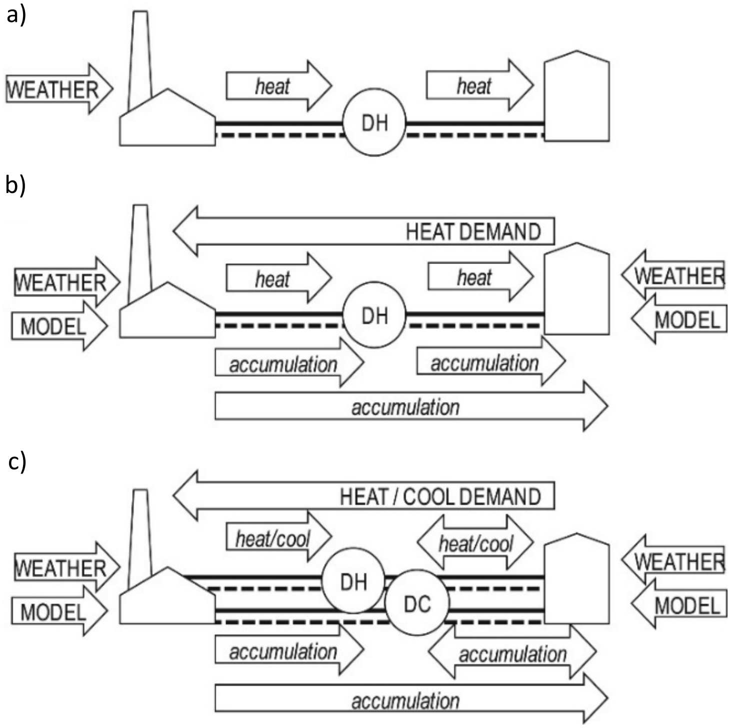


Fig. 2.6. Evolution of technical management of DH [7]

This relation with the weather has led to a discrepancy between the predicted requirement or thermal demand management and the supplied heat. Attempts were made to eliminate this disadvantage, by taking into account additional metrological factors, weather data reports and demand forecasts. Good results in DH management were achieved by using weather data control, modelling of buildings' consumption and modelling of DH systems as in Figure 2.6b. Different models are described in the literature: simple, complex, statistical, simulations, learning, adaptive and other. Currently, the most successfully model-based method uses both hierarchical and multi-agent control systems [26]. Improved automatics and smart metering methods which can respond to signals from smart grid to maximise the value of the produced heat and power and lead to better management of the heat source, the DH network's distribution and the heat consumption, simultaneously including DH and DC, heat/cool accumulation in network or in buildings, effective integration of prosumers, these arrangements leads to better operation and investment-design optimization of the heat network. Many existing DH systems operate on model-based methods [12, 26, 60]. Smart DH networks use multi-variant simulations, online monitoring, supervisory control and data acquisition (SCADA), emulators, thermal and hydraulic models, geographic information system (GIS) and other decision support tools. The most favourable operation scenario of DH networks is to determine automatically the predictions and to implement the necessary control functions as illustrated in Fig. 2.6c.

2.2.5. Heat generation in DH

The basic energy fuels still used in DH systems are FFs such as coal, gas and fuel oil, as well as RESs. However, the fuel choice and heat distribution may differ for each EU country [3, 6, 61].

DH systems can use different energy sources in a common cycle, creating hybrid systems, which gives a significant technological advantage and the potentials of further development. These hybrid systems combine conventional methods of energy production from fossil fuels, with the use of alternative and RES technologies, like heat pumps, solar collectors or gasification of fuels (coal, biomass). As a result, hybrid systems manage to achieve higher energy efficiency and greater fuel savings, while minimizing their environmental impact. The transition from conventional energy technologies to combined DH systems is already noticeable in Europe [62].

An extremely vital characteristic of DH is its flexibility in the fuels or heat sources. Many different centralized and decentralized sources can be connected for reliable operation and flexibility to a DH network, with basic control strategies. Depending on the geographical location and requirement, the same DH network can be used for district cooling (DC) in the summer season, with the same heat source. Some conventional energy generation sources are as follows [35, 57–62]:

- CHP plants: producing both heat and electricity with different ratios or either one, including large and micro CHP facilities. Can be used with a variety of fuels including renewable biomass.
- Waste heat: either from industrial processes, agricultural processes, combustion of waste.
- Geothermal heat: a renewable source found beneath the earth’s surface.
- Solar thermal heat: both large and small scale setups.
- Heat pumps: usually large and small-scale electrically driven, when there is an excess of electricity, e.g., in Scandinavia when there is an excess of wind energy.
- conventional boilers: normally used as a back-up, in events where peak load exceeds production. Can be used with a variety of fuels including renewable biomass.

The most common heat generation technologies have been ranked according to economic, energy and environmental factors. However, DH systems using only RE sources are not very common. They usually combine conventional energy sources with other RE sources and thermal energy storage. Energy storage is an essential part of DH systems due to the fluctuating energy supply from RE resources such as solar (thermal, photovoltaic, photovoltaic/thermal) or wind energy. RE can be integrated into the DH systems by central or onsite heat sources. Local RE installations reduce the heat consumption of the DH system, without any physical connection to the DH network. Figure 2.7 represents the possible connections of RE sources in DH systems. In central mode as shown in Fig. 2.7a, the RE sources deliver heat to the main heat source with large seasonal heat stores. In distributed mode as in Fig. 2.7b, the RE sources are placed at suitable locations and connected directly to the DH system. These plants usually utilize the DH network as a storage [7, 8, 60–64].

There are thousands of DH systems in Europe but a small percentage of them uses RESs as an energy source in the heating/cooling system. The legislation of using RE sources in DH installations varies both at national and regional levels in the EU. Most of the heat requirements comply with the EU Energy Efficiency Directive 2012/27/EU. There are different barriers for large scale RE resources for DH systems, like the price of the land or restricted application on historic or protected areas, financial incentives for RE, etc.

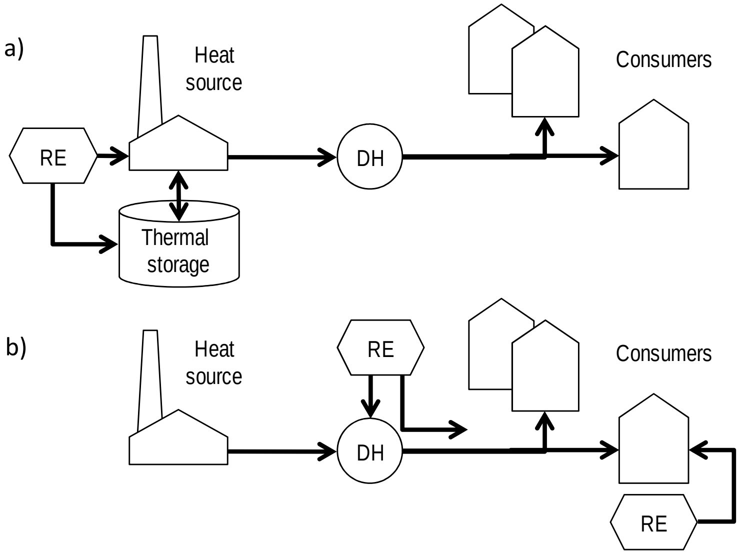


Fig. 2.7. Integration of RES and TES into a DH network [7]

However, all DH systems in Europe are operated at temperatures over 70 °C. The implementation of RE sources in the DH may reduce the conventional annual total energy demand for buildings. However, the strict legislation and the lack of practice experience and knowledge considerations and thermal management of the RE integration choices in DH systems are the main reasons why there are few applications of those large scale RE applications in DH systems [63–65]. The EU tries to overcome these barriers by updating the directives and providing local and regional support policies and funding.

2.2.5.1. Heat sources in DH

DH systems are open to high efficiency and low carbon heat generation and heat delivery technologies such as CHP, RES, TES, etc. [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, and ability to integrate with smart systems [20, 68–71].

The proportions and types of used fuels and the heat source technologies vary greatly in European DH systems [7, 8, 61–64]. Conventional technologies, fuels and energy carriers are well known and analysed more deeply in many references, which consider their environmental impacts too. The next chapter will focus on the details of heat pump integration into residential DH systems.

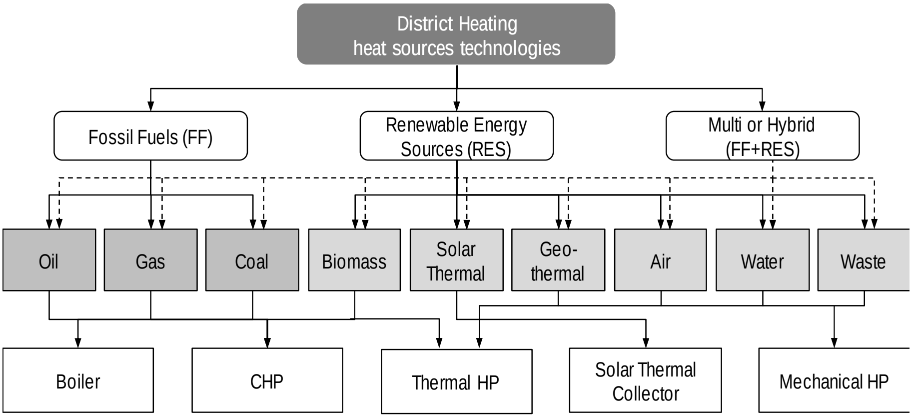


Fig. 2.8. Applied heat sources and technologies in European DH systems [8]

Figure 2.8 shows an overview of general heat sources and technologies in European DH systems. It is obvious that it is possible to use different heat source technologies from fossil fuels, RESs or even hybrid heat 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 RESs, where these sources alone are not able to supply the DH system, thus increasing the use of renewable energy and reducing the consumption and emissions from FFs. 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 [2–6, 64–69].

The flexibility advantage of DH system allows the integration of different energy conversion technologies and heat sources in order to meet sustainability targets. The inclusion of DH in sustainable smart cities of the future allows 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 [25–27, 72, 73]. 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 [74–76].

2.2.6. Mono- and multi-fuel DH

Traditional first DH systems were based only on single fuel heat sources (mono-fuel) and mostly it was FF. In the extensive urban systems, two or more heat sources are combined to cover the heat demands, most importantly is to include a backup heat source, which will be implied in case of failure of other sources.

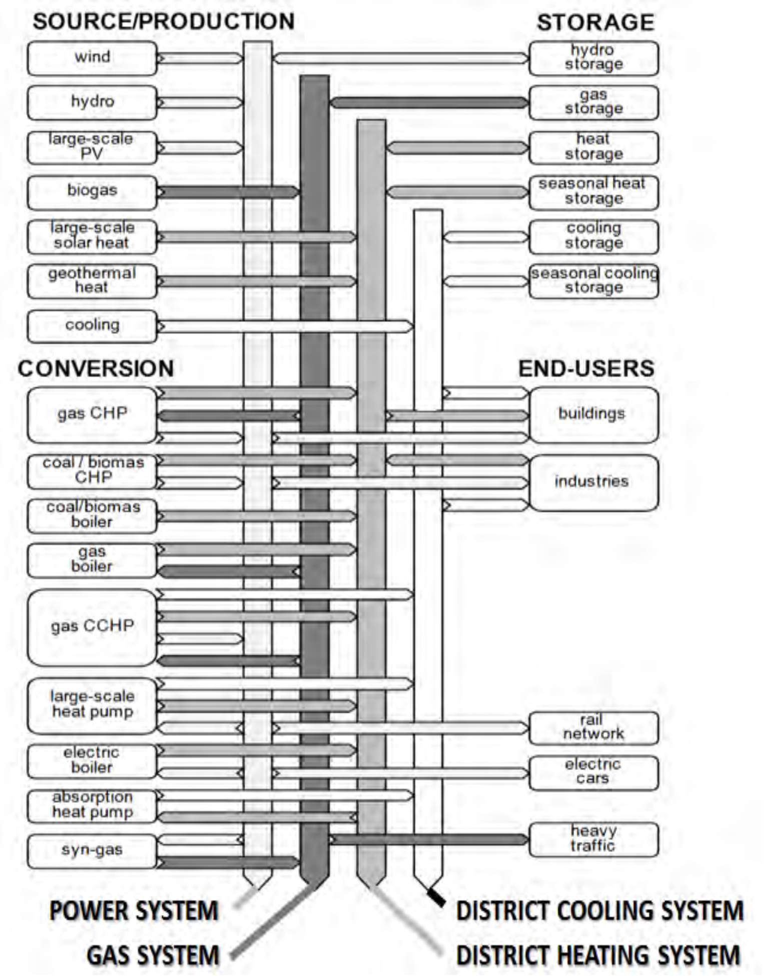


Fig. 2.9. Multi-fuel energy conversion technologies [7]

These multi-fuel DH sources operate according to the energy demands and the sources' availability as shown in Fig. 2.9. The integration of energy sources with thermal storage increases the utilization of RE and DH efficiency [58, 59, 74–76]. The more significant heat sources of DH systems are recycled heat from FFs, CHP and from industries, or recycled heat from renewable CHP (waste and biomass) and at last by direct use of RE sources, like geothermal, biomass and waste.

The DH flexibility and efficiency can be improved by joining the DH networks with city energy grids. The integrated MES uses the energy obtained from multiple energy sources and produces electricity, heat and cooling as a switched network. This integration increases the technical, economic and environmental performance of the network. MES is the main part of smart energy systems or smart cities. Smart energy systems enable the suitable and efficient choices of the sources and the storage and transfers the energy between the networks as illustrated in Fig. 2.9. Till now DH as a full system does not exist in smart energy systems or smart cities [58–77]; only a few DH projects operate as a switched part to the smart energy network.

2.2.7. Technical interfaces in DH systems

This section aims to provide an overview of the most relevant topics and issues related to the technical interfaces in the DH network, energy system technologies and community. Interfaces in the DH systems context present different types of links between heat supply and demand of buildings by means of water-based systems. The technical and research field of the interfaces covers a broad range of issues as shown in Fig. 2.10. The challenge of the improved interfaces in DH systems may be explained via so-called hard and soft issues:

Hard issues cover the following areas: DH network structures (temperature, pressure and flow levels), predicted thermal requirements for consumers in buildings, substations configuration, connection choices, applied techniques and alternatives for distributed heat sources.

Soft issues cover the following topics: technical (measurements and optimization) and economic modelling of the distribution system, optimization between heat generation and demand side, innovative control concepts and energy measurement, transition of the existing DH system to the low-temperature DH network and new pricing estimations and business models.

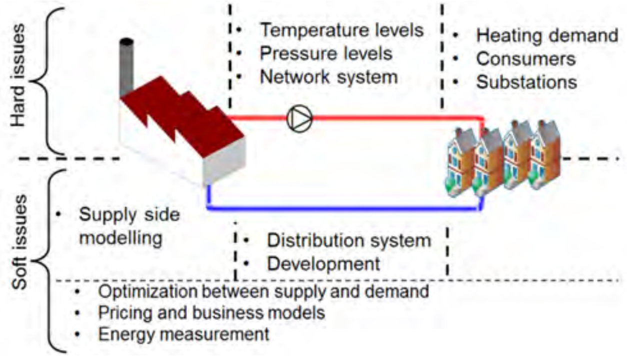


Fig. 2.10. Technical interfaces in district heating systems

European different DH promising project models, concepts, and technologies to meet the goals of future renewable and heat pump based energy systems have been collected and identified [46, 49, 66]. Some of the relevant technologies have been described, as new pipe technologies, substation configurations, and renewable technologies. The issue of the interface is highly relevant for a successful implementation of the low-temperature DH and thereby enabling the transition to the heat pump based, supplied by the renewable sources and secure energy supply for the future development of society. By introducing better interfaces between the predicted demand profiles and the supply side. DH systems can be transformed into a smart energy system on a district level [70–76].

In the case of low-temperature DH (supply and return temperature), the heat generation helps to improve the CHP plant power to heat ratio and recover waste heat through flue gas condensation, achieves higher heat pump efficiency COP values, and enlarges the utilization of low-temperature waste heat and encourages to share RESs. Low-temperature DH has been continuously developed as the next generation of DH, to replace the current medium temperature DH system with the low-temperature DH system [72–78].

2.2.8. Technical management in DH network

Traditional public supply of heat in a DH network, when the DH services are provided by the government or municipality and administrative authorities or by a public authority or a publicly owned company is shown in Fig. 2.11, which illustrates the DH chain from fuel supply, heat generation and transmission to the heat distribution to the end consumers (including possible buildings association).

National frameworks define exact procedures and options for public provision of DH. The legislation can vary from country to country, there are many suggested examples from European countries [58–62, 71–76].

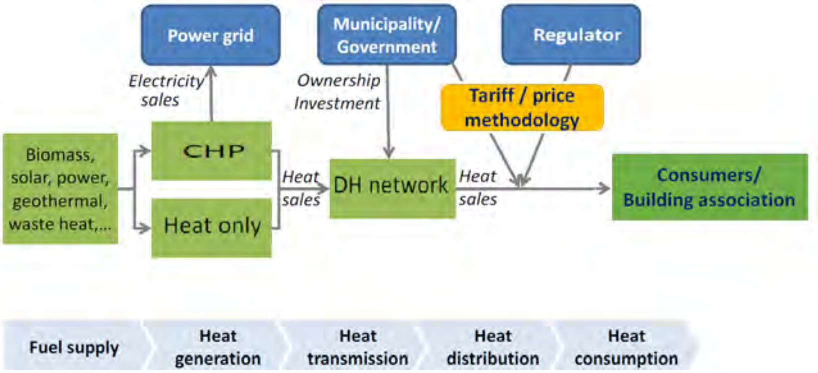


Fig. 2.11. DH chain from fuel supply, to heat consumption by the end users

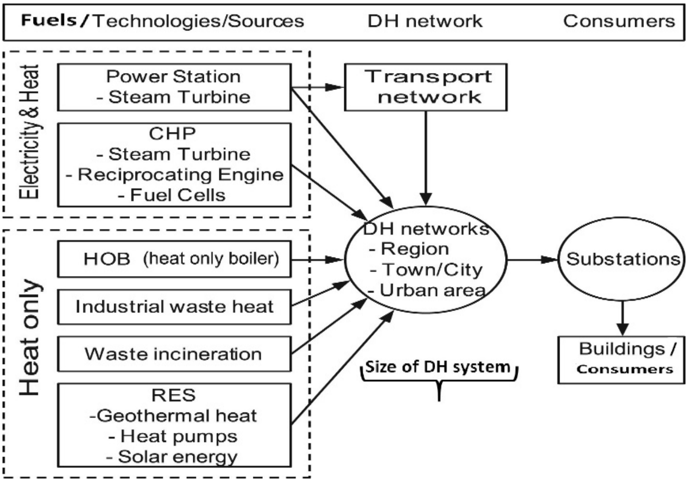


Fig. 2.12. Scheme of technical arrangement in DH networks [7]

The main investment in a DH or DC systems is the technology for the required heat generation from the energy sources. There are different energy sources that can be utilised in a DH or DC project. The DH heat generation technologies vary in many EU countries, depending on each country's energy policy, energy security, economic development, access to new and innovative technologies, the reliance of own fuel resources, regulations, climatic and local conditions, etc. Therefore, the development of DH systems differs in terms of energy efficiency, CO_2 emissions and use of RESs in each country [16–18, 36–39]. The investment and planning trend in new DH projects usually focuses on RESs as the core of heat generation sources, besides the conventional sources.

A general scheme of technical arrangements in DH is presented in Fig. 2.12, which describes the operation and the connection options of the DH network. The energy technologies used for DH applications can be categorized into two groups: CHP system and heat only systems as shown in Fig. 2.12. CHP systems use the rejected or wasted heat from the power generating units to produce hot water. The CHP systems have been widely used for several decades. According to Fig. 2.12, DH technologies are divided into CHP and heat-only technologies, presented as follow [7, 8]:

The main part of the DH system consists of one or more central heat sources, a network of insulated pipes for heat distribution, and several substations to supply the hot water to the consumers. In this way, the end users have only a simple on-site unit consisting of HX, pumps and valves. Some of the benefits of DH installations are that the on-site units of the consumers do not require annual maintenance comparing to the combustion chambers and that the consumers are not facing the risks associated with on-site fuel storage and delivery [56, 68, 71–76]. The most common technologies of these systems are steam turbines with coal, and gas engines with the possibility of innovative fuel cell technologies. The term “heat only systems” refers to the steam generating systems or hot water boilers, with the use of conventional or renewable fuels (biomass), industrial waste heat, municipal waste incineration plants and RESs, such as geothermal heating plants, heat pumps and solar energy.

2.2.8.1. Combined heat and power systems

Heat is usually generated in two types of plants. The basic one is a heat generation plant with a boiler that only generates heat, so we call it a heat only system. The second type is a cogeneration plant, often called combined heat and power plant (CHP). As it generates both heat and electricity, it benefits from considerable economies of scale. Upon generating electricity by incineration, the steam from the boiling water that drives the turbines is lead also to heat water in a closed circuit DH system. It can also be used as steam in industrial processes [22, 79].

One of the most desired characteristics of CHP plants is their electricity production. The generation of electricity is a result of the conversion of fossil fuel’s chemical energy to thermal and mechanical energy, which powers the generator of the system. Electricity production by conventional-separated methods is characterized by low-efficiency rates, around η_{el} = 0.15–0.4, with the average efficiency of conventional plants in the EU being around 0.38. CHP systems achieve higher energy efficiency rates and less fuel consumption and carbon footprint, compared to the separated processes of heat and power generation [80]. Moreover, more advanced CHP technologies allow the recovery of the system's waste heat to provide cooling, along with heating and power. These systems are called combined cooling, heating and power (CCHP) or polygeneration plants [22, 79–81].

Currently, the most widespread technologies of power generation in CHP systems are steam turbines, gas turbines, combined gas-steam turbines (GTCC –gas turbine combined cycle), gas engines with spark ignition and diesel engines [81]. The thermal energy produced during the fuel combustion is later used for heating the water of DH systems or to produce high-pressure steam, for further system's operations. In that way, the waste heat of the system is continuously used in the generation process, improving the electrical efficiency of the system.

The electrical power produced by individual units in power plants ranges from 40 to 1000 MWel. Typical components of power generation plants are steam boilers, steam turbines, condensers, circulating pumps and a closed power cycle of a working fluid, which is usually water. The power efficiency of these generation units depends on steam's and water's thermodynamic cycle parameters.

One of the greatest concerns of conventional power plants is their pollutants emissions, particularly of CO_2, caused by coal combustion. It is estimated that the global rate of CO_2 emissions from coal power plants with an efficiency of η_{el} = 0.30 is approximately 1 115 g CO_2/kWh a value that exceeds the limit of 454 g CO_2/kWh, set by the US Environmental Protection Agency (EPA) by 2.5 times. It is possible to reduce the CO_2 emissions by implementing coal/biomass co-burned technologies, combined coal-burned boilers with biomass boilers or newly constructed biomass boilers.

One of the benefits of CHP units is that the user can control the ratio between the thermal energy supplied to the DH system and the generated electricity from the unit. The thermal and the electrical energy produced by the CHP plant is characterized by an inversely proportional relationship; the production of a higher amount of heat corresponds to less generated power. In the literature, this behaviour is compared to the operation of virtual heat pumps. The virtual heat pump coefficient of performance (COP) is described as a proportion of the heat supplied to the DH system and the unproduced electricity. For a traditional heat pump, the COP is 3–4, while for a virtual heat pump the COP ranges between 6 and 10. Power plant units are more efficient when being operated in baseload mode. Peak water boilers can be integrated to produce extra heat load, in order to cover the heat demands [7, 8, 22, 78–81].

The last twenty years, the driving technology in the field of electricity generation is gas turbines or engines. The developed gas technologies find application in large scale CHP plants and in small and microscale systems. The EU encourages CHP as an efficient energy production technology. CHP offers 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 RESs and CHP based heat generation for DH schemes [22, 55–58].

High proportions of renewable energy and CHP heat generation in DH is characteristic of those countries with high levels of DH penetration. Although amongst the EU member states only Poland reached a sizeable increase in absolute terms. Slovakia, Lithuania and Estonia made significant increases in RES based heat generation. Most newer 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. 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. Researches indicate that CHP based heat production is set to decrease 68–73% by 2030. Heat pumps represent the most flexible and interesting option for heat supply with good performance on all economic, environmental and energy efficiency viewpoints [78–82].

Gas turbines (GT). Gas turbines consist of an electricity generator, a gas turbine, several compressors installed on the same shaft and a combustion chamber. The electrical efficiency η_{el} of a GT usually ranges between 0.35 and 0.42. The typical range of electrical generation by GT rates from 1 to 40 MWel, and from 1 to 250 MWel for industrial turbines. The ratio of power to heat produced by GT is in the range of 0.5–2, which is considered to be one of the highest ratios compared to other systems. The high-temperature of the exhaust gases of the GT (>450 °C) allows the production of hot water and high- or low-pressure steam. However, the cost of electricity production by GT is higher than coal-burning technologies, mainly due to the price of gas. For that reason, GTs are used in cases of peak demand electricity [7, 8, 22, 55–57, 83].

Gas-steam turbines. Gas-steam turbines combined cycle (GTCC) have higher electrical efficiency comparing to GT. GTCC systems have the ability to further use their waste heat back to the process of the electricity generation. GTCC consist of a heat recovery steam generator (HRSG), a steam turbine and a condenser. The heat supplied in the DH network is produced by the condenser of the steam turbine, the waste heat exchanger and the exhaust gases boiler. The existing GTCC systems can achieve η_{el} up to 0.59. GTCC power plants are suitable for covering a large proportion of DH demands.

Gas engines. Reciprocating gas engines are widely used in CHP units, especially for small DH applications and individual buildings. These systems can provide 5–8 MWel of electrical power. Their electrical efficiency is in the range of 0.2–0.4, while their power to heat ratio is between 0.5 and 1. Furthermore, this type of systems considers being very competitive in terms of volumetric investment cost, compared to other thermal and power solutions. The heat recovery system uses the temperature of the exhaust gases, which is between 380 and 550 °C, and the engine cooling temperature, which is below 90 °C. Hence, they are most often used for low-temperature DH applications. Spark-ignition engines or diesel engines can also be used, but they require constant cooling of their engines. Usually, they are working in the base heat load and the peak heat demand is covered by water boilers. In some cases, heat storage is also installed in order to maximize the production of electricity in cases of which the base load production is not sufficient [7, 8, 22, 55–57, 83].

Fuel cells. Fuel cells enable the production of electricity and heat by the direct conversion of chemical energy of the fuel. They are characterized by higher efficiency rates compared to the traditional energy technologies formerly described. The achieved efficiency of electricity depends on the type of fuel cell used and usually ranges from 30 to 60%. The use of fuel cells in DH systems increases the efficiency of the fuel cells up to 90%. The operating temperature depends on the catalyst design and the type of electrolyte used and ranges from 50 to 200 °C and from 600 to 1000 °C. The generated electric power by current fuel cells ranges from 3 to 1000 kW and can reach up to 10 000 kW. Fuel cell technology is mainly used in applications of small and medium scale power systems. The power to heat ratio of fuel cells ranges from 0.5 to 1.4. The basic fuel used in fuel cell technology is hydrogen, but it is possible to convert other hydrocarbon fuels to hydrogen by the process of reforming. In combination with other technologies (gas, steam turbines) fuel cells can achieve electrical efficiency rates up to 60%. However, until now large scale fuel cell DH systems do not exist, due to the high costs of the fuel cell production.

In any case, fuel cells are the next most promising environmentally friendly generation technology which combines heat and power. Fuel cells operating as CHP plants could supply small DH systems, as an alternative to conventional power production. Initially, these will use natural gas as a fuel but in the future, the use of hydrogen may become more common. If hydrogen fuel has been derived from excess renewable energy, the fuel cell CHP could play an important role. As mentioned at the present, fuel cell technology is still under development, it is capable of operating in applications with a large power range and different kinds of fuel cells. The capital costs are still relatively high but cost reductions are predicted.

Micro CHP. Most of the installed combined heat and power (CHP) capacity worldwide is within large scale power plants, but with the increased focus on energy efficiency over the past years, small- and micro-scale CHP below 2 MW and 100 kW, respectively, has experienced considerable growth. Micro-scale CHPs are typical installations for single-family houses whereas small scale CHP can play a part in local DH thermal networks. The CHP technologies reviewed in literature are reciprocating internal combustion engines, micro gas turbines, organic Rankin cycle (ORC), Stirling engines, fuel cells, etc.

Different technologies have different characteristics regarding cost-effectiveness, part load ability, power ranges and efficiencies. Due to relatively low investment costs and current fuel and energy prices, the reciprocating internal combustion engine is the most widespread alternative for small and micro CHP today. Both of ORC and Stirling engines can have a future due to their ability to utilize low-temperature waste heat. Fuel cells have been considered relatively expensive for several years, and this seems to be the case still. Their need for very pure fuels, in order not to significantly reduce fuel cell component lifetime, makes it necessary with additional cleaning processes if they are to be run on biogas [84].

The CHP is highly flexible in its operation (daily modulation thanks to heat storage), and since its electricity generation follows the heat demand (higher in winter) it offers a good complement to PV in terms of equalizing the energy exchange between a neighbourhood and the grid.

2.2.8.2. Heat-only systems

Boilers. Heat-only boilers (HOB) are probably the oldest system of DH networks. They can be stand-alone, as a heat source in DH applications or they can be part of a greater heat system of power plants. The boilers use conventional solid fuels like coal, oil, natural gas, etc. However, one of the recent developments in this field is the implementation of boilers using two types of burning fuels; conventional fuels and biomass [84, 85]. Biomass is used as a fuel in the form of straw, wood chips, forest waste, biofuels and biogas. The thermal efficiency of a system ranges between 0.85 and 0.97. In addition, higher efficiency is achievable by gas-fired boilers, using exhaust condensation techniques. Solid fuel boilers with grate furnaces show the lowest thermal efficiency. Water boilers are characterized by long-term employment without a significant reduction of efficiency, as long as regular maintenance is provided. HOB can be used in small and medium-sized heating systems (<100 MWth), in which the use of CHP units is not profitable.

Heat pumps. Multi-stage heat pumps (compressor and absorber) and hybrid systems (absorption-compression) are often used in DH systems. The COP of heat pumps ranges from 2.5 to 5.5, depending on the cooling and temperature levels of the lower heat source, the properties of the working fluid (CO_2, NH_3) and the temperature range of the upper heat source in the heat pump. The COP of absorption heat pumps ranges between 1.7 and 2.3 for two-stage systems. Absorption heat pumps require high-temperature steam, gases or water as a lower heat source. The next chapter will focus on the details of heat pump integration into residential DH systems [82, 84, 85].

Geothermal heating plants. Geothermal DH plants are another example of RE use, where the thermal energy stored in the ground is used to supply the DH network. Geothermal heating plants are installed in depth of 800–3000 m underground where the temperatures range between 30 to 90 °C with low salt levels. Typical geothermal DH systems consist of heat exchangers (geothermal water/network water), a compression or absorption heat pump (for additional cooling of geothermal water) and a peak water boiler. Gas burners or hot-water boilers fired by gases or biomass are used for driving the absorption heat pumps.

RES and TES utilization in DH. Existing DH systems can be integrated with RE technologies, with small modifications and reasonable cost. The modifications require low-temperatures and the incorporation of a heat losses network. As mentioned before, out of the approximately 6000 DH systems in Europe, more than 250 are using geothermal DH technology, while it is estimated that over 25% of the EU population live in areas suitable for geothermal DH applications. Some of the RE sources used in DH systems are solar energy, geothermal energy, biogas and biomass. The ultimate goal of EU countries is their independence from FFs [22,86]. TES can be integrated into various ways in DH and such combination can be beneficial for heating and/or cooling applications. Improved charging and discharging rate make direct contact with the TES system more flexible in the DH network. In general, central storage is needed on a large scale DH network with complimentary local buffer storage close to each end user or group of users to smooth thermal load fluctuation [86-87]. The storage can be accomplished by using ground-based storage, combined with latent thermal energy storage, or the use of RESs for various storage modes. 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 RES technologies are 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.

Thermal storage technologies in DH play a very important role in achieving the European targets for renewable energy heat generation and energy efficiency. TES enables a higher proportion of renewables to be utilised and better efficiencies to be achieved by balancing the supply of RESs and the energy demand for an extended range of energy conversion technologies. Combining heat pumps with seasonal TES has many advantages for both large and small applications [88]. TES can enlarge the proportion of renewable energy and heat pumps in the energy supply of DH and cooling. TES allows the use of long term hot or cold storage for seasonal accumulation or short-term storage for periodic excess energy accumulation for supplying DH 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 TES applications in a heat pump based DH [88, 89].

Depending on the time when the heat is needed from the storage, a typical classification is made between short term storages and seasonal storages. Short-term storages balance the heat supply and demand of a few hours or a few days. They are also called buffer tanks. Seasonal storages are much larger, as they balance the heat supply and demand from one season to another. This is mainly applied for storing solar thermal heat from summer to wintertime.

Storage technologies can help to detach the production from the demand and to balance (buffer) fluctuations of energy production. Storages increase the flexibility to utilize sources of energy that are not available at the same time as the demand. They can also store cheap energy, e.g., low prized electricity that can be converted to heat. Furthermore, storages help to increase the efficiency of production units [90, 91]. They enable, e.g., biomass boilers and CHP plants to operate continuously at a higher capacity.

There are many thermal energy storage technologies for DH. Seasonal storage is more complex and expensive compared to short term storage. In heat pump based DH systems, TES has a buffer function too, which allows the integration and management of different heat sources, in order to store excess energy and to cut off or shift peak energy demands [92]. 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 [93]. 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.

The purpose of the storage is to produce heat or cooling while the production conditions are as effective and favourable as possible, e.g., production of solar thermal during the day or production of electricity while electricity prices are high in relation to CHP. The size of the storage depends on the time and amount of stored energy [86–93]. The following types of storage technologies exist:

- **Sensible storage:** use the heat capacity of the storage material. The storage material is mainly water due to its high specific heat content per volume, low cost and non-toxic media.
- **Latent storages:** make use of the storage material's latent heat during a solid/liquid phase change at a constant temperature. They use phase change materials (PCM).
- **Thermochemical storages:** utilize the heat stored in a reversible chemical reaction.
- **Sorption storages:** use the heat of adsorption or absorption of a pair of materials such as zeolite–water (adsorption) or water–lithium bromide (absorption).

Heat pump technology in DH gives an opportunity of using heat and electricity from waste and a wide variety of RESs. RESs 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[94]. This aspect coupled to the need for flexibility with DH 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.

2.2.9. Scales of DH systems

As mentioned, traditional DH is a system where the heat is produced centrally and distributed by a network. A DH network with water as the medium of heat transfer can be divided into the generation side where there are different facilities of heat production as shown in Fig. 2.13. The generation side is connected to a DH transmission network of pipes covering a distance to the distribution network, where the heat is finally used by the end consumers. The size of a typical DH network may range from a residential building connected to a regional or an entire city, independent of the building types [10, 85].

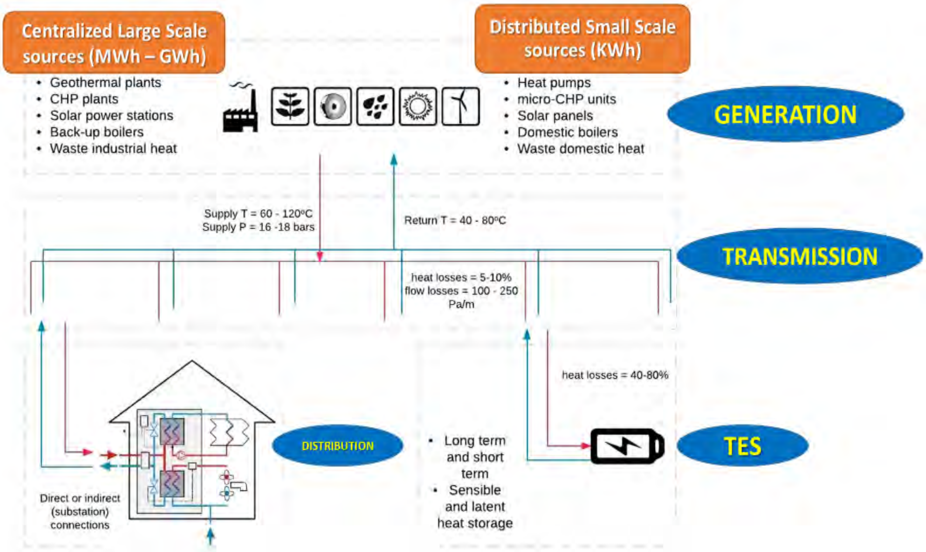


Fig. 2.13. Size of generation, transmission and distribution of typical DH [10]

DH system can vary in all sizes, it can be differentiated due to scale as small or large from covering a large area like big cities to a small area or village consisting of only a few houses [11, 13, 58]. In large DH systems, the DH network may consist of both, a transmission part of the network where the heat is transported at high-temperature/pressure over long distances, and a distribution part where the heat is distributed locally at a lower temperature/pressure. 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. 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. These distances can be extended by installing additional local and onsite heat sources along the way [7, 8, 22, 74].

2.2.9.1. Small DH

Small modular DH and DC networks are local concepts to supply households as well as small and medium industries with renewable heat and/or cool. In some cases, they may be combined with large-scale DH networks, but the general concept is to have an individual piping network which connects a relatively small number of consumers. Often, these concepts are implemented for villages or towns. They can be fed by different heat sources, including solar collectors, biomass systems and surplus heat sources (e.g., heat from industrial processes or a biogas plant that is not yet used). A principle of these networks is presented in Fig. 2.14. Fossil fuel boilers could be installed for peak requirements or thermal loads and as a backup option in order to increase the economic feasibility of the overall system. Small networks do normally have commercial operators and are larger than micro networks [84, 85].

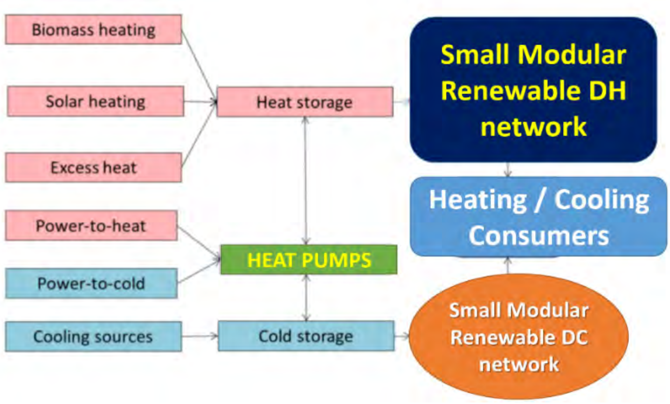


Fig. 2.14. The principle of small DH and cooling networks

2.2.9.2. Micro DH

Micro DH usually the installed heating/cooling networks for fewer customers, e.g., 2 to 10. An advantage of micro-networks is that these systems could be built easier and faster, because of the small amount of the customers. The customers will be supplied by heat/cool on the base of agreements with the customers and due to suitable accounting estimations and business model including who will be the operator of the system [85]. Apart from the network size, it is important not to oversize the network during planning. Large dimensions of the network cause higher heat losses and higher investment costs.

There is a characteristic factor called heat density of the network, which is calculated by the annual sold heat (MWh/a), divided by the length of the network (in meter, length of water pipeline). A common rule says that this factor should be at least 900 kWh/m per year. The goal should be to sell a high amount of heat at a network with a short length. In case that the heat density of a potential network is too low, individual household heating systems may be preferred. Nowadays in the EU, it is common to build small or microscale DH networks, where all components would be designed to maximize the use of heat pumps [7, 8, 22, 54, 85]. The main barrier for small and microscale DH is the accessibility to a stable and efficient heat source, in case if a heat pump will be used.

2.2.10. Temperature ranges and heat generation technologies

From the evolvement of the DH generation systems through the years and the definition of the 4GDH, one can observe that the main parameter in focus is the temperature level which is a function of outdoor temperature. The temperature level of the DH system has been steadily decreasing since the first DH generation steam-based systems [22, 52, 95, 96].

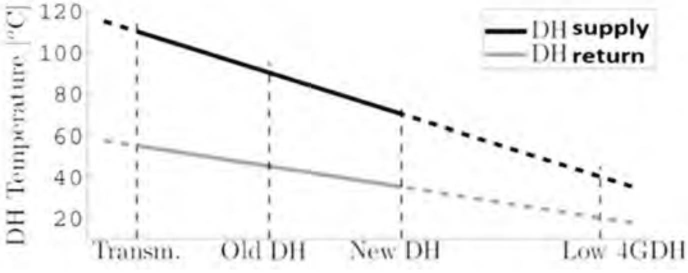


Fig. 2.15. Trends of DH networks water supply and return temperatures [95]

Figure 2.15 shows the temperature ranges for water supply and return temperatures in DH evolution. A qualified estimate of the relation between supply and return stream temperatures were found by interpolating temperatures for the range of supply from 110 to 70 °C and return from 55 to 35 °C as presented in Fig. 2.15. The lower limit for DH temperatures, with water as the working fluid, may be considered the 4GDH concept [97–99].

2.2.11. Transition to the 4GDH

From a historical perspective, traditional DH distribution technologies went through four generations with the following energy efficiency and temperature ranges, the summary of DH evolution scopes are presented in Fig. 2.16 [7, 8, 58, 74]:

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

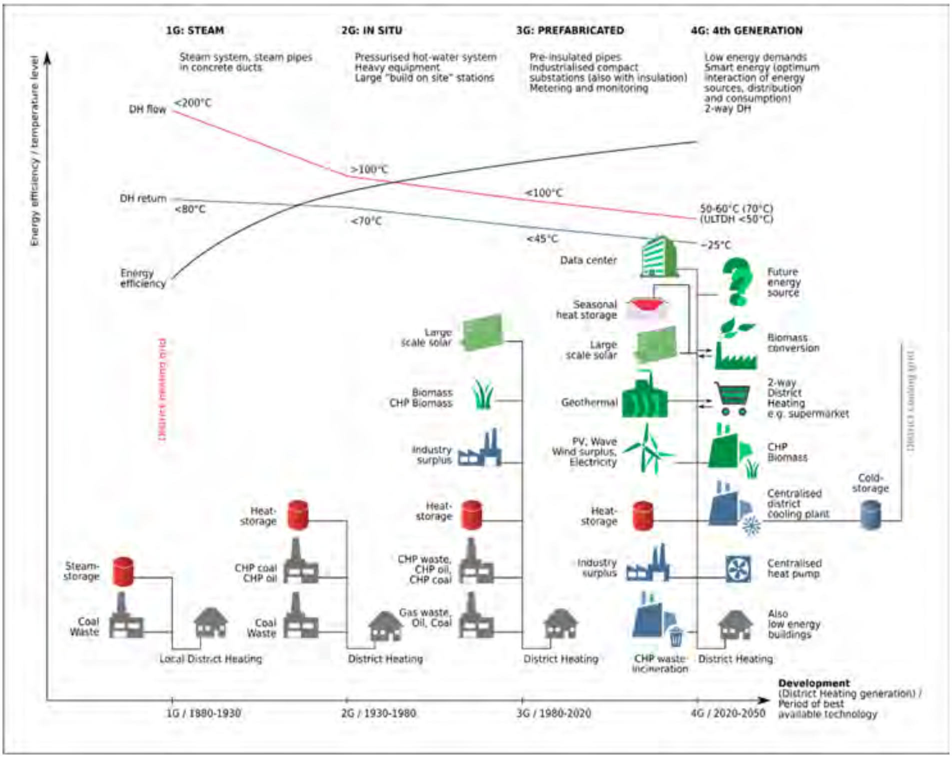


Fig. 2.16. Summary of DH and energy evolution toward 4GDH system [2, 58]

In the historical development of DH, the first three generations of DH developed successively. Almost all DH systems established until 1930 treated as the first generation DH used steam technology as the heat carrier. The typical components were steam pipes in concrete ducts, steam traps, and compensators. This generation characterized by a high-temperature DH. The second generation DH systems used pressurized hot water as the heat carrier, with supply temperatures mostly higher than 100 °C. Typical components were water pipes in concrete ducts, large tube-and-shell HXs, and material-intensive, large and heavy valves. These systems emerged in the 1930s and dominated all new systems until the 1970s. The third generation DH systems still use pressurized water as the heat carrier, but the supply temperatures are often below 100 °C. Typical components are prefabricated, pre-insulated pipes directly buried into the ground, compact substations using plate stainless steel HXs, and material lean components. The systems were introduced in the 1970s and took a major share of all extensions in the 1980s and beyond [62, 99].

The development direction of these three generations has been in favour of lower distribution temperature, material-lean components, good insulation and prefabrication. On the basis of the trends identified above, the future DH technology should include lower distribution temperatures, assembly-oriented components, and more flexible materials [62, 97–99]. The revolutionary temperature level, with supply temperature below 50–60 °C, will become the most important feature of the 4GDH, so the energy supply system, end consumers, and occupants will benefit from the low-temperature level of DH.

Some authors [11, 28, 58] described the following challenges that the future 4GDH system needs to meet:

- Ability to supply low-temperature DH for SH and DHW to existing buildings, energy-renovated existing buildings and new low-energy buildings.
- Ability to distribute heat in networks with low losses in the DH network.
- Ability to recycle heat from low-temperature sources and integrate RESs such as solar and geothermal heat.
- Ability to be an integrated part of smart energy systems (i.e., integrated smart electricity, gas, fluid and thermal grids) including being an integrated part of 4G district cooling systems.
- Ability to ensure suitable planning, cost and motivation structures in relation to the operation as well as to strategic investments related to the transformation into future sustainable energy systems.

Transition to the 4GDH is a challenging issue. The process requires the upgrades of the DH system and the collaboration with other energy systems. In addition, buildings may also need more refurbishment to coordinate the changes in those systems. The final goal of the transition is to make the future DH system more flexible, reliable, intelligent, and competitive, and become an essential part of the future smart and RES based system [62, 96–99].

2.2.11.1. High-temperature systems

In general, traditional European DH systems depend on FFs, being large, high-temperature systems for distributing heat generated in centralized units [96–100]. The bigger the difference between flow and return temperature (differential temperature), the better it for the heat supplier is. A high differential temperature reduces the mass flow and the heat losses of the DH network. In addition, the power consumption of the pumps is reduced. The flow temperature of the network can be higher or lower, depending on the outside temperature as it is shown in Fig. 2.17.

A high-temperature DH system is operated with hot water above 90 °C. High-temperatures cause higher heat losses and shorter life of the DH network. The heating plant should be located close to the industrial users that need the high supply water temperature of the DH system.

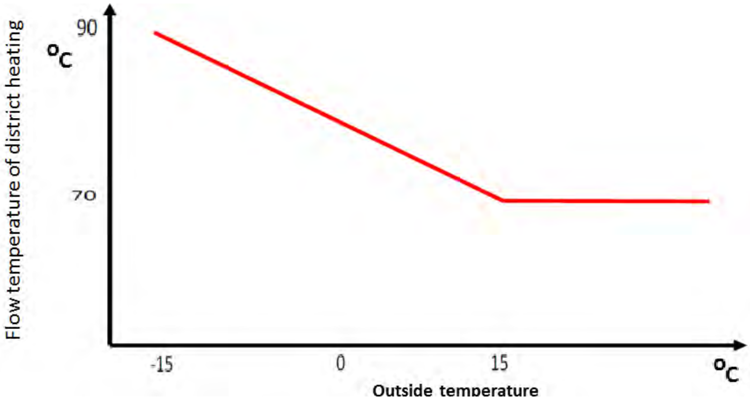


Fig. 2.17. Flow-temperatures of a DH network depending on the outside temperature

Among the disadvantages of high-temperature DH 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 DH systems can also preclude some technologies [53, 54, 62–68]. 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.

2.2.11.2. Medium temperature systems

Medium temperature systems are the most common systems. The flow temperature ranges from 65 °C to 90 °C. These temperature levels are often used for space heating and to provide DHW for the buildings (e.g., residential, office or public buildings). Existing old buildings often need flow-temperatures of 80 °C and more. Newer buildings could use flow-temperatures between 50 and 70 °C, depending on the status of their insulation and on which heating system they have installed (e.g., floor heating). To produce DHW, the flow temperature of the DH needs to be at least 65 or 70 °C for the whole year in order to prevent the growth of Legionella which can cause health diseases [62, 55, 58].

2.2.11.3. Importance of low-temperature systems

Controlling and monitoring the supply and return flow of the DH system is important. The amount of heat utilised from the DH system depends mainly on the design and adjustment of the buildings' internal space heating systems, but also on the performance and the condition of the DH substation. Decreasing the DH return flow-temperature (i.e. more heat subtracted) and good performance of the DH substations are in the interests of both the heat consumers and the heat supplier.

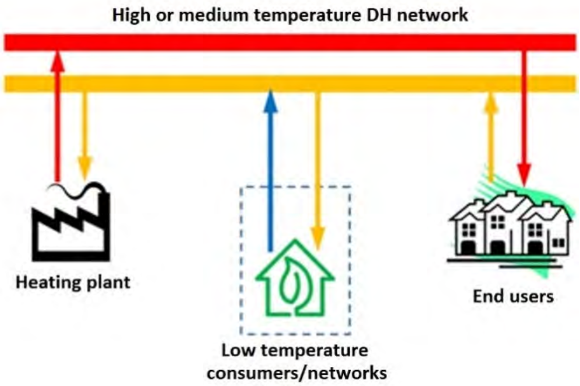


Fig. 2.18. Usage of return temperature for low-temperature customers/networks

Low-temperature systems can also be used as subsystems in high or medium temperature networks as shown in Fig. 2.18. The return pipe can be used as the flow pipe for the low-temperature system. After using the heat, water can be returned through the return pipe.

The return temperature on the customer side should be reduced, and thereby the return temperature of the DH system, which is the important goal of the DH temperature range. This results in lower mass flow, pumping costs, lower heat losses and higher heat load capacity of the DH network. That is the reasons why DH operators should review the hydraulic scheme of the customers and encourage the consumers to adapt their heating installation to reduce the return temperature [62, 88, 96–100].

Depending on the temperature level, there are several possibilities for connecting distributed heat sources. The most common and with the highest potential is a return-supply connection, where water from the return line is heated to the supply temperature and pumped into the supply line. There are several examples of successful utilization of distributed heat sources, however, it is important to consider how to secure a stable connection for both pressure and temperature.

2.2.11.4. Trends to low and ultra-low-temperature DH system

DH technology can be categorized according to the temperatures range of the system it uses, modern DH systems are often based on lower temperatures, which ensure increased efficiency in both heat production and heat distribution.

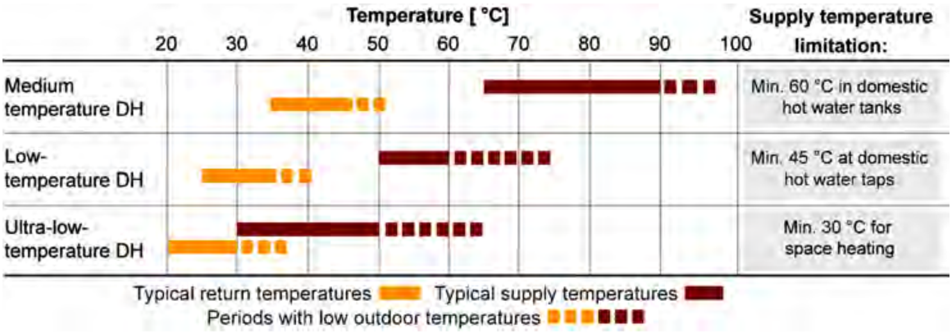


Fig. 2.19. The limits of DH temperatures set by residential customer demands

Figure 2.19 illustrates the temperature limits of the DH network for residential demands, these demands consist of the possibility of maintaining an indoor air temperature of up to 22 °C. To achieve an inexpensive transition to a new sustainable energy system, the future DH system should, therefore, be based on temperatures that are lower than the current DH temperatures of around 80–85 °C for water supply and return. Low-temperature DH systems can also increase the flexibility of the energy system by using heat pumps, solar energy and large TES.

According to the principles of 4GDH, the efficiency of the advanced generation of DH systems can be increased significantly, if they are operated with low supply and return temperatures as is shown in Fig. 2.16. DH temperature reduction has two positive effects on the energy efficiency of the heat supply. Firstly, when the DH temperatures are reduced, the heat losses from the pipe networks are also reduced. This can generate significant energy savings, as the reductions in heat loss can be estimated to 30% when supply and return temperatures are reduced from 80/40 °C to 60/30 °C. Secondly, the efficiency of the heat production is increased for heat sources such as geothermal heat, heat pumps or solar heating. The efficiency of the heat production is estimated to increase by approximately 10% in solar thermal plants and 30% in heat plants supplied by heat pumps if supply and return temperatures are lowered as mentioned above. Additionally, the heat production efficiency is increased when return temperatures are lowered in heat plants with flue gas condensation supplied by natural gas or wet biomass. The reduction in the DH temperatures can amount to significant total energy savings. Consequently, the smart DH system has greater advantages than the traditional heating system in many aspects (e.g., energy saving, regulation and control, troubleshooting), and it shows great development potential and broad market prospect in the future.

2.2.11.5. Monitoring temperature levels

The monitoring of temperature levels helps to reduce the flow and return temperatures of the DH, and at the same time to maintain a large differential temperature. In order to minimize heat loss in the DH network, to optimize the heat production, to save fuels, and to reduce CO_2 emissions, many DH plants use temperature software optimization. The advantages of lower temperatures in DH networks lead to: more technical flexibility, to lower distribution losses, which gives energy savings and lower fuel costs, higher integration possibilities for heat pumps, lower electricity supply and an improvement in heat storage possibilities [56, 57], simultaneously allow to use a larger range of heat sources including more RESs and surplus heat from industrial processes. Low-temperature DH is not considered to be more expensive to build than conventional DH [22, 58, 74, 101–103].

It is necessary to mention that the heat pump technology and the corresponding design solutions can be easily integrated into 4GDH. With the 3GDH 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 2GDH systems, the heat pump can support only the central conventional heat source, for example, they can provide the heat for DHW 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 [22, 74, 101–105].

Currently, in EU countries, it is clear that DH supply-return line temperature ranges are characterized by a great diversity due to the applied technologies at the national level. It is also evident currently that low-temperature DH 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 [7, 8, 22, 54, 68, 102–107].

Low-temperature DH can operate with supply line water temperatures in the range of 50–55 °C or 60–70 °C with return line water temperatures of 25–40 °C and meet heating requirements for SH and DHW 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.

2.2.11.6. The heat pumps and temperature range due to heat generation technologies

It is obvious that heat pump technology does not cover the entire working temperature range in European DH systems. Thermodynamic constraints do not allow to achieve the parameters needed for high-temperature DH, especially in peak periods for the heat requirements.

Figure 2.20 shows an overview of DH water temperature ranges from the heat generation technologies used for high- and low-temperature DH. The comparison with conventional and renewable heat sources defines the ability of heat pump units to be used and integrate with the DH network. 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 DH system. The type of heat source for a heat pump determines the water supply temperature. Water, ground or air source heat pumps can provide heat for low-temperature DH from the air, seawater, river water, waste, sewage, shallow geothermal, etc. Supplying high-temperature DH requires special solutions like industrial waste heat or deep geothermal sources, which limits their use.

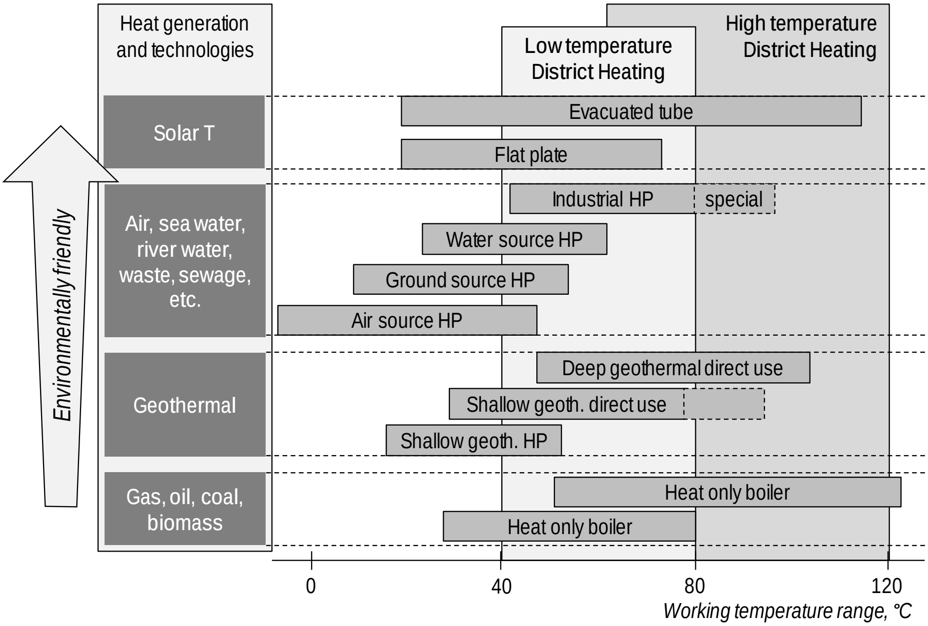


Fig. 2.20. Overview of DH temperature range due to heat generation technologies and sources [8]

Low-temperature DH enables the use of low-grade heat sources and the absorption of more thermal energy from these sources by using different heat pump technologies [7, 8, 22]. From Figure 2.20 it is clear that low-temperature DH has several advantages. First of all, it ensures energy efficient supply and increases the utilisation of RESs and heat pumps. Low-temperature DH networks allow access to different heat sources to increase the flexibility in matching heating requirements with the 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 DH systems with heat pump technologies are fully competitive, but for high-temperature DH systems, the heat generation technologies (mainly fossil fuel) are very limiting for heat pumps. However, development trends of DH show a preference application of heat pumps because they allow the use of so far unnoticeable waste heat sources or inaccessible heat sources for DH. Heat pumps contribute also to reduce GHG emissions and they integrate RESs and to decarbonize the DH system [52,108].

2.2.12. Scope of solar DH systems

Solar thermal technology is commercially available to meet heating demand in the ranges of lower temperatures. Compared to DHW systems, considerably larger collector areas and storage tank volumes are required. However, solar heating has been developed for large-scale to be commercial heat source in European countries like Denmark, Germany in a mild climate zone. Solar thermal systems have been applied in Europe since the early 1980s, there are numerous solar DH projects which contribute to DH networks. Most notably in Scandinavian countries (Sweden, Denmark) but also in Austria, Germany, Spain and Greece a number of large scale solar applications >350 kWth (500 m^2) exist. Large scale solar thermal systems connected to heating or cooling networks were in operation in Europe by 2015 [109–114]. The total installed capacity of these systems equals 694 MWth (equal to 991 000 m^2). However, compared to the cumulated installed solar thermal capacity in Europe, these large scale applications only cover a small niche segment with a market share of around 2%.

Denmark is the only country worldwide, where a commercial market for large scale solar thermal plants connected to thermal networks could establish. By October 2015, seventy solar DH plants with a total installed capacity of 531 MWth (759 000 m^2) were in operation (more than 3/4 of the total installed capacity in Europe). Average system size calculates to 7.6 MWth (10 850 m^2).

Urban environments provide a wide range of possibilities for the hydraulic integration of solar thermal systems. Basically, solar thermal systems can be attached directly to the individual buildings (residential or non-residential) and they are hydraulically connected to a thermal network (as a block heating or DH network) to supply multiple buildings by heat. The utilization of solar energy by means of solar thermal collectors is for DHW preparation and SH purposes. Solar

PV is partially considered as optional heating technology in combination with electrical heaters or heat pumps [112–116].

2.2.12.1. Classification of urban solar DH systems

From a technical point of view, a large variety of various concepts for the hydraulic integration of solar thermal systems in urban environments exist. Solar DH network can be defined as a network of pipes connecting buildings in a neighbourhood, city quarter or whole city, so that they can be served from centralised and/or distributed thermal energy supply technologies (such as boilers, CHP plants, solar thermal systems, heat pumps, waste heat from industry, etc.) [64, 112–118]. Depending on the size of the network it can be distinguished between larger DH networks (solar assisted heating for communities up to whole cities) and smaller or block heating networks (smaller networks for solar heat supplying for multiple buildings in a neighbourhood). Most commonly applied solar thermal system concepts suitable for urban applications are two basic schemes: central and distributed solar DH as they are presented in Figs. 2.21 and 2.22.

Depending on space availability, the solar collector installation can be mounted on the ground or on buildings' roofs. Most of the realized solar DH plants have short term (diurnal) storages attached in order to utilize the thermal energy gains from the sun most efficiently [112–117].

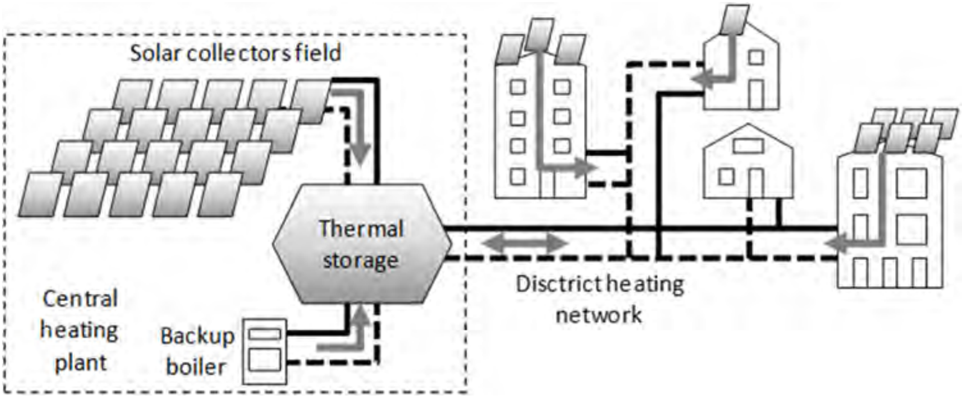


Fig. 2.21. Central solar DH [64]

In the central solar DH, large field of solar collectors feeds the long term thermal storage in parallel with a backup boiler and the solar collectors on the building roofs convey heat to the DH network as in Fig. 2.21. Solar heat from the field of solar collectors feeds the long term thermal storage in the period of excess solar heat (e.g., in summer). The stored heat is used in DH during the deficit of solar energy (in winter). In the distributed solar DH, the field of solar collectors feeds the DH network by heat. The heat from solar collectors on the roofs of the buildings is consumed locally relieving DH as in Fig. 2.22.

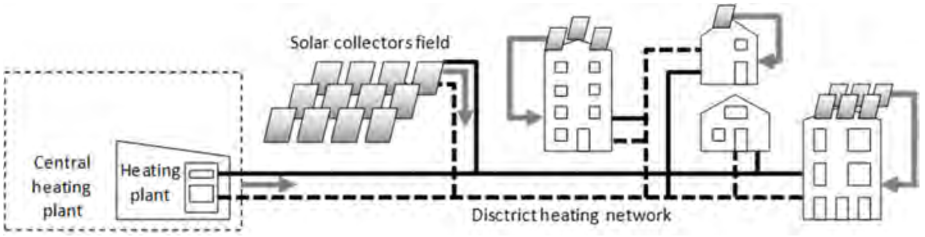


Fig. 2.22. Distributed solar DH [64]

In the case of solar assisted DH, solar thermal systems are part of larger DH systems consisting of widespread pipe networks and various distributed (mainly RESs) energy conversion technologies and storages [112–118]. Best practice examples show that solar thermal system may be centralized (close to the boiler house/heating plant) or distributed (at different places of the thermal network) to supply only the building (DH as back up) or to supply both the building and the DH network (bi-directional thermal feed in) [112, 116–120].

2.2.12.2. Technical parameters of the solar DH system

There are several technical and economic parameters which are elaborated for the whole solar thermal system as a solar loop and solar energy storage. Of course there are more investigated parameters (which are not ranked according to importance) like size and kind of solar collector field, annual solar DH system yield, connection to DH network, heat demand, heat prices, storage capacity, land value and space availability, experience of the DH utilities, etc. [121–123].

In general, the solar energy yield is referred to as specific annual useful thermal energy delivered by the solar thermal system in kWh per m² gross installed collectors area (where the thermal losses in the piping of solar loop and thermal energy storage are considered). Solar fraction (*SF*) is a key factor and defined as the share of annual useful solar thermal supply E_{solar} to the total thermal energy supply (E_{solar} + E_{aux}). SF considers the share of heat delivered to the DH network which is converted by solar heat, *SF* is the ratio of net solar energy gain to total heat demand in the DH system [64, 124–127]. SF varies from one DH plant to another, but most values are concentrated around approximately 20%, *SF* can be defined as follow:

$$SF = \frac{E_{\text{solar}}}{E_{\text{solar}} + E_{\text{aux}}} \tag{1}$$

Due to the best practice solar assisted DH installations SF range from very low (<2%) for solar DH plants without storage (e.g., several examples for distributed solar feed-in DH networks in Austria) up to 5–15% for solar DH plants with short-term (diurnal) storages (e.g., most of the Danish solar DH plants [121], as well as solar, assisted biomass heating plants in Austria and Germany [122]). Higher SF around 45–55% can be reached if seasonal storages are installed [123, 124].

2.2.12.3. Solar assisted heating

Individual buildings. Solar assisted heating is commonly applied in many countries all over the world for residential and non-residential buildings (e.g., single and multi-family houses, terraced houses, apartment blocks, hotels, schools, hospitals, production halls, etc.).

Characteristic applications for solar heating are integrated with the building (solar collectors on-roof, in-roof). These applications supply the building's with thermal energy directly for DH network for either DHW or both of DHW and SH (the latter are referred to as solar combi-systems). Usually, this kind of solar thermal applications in buildings is a part of bivalent or multivalent heating and cooling systems including a thermal (diurnal) storage [64, 112, 125, 129].

Multiple buildings. In dense urban areas, multiple buildings and up to whole cities may be attached to building block or DH networks. Compared to the heating of single buildings, thermal networks provide several advantages such as the spatial separation of thermal energy conversion and thermal energy demand, the utilization of various heat sources within one connected system or the utilization of waste heat from CHP plants and/or from the industry [124].

2.3. Toward smart DH system

Recently, the terms smart energy and smart energy systems have been used to express an approach that reaches broader than the term smart grid. Where smart grids focus primarily on the electricity sector. Smart energy systems take an integrated holistic focus on the inclusion of more sectors (electricity, heating, cooling, industry, buildings and transportation) and allow the identification of more achievable and affordable solutions to the transformation into future renewable and sustainable energy solutions. Focusing only on the term smart electricity grid reduces the potential for fluctuating RES, it is essential to integrate smart electricity, smart thermal and smart gas grids to enable 100% renewable energy.

Traditionally, significant focus is put on the electricity sector alone to solve the renewable energy integration puzzle [130–133]. In addition, smart grid research traditionally focuses on information communication technology (ICT), smart meters, electricity storage technologies, and local (electric) smart grids. In contrast, the smart energy system focus on merging the electricity, heating and transport sectors, in combination with various intra-hour, hourly, daily, seasonal and biannual storage options, to create the flexibility necessary to integrate large penetrations of fluctuating renewable energy. The smart energy system concept is essential for 100% renewable energy systems to harvest storage synergies and exploit low-value heat sources [133].

Design of smart DH solutions is essential for the implementation of future sustainable energy systems for first, savings in heat demands and heating infrastructures in the form of DH, which have an important role to play in the task of increasing energy efficiency and thus making scarce resources meet future demands; and second, the heating sector carries one of the most important and least cost options of integrating fluctuating RESs into the overall energy system. To enable this, a holistic smart DH must coordinate between a number of smart grid infrastructures for different sectors in the energy system, which includes electricity grids, DH and cooling, gas grids and different fuel infrastructures.

The 4GDH will be available in the coming years. However, one of the main ideas of smart DH system is shown in Fig. 2.23. The main features of smart DH are characterised by low and even ultra-low temperatures, various or multi-heat sources, TES, intelligent management, and integration with smart DES, the transition from the current 2nd or 3rd generation to the future 4GDH is a challenging task. The technical issues associated with the transition to the 4GDH systems are following: supplying low-temperature to new and existing refurbished buildings, integrating various heat sources including mainly renewable and recycled sources, different TES technologies, and smart DH systems [131–136].

The idea of designing a new smart generation DH is to develop a flexible, predictable and secure energy supply, transmission and distribution system with effective integration of energy-efficient buildings and low-temperature energy sources, to provide more diversified heat supply options, greater heat supply efficiency, and greater heat distribution efficiency [133–136]. The transformation toward the future renewable energy system poses a challenge for all the subsystems. Facing the challenge, all the subsystems should benefit from the use of modern IC technologies, and uprated themselves to become smart systems.

Each smart grid of the future will encompass different goals, expectations, and assumptions. The heat grid or the thermal network is a very complex arrangement of infrastructure that interacts with natural laws. Its functioning depends on a large number of interconnected elements (monitoring, control, protection, telecommunications, etc.). A smart grid vision, which will further develop into specific applications and investments, needs to follow from clearly defined energy sector goals. Two main subsystems are involved in smart DH system, the physical system as well as the virtual system [62, 99, 107, 134–136]. They are concerned with two main structures – a physical security structure and integrated cybersecurity structure. The simplified visualization of the smart grid with its major layers are:

- **Hard layer or physical infrastructure** or all the physical components of smart DH network, such as the generation, transmission, and distribution assets that produce, transport, and deliver energy to the consumers. This layer includes all generation technologies.
- **Telecommunications layer** that is, all communications services that enable applications to monitor, protect, and control the network. This layer includes all forms of communication from wide area networks, field area networks, home area networks, and local area networks, optical fibre, leased lines, wireless communications, mesh radio, Wi-Fi, and others.
- **Data management layer** with the abundance of data and information across various levels.
- **Smart applications layer** or the tools and software technologies that use and process information collected from the network to monitor it, protect and control the hard infrastructure layer, and reinforce the network to allow the participation of all forms of RESs, as energy storage facilities.

The main three essential parts of smart DH system consists of the infrastructure of the physical network (PN), internet of things (IoT), and intelligent decision system (IDS). PN includes pipes, heating equipment, local meters, and control devices. IoT is the network of sensors, data collecting and transmission devices, and other items, which enables these objects to be connected and exchange data. IDS makes the optimal decisions based on collected data, heat demands, and system responds, the main parts of smart DH concept is shown in Fig. 2.23.

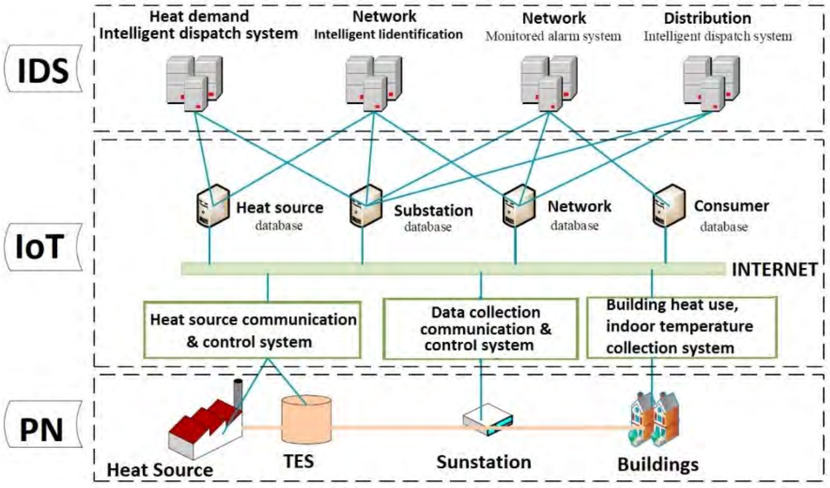


Fig. 2.23. The main idea of smart DH system [62]

The final goal of the smart DH system is to become an essential component and integrated part of the future smart cities. In the future smart energy system, the focus will be on the integration of the electricity, heating, cooling, and transport sectors and on the use of flexibility in demands and coordination with various storages of different sectors in smart cities [62, 99, 127, 133].

2.3.1. Upgrading toward smart DH system

The upgrades of the DH system involve the physical system as well as the virtual system. For the physical system, the transition will focus on lowering the system temperature levels and integrating various heat sources with RES and TES. Two steps will be conducted to lower the temperature level. The first step is to achieve the temperature potentials of the current DH system by the means of eliminating system errors and improving system control. The second step further is to reduce the temperature levels through enhancing heat transfer performance of heat exchangers and improving DH system design. The building's renovation as a priority need may also be conducted through those two steps when it is necessary. Various heat sources and different sizes and configuration features of TESs will be integrated into the future smart DH system. Transition to 4GDH should take into consideration all the consisting issues such as the way of heat feed-in, type of heat sources and TESs, distribution heat losses, the design of DH system, and operation strategies. Finally, the decisions should be made depending on the local natural and economic conditions. For the virtual system, the transition toward smart DH will be based on the intelligent physical system, which is able to measure, transmit information, collect data, and control [130–133]. In addition, IDS will become more powerful with advanced functions in the future DH system, such as the reliability assessment, accident analysis, accident alarm, operation evaluation, operation supervision, and operation optimization. The potential solutions involve innovating system design, upgrading physical and virtual systems, integrating energy efficient, economical heat sources, and the feasibility for introducing new heat requirements or thermal demand.

Comprehensive consideration must focus on the energy status, condition of the existing infrastructure of energy systems, and the operation custom in different regions or countries. In addition, the technologies for the future requirements need further development, and the operational energy savings, as well as management strategies, should be innovated, the transition to the future DH generation should be conducted carefully and gradually, including the evaluation of how smart DH systems can be integrated into the smart city concept [134–136].

2.4. Third party-access to DH

The supply of the heat produced by other producers to the network is called third-party access (TPA).

- TPA on a wholesale level for producers allows access to the DH network for third parties (eligible producers) to feed-in heat. The owner of the network/single supplier buys the heat from multiple competing producers and transport the heat to the DH consumers.
- With TPA on a retail level for suppliers, third parties are not only granted access to feed-in heat but also to transport heat to consumers. In the first case,

only competition between multiple producers is introduced, whereas in the second case also competition between suppliers is created, allowing consumers to choose their own supplier.

It is important to understand the means of TPA for understanding the utility markets such as electricity, gas and water and the possibilities of integration with the open access in DH networks. However, part of the heat market is supplied by a third network industry, DH, which provides a market for several competing types of fuels and technologies, including natural gas, various types of biomass combustion including incineration of urban waste, and CHP. For example, approximately one-third of all annual district heat produced in Finland is purchased from third party producers, such as industrial CHP plants and waste heat sources [57, 137].

Similar to natural gas, DH is an important network industry in a number of countries (e.g., Sweden, Finland, Denmark, Austria, Lithuania, etc.). In these countries, DH represents an efficient technology for providing space heating and DHW. Still, although the DH sector shares many of the above network characteristics, market opening and TPA in this industry has so far not been addressed to the same extent. TPA is currently based on voluntary agreements between the third party producers and DH companies.

It is mostly argued that the distribution of hot water in a DH network constitutes a natural monopoly. However, if the production of heat is not considered to be a natural monopoly, TPA can be an interesting alternative to price regulation. A regulated TPA to the DH network requires means of separation between the production and distribution of hot water to the DH network, as well as the introduction of competition at the production stage.

2.4.1. Current status and TPA access

During recent years, though, appeals for the introduction of TPA in DH have become more frequent, not only in Sweden but in other European countries too. Since DH networks also offer the possibility of competition between natural gas and electricity in the market for space heating the economic efficiency of the DH sector is critical to a synergetic use of various energy carriers.

However, a number of clients in some European countries have switched from DH to other heating methods, which proves that there is competition in the market. Currently, this competition is affected by various energy policies that impact customer preferences of the selected heating method. Such policies include fossil fuel taxation, emissions trading, energy labelling of buildings and building energy and environmental codes that are in place to promote the use of renewables and energy efficiency. Numerous studies have shown that alternative heating methods are competitive against DH networks. In general, there is no obligation to connect to DH and the customers can disconnect from it in short notice, which means that sellers of district heat have the incentive to keep the price of DH on a competitive level.

2.4.2. Competition features and district forms of TPA

TPA in general means the separation between generation and retailing of DH in order to open up the network for more competitors. This is one of the suggestions that have been addressed in order to increase competition in the market. The electricity market is an example of where TPA has been established in Sweden. The overall conclusion of the electricity market reform has been that it has been relatively successful, given that competition has increased and as consequence prices have decreased. This is one important reason for the proposal of introducing TPA in the Swedish DH market. However, there are substantial differences between the electricity and the DH markets, which imply that it is not obvious that TPA in the DH market necessarily implies increased competition, so the interface between these two markets is an essential issue. The main obstacle for the DH market is that each DH network is local, thus implies that even if the market is opened up for competition it will only create a situation with few firms.

Large scale DH networks have some characteristics that are similar to the electricity market. Although there is no example of an urban DH network with full feature of TPA and competition between many suppliers, there are examples of unbundling between competing heat producers using a variety of primary fuels and technologies, a monopoly transmission company, and several local distribution companies. The latter may be subject to various elements of competition, in particular competition between local heat production and heat purchase from the heat transmission network [135–138].

Furthermore, if industrial waste heat can be recovered it is also very beneficial for the environment. The studies found that allowing TPA is technically feasible, but it requires substantial investments, thus the results concluded that allowing TPA would increase the costs for the consumers, and only will increase the competitive situation marginally. The only technology that is competitive in the above mentioned analysed networks is waste heat from either industry or from data centres. In the large fossil fuel based network, waste heat from the service sector, industrial size biomass boilers and deep geothermal heat were also considered competitive.

However, there are several different forms of TPA, which are all compatible with the above mentioned general definition. It found that it is useful to distinguish three different TPA types, which mainly differ in degree of openness, generally, TPA implies that *a third party can access the DH networks in a non-discriminatory way*. Within this definition, a distinction can be made between three models which are: regulated TPA model, negotiated TPA model and single-buyer model.

- **Regulated TPA.** Implies the owner of the networks has a legal obligation to allow access to the networks. When the conditions for access, which are determined in advance, ex-ante, are met by the third party, access is provided by the owner of the network.
- **Negotiated TPA.** The owner of the network is required to negotiate with producers about access to the network and, in contrast to regulated TPA, the access conditions are regulated ex-post. Besides the distinction between regulated and negotiated TPA, the degree to what TPA is introduced can be distinguished in TPA on a wholesale level for producers and TPA on a retail level for suppliers.
- **Single-buyer TPA.** Multiple producers are granted access to the network and supply heat to the single-buyer, who then distributes it to consumers. The single buyer ensures that demand is met, either by producing its own heat or by buying it from independent producers.

2.4.3. Implementation of TPA in DH

TPA can be implemented in the DH network in various ways. TPA can be realised without regulation based on voluntary agreements, auctions for production and heat capacity and other measures for setting transparent market places. On the other hand, many TPA models can result in requirements for increased regulation for the DH distribution and/or production. Especially from a transparency point of view, many TPA models can require unbundling of network operations from heat production and/or sales. Unbundling can be realized with different levels, but according to full ownership unbundling, the costs are high for the DH sector taking into account the small size of the companies [138–140].

DH competes with property-level heating technologies such as biomass or oil-fired boilers, electric heating and heat pumps. DH has gained a high market share due to its competitive cost, reliability and easiness. On the other hand, there are also many networks, where a significant share of district heat comes from third-party producers, typically from industrial CHP plants or waste heat sources.

TPA has been presented as a means to improve energy efficiency by utilising waste heat and to increase the penetration of renewable energy. However, these targets are already promoted by other policy measures, such as emissions trading, energy taxation and building codes. Because the DH system operations, such as heat production, sales and distribution, are currently integrated, any regulated TPA would require significant changes to the current systems and regulation.

It is essential to analyse the potential models for TPA to DH and to identify the resulting impacts on heat customers, potential heat producers, current district heat companies and on the society. Some analysis in Finland is based on the current market design, there are some experiences from other countries and analysis of the potential models for TPA. The impacts of these analyses are quantified with simulation examples of different size heat networks (small 50 GWh, medium 500 GWh and large 5000 GWh annual heat sales) and potential third--party production types utilising various heat technologies. Based on the examples and analysis of the current situation, the results pursue to identify whether there would be competition in the DH networks, which could benefit the customer and/or society. The question is what kind of regulation could be required, and what kind of additional costs could be borne by the DH companies implementing the new model of TPA [140].

2.4.4. Technical considerations of TPA

It seems that the DH companies have been interested in utilising any heat sources that would potentially decrease the cost of heat sourcing to keep the price of DH competitive compared to other heat sources and increase the profitability. However, DH has some fundamental differences compared to the electricity market. The main differentiating factor is that heat cannot be transferred similarly to electricity and the heating networks are always local and small in size. In addition, the end-product is not as homogenous as in electricity markets; the needed temperature level varies throughout the year and also between the

DH networks or location in the network. Also, unlike electricity and gas, the water in the DH network is circulated back to the producers and there are requirements for the return water temperatures. Even though the existing DH systems already actively search and utilise potential heat streams, on the other hand, the DH sector is interested in further increasing the utilisation of waste heat and improving energy efficiency to decrease the cost of DH and environmental impacts.

As known the introduction of open DH networks requires structural changes in both of the physical infrastructure level and on an institutional level since different rules and agreements are needed between heating market participants. There is also a need to develop new services and encourage innovations in DH and cooling sector. One option could be to develop common conditions for more open DH and cooling systems, which include:

- First, what kind of waste heat streams or renewable heat production there could be available for DH networks, due to the infrastructure and different sizes of DH networks and whether it is feasible from techno-economic perspective to invest in those networks.
- Additional costs resulting from TPA models that could encourage these investments.
- Finally, it is quantitatively and qualitatively assessed whether adding more renewable production to the DH system through various TPA models could bring any benefits compared to current states.

TPA might gradually transform the topology of the DH system that is rather centralised today to a decentralised system with a variety of different heating/cooling sources with different characteristics being connected to the DH network. This change in the topology might require technical adaptations to ensure the efficient technical performance of the network. In addition, specific technical requirements for DH network access and usage configurations of the DH network need to be defined. The respective rules need to ensure that independent heat/cold producers gain network access on equivalent terms compared to the production plants of the integrated network operator.

In addition to the technical challenges TPA regulations need to be adapted as to ensure that, e.g., network losses or the costs of DH network technical adaptations or upgrading the DH network infrastructure are distributed among the DH participants in a fair and in a non-discriminatory way. The same applies to the establishment of technical requirements regarding feed-in and offtake from the DH network, the provision of reserve capacity and balancing heat and how the network charges are set. Finally, if the proposed preferential TPA stimulates many renewable energy producers to access a DHC system and if increasing demand within the DHC does not compensate for the additional renewable production, existing non-renewable heat and/or cold producers (e.g., operated by the integrated DHC system operator) will be replaced by the new entrants. This might lead to stranded investments if the replaced capacities had not been fully amortised. Even more, the problem of stranded investments could also affect renewable capacities, if the corresponding DH network is moving towards a high share of renewables and if in contrast to currently proposed by the European Commission where the TPA should not only be applied in case of fossil DH supply [139–141]. Accordingly, the question arises of how to allocate the respective stranded investment costs.

References

[1] *EU Handbook: District Heating*, Cross Border Bioenergy Working Group on District Heating Technologies, Austrian Energy Agency, October 2012.

[2] Millar M.A., Burnside N.M., Yu Z., *District Heating Challenges for the UK*, Energies, 2019, 12, 310.

[3] *Accellerating the Clean Energy Revolution – Perspectives on Innovation Challenges*, DTU International Energy Report, May 2018.

[4] *EU Handbook: CHP Markets*, Cross Border Bioenergy Working Group on CHP Technologies, Austrian Energy Agency, October 2012.

[5] Woods P., Overgaard J., *Historical development of district heating and characteristics of a modern district heating system*, [In:] R. Wiltshire (Ed.), *Advanced District Heating and Cooling (DHC) Systems*, Woodhead Publishing, Oxford, UK, 2016, 3–15.

[6] Lake A., Rezai B., Beyerlein S., *Review of district heating and cooling systems for a sustainable future*, Renew. Sust. Energy Rev., 2017, 67, 417–425.

[7] Sayegh M.A., Danielewicz J., Nannou T., Miniewicz M., Jadwiszczak P., Piekarska K., Jouhara H., *Trends of European research and development in district heating technologies*, Ren. Sust. Energy Rev., 2017, 68, 1183–1192.

[8] Sayegh M.A., Jadwiszczak P., Axcell B.P., Niemierka E., Bryś K., Jouhara H., *Heat pump placement, connection and operational modes in European district heating*, Energy Build., 2018, 166, 122–144.

[9] Jradi M., Riffat S., *Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies*, Ren. Sust. Energy Rev., 2014, 32, 396–415.

[10] Mazhar A.R., Liu S., Shukla A., *A state of art review on the district heating systems*, Ren. Sust. Energy Rev., 2018, 96, 420–439.

[11] Connolly D., Lund H., Mathiesen B.V., Werner S., Möller B., Persson U., Boermans T., Trier D., Østergaard P.A., Nielsen S., *Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system*, Energy Pol., 2014, 65, 475–489.

[12] Rezaie B., Rosen M.A., *District heating and cooling: Review of technology and potential enhancements*, Appl. Energy, 2012, 93, 2–10.

[13] Johansson P., *Buildings and district heating – contributions to development and assessments of efficient technology*, Lund University, Lund 2011.

[14] Thornton A., Monroy C.R., *Distributed power generation in the United States*, Ren. Sust. Energy Rev., 2011, 15, 4809–4817.

[15] *EU Strategy on Heating and Cooling*, 24 final report, European Commission, Brussels, 2016.

[16] Connolly D. et al., *STRATEGO: Enhanced heating and cooling plans to quantify the impact of increased energy efficiency in EU member states*, Project No. IEE0, Aalborg University, Denmark, 2016.

[17] Connolly D. et al., *STRATEGO: Creating NATIONAL energy models for 2010 and 2050*, Project No. IEE0, Aalborg University, Denmark, 2015.

[18] International Energy Agency, *Energy Balances of OECD Countries*, 2011, available from http://www.iea.org/

[19] International Energy Agency, *Energy Balances of Non-OECD Countries*, 2011, available from http://www.iea.org/

[20] Foster S. et al., *Heat pump in district heating. Final report*, DECC by Element Energy and Carbon Alternatives, 2016.

[21] Gładysz P., Ziębik A., *Complex analysis of the optimal coefficient of the share of cogeneration in district heating systems*, Energy, 2013, 62, 12–22.

[22] Ommen T., Markussen W.B., Elmegaard B., *Heat pumps in combined heat and power systems*, Energy, 2014, 76, 989–1000.

[23] *Mapping and analyses of the current and future (2020–2030) heating/cooling fuel deployment (fossil/renewables)*, European Comission, Studies, ENER/C214-641, 2015.

[24] Frederiksen S., Werner S., *District Heating and Cooling*, University of Lund, Lund 2012.

[25] Alkan M.A., Keçebas A., Yamankarademiz N., *Exergo economic analysis of a district heating system for geothermal energy using specific exergy cost method*, Energy, 2013, 60, 426–434.

[26] Dumas P., Bartosik A., *Geothermal DH Potential in Europe*, GeoDH-Report-D-2.2-final, 2014.

[27] Dumas P., Angelino L., Latham A., Pinzuti V., *Developing geothermal district heating in Europe*, GeoDH-Report-2014_web

[28] Persson U., Werner S., *District heating in sequential energy supply*, Appl. Energy, 2012, 95, 123–131.

[29] Capros P., Mantzos L., Papandreou V., Tasios N., E*nergy and Transport Outlook to 2030 – Update 2007*. European Communities, 2008, Available from: http://www.e3mlab.ntua.gr /reports/energy_transport_trends_2030_update_2007_en.pdf

[30] Kamel R.S., Fung A.S., Dash P. R.H., *Solar systems and their integration with heat pumps: A review*, Energy Build., 2015, 87, 395–412.

[31] Lunghi P., *Energy recovery from industrial waste of a confectionery plant by means of BIGFC plant*, Energy, 2004, 29, 2601–2617.

[32] Faninger G., *Combined solar biomass district heating in Austria*, Sol. Energy, 2000, 69, 425–435.

[33] Ozgener L., Hepbasli A., Dincer I., *Energy and exergy analysis of geothermal district heating systems: An application*, Build. Environ., 2005, 40, 1309–1322.

[34] Rosa A.D. et al., *Annex X Final report: Toward 4th Generation District Heating*, Technical University of Denmark, Copenhagen 2014

[35] Connolly D., Mathiesen B.V., Dubuisson X., Lund H., Ridjan I., Finn P., Hodgins J., *Climate change strategy*, *Limerick Clare Energy Plan 2012*, Aalborg University, Aalborg 2012.

[36] Zhen L., Duanmu L., Shu H.W., Jiang S., Zhu Y.X., *District cooling and heating with seawater as heat source and sink in Dalian, China*, Ren. Energy, 2007, 32 (15), 2603–2616.

[37] Åberg M., Widén J., Henning D., *Sensitivity of district heating system operation to heat demand reductions and electricity price variations: A Swedish example*, Energy, 2012, 41, 525–540.

[38] *Advanced District Heating and Cooling (DHC) Systems*, R. Wiltshire (Ed.), Woodhead Publishing, Oxford 2016.

[39] Taylor S., Hann S., Bines C., Ettlinger S., *Drivers of growth and cost changes in European renewable heat technologies*, The Department of Energy and Climate Change, London 2016.

[40] IEA-ETSAP and IRENA, *Heat Pumps Technology Brief*, 2013.

[41] Forsén M., Nowak T., Hübsh C., Hirvonnen J., Coevoet M., Blume O., *European heat pump statistics outlook*, The European Heat Pump Assocation, Brussels 2009.

[42] Lauka D., Gusca J., Blumberga D., *Heat pumps integration trends in district heating networks of the Baltic states*, Proc. Comp. Sci., 2015, 52, 835–842.

[43] Critoph R.E., *Gas driven heat pumps: Market potential, support measures and barriers to development of the UK market*, University of Warwick, November 2013.

[44] Carvalho A.D., Mendrinos D., De Almeida A.T., *Ground source heat pump carbon emissions and primary energy reduction potential for heating in buildings in Europe – results of a case study in Portugal*, Ren. Sust. Energy Rev., 2015, 45, 755–768.

[45] The European Heat Pump Association (EHPA), *European Heat Pump Statistics (Outlook 2009)*, Brussels 2009.

[46] *United Nations Environment Programme. District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy*, UNEP DTPE, France, 2015.

[47] Zimny J., Michalak P., Szczotka K., *Polish heat pump market between 2000 and 2013: European background, current state and development prospects*, Ren. Sust. Energy Rev., 2015, 48, 791–812.

[48] McKenna R.C., Norman J.B., *Spatial modelling of industrial heat loads and recovery potentials in the UK*, Energy Pol., 2010, 38, 5878–5891.

[49] Eurostat, *Landfill still accounted for nearly 40% of municipal waste treated in the EU27 in 2010*, News release 4912 of March 27, 2012.

[50] Sun J., Fu L., Sun F., Zhang S., *Experimental study on a project with CHP system basing on absorption cycles*, Appl. Thermal Eng., 2014, 73, 732–738.

[51] Kemna R., *Average EU building heat load for HVAC equipment*, Contract No. ENER/C32 -2010/FV2014-559/SI2.680138, August 2014.

[52] Bach B., Werling J., Ommen T., Münster M., Morales J.M., Elmegaard B., *Integration of large--scale heat pumps in the district heating systems of Greater Copenhagen*, Energy, 2016, 107, 321–334.

[53] Soltero V.M., Chacartegui R., Ortiz C., Velazquez R., *Evaluation of the potential of natural gas district heating cogeneration in Spain as a tool for decarbonisation of the economy*, Energy, 2016, 115, 1513–1532.

[54] European Commission, *A roadmap for moving to a competitive low carbon economy in 2050*, Communication COM, March 8, 2011, 112.

[55] Bertoldi P., Atanasiu B., *Electricity Consumption and Efficiency Trends in European Union: Status Report 2009*, Joint Research Centre, Institute for Energy, European Communities, 2009. Available from: http://re.jrc.ec.europa.eu/energyefficiency/pdf/EnEff_Report_2009.pdf

[56] ASHRAE, American Society of Heating Refrigeration and Air-Conditioning Engineers, *District Cooling Guide*, Atlanta 2013.

[57] Grohnheit P.E., Mortensen B.O.G., *District heating as the infrastructure for competition among fuels and technologies*, J. Energy Chall. Mech., 2016, 3 (2), 64–69.

[58] Lund H., Werner S., Wiltshire R., Svendsen S., Thorsen J.E., Hvelplund F., Mathiesen B.V., *4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems*, Energy, 2014, 68, 1–11.

[59] Persson U., Möller B., Werner S., *Heat Roadmap Europe: Identifying strategic heat synergy regions*, Energy Pol., 2014, 74, 663–681.

[60] Persson U., Werner S., *District heating in sequential energy supply*, Appl. Energy, 2012, 95, 123–131.

[61] Gadd H., Werner S., *Achieving low return temperatures from district heating substations*, Appl. Energy, 2014, 136, 59–67.

[62] Li H., Nord N., *Transition to the 4th generation district heating – possibilities, bottlenecks, and challenges*, Energy Proc., 2018, 149, 483–498.

[63] Sunko S. et al., *Guidelines on improved business models and financing schemes of small renewable heating and cooling grids*, Project No. 691679 (INEA), 2017, https://commons.wikimedia.org/wiki/File:Generations_of_district_heating_systems_EN.svg

[64] Sayegh M.A., Cyba B., Jadwiszczak P., *Solar thermal potential for supplying district heating in European different locations*, Proc. int. conf. Indoor air and environmental quality, Greece, 18–29 September 2016, 245–252.

[65] European Commission, *Proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources* (recast), Brussels 2016.

[66] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency.

[67] Malinauskaite J., Jouhara H., Spencer N., *Waste prevention and technologies in the context of the EU waste framework directive: Lost in translation?*, 26 European Energy and Environmental Law Review, 2017, 3, 66–80.

[68] Danielewicz J., Śniechowska B., Sayegh M.A., Fidorów N., Jouhara H., *Three-dimensional numerical model of heat losses from district heating network pre-insulated pipes buried in the ground*, Energy, 2016, 108, 172–184.

[69] Olabi A.G., *Renewable energy and energy storage systems*, Energy, 2017, 136, 1–6.

[70] Jouhara H., Czajczyńska D., Ghazal H., Krzyżyńska R., Anguilano L., Reynolds A.J., Spencer N., *Municipal waste management systems for domestic use*, Energy, 2017, 139, 485–506.

[71] Bartolozzi I., Rizzi F., Frey M., *Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy*, Ren. Sust. Energy Rev., 2017, 80, 408–420.

[72] Gebremedhin A., *Optimal utilisation of heat demand in district heating system a case study*, Ren. Sust. Energy Rev., 2014, 30, 230–236.

[73] Ben Hassine I., Eicker U., *Impact of load structure variation and solar thermal energy integration on an existing district heating network*, Appl. Ther. Eng., 2013, 50, 1437–1446.

[74] Lund H. et al., *4th Generation District Heating (4GDH) – integrating smart thermal grids into future sustainable energy systems*, Energy, 2014, 68, 1–11.

[75] United Nations, *World Urbanization Prospects: The 2009 Revision*, Data in digital form (POP/DB/WUP/Rev.2009), Department of Economic and Social Affairs, Population Division, New York 2010, available at: http://esa.un.org/unpd/wup/index.htm (2011-09-20).

[76] Bertoldi P., Atanasiu B., *Electricity consumption and efficiency trends in the enlarged European Union*, Status report 2006, European Commission Report EUR 22753 EN, European

Commission Directorate – General Joint Research Centre and Institute for Environment and Sustainability, Luxembourg 2007.

[77] Madrigal M., Uluski R., *Practical Guidance for Defining a Smart Grid Modernization Strategy – The Case of Distribution*, International Bank for Reconstruction and Development, 2017.

[78] Li H., Svendsen S. et al., *Future low-temperature district heating design guidebook*, Final Report of IEA DHC Annex TS1, DTU, 2017.

[79] Sun F., Fu L., Sun J., Zhang S., *A new waste heat district heating system with combined heat and power (CHP) based on ejector heat exchangers and absorption heat pumps*, Energy, 2014, 69, 516–524.

[80] Sun F., Fu L., Zhang S., Sun J., *New waste heat district heating system with combined heat and power based on absorption heat exchange cycle in China*, Appl. Therm. Eng., 2012, 37, 136–144.

[81] Liao C., Ertesvåg I.S., Zhao J., *Energetic and exergetic efficiencies of coal-fired CHP (combined heat and power) plants used in district heating systems of China*, Energy, 2013, 57, 671–681.

[82] Rämä M., Wahlroos M., *Introduction of new decentralised renewable heat supply in an existing district heating system*, Energy, 2018, 154, 68–79.

[83] The European Parliament and the Council of the European Union, Regulation (EU) No. 51714 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing, Regulation (EC) No. 84306. Off. J. Eur. Union 2014, 2014, 195–230.

[84] Rutz D. et al., *Small modular renewable heating and cooling grids*, 1st Ed., WIP Renewable Energies, Munich 2017.

[85] Mazhar A.R., Liu S., Shukla A., *A state of art review on the district heating systems*, Ren. Sust. Energy Rev., 2018, 96, 420–439.

[86] D'Agostino D., Zangheri P., Castellazzi L., *Towards nearly zero energy buildings in Europe: A focus on retrofit in non-residential buildings*, Energies, 2017, 10, 117.

[87] Delmastro C., Martinsson F., Dulac J., Corgnati S.P., *Sustainable urban heat strategies: Perspectives from integrated district energy choices and energy conservation in buildings*. *Case studies in Torino and Stockholm*, Energy, 2017, 138, 1209–1220.

[88] Pakere I., Ziemele J., Blumberga D., *DH company in prosumers role*, Energy Proc., 2017, 128, 234–239.

[89] Chen H., Cong T.N., Yang W., Tan C., Li Y., Ding Y., *Progress in electrical energy storage system: A critical review*, Progr. Nat. Sci., 2009, 19 (3), 291–312.

[90] Ibrahim H., Ilinca A., Perron J., *Energy storage systems: Characteristics and comparisons*, Ren. Sust. Energy Rev., 2008, 12 (5), 1221–1250.

[91] Hesaraki A., Holmberg S., Haghighat F., *Seasonal thermal energy storage with heat pumps and low-temperatures in building projects: A comparative review*, Ren. Sust. Energy Rev., 2015, 43, 1199–1213.

[92] Philippe M., Marchio D., Riederer P., Partenay V., *Analysis of 30 underground thermal energy storage systems for building heating and cooling and district heating*, Proc. 15th International Scientific Conference on Renewable Energy, Effstock–Stockholm 2009.

[93] Zeghici R.M., Damian A., Frunzulica R., Iordache F., *Energy performance assessment of a complex district heating system which uses gas-driven combined heat and power, heat pumps and high-temperature aquifer thermal energy storage*, Energy Build., 2014, 84, 142–151.

[94] Carvalho A.D., Moura P., Vaz G.C., De Almeida A.T., *Ground source heat pumps as high efficient solutions for building space conditioning and for integration in smart grids*, Energy Conv. Manage., 2015, 103, 991–1007.

[95] Ommen T.S., Elmegaard B., Markussen W.B, *Heat Pumps in CHP Systems High-efficiency Energy System Utilising Combined Heat and Power and Heat Pumps*, Technical University of Denmark, 2015.

[96] Ommen T., Markussen W.B., Elmegaard B., *Lowering district heating temperatures. Impact to system performance in current and future Danish energy scenarios*, Energy, 2016, 94, 273–291.

[97] Frederiksen S., Werner S., *District Heating and Cooling*, Studentlitteratur, Sweden, 2013.

[98] Averfalk H., Werner S., Felsmann C., Rühling K., Wiltshire R., SvendsenS., Li H., Faessler J., Mermoud F., Quiquerez L., Annex XI to final report: *Transformation Roadmap from High to Low-temperature District Heating Systems*, IEA, France, 2017.

[99] Schmidt D., Kallert A., Blesl M., Svendsen S., Li H.W., Nord N., Sipila K., *Low-temperature district heating for future energy systems*, Energy Proc., 2017, 26–38.

[100] Shakerin M., *Analysis of district heating systems integrating distributed sources*, Master Thesis, Norwegian University of Science and Technology, May 2017.

[101] Union I. *An EU Strategy on Heating and Cooling*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels 2016.

[102] Lund H., Möller B., Mathiesen B.V., Dyrelund A., *The role of district heating in future renewable energy systems*, Energy, 2010, 35, 1381–1390.

[103] EU, *Proposal for a directive of the European Parliament and the council on the promotion of the use of energy from renewable sources (recast)*, Official Journal of the European Union, 2016, 2, 767.

[104] Grosswindhager S., Voigt A., Kozek M., *Efficient physical modelling of district heating networks*, Proc. Conf. Modelling and Simulation, Canada, 2011, 735–794

[105] Haiyan L., Valdimarsson P., *District heating modelling and simulation*, Conf. District Heating Modelling and Simulation, Stanford University, Stanford, California, 2009.

[106] Ancona M., Branchini L., de Pascale A., Melino F., *Smart district heating: Distributed generation systems' effects on the network*, Energy Proc., 2015, 75, 1208–1213.

[107] Guan J., Nord N., Chen S., *Energy planning of university campus building complex: Energy usage and coincidental analysis of individual buildings with a case study*, Energy Build., 2016, 124, 99–111.

[108] Skagestad B., Mildenstein P., *District Heating and Cooling Connection Handbook*, IEA District Heating and Cooling, IEA, the Netherlands, 2002, 199.

[109] Murphy P., *Solar and Heat Pump Systems*, IEA Solar Heating and Cooling Programme Annual Report 2013, Austria, June 2014.

[110] Nault E., Rey E., Andersen M., *Early design phase evaluation of solar potential: Insights from the analysis of six projects*, Proceedings of IBPSA, Chambéry 2013.

[111] Kanters J., Dubois M.-C., Wall M., *Active solar energy in urban planning: Effect of design, density and orientation of urban districts on annual energy production*, Proc. International Conference on Solar Heating and Cooling for Buildings and Industry, Freiburg 2013.

[112] Trier T., Skov C.K., Sørensen S.S., Bava F., *Solar District Heating Trends and Possibilities, Characteristics of Ground-Mounted Systems for Screening of Land Use Requirements and Feasibility*, Subtask B, IEA SHC Task 52 Programme, Copenhagen 2018.

[113] ISO 9806:2017, *Solar energy – Solar thermal collectors – Test methods*, September 2017, www.iso.org/standard/67978.html

[114] Screen shot of video from 12. Jan. 2017, 22:21 on Danish TV 2 website (accessed 2018-02-18), nyheder.tv2.dk/samfund/2017-01-12-verdens-stoerstesolfangeranlaeg-bugter-sig-i-de-midtjyske-bakker

[115] Danish District Heating Association, *Benchmarking Statistik 2014/2015*, www.danskfjernvarme.dk/viden-om/statistik-subsection

[116] Statistics of the Danish District Heating Association 2015-2016, *Comparison DH Costs*, www.danskfjernvarme.dk/-/media/danskfjernvarme/videnom/aarstatistik/%C3%A5rsstatistik-2016-sammenligning-af-fjernvarmepriser.pdf

[117] *Denmark listed as partner country as of 16-11-2017 in the Powering Past Coal Alliance: Declaration* (accessed 18-06-2018), assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/660041/powering-past-coal-alliance.pdf

[118] Furbo S., Fan J., Perers B., Kong W., Trier D., From N., *Testing, development and demonstration of large scale solar district heating systems*, Energy Proc., International Conference on Solar Heating and Cooling for Buildings and Industry, SHC, Beijing, China, 2014, orbit.dtu.dk/files/110866750/elsevier_39.pdf

[119] Paris Agreement, United Nations, 2015, unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

[120] Enhanced Heating and Cooling Plans to Quantify the Impact of Increased Energy Efficiency in EU Member States, STRATEGO main report, 2016, stratego project.eu/wp-content/uploads/2014/09/STRATEGO-WP2-Executive-Summary-Main-Report.pdf

[121] IEA SHC Task 44 (2010–2013): *Solar and Heat Pump Systems*.

[122] Fink C., Riva R., *Solar-supported heating networks in multi-storey residential buildings: A planning handbook with a holistic approach*, Abeitsgemeinschaft Erneuerbare Energie GMBH, Austria, 1997.

[123] Mauthner F., Weiss W., Spörk-Dür M., *Solar Heat Worldwide, Markets and Contribution to the Energy Supply 2014*, IEA Solar Heating and Cooling Programme, Austria, May 2016.

[124] Herkel S., *Technology and demonstrators*, Technical Report, Subtask C, Part C1, SHC Programme IEA, Austria–Switzerland, January 2016.

[125] Sayegh M.A., Danielewicz J., Miniewicz M., Jadwiszczak P., Piekarska K., Nannou T., Jouhara H., *Trends of European research and development in district heating technologies*, 8th International Conference on Sustainable Energy and Environmental Protection (SEEP 2015) Paisley, Scotland, August 2015.

[126] *Ranking List of European Large Scale Solar Heating Plants*, http://solar-district-heating.eu

[127] Trier D., *Towards solar district heating with more than 70% solar fraction*, Energy Proc., 2015, 70, 580–586.

[128] Carpaneto E., Lazzeroni P., Repetto M., *Optimal integration of solar energy in a district heating network*, Ren. Energy, 2015, 75, 714–721.

[129] Le Truong N., Gustavsson L., *Solar heating systems in renewable-based district heating*, Energy Proc., 2014, 61, 1460–1463.

[130] *Large Systems: Large Solar Heating/Cooling Systems, Seasonal Storage, Heat Pumps*, IEA Intelligent Energy Europe (IEE) project SDH, Solar District Heating, SHC Task 45, 2011–2014.

[131] Database on Danish solar district heating plants, solvarmedata.dk, accessed on 09.12.2015.

[132] solarthermalworld.org, 2011: Canada: District Heating with 90% Solar Fraction, (Link), accessed on 09.12.2015.

[133] Mathiesen B.V., Lund H., Connolly D., Wenzel H., Ostergaard P.A., Moller B., *Smart energy systems for coherent 100% renewable energy and transport solutions*, Appl. Energy, 2015, 145, 139–154.

[134] Madani H., Fischer D., Lundqvist P., *The Role of Heat Pumps in Future Urban Energy Systems*, Heat Pump. Techn. Mag., 2017, 35, 50–53.

[135] Fischer D., Madani H*., On heat pumps in smart grids: A review*, Ren. Sust. Energy Rev., 2017, 70, 342–357.

[136] Firpo F., *Smart Cities Stakeholder Platform Heat Pump and Micro-CHP as complementary boiler alternatives*, Electronic Communications Network, 2013.

[137] Söderholm P., Wårell L., *Market opening and third party access in district heating networks*, Energy Pol., 2011, 39, 742–752.

[138] *Third party access to district heating networks, Report to Finnish Energy*, 2018 Pöyry Management Consulting Oy, May 2018.

[139] Wårell L., Sundqvist T., *Market Opening in Local District Heating Networks*, Energy Pol., 2011, 39 (2), 742–752.

[140] Bijvoet X., *Learning and competitive behaviour in district heating networks*, Master thesis TU Delft University of Technology, 2017.

[141] Kranzl L., Bürger V., Steinbach J., Müller A., *Third party access for district heating: first steps to unbundling the heating sector?*, Energy Economics Group, TU-Wien 2017, https://www.eeg.tuwien.ac.at/conference/iaee2017/files/abstract/690_Kranzl_abstract_2017-07-29_15-51.pdf

CHAPTER 3.
HEAT PUMP BASED DISTRICT HEATING

3.1. Overview of heat pumps in DH

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 mechanical and thermal heat pump technology, which is 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., by using electricity) or for thermal heat pumps (e.g., absorption heat pumps). 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 (GHG) emissions. In this way, they provide stable, affordable, and efficient energy supply, to create new employment in Europe and to contribute to a sustainable energy future [1–8]. 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.) [1, 9–12]. 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.) [3, 9–12].

3.1.1. The role of heat pumps

In the EU, the Renewable Energy Directive has recognised this fact by identifying the ambient energy from the air, water, and ground as renewable [13, 14].

Heat pumps are considered 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 [15–17]. 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 [17].

A heat pump is a device that can provide heating, cooling, and hot water for residential, commercial, and industrial applications. 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 apparent, 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 [18–22].

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 enormous possibilities for interaction with novel technologies. Heat pumps provide a holistic view of their role in the context of smart grids and future urban energy systems. Connection of a heat pump into DH allows for easy integration with automatic systems so that the heat pump identifies the boundary conditions aiming for optimal system specifications [23].

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 [1, 15, 23–25].

3.1.2. The current state of heat pumps in Europe

The EHPA statistics for 2017 report more than 1.1 million heat pumps (+11%) sold in Europe, leading to an installed capacity of 10.6 million units [26, 27]. This installed stock contributed 29.8 Mt of carbon emission reduction and 116 TWh to energy generated from a renewable source. It helped reduce final energy demand by 148 TWh. If properly connected, the current stock of heat pumps could provide demand-side flexibility between 1 and 3.2 TWh over a year. Signs from several markets in Europe indicate that the growth continued in 2018 since more than 11 million heat pumps in total were installed by the end of the first half of 2018. This is a hopeful direction of the growing market, not only for consumers but also for the energy sector and society as a whole, as it would ensure tens of thousands of equivalent jobs in Europe. Also, it puts a particular focus on accelerating the use of RES in heating and cooling. The deployment of the heat pump technology will benefit from fulfiling the various obligations arising from adopted EU energy policies of RES penetration in heating and cooling sectors, energy savings, energy efficient buildings, increased demand response, etc. [28].

3.1.3. Challenges of heat pumps in heating networks

Heating and cooling (H&C) account together for approximately 50% of Europe’s total energy consumption, considering residential, service, and industrial sectors. Whereas heating demand is forecasted to decrease, cooling is expected to grow incrementally in the next decades. In this perspective, the promotion of RES in heating and cooling is essential for achieving the European directive’s targets. Within the European technological platform, heat pumps represent a powerful resource towards the realisation of the European Commission’s goals. Synergies between HP technologies on the demand side and decarbonisation on the supply side could significantly contribute to achieving the low carbon energy challenge.

Reduction of primary energy consumption and GHG emissions are currently two main drivers for encouraging the adoption of heat pumps. However, a correctly coupled heat pump system with an energy storage system and implemented in the buildings with adequate controls can also improve thermal load management and DH network balancing in the prospect of an increased future renewable power production. Heat pumps can thus have a beneficial effect on the entire energy system and contribute to realising the smart thermal network of the future. This favourable fact can further boost the implementation of heat pump systems in the buildings and heating sector [29].

The decarbonisation of the energy system is one of the main challenges that the European Union is facing in the coming years and decades. In order to achieve the EU's renewable energy and emission reduction targets of 80–95% by 2050 compared to 1990, a fundamental transformation of the energy system is required. The further expansion of RES and TES plays an important role in the decarbonisation pathway. Especially in the electricity sector, the increasing share of RES leads to several challenges that are mainly induced by weather dependency and volatile feed-in of PV and wind power plants. In an energy system with high RES capacity, situations occur when the electricity generation from RES exceeds total demand as well as situations when RES production cannot fulfil total demand.

In order to compensate the fluctuation of the intermittent RES feed-in, flexible options are required. Situations with excess electricity generation from RES as well as situations with RES deficit need to be compensated in some way. A range of flexible options exists to provide the necessary compensation in these situations [30].

3.1.4. Technical background of heat pumps in DH

Heat pumps can be classified according to various criteria. The most commonly used are classifications according to heat pump functions (heating, cooling, heating and cooling, heating water, etc.), the type of heat source (ground, water, air, solar power, waste or multi-source, etc.), the kind of energy supplied to a heat pump (thermally driven; mechanical-compressor; electric-thermoelectric), or according to heat sink or their purpose (residential and commercial buildings, district heating, industry) [10, 31]. The heat pump is an efficient technology based on thermodynamic refrigeration cycles that achieve high energy efficiency by using low-grade heat from the 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 pipe 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 stable and affordable energy supply. By doing so, it contributes to a sustainable energy future by reducing fossil fuel combustion and GHG emissions [10, 32–36].

Heat pump technology includes heating, air conditioning, and 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. As shown in Fig. 3.1, the mechanical HP units (based on the vapour compression refrigeration cycle with the use of a compressor) can be powered by non-renewable electricity (e.g., from power plants) or by renewable electricity (e.g., PV, hydro, wind power, etc.) [1, 2]. For absorption heat pump units (i. e. absorption and adsorption), the driving energy can be supplied from various sources: fossil fuel combustion (coal, gas, oil and derivatives), the use of renewable energy sources (geothermal, solar, biofuel) and waste heat (solid waste, industrial wastes, etc.). Also, the heat pump systems can be classified in many different ways, and therefore, the possible system components terminologies vary. Common classifications of heat pumps are based on nature of the heat source/sink exploited, type of adopted heat pump (using refrigerant compression and expansion in case of mechanical heat pumps) and kind of thermal demand profile or the covered heating load [29].

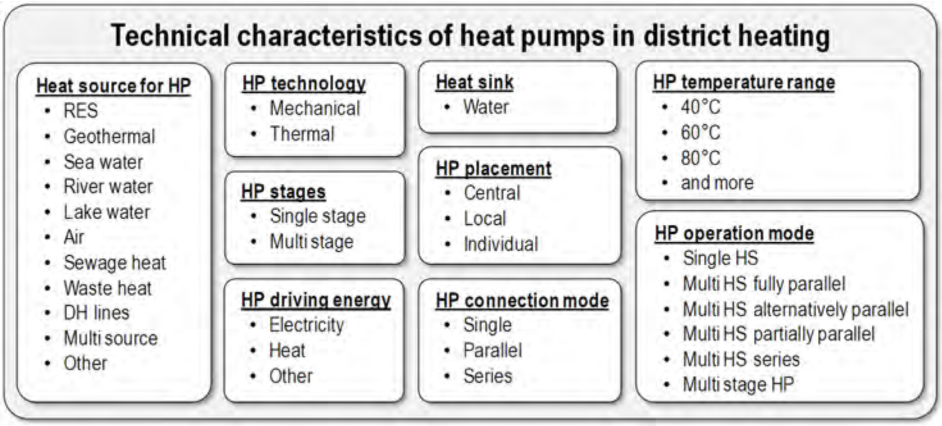


Fig. 3.1. Technical background of heat pumps in district heating [10]

Heat pump units can be installed in individual dwellings or as production units in district heating networks, constitute a central, local or individual heat source or be connected to the district heating network using serial or parallel connection modes [10, 37–42]. The integration of heat pump technology into district heating considers at least placement, connection, and operational mode of the heat pump unit. Figure 3.1 shows the technical details of heat pump technology, which can be used in district heating networks. The details include the design framework such as heat sources, driving energy, heat sink, connection, and operational mode. Evaluation of the technical design parameters of the heat pump should take into consideration different technical aspects, connection, and operational modes [10].

The use of heat pumps is one of the methods to provide stable and affordable energy supply, create employment, ensure new jobs, and contribute to a sustainable energy future [10, 32, 33, 43]. Heat pumps can play an essential role in the necessary conversion of European heating markets. It is estimated that widespread use of heat pumps for space heating and cooling and DHW in the commercial sector could reduce GHG emissions by 1.25 billion tonnes by 2050 [21, 22, 27].

3.1.5. Heat pump deployment phases in European DH

There has been the active deployment of heat pump technology in the EU since 1970 in Austria, Denmark, Germany, etc. The heat pump market has experienced both the growth and decline rates over the last decades [44]. The literature review findings suggest that the deployment of heat pipe technology in the EU can be divided into two separate growth phases [10, 45].

In the first phase, i.e., from the 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, i.e., from the 2000s to the present day, the deployment of heat pumps began to grow at higher rates. Large capacity bespoke units (1MW and more) were manufactured, and some industrial heat pump designs were suitable for district heating and cooling. The change in growth was due to several reasons: financial support, education, and training, preferential tariffs for the operation of heat pumps, EU energy efficiency regulations for buildings, 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 [16, 46, 47].

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 for the national priorities of each EU country in the renewable energy field need 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. Besides, a life cycle assessment is also needed 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 [10, 48–54].

3.2. Alternatives to heat pump integration into DH

At least four basic scenarios can be distinguished for heat pump integration into district heating networks [10]:

- heat pump placement into the existing network without major changes,
- heat pump placement in an expanded heating network,
- deep refurbishment of the existing district heating,
- 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 [8]. In the first scenario, the placement of the heat pump in the existing network depends mainly on the technical parameters of the district heating network and the available heat sources for the heat pump. The two critical barriers in the existing district heating systems are the high temperatures of 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 boiler only) or a local heat source. The heat pump unit thus co-operates 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 GHG 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 in the district heating components involve enormous costs (heat sources, the pipeline network, substations, and heating installations) and amount of time, including those related to the refurbishment of the consumers' buildings. The refurbishment costs depend on the technical conditions of the existing system, the scale of changes on the supply and demand side, and specifically, the necessity to add new heat sources for the heat pump.

The last scenario predicts 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. However, the integration of heat pump units into district heating networks needs defining the connection and the operational modes.

The connection mode refers to the pipeline connection of heat pumps into the district heating network, the geographical location of the heat source, 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 and technical features of the required heat sources in the district heating system.

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.

3.3. Technical triangle of heat pump based DH

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 principal heat source for the heat pump, the applied technology of the heat pump and the profile of the heating requirement [55–57]. The available heat sources 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 the key points to be considered for heat pump integration into the district heating system. Figure 3.2 illustrates the relationship between all the mentioned parameters, referred to as a technical triangle that is formed to show their interdependencies. This technical triangle is an efficient instrument to identify all essential interdependencies for selecting the heat pump technology to link the renewable energy based district heating [11, 55, 56].

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 no 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 when designing heat pump based district heating. It is a key approach to avoid 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 implementing different building renovation measures and new long term technological investment choices in cities or urbanized areas, adopting heat pump based district heating and sustainable urban energy strategies. According to the triangle in Fig. 3.2, 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 or pool of heat pump units, 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.

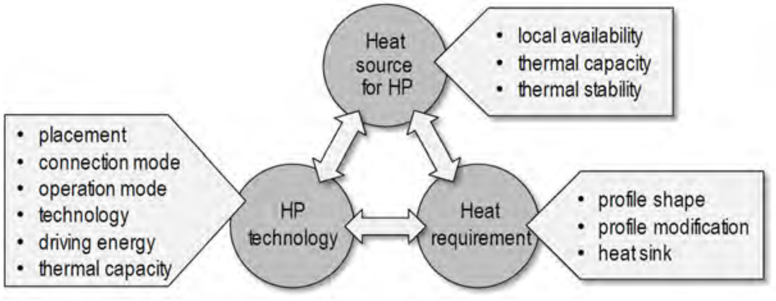


Fig. 3.2. Technical triangle for heat pump integration into district heating [10]

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 heating demands with the available heat sources. All mentioned considerations like heat sources, heating requirements and heat pump technology have bidirectional based dependencies.

3.3.1. The characteristics of a technical triangle

The technical triangle allows the definition of the concept and the approach to 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 of the technical triangle can be redefined depending on the choice of heat pump technology for a given system. In some cases, it is necessary to modify components of the future system. According to the technical triangle, there are many modification options such as reduction in heating requirement (e.g., through thermal modernization or refurbishment of 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 with renewable energy (e.g., PV, hydro, wind). The heat source can be expanded (e.g., additional geothermal boreholes) or diversified (two or more heat sources), etc. The proper choice between the options mentioned above is a major and complex engineering challenge that requires a special thermal approach and financial investigation.

3.3.2. Technical triangle framework functionality

Figure 3.3 shows four cases chosen to illustrate the use of the 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. Figure 3.3a 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 source to support the heat pump to fulfil peak heating requirements. Figure 3.3b shows the next scenario where the heating requirements are decreased by refurbishment and modernisation of the buildings so that the supplementary heat source became smaller or completely unnecessary. Figure 3.3c 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. Figure 3.3d shows the technical triangle for heat pump based district heating, which is supported by the 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.

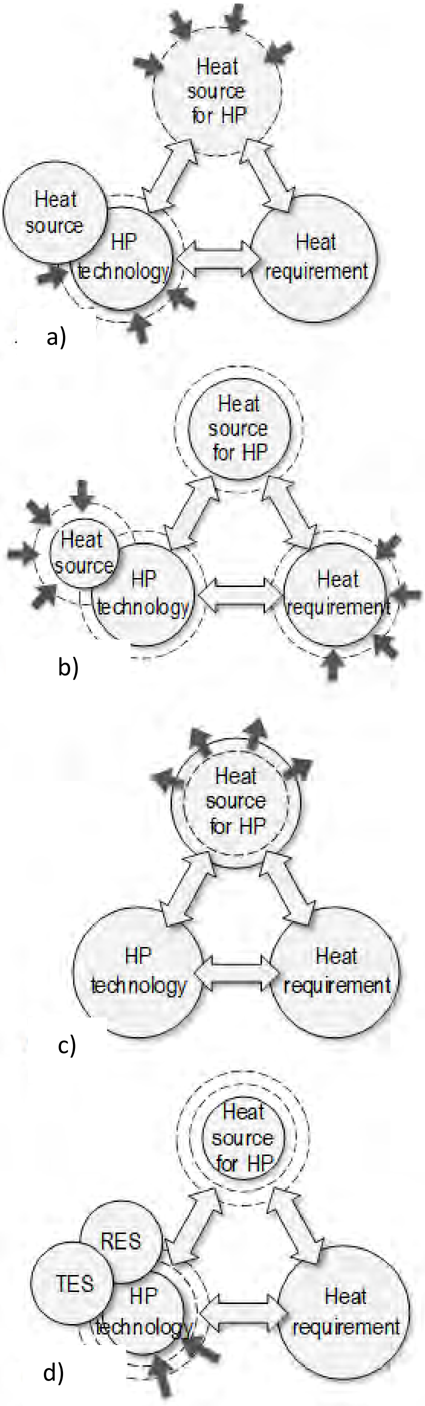
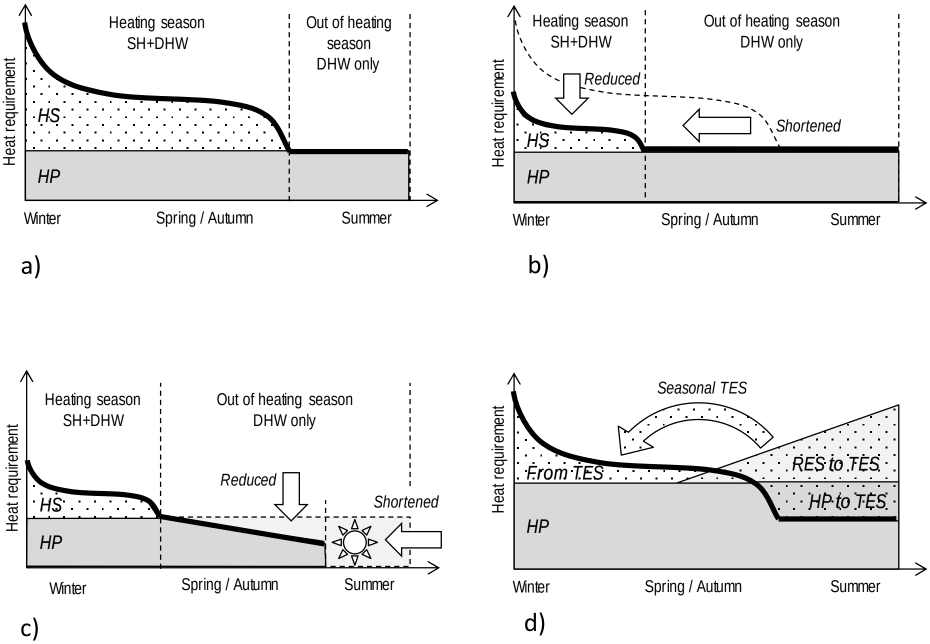


Fig. 3.3. Framework cases of the technical triangle [10]



a) b) c) d)

Fig. 3.4. 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 [10] (details in the text)

3.3.3. Heat requirement profiles in DH

The first component of the analysed technical triangle is the profile of the heating requirement, as shown in Fig. 3.4. 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 what is required for possible connection and operational modes. According to the technical triangle, it is necessary to acknowledge the needed heating profile and the possible modifications to reduce requirements [2]. The variation of the heating requirement profile determines directly the required thermal capacity and operational mode of the heat sources.

Figure 3.4a illustrates the participation cases of heat pump to cover the heating requirement for a residential building supplied by a district heating network. It is assumed that the demand for domestic hot water is approximately stable throughout the year, the requirement for space heating occurs in the heating season only, and it varies according to the external temperature. The peak requirement for such district heating occurs for a short period due to 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 its control system [2, 46]. In this case, the district heating network is supplied by two heat sources in parallel connection and operational mode. Here, the heat pump unit is the primary 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 both 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 at both stable and variable thermal capacities, depending on the local heat source and its thermal characteristics.

Figure 3.4b shows the reduced and shortened heating requirement profile due to energy-efficient, refurbished, or modernised buildings in the district heating network [47, 58]. 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. 3.4a), the district heating network is powered by multiple heat sources connected in a parallel operational mode. The reduced and shortened heating requirement is preferred when the heat is supplied from heat pumps; increasing the heat pump energy production in district heating systems decreases primary energy consumption and the emissions. According to the technical triangle, the stable heating requirement for more extended periods over the year needs a stable thermal capacity of heat pump units, which requires an appropriate heat source for the heat pump [47, 58].

The next case is presented in Fig. 3.4c, 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 the case of Fig. 3.4b [59]. 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 GHG emissions [57]. The heat pump unit, in this case, operates in a multiple heat source connection mode and a parallel operational mode with renewable energy sources and a small proportion of fossil fuel-based supplementary heat [10].

Finally, Figure 3.4d shows the case of 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 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. According to 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 needs throughout the year. The thermal energy storage can deliver substantial benefits in stabilising district heating network operation, but this option is characterised by a high cost, due to the needed large storage capacity and the required efficiency 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 potential of heat pump technologies and the heating requirements in district heating systems. This section 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 further.

3.3.4. Heat pump placement in DH

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. 3.5b: a central heat pump, local heat pump, and individual heat pump. The central heat pump unit has a high thermal capacity, and it is a part of the main power plant, as shown in Fig. 3.5b (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. 3.5b (2). Finally, the individual – or so-called distributed – heat pump units have a medium to low thermal capacity, they are installed in the consumer's 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. 3.5b (3). With an indirect connection mode, the heat pump units are powered by electricity generated from CHP, as shown in Fig. 3.5b (4). All individual heat pump units are components of the district energy system with central management of heat and electricity for both supply and demand sides.

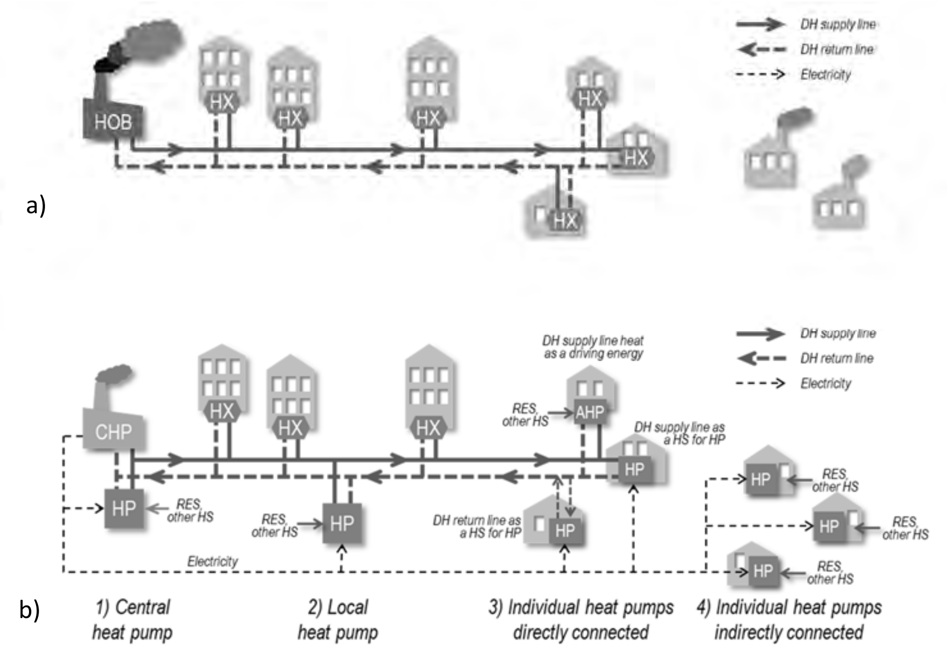


Fig. 3.5. The schemes of: a) traditional fossil fuel-based DH, b) heat pump placement options in advanced DH; DH – district heating, HOB – heat only boiler, HX – heat exchanger, HP – heat pump, HS – heat source, RES – renewable energy source [10]

The centrally placed large scale heat pump units require 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 primary heat source, and the other sources (e.g., fossil fuels or RESs, waste) are used to cover the needed 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 in parallel or series 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 predicted 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. 3.5b (3). An absorption heat pump can use the district heating water supply line as a source for driving energy. The next available option is to use various individual heat pumps (in addition to the locally placed heat pumps) to increase the thermal capacity of the 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 the 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 DHW 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., PV, wind power).

3.3.5. Connection and operational modes of heat pumps in DH

There are two primary aspects of heat pump integration into district heating: its connection mode, and operational mode. The connection mode is concerned with many factors such as the maximum heating requirement, the placement, and specification of heat sources to feed the heat pumps, adequate heat pump technology, supplementary heat sources, etc. The operational mode is concerned with the seasonal heating requirement, the seasonal behaviour of heat sources, and their flexibility in heat generation.

The type of heat source for heat pumps defines the variability of their thermal capacity over the year. The thermal capacity may be stable throughout the year or it can increase or decrease in winter. DESs such as geothermal, industrial waste, and deep sea water can ensure stable heat pump capacity throughout the whole year. Heat sources from air, lakes, river water and shallow seawater decrease the heat pump capacity in winter [36, 37, 60]. When the district heating is used as a heat source for the heat pump units, the thermal capacity of the units increases during the heating season with the operational temperature of the district heating.

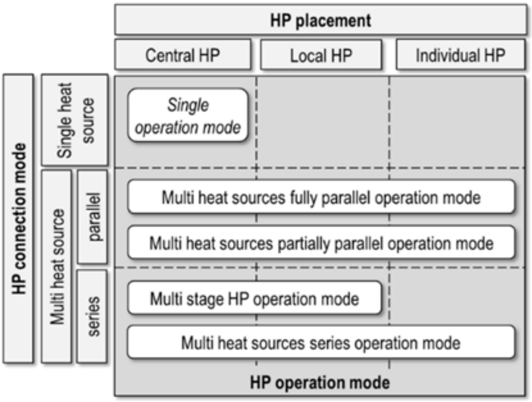


Fig. 3.6. The possibilities of operational and connection modes due to heat pump placements in district heating [10]

Figure 3.6 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 fulfilling the entire heating requirement of the district heating, which can supply heat in a single operational mode only.

Multiple heat source connection mode means two or more heat sources for supplying heat in parallel or series connection modes. 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).

Multiple heat sources with fully parallel operation mean cooperation of all heat sources to supply the district heating through 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 the heating season, for the rest of the season, a single heat source supplies the network, the heat pump which is 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 contribute to supply the district heating, and they are interdependent. The heat pump units in multi-stage operation can be placed as central or local heat sources. According to Fig. 3.6, in multiple source series operation, two or more heat sources are connected in series to cooperate all year round, and the heat pump unit can high-temperature centrally or locally.

3.4. Scenarios of heat pump connection and operation in DH

Heat pump applications in district heating can be summarised in the layout of heat sources, driving energy, and connection modes presented in Fig. 3.7, which illustrates the general range of technically possible scenarios. There are three main types of heat pump technologies using different driving energies: a mechanical HP driven by electricity (from both the power grid and renewable energy source), a thermal heat pump (i.e., an absorption heat pump) driven by a high-temperature renewable source, waste or other heat source, and a thermal heat pump driven by heat from the district heating supply line. The needed driving energy 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 resource or the district heating return line. A thermal heat pump can use the heat from the supply line of the district heating as the driving energy. In this case, the heat pump can depend on the local renewable sources as heat sources.

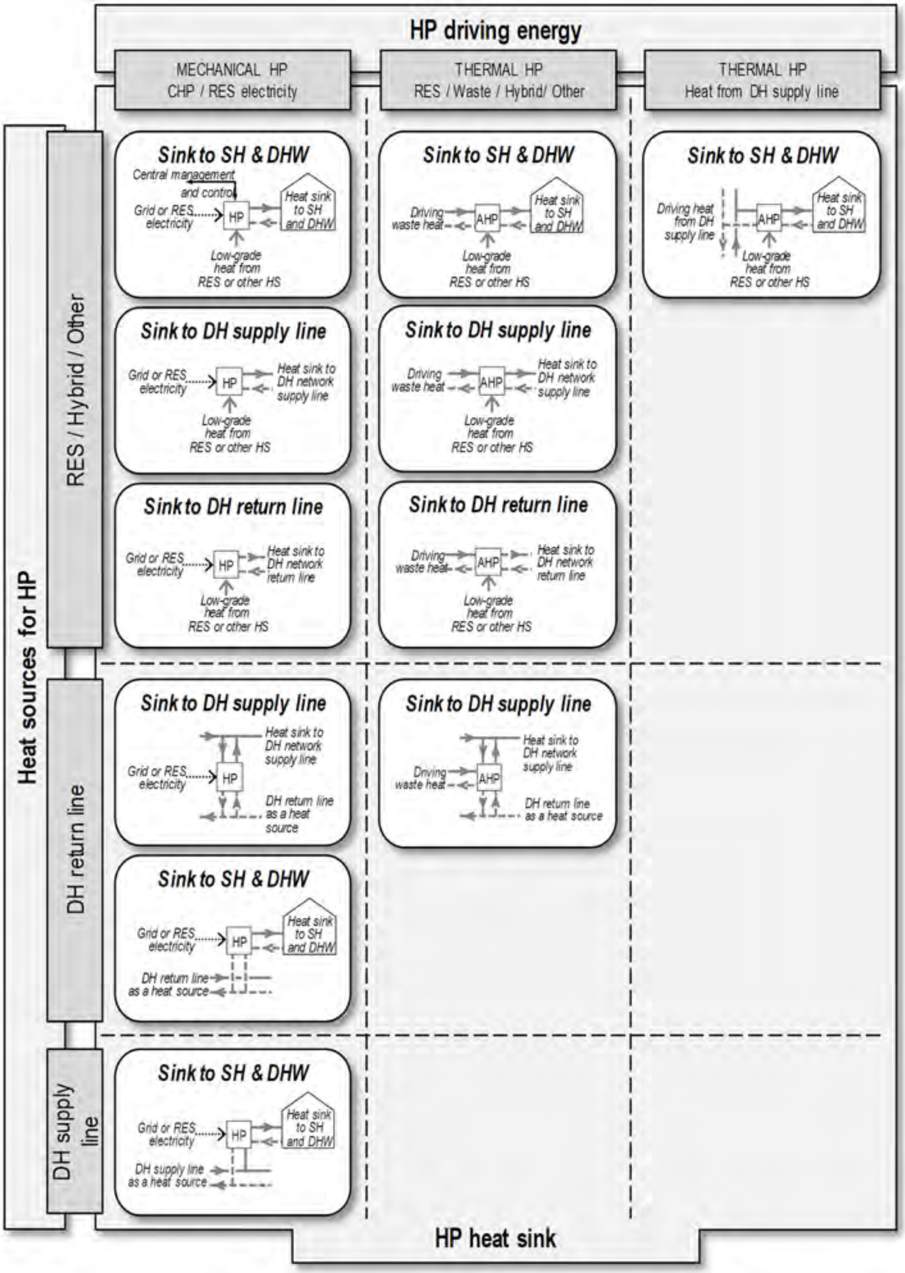


Fig. 3.7. Chart of heat sources, driving energy and connection modes for heat pump integration into district heating: AHP – absorption HP, DH – district heating, DHW – domestic hot water, HP – heat pump, HS – heat source, RES – renewable heat source, SH – space heating) [10]

The heat sink is the next important component for heat pump integration into district heating: the supplied heat by the heat pump can be submitted to the supply line or the return line or directly to the buildings for space heating and DHW 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 wide range of the possible solutions for heat pump technology integration into the district heating network.

3.4.1. Heat pump with a single heat source

With this arrangement, the heat pump is placed centrally, as shown in Fig. 3.8. From the technical triangle, the heat pump as a single heat source should have a sufficient and flexible thermal capacity to fulfil the heating requirement entirely throughout the year. The challenge here is to ensure that the thermal capacity of the heat source is adequate for covering the peak heating requirement. The design condition of heating requirement occurs rarely and even for very short periods, so such an operational mode is not cost effective and decreases the use of the installed heat pump thermal capacity.

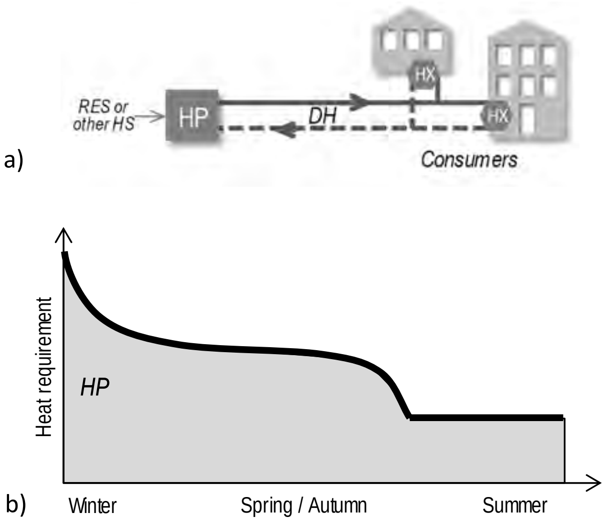


Fig. 3.8. Heat pump as single heat source option: A) heat pump placement and connection mode, B) heat requirements profile and operation mode (DH – district heating, HP – heat pump, HS – heat source, HX – heat exchanger, RES – renewable energy source) [10]

3.4.2. A heat pump as a single heat source with thermal energy storage

Providing seasonal thermal energy storage to the single heat pump based district heating, previously illustrated in Fig. 3.8, will decrease the needed thermal capacity of the heat pump to less than the maximum heating requirement. Thermal energy storage plays a buffer role in stabilising network operations, as shown in Fig. 3.9a.

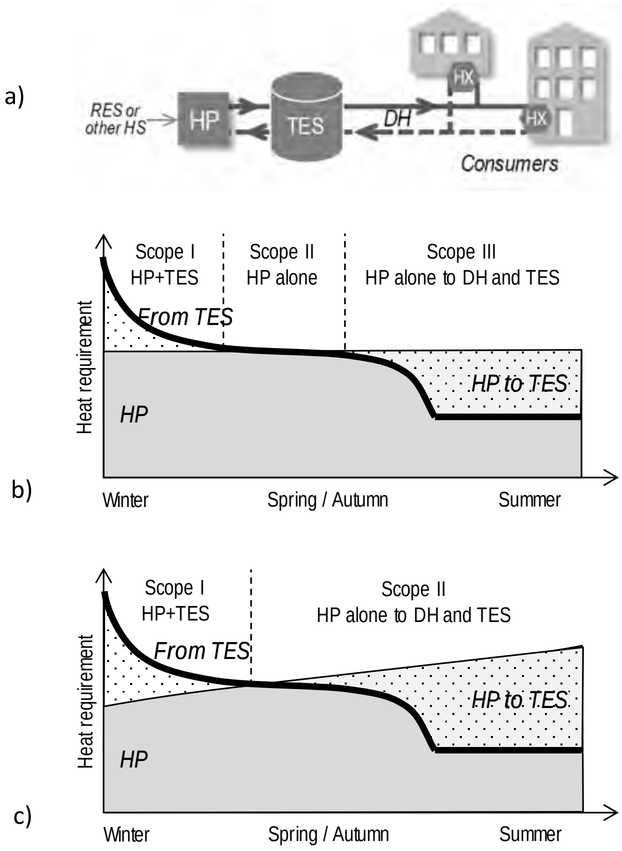


Fig. 3.9. Heat pump in single heat source option with TES: a) heat pump placement and connection mode, b) heat requirement profile and operational mode for the stable thermal capacity of heat pump, c) heat requirement profile and operational mode for the variable thermal capacity of a heat pump (DH – district heating, HP – heat pump, HS – heat source, HX – heat exchanger, RES – renewable energy source, TES – thermal energy storage) [10]

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 Figs. 3.9b and 3.9c, respectively), according to the heat source characteristics. In 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 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 [10].

According to the technical triangle, using thermal energy storage in heat pipe 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 thermal capacities for heat pump and thermal energy storage in such an operational mode can fulfil the yearly heating requirement, as shown in Fig. 3.9. It should be mentioned that using a seasonal TES tank in the network is favored, but it is a costly option due to the large storage capacity needed; the heat storage efficiency for such option should be taken into account, too.

3.4.3. Heat pump with a single heat source and multi-stage operation

For the best fulfilment of the heating requirement, it is possible to use a multi-stage connection of the heat pump units. In this operational mode, the heat pumps could have similar or different technologies and thermal capacities [63, 64]. The heat pump units contribute sequentially to the district heating supply line water temperature.

Figure 3.10a shows an example of a 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 or scopes are dependent and cannot be changed.

As shown in Fig. 3.10b, for scope I all three heat pumps (scopes I+II+III) are operating together to fulfil the heating requirement, in scope II the HP3 unit is switched off, leaving units HP2 and HP1 to fulfil the reduced heating requirement, and in scope III the HP1 unit continues alone to fulfil the reduced heating requirement outside 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. 3.10b. It should be mentioned that with multi-stage heat pumps different kinds of heat sources can be used for each scope, 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.

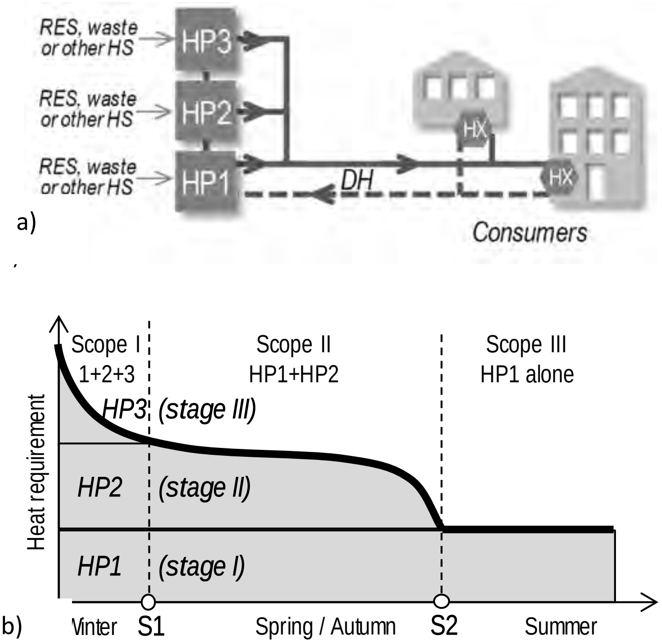


Fig. 3.10. Heat pump in single heat source with multi-stage option:
a) heat pump placement and connection mode, b) heat requirement profile and operational mode (DH – district heating, HP – heat pump, HS – heat source, HX – heat exchanger, RES – renewable energy source) [10]

3.4.4. 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 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, environmental aspects, and technical requirements. With multiple heat sources option, the heat pump generally operates as the primary heat source with its full thermal capacity 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 district 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. 3.11a 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. 3.11b. In both connections and due to the technical triangle, 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. 3.11c. In scope I, both the heat pump and the conventional heat source supply the district heating by heat 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 outside the heating season. It is noticeable that the heat pump operates with its full thermal capacity over the whole year.

In Fig. 3.11d the variable capacity heat pump operates in a partially parallel operation mode. In scope I, the conventional heat source supplies alone the needed heating requirement 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 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 as a group or pool of heat pumps in different locations, different thermal capacities, and heat pump technologies. This helps to increase the supplied thermal capacity by renewable energy and to save the consumption of fossil fuels.

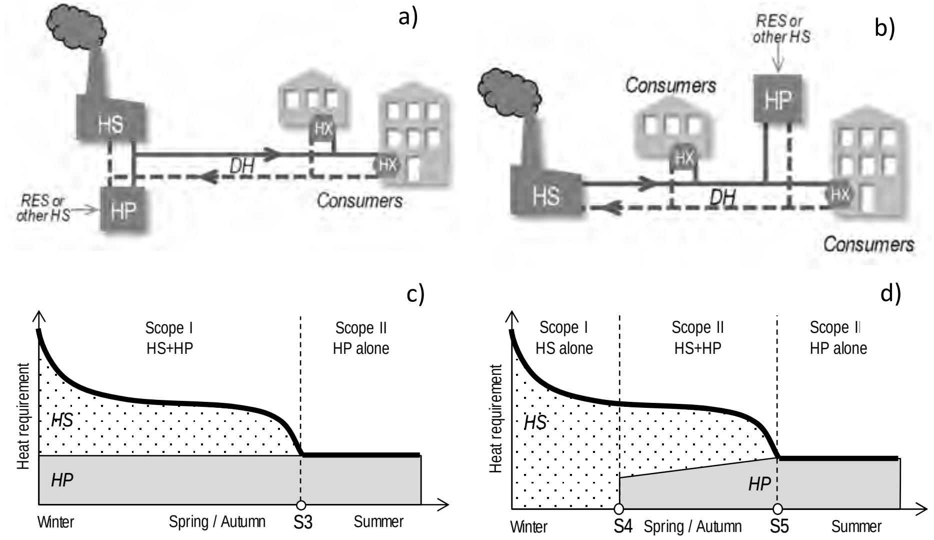


Fig. 3.11. Heat pump with multiple heat sources connected in parallel: a) centrally placed heat pump connection, b) locally placed heat pump connection, c) heat requirement profile for fully parallel operational mode (stable thermal capacity of heat pump), d) heat requirement profile with partially parallel operational mode (variable thermal capacity of heat pump): DH – district heating, HP – heat pump, HS – heat source, HX – heat exchanger, RES – renewable energy source [10]

3.4.5. 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 by means of multiple heat sources connected in parallel (e.g., a heat pump with solar thermal collectors) connected to a seasonal TES tank. As shown in Fig. 3.12, 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 regimes or scopes: scope I where heat pump and thermal energy storage tank supply the district heating by heat; scope II where the heat pump and the renewable source supply the network; scope III where the heat pump supplies the district heating and simultaneously with the renewable source charges the TES tank. It is obvious that in scope III the heat pump charges excess heat to the 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 RESs to supply the district heating and better use of the heat pump's thermal capacity, but using seasonal TES is a costly option. The seasonal heat storage efficiency should also be taken into account.

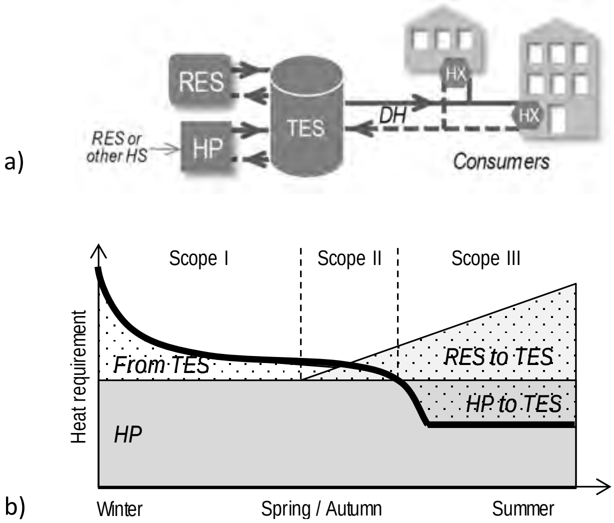


Fig. 3.12. Heat pump with multiple heat sources connected in parallel with renewable energy sources and thermal energy storage: a) heat pump placement and connection mode, b) heat requirement profile and operational mode (DH – district heating, HP – heat pump, HS – heat source, HX – heat exchanger, RES – renewable energy source, TES – thermal energy source) [10]

3.4.6. 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. Figure 3.13a shows the unit as 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.

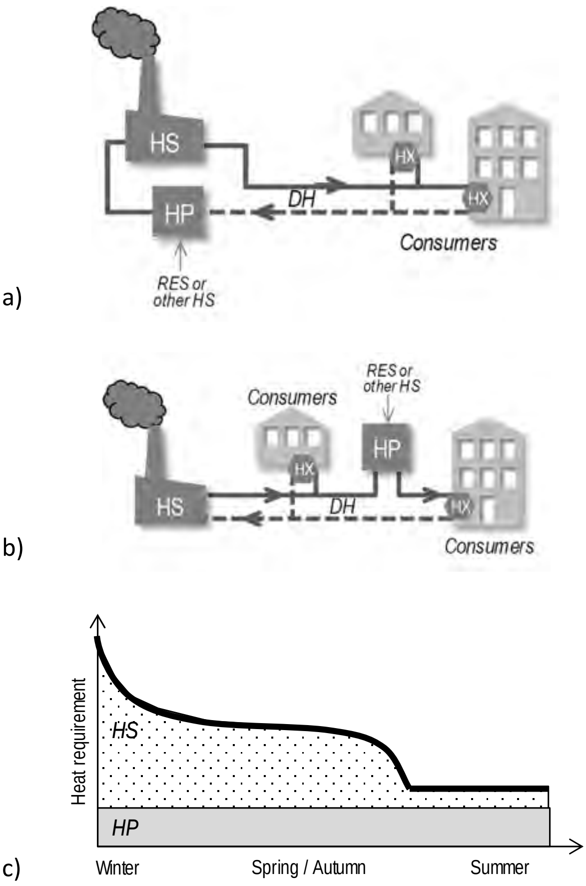


Fig. 3.13. Heat pump with multiple heat sources connected in series: a) heat pump central placement in series connection, b) series connection for central heat source and local heat pump, c) heat requirement profile and operational mode: DH – district heating, HP – heat pump, HS – heat source, HX – heat exchanger, RES – renewable energy source) [10]

Figure 3.13b 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, so increases the overall thermal capacity of the district heating system. In this way, 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.

3.4.7. Heat pump with multiple heat sources connected in series using a 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. 3.14.

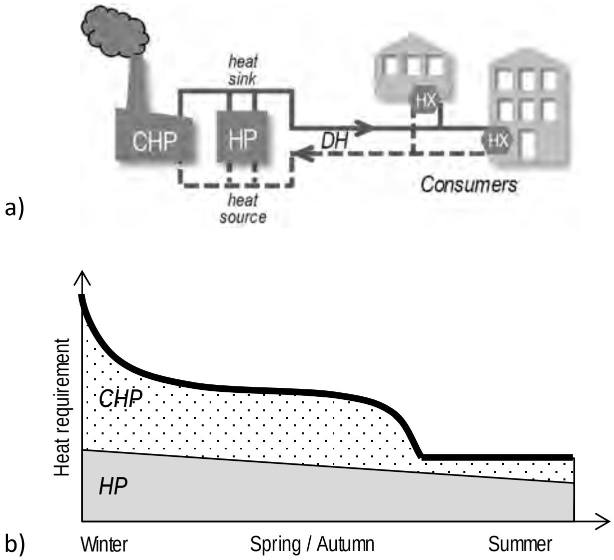


Fig. 3.14. Heat pump with multiple heat sources connected in series (heat pump in return to supply operational mode): a) heat pump placement and connection mode, b) heat requirement profile and operational mode (CHP – combined heat and power, DH – district heating, HP – heat pump, HX – heat exchanger, RES – renewable energy source) [10]

Traditionally, in 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 energy management in the district energy system [59–63].

3.4.8. Individual heat pumps in district heating

Figure 3.15 shows five examples of connection modes for integrating individual heat pump units into the district heating network:

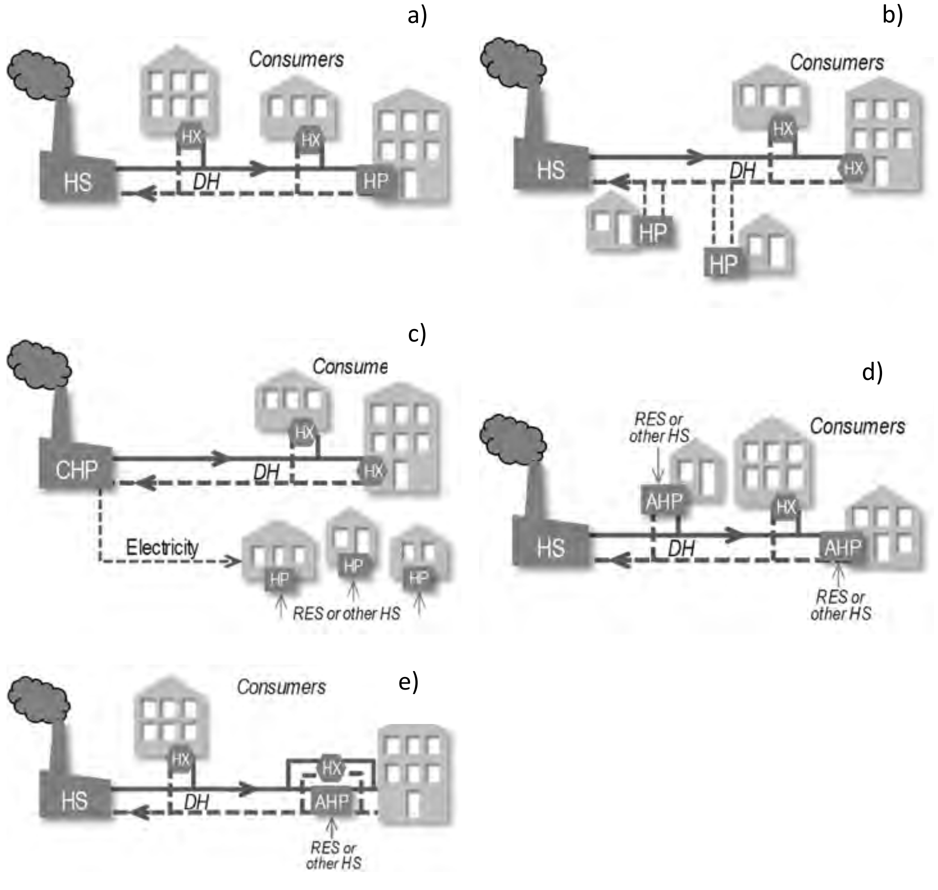


Fig. 3.15. Placement and connection modes for individual heat pump units: a) heat pump in place of heat exchanger, b) heat pumps using the district heating return line as a heat source, c) heat pumps powered by CHP and not connected to district heating network, d) absorption heat pumps in place of heat exchangers in buildings, e) absorption heat pumps connected in parallel with heat exchangers in buildings (AHP – absorption HP, CHP – combined heat and power, DH – district heating, HP – heat pump, HS – heat source, HX – heat exchanger, RES – renewable energy source) [10]

- individual heat pumps in place of heat exchangers in selected buildings,
- individual heat pumps using the return line of the DH as a heat source,
- individual heat pumps units connected indirectly with the DH network and powered by a CHP plant,
- individual absorption heat pumps as single heat sources in buildings,
- individual absorption heat pumps connected in parallel with heat exchangers in buildings.

3.5. Environmental obstacles of heat pumps in district heating

Heat accounts for over 40% of energy consumption and nearly a quarter of all carbon emissions. Even though the end-use heat service requirements may remain at current levels, most future scenarios show potential for efficiency savings of between 20% and 30% for space heating demand by 2050.

The decarbonisation of the energy system is one of the main challenges that the European Union is facing today, and it will become an increasingly important area for energy policy to address in the coming years and decades. Achieving the targeted emission reductions of 80 to 95% compared to 1990 levels by 2050 requires a fundamental transformation of the energy sector. Especially in the electricity sector, RESs play a major role to achieve these targets [67]. Heating is arguably one of the most challenging sectors to decarbonise in the energy system. There is a significant amount of uncertainty in what the DH heat supply might look like in the period from now to 2030 and beyond [68].

Many recent academic reports have concluded that decarbonising heat at a larger scale would need to be well underway by the 2030s and continue beyond 2050 in order to meet the legally binding carbon reduction targets set in the Climate Change Act, let alone to deliver on commitments made in the Paris Agreement to keep global temperature increases well below 2 °C [69–71]. It is evident that since over 90% of today’s homes, buildings will still be in use in 2050, alongside the development of sensible measures and standards for new buildings, a major retrofit programme will be required. There are likely to be at least three main routes to decarbonise heat:

- district heating schemes with centralised, low-carbon heat generation,
- electrification with some combination of direct electric heating, storage heaters, and heat pumps,
- repurposing the gas grids with low carbon gas, e.g., hydrogen.

It is necessary to notice that two routes are strongly concerned with district heating and heat pumps. District heating can supply heat very efficiently and at a low running cost. Although currently there is only a restricted choice for low carbon heat generation, having a central production point means that changing the source in the future could be much simpler and more cost-effective than changing multiple individual household solutions.

District heating is well suited to areas of mixed use with strong anchor clients, such as municipal buildings, offices, and leisure centres. Although most readily installed as part of new developments, district heating can also be suitable for retrofit in less populated areas as part of community energy schemes, as well as for flats in multi-storey buildings. The main challenge is to achieve sufficient customer density so that the high up-front capital costs can be recovered over sufficient users and offset by sufficient fuel savings to keep bills affordable.

The seasonal fluctuations in space heating requirements can be lower in mixed-use district heating schemes, and heat storage can be incorporated which is considerably less expensive than electricity storage (one-hundredth of the cost), although still considerably more than fuel storage (one hundred times). As in the electricity system, consideration should be given at the design stage to the storage, demand-side management, and back-up solutions [72]. As is clear from the overview of different approaches to delivering low carbon heating, the elements of investment that are required can be grouped under three headings:

- investment in individual homes either to fit a new low carbon heat source (such as a heat pump) or to change/adjust appliances to be able to cope with new forms of gas or a move to district heating,
- investment in monopoly networks such as district heating systems or upgrades to existing gas networks to accommodate, e. g., hydrogen,
- investment in new sources of heat for district heating or new sources of gas to feed into the networks, which could be competitively provided.

District heating networks and service provision are relatively unregulated in comparison to gas and electricity, so all the proposed options for heat decarbonisation are likely to be more expensive than the baseline of natural gas and electricity [70].

3.5.1. Heat pump deployment for decarbonisation of district heating

DH can provide a very energy efficient means of supplying heat; DH is also flexible and has the potential to modify or exchange the heat source without disrupting individual users. Heat pumps and DH have been widely deployed in Europe; heat pumps can offer the benefit of high-efficiency heat production. Heat pumps are the recognised technology for decarbonising the hot water and space heating demands of residential and non-residential buildings. Thus the performance of heat pumps is of paramount importance. Many scenarios have relied heavily on the assumption that heat will be decarbonised through electrification, and heat pumps in particular. There are two main routes to electrify heat: by direct resistive heating and heat pumps; the choice between them is dependent on consumption patterns and the availability and attractiveness of off-peak tariffs [71]. On the other hand, the assumption is that most if not all types of heat pumps will have an SPF of at least 2.5. Comparatively higher efficiencies of SPF around 2.5 for air source heat pump systems and 3.0 for ground source heat pump systems and the potential decarbonisation of the electricity supply make them highly attractive in the choice to replace gas boilers. Even though heat pumps are a mature technology and relatively new technology for heat supply in different parts of Europe [68].

The reviews and modelling analysis showed that lower SPF values could increase emissions by 2 Mt CO_2 and the impact would be greater if the electricity grid does not decarbonise to an intensity of 50 g CO_2/kWh by 2030. So there is a great emphasis on improving the performance of heat pumps until 2020 and beyond. The use of heat pumps is relatively steady now, and it can increase in the future, so the technological knowledge should widely be implemented [73, 74]. Currently, the levelled energy cost of heat pumps is high when compared with gas boilers. This most likely will not change until 2030. This is a major barrier for the deployment of heat pumps and other technologies such as biomass boilers [75–77]. Most of these technologies have high upfront capital costs that largely contribute to their levelled energy costs in comparison with incumbent technologies such as gas boilers. This issue will only resolve itself with technological learning (cost reductions and efficiency improvements) and experience gained by installers to efficiently design heat based systems [68].

3.5.2. Environmental impact of heat pumps

Buildings account for about one-third of GHG emissions in developed economies and 55% of electricity consumption in Europe. The incremental deployment of heat pumps can reduce the use of fossil-fuelled energy in the building sector and thus limit the environmental pollution and adverse health impacts on societies caused by exploration and extraction of fossil fuels.

Nonetheless, heat pumps are not an emission-free heating system, and thus, their environmental footprint needs to be observed, too [22, 27]. Like for other boiler technologies, a heat pump impact on the environment can be assessed during production use dismantling. Heat pumps are subject to building and waste reduction regulation. The environmental impact from the operation of heat pumps can be split into emissions from energy use and CO_2 equivalent emissions from the use of refrigerants. The former can hardly be influenced by the technology itself, as the decarbonisation of electricity is a key aim of European energy policy. Since the emission levels of electricity generated are continuously decreasing as a result of an increasing amount of RESs, the emissions of all heat pumps are continuously going down [22, 27, 73–77].

Regarding the environmental impacts associated with the use of heat pumps, it is possible to distinguish between direct and indirect effects. Direct effects are those related to the global warming potential (GWP) of the flue gases released in the case of accidental leakage, while indirect effects are provoked by the emissions associated with electricity production. Indirect effects are usually more serious than the direct ones [78–80]. Among the indirect emissions, CO_2 emissions are to be primarily taken into account since CO_2 is the most common GHG and is considered the main contributor to climate change [81]. Therefore, the environmental impacts of heat pumps depend on the CO_2 emission factors of the region where the electricity used by the heat pump is produced. Locations, where electricity is mainly produced by nuclear, hydroelectric or other renewable power plants, have lower CO_2 emission factors than regions relying on thermal fossil-fuel power plants; therefore, in the locations with low carbon emissions, heat pump systems can be an environmentally-friendly alternative [82]. If the regional emission intensity is less than 0.76 kg/kWh, then a gas heat pump system offers environmental advantages (i.e., emission reduction) compared to a natural gas furnace with an efficiency of 0.95. Higher efficient heat pumps are environmentally advantageous even in regions with higher emission intensity [22, 27, 81].

3.5.3. Environmental impact of refrigerants

Environmental concerns have always been the driving force in the development of environmentally friendly refrigerants. Active research in fields of energy system design optimization, energy efficiency increase, a search of the new refrigerants and efficient use of the old systems are important for both heat pump and refrigeration systems. Based on the increasing contribution of refrigeration systems to climate change, it is necessary to use environmentally friendly refrigerants to mitigate global warming [83, 84].

The refrigerant is an essential component of a heat pump. Its characteristics allow the heat pump to operate and to use RESs for the generation of heat and cold; yet, these positive characteristics come at a cost. On the other hand, different environmental metrics are used to facilitate the decision-making process of selection of refrigerant with low global warming potential. Three environmental metrics are mostly used in the process of refrigerant selection: GWP, TEWI, and LCCP. Although each serves the similar aim of quantifying the impact of refrigerants on global warming, their usage can lead to different conclusions. Besides the environmental metrics, other basic and practical considerations need to be taken into account when selecting a refrigerant, like safety, toxicity, flammability [83, 84]. The refrigerants can be toxic, flammable, even explosive, or act as GHGs with a specific global warming potential (GWP). None of these issues occurs if the refrigerant remains inside the unit. By consequence, high-quality design and manufacturing of units as well as the skills of installers to dismantle and to recover refrigerants are crucially important.

If the refrigerant is released into the environment, it can harm the atmosphere. Figure 3.16 presents the most common refrigerants currently used in terms of their global warming potential. In adition to global warming potential GWP, it is necessary to remind the environmental impact complexity involved in making the right choice of refrigerants considering other key factors such as toxicity and flammability. The majority of residential units deployed today use hydrofluorocarbons while in large or industrial size heat pumps the use of natural refrigerants like ammonia, propane or CO_2 is more common [27, 83, 84].

NAME	GROUP	FLAMMABILTY	SAFETY CLASS	GWP
R32	HFC	Mild	A2L	675
R125	HFC	No	A1	3500
R134A	HFC	No	A1	1430
R152A	HFC	Yes	A2	124
R245FA	HFC	-	B1	1030
R404A	HFC	No	A1	3922
R407C	HFC	No	A1	1774
R410A	HFC	No	A1	2088
R1234YF	HFO	Yes	A2L	4
R1234ZE	HFO	Yes	A2L	7
R448A	HFO	No	A1	1387
R449A	HFO	No	A1	1397
R290 PROPANE	Hydrocarbon	High	A3	3
R600	Hydrocarbon	High	A3	3
R717	Amonia	No	B2L	0
R744	Carbondioxide	No	A1	1

Fig. 3.16. Currently used typical refrigerants [27] and GWP ranges: >2500 – very high, 1500–2500 – high, 750–1500 – moderate, 150–750 – low, 10–150 – very low, <10 – ultra low

The use of hydrofluorocarbons in Europe is regulated under EU 517/2014. The implemented phase-down will reduce the availability of flue gases continuously until 2030. Effects on availability and prices are already becoming visible in the market today. This allows searching for alternatives as a key challenge for the heat pump industry. New mixes with a lower GWP are the available solutions, but these substances are usually at least mildly flammable. Other options include natural refrigerants like propane and butane (highly flammable), ammonia (toxic) or carbon dioxide (high operating pressure). It must be stressed, however, that the largest share of emissions from any heating/cooling system results from the fuel used to operate the unit. The total equivalent warming impact (TEWI) calculation is an established approach to asses emissions over the useful life cycle of a unit. Emissions are distinguished as direct emissions (chemical) and as indirect emissions (the energy use) of greenhouse gases from production, operation, and recycling [27, 85].

Figure 3.17 shows a comparison of the lifetime emissions of different heating solutions. The assumptions are identical to those which are shown in Fig. 3.16. For simplicity, heat pumps are assumed to use one refrigerant (R410A) only, except the last column, where the future scenario of a heat pump with a new low GWP refrigerant (GWP < 1) also using green electricity (CO_2 emission of 15) is presented. This is a realistic consequence of the ongoing greening of the electricity mix and the phase-down of the current refrigerants. Figure 3.17 also shows that a fast reduction of emissions from electricity has a more significant impact on the life-cycle-based emissions of the heat pumps than the deployment of refrigerants with a low GWP. It also shows that even the heat pumps with the lowest currently allowed efficiency have lower emissions than the best fossil combustion system.

Consequently, the key challenge for the industry is the development of products and procedures that keep refrigerant losses to a minimum by designing and producing high quality, hermetically sealed units. On the other hand, heat pump installers and technical experts should be adequately skilled to reduce the impact of the used refrigerant [27, 85]. From the environmental perspective, the use of existing refrigerants – if appropriately handled – already contributes to a reduction in GHG emissions, which is accelerated by every reduction step of emissions from electricity. It should thus be kept in mind, that the priority when addressing climate change is the reduction of CO_2 emissions to the atmosphere and not a ban on current refrigerants.

From an industry perspective, the development of low and no GWP alternatives in the efficient heat pump systems must be the ultimate goal in order to deploy a near-zero emission heating technology – both from the component and the operation side [22, 27, 85].

The future poses several challenges and opportunities for manufacturers of heat pump systems. Most notable is the sustained effort to develop new refrigerants. Concurrently, there will be pressure to improve efficiency to maintain the competitive edge over new technologies such as gas heat pumps and to

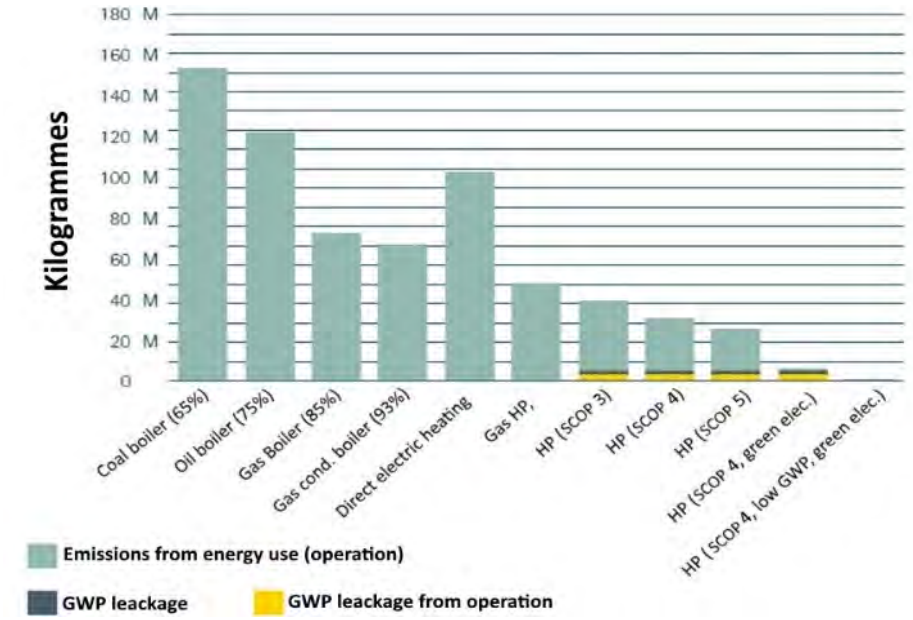


Fig. 3.17. A comparison of the lifetime emissions of different heating solutions [27]

satisfy minimum efficiency requirements imposed by legislation. New performance-enhanced refrigerants must be equipped with improved cycle controls, higher-efficiency motors, compressors, and new cycles to realise optimum cycle efficiencies in order to meet varying refrigerating capacities [30]. Besides the issue of the impact caused by refrigerants, extensive works continue to progress in testing new refrigerant mixtures to improve the energy efficiency and operation of heat pumps [22, 27, 30, 31].

3.5.4. Emissions associated with the use of 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, as mentioned previously. In EU countries that generate electricity and heat produced from different heat sources and technologies such as fossil fuels, nuclear, RESs, the emissions from each source must be carefully examined to determine the mass of emissions per unit energy generated [86]. 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 [10, 27].

Figure 3.18 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 the 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 [87]. 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 the mix of both.

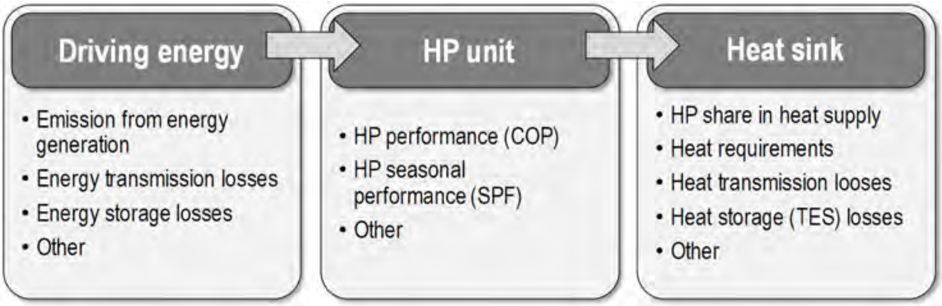


Fig. 3.18. Emission considerations for heat pump based district heating [10]

According to Fig. 3.18, the emissions from the heat pump driving energy are provided by generation technology (e.g., fossil fuel based, cogeneration, fuel mix, hybrid, RESs, 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 heat pump applications. At the heat sink, a large heating requirement has the worst impact on emissions. Heat transmission and thermal storage losses need additional driving energy production, which contributes to even more emissions. Increasing the contribution from heat pumps in multiple heat sources allows decreasing the emissions due to the higher efficiency of heat pumps compared with conventional heat sources. Heat pumps in district heating systems have great potential for contributing to a significant reduction in emissions [88]. 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, limiting the energy use and the heat losses, and by adjusting the energy generation and heat sinks [89, 90].

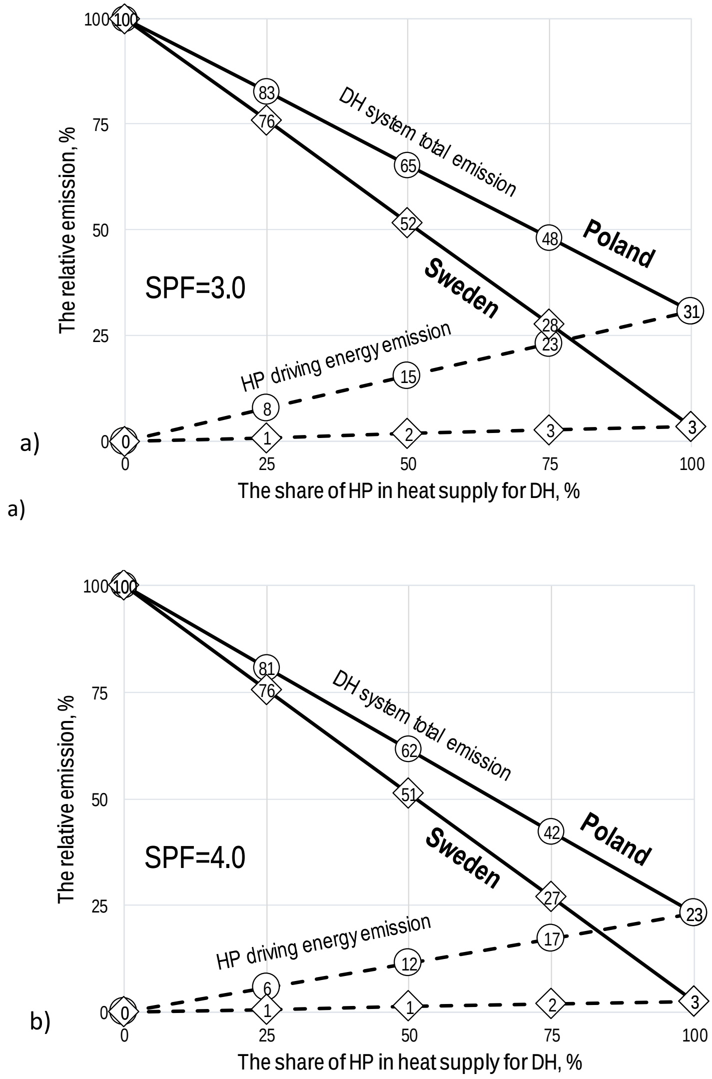


Fig. 3.19. The relative emission from DH system vs HP share in heat supply for Poland and Sweden: a) SFP = 3.0, b) SPF = 4.0 [10]

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 [10, 27]. The calculations considered energy generation technologies and emissions from national energy systems in both countries and were based on allocations of emission to the electricity and heat according to the fixed-heat-efficiency approach methodology [91–94]. The countries were selected from among the EU countries based on the renewable proportion in national power generation. The renewable contribution in power generation is maximum in Sweden and 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 [95].

Figure 3.19 shows the relative emission changes in district heating due to the contribution of electrically driven heat pumps in the heat supply. In the figure, where the SPF = 3.0, the total relative emission for Poland decreases to 65% with the 50% of heat pump contribution, in which 15% comes from the generation of driving energy consumed by the heat pump. Even a 100% heat pump contribution in district heating reduces emissions to 31% only. In Sweden, a 50% contribution from heat pumps reduces the emissions to 52%, and 100% contribution reduces emissions to 3%, due to a large share of renewables in the Swedish power system.

From Figure 3.19b for SPF = 4.0, it is clear that emissions for Poland will be reduced to 23% if the contribution of heat pumps in district heating will equal 100%. Meanwhile, the emissions for Sweden will be 3% for 100% heat pump contribution. 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 [10, 27].

References

[1] Rosa D.A., Li H., Svendsen S., Werner S., Persson U., Ruehling K., Bevilacqua C., *Annex X. Final report – Toward 4th Generation District Heating*, Technical University of Denmark, 2014.

[2] *Advanced District Heating and Cooling (DHC) Systems*, R. Wiltshire (Ed.), Woodhead Publishing, Oxford 2016.

[3] Promelle J., *Gas heat pumps: product overview. Engine driven heat pumps. Thermally driven heat pumps*, GDF SUEZ, Research Division, Suez 2011.

[4] Directive 2009/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/EC and 2003/EC, L 141, European Parliament, Brussels 2009.

[5] Vellei M*., A review of factors affecting environmental and economic life-cycle performance for electrically-driven heat pumps*, JRC Science and Policy Report, Luxembourg 2014.

[6] Delmastro C., Martinsson F., Dulac J., Corgnati S.P., *Sustainable urban heat strategies: Perspectives from integrated district energy choices and energy conservation in buildings. Case studies in Torino and Stockholm*, Energy, 2017, 138, 1209–1220.

[7] Averfalk H., Werner S., *Essential improvements in future district heating systems*, Energy Proc., 2017, 116, 217–225.

[8] Maxwell V., Sperling K., Hvelplund F., *Electricity cost effects of expanding wind power and integrating energy sectors*, Int. J. Sust. Energy Plan. Manage., 2015, 6, 31–48.

[9] *Heat Pumps, Energy Efficiency Reference Guide*, CEATI International, Elsevier, London 2007.

[10] Sayegh M.A., Jadwiszczak P., Axcell B.P., Niemierka E., Bryś K., Jouhara H., *Heat pump placement, connection and operational modes in European district heating*, Energy Build., 2018, 166, 122–144.

[11] Sayegh M.A., Danielewicz J., Nannou T., Miniewicz M., Jadwiszczak P., Piekarska K., Jouhara H., *Trends of European research and development in district heating technologies*, Ren. Rev, Sust. Energy Rev., 2017, 68, 1183–1192.

[12] Sayegh M.A., Danielewicz J., Miniewicz M., Jadwiszczak P., Piekarska K., Nannou T., Jouhara H., *Trends of European research and development in district heating technologies*, Proc. SEEP, 2015, 11–14 August 2015, Paisley.

[13] Jouhara H., Szulgowska-Zgrzywa M., Sayegh M.A., Milko J., Danielewicz J., Nannou T.K., Lester S.P., *The performance of a heat pipe based solar PV/T roof collector and its potential contribution in district heating applications*, Energy, 2017, 136, 117–125.

[14] *Energy Balances of Non-OECD Countries*, International Energy Agency, 2011, available from: http://www.iea.org/

[15] Zhen L., Duanmu L., Shu H.W., Jiang S., Zhu Y.X., *District cooling and heating with seawater as heat source and sink in Dalian, China*, Ren. Energy, 2007, 32 (15), 2603–2616.

[16] Critoph R.E., *Gas driven heat pumps: Market potential, support measures and barriers to development of the UK market*, University of Warwick, Warvick 2013.

[17] The European Parliament and the Council of the European Union, *Regulation (EU) No. 51714 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing*, Regulation (EC) No. 84306. Off. J. Eur. Union, 2014, 195–230.

[18] *Heat pumps, energy saving and renewable energy in vocational education*, Leonardo da Vinci project ENERSOL EU, European Parliament, 2004.

[19] *Heat Pump Planning Handbook*, J. Bonin (Ed.), Routledge, Abingdon 2015.

[20] Magagna D., Shortall R., Telsnig T., Uihlein A., Vázquez Hernández C., *Supply chain of renewable energy technologies in Europe. An analysis for wind, geothermal and ocean energy*, European Commission, Joint Research Centre, 2017.

[21] Fischer D., Madani H., *On heat pumps in smart grids: A review*, Ren. Rev, Sust. Energy Rev., 2017, 70, 342–357.

[22] Nowak T., Westring P., *European heat pump market and statistics report 2015. Technical report*, The European Heat Pump Association AISBL (EHPA), Brussels 2015.

[23] Szabó L. et al., *Renewable Based District Heating in Europe: Policy Assessment of Selected Member States*, European Parliament, Brussels 2015.

[24] Connolly D., Mathiesen B.V., Dubuisson X., Lund H., Ridjan I., Finn P., Hodgins J., *Climate change strategy*, Limerick Clare Energy Plan, Limerick 2012.

[25] Zhen L., Duanmu L., Shu H.W., Jiang S., Zhu Y.X., *District cooling and heating with seawater as heat source and sink in Dalian, China*, Ren. Energy, 2007, 32 (15), 2603–2616.

[26] http://stats.ehpa.org/hp_sales/

[27] Nowak T., *Heat pumps: Integrating technologies to decarbonise heating and cooling*, European Copper Institute, Brussels 2018.

[28] *European heat pump market and statistics report 2018*, https://www.researchandmarkets.com/research/92hl4n/european_heat?w=4

[29] Vellei M., *A review of factors affecting environmental and economic life-cycle performance for electrically-driven heat pumps*, JRC Science and Policy Report, European Parliament, 2014.

[30] Müller T., Schreiber S., Herbst A., Klingler A. L., Wyrwa A., Fermi F., Reiter U., *How to balance intermittent feed-in from renewable energies? – A techno-economic comparison of flexibility options*, REFLEX, European Parliament, Brussels 2017 .

[31] Zimny J., Michalak P., Szczotka K., *Polish heat pump market between 2000 and 2013: European background, current state and development prospects*, Ren. Rev, Sust. Energy Rev., 2015, 48, 791–812.

[32] Dumas P., Bartosik A., *Geothermal DH Potential in Europe*, 2014, GeoDH-Report-D-2.2-final

[33] Dumas P., Angelino L., Latham A., Pinzuti V., *Developing geothermal district heating in Europe*, 2014, GeoDH-Report-2014_web

[34] Münster M., Morthorst P.E., Larsen H.V., Bregnbaek L., Werling J., Lindboe H.H., Ravn H., *The role of district heating in the future Danish energy system*, Energy, 2012, 48 (1), 47–55.

[35] Lorentzen G., Sarlos G., Favrat D., *Thermodynamic heating, a powerful means of energy conservation*, Proc. Int. Conf. Conventional and Nuclear Heating, Lausanne 1991, 27–37.

[36] Haiwen S., Lin D., Jing S., Xin J., Zhiyong R., Haiyang Y., *Field measurement and energy efficiency enhancement potential of a seawater source heat pump district heating system*, Energy Build., 2015, 105, 352–357.

[37] Favrat D., Marechal F., Epelly O., *The challenge of introducing an exergy indicator in a local law on energy*, Energy, 2008, 33 (2), 130–136.

[38] Huculak M., Jarczewski W., Dej M., *Economic aspects of the use of deep geothermal heat in district heating in Poland*, Ren. Rev, Sust. Energy Rev., 2015, 49, 29–40.

[39] Lund H., Clark W.W., *Management of fluctuations in wind power and CHP comparing two possible Danish strategies*, Energy, 2002, 27 (5), 471–483.

[40] Rinne S., Syri S., *Heat pumps versus combined heat and power production as* CO_2 *reduction measures in Finland*, Energy, 2013, 57, 308–318.

[41] Hedegaard K., Mathiesen B.V., Lund H., Heiselberg P., *Wind power integration using individual heat pumps: Analysis of different heat storage options*, Energy, 2012, 47 (1), 284–293.

[42] Persson U., *Enhanced heating and cooling plans*, [In:] U. Persson (Ed.), *Quantifying the Excess Heat Available for District Heating in Europe*, WP2, Background Report 7, Aalborg University, Denmark, 2015.

[43] De Carli M., Galgaro A., Pasqualetto M., Zarrella A., *Energetic and economic aspects of a heating and cooling district in a mild climate based on closed loop ground source heat pump*, Appl. Thermal Eng., 2014, 71, 895–904.

[44] Lund R., Persson U., *Mapping of potential heat sources for heat pumps for district heating in Denmark*, Energy, 2016, 110, 129–138.

[45] IEA-ETSAP and IRENA, *Heat Pumps Technology Brief*, Masdar City, Abu Dhabi, 2013.

[46] Taylor S. et al., *Drivers of growth and cost changes in European renewable heat technologies*, European Comission, Brussels 2016.

[47] Foster S. et al., *Heat Pump in district heating: Final report*, DECC by Element Energy and Carbon Alternatives, European Comission, Brussels 2016.

[48] Bartolozzi I., Rizzi F., Frey M., *Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy*, Ren. Rev, Sust. Energy Rev., 2017, 80, 408–420.

[49] Ristimäki M., Säynäjoki A., Heinonen J., Junnila S., *Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design*, Energy, 2013, 63, 168–179.

[50] Fröling M., Holmgren C., Svanström M., *Life cycle assessment of the district heating distribution system. Part I: Pipe production*, Int. J. Life Cycle Assess., 2004, 9 (2), 1300–1306.

[51] Persson C., Fröling M., Svanström M., *Life cycle assessment of the district heating distribution system. Part 3: Use phase and overall discussion*, Int. J. Life Cycle Assess., 2006, 11 (6), 437–446.

[52] Fröling M., Svanström M., *Life cycle assessment of the district heating distribution system. Part 2: Network construction*, Int. J. Life Cycle Assess 2005, 10 (6), 425–435.

[53] David A., Vad Mathiesen B., Averfalk H., Werner S., Lund H., *Heat roadmap Europe: Large scale electric heat pumps in district heating systems*, Energies, 2017, 10, 578.

[54] *Connolly D., Lund H., Mathiesen B.V., Werner S., Möller B., Persson U., Boermans T., Trier D., Østergaard P.A., Nielsen S., Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system*, Energy Pol., 2014, 65, 475–489.

[55] Lund H. et al., *4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems*, Energy, 2014, 68, 1–11.

[56] Ben Hassine I., Eicker U., *Impact of load structure variation and solar thermal energy integration on an existing district heating network*, Appl. Thermal Eng., 2013, 50, 1437–1446.

[57] Calm J., *Heat pump centered integrated community energy systems*, Argonne Nat Lab Report for US contract W-31-1009-Eng-38, Lemont, Illinois, 1980.

[58] Molyneaux A., Leyland G., Favrat D., *Environomic multi-objective optimisation of a district heating network considering centralized and decentralized heat pumps*, Energy, 2010, 35, 751–758.

[59] Baik Y.J., Kim M., Chang K.C., Lee Y.S., Ra H.S., *Potential to enhance performance of seawater--source heat pump by series operation*, Ren. Energy, 2014, 65 (5), 236–244.

[60] Sun F., Fu L., Sun J., Zhang S., *A new waste heat district heating system with combined heat and power (CHP) based on ejector heat exchangers and absorption heat pumps*, Energy, 2014, 69, 516–524.

[61] Sun F., Fu L., Zhang S., Sun J., *New waste heat district heating system with combined heat and power based on absorption heat exchange cycle in China*, Appl. Thermal Eng., 2012, 37, 136–144.

[62] Ommen T., Markussen W.B., Elmegaard B., *Heat pumps in combined heat and power systems*, Energy, 2014, 76, 989–1000.

[63] Liao C., Ertesvåg I.S., Zhao J., *Energetic and exergetic efficiencies of coal-fired CHP (combined heat and power) plants used in district heating systems of China*, Energy, 2013, 57, 671–681.

[64] Qunli Z., Mingkai C., Qiuyue Z., Hongfa D., *Research on a new district heating method combined with hot water driven ground source absorption heat pump*, Energy Proc., 2015, 75, 1242–1248.

[65] Wu W., Shi W., Li X., Wang B., *Air source absorption heat pump in district heating: Applicability analysis and improvement options*, Energy Conv. Manage., 2015, 96, 197–207.

[66] Li Y., Fu L., Zhang S., Zhao X., *A new type of district heating system based on distributed absorption heat pumps*, Energy, 2011, 36, 4570–4576.

[67] Müller T., Michaelis J., Elsland R., Reiter U., Fermi F., Wyrwa A. et al., *Overview of techno--economic characteristics of different options for system flexibility provision, Analysis of the European Energy System*, European Union, Brussels 2016.

[68] Chaudry M., Abeysekera M., Reza Hosseini S.H., Jenkins N., Wu J., *Uncertainties in decarbonising heat in the UK*, Energy Pol., 2015, 87, 623–640.

[69] Publications of Imperial College, https://www.imperial.ac.uk/people/g.mclean/publications.html/, 2017.

[70] Frerk M., MacLean D., *Providence policy heat decarbonisation: Potential impacts on social equity and fuel poverty*, Final Report NEA, Washington 2017, Heat-Decarbonisation-Report-September-2017

[71] MacLean K., Sansom R., Watson T., Groos R., *Managing Heat System Decarbonisation, Comparing the impacts transitions in heat infrastructure*, Imperial College Centre for Energy Policy and Technology, Final report, London 2016.

[72] http://www.svenskfjarrvarme.se/Global/EU-fr%C3%A5gor/Consultation%20Forum%2009092015%20-%20Issue%20Paper%20IV%20-%20Linking%20heating%20and%20cooli.pdf

[73] EUREL, Electrical Power Vision 2040 for Europe, Study by EUREL, Convention of Nat. Ass. of Electrical Engineers of Europe, Brussels 2013.

[74] IPCC, *Climate Change: Mitigation of Climate Change*, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva 2014.

[75] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (EPBD), European Parliament, Brussels 2010.

[76] *Impact of the financial crisis on carbon economics: Version 2.1 of the global*, McKinsey Company, New York 2010.

[77] *IEA energy efficiency market report 2015, Market trends and medium-term prospects*, 2015.

[78] Vellei M., *A review of factors affecting environmental and economic life-cycle performance for electrically-driven heat pumps European Commission*, European Union, Luxembourg 2014.

[79] Bernier M.A., *Closed-loop ground-coupled heat pump systems*, ASHRAE J., 2006, 48, 12–19.

[80] Chengmin C., Yufeng Z., Lijun M., *Assessment for central heating systems with different heat sources: A case study*, Energy Build., 2012, 48, 168–174.

[81] Hanova J., Dowlatabadi H., *Strategic GHG reduction through the use of ground source heat pump technology*, Environ. Res. Lett., 2007, 2, 1–8.

[82] Self S.J., Reddy B.V., Rosen M.A., *Geothermal heat pump systems: Status review and comparison with other heating options*, Appl. Energy, 2013, 101, 341–348.

[83] *Refrigerant and Materials Selection to Mitigate Climate Impact: EDGE Guidance Document for the Building Sector*, International Finance Corporation, Washington 2017.

[84] Makhnatcha P., Khodabandeh R., *The role of environmental metrics (GWP, TEWI, LCCP) in the selection of low GWP refrigerant*, Energy Proc., 2014, 61, 2460–2463.

[85] http://stats.ehpa.org/hp_sales/country_cards/

[86] Rosen M.A., Koohi-Fayegh S., *Geothermal Energy: Sustainable Heating and Cooling Using the Ground*, Wiley, 2017.

[87] Firpo F., *Smart Cities Stakeholder Platform Heat Pump and Micro-CHP as complementary boiler alternatives*, Electronic Communication Network, Lancaster 2013.

[88] IRENA, *Renewable Energy in District Heating and Cooling: A Sector Roadmap for REmap*, International Renewable Energy Agency, Abu Dhabi 2017, www.irena.org/remap

[89] Garcia N.P. et al., *Best available technologies for the heat and cooling market in the European Union*, European Commission, Petten, the Netherlands, 2012.

[90] Pratt R.G., Kintner-Meyer M.C.W., Balducci P.J., Sanquist T.F., Gerkensmeyer C., Schneider K.P., Katipamula S., Secrest T.J., *The Smart Grid: An Estimation of the Energy and* CO_2 *Benefits*, Pacific Northwest National Labolatory, Richland 2010.

[91] IEA, *Sankey diagram*, http://www.iea.org/Sankey

[92] Eurostat data, https://ec.europa.eu/eurostat/data/database/

[93] National Inventory Submissions 2017, United Nations Convention on Climate Change.

[94] IEA, CO_2 *emission from fuels combustion. Highlights*, 2016.

[95] https://yearbook.enerdata.net/renewables/renewable-in-electricity-production-share.html

CHAPTER 4.
ASSESSMENT OF FLEXIBILITY FOR HEAT PUMP-BASED DISTRICT HEATING

4.1. Introduction

The term smart grid is used to refer to smart electricity or smart power grids. The problem of this one-sided vision to the term of smart often leads the researchers to concentrate on electricity challenges like transmission lines, flexible electricity consumption, electricity storage, etc., as being the main ways to deal with the integration of fluctuating energy sources from RESs. The efficiency of the energy system is increased when it is combined with thermal energy systems such as heating and cooling systems, gas grids, and transportation [1, 2]. It is evident that the most important factors for smart thermal networks are intelligence, efficiency, and flexibility in heat production and consumption, integration with other energy systems, reliability and customer involvement.

DH and cooling are argued to be important tools for reaching European energy and environmental targets. The major objective of this chapter is to study the special characteristics of flexibility in heating networks, concerned with heat production and consumption integrated with RESs, thermal storage, CHP plants and heat pumps in the infrastructure of smart energy systems and how DH networks are adapting to them [3, 4].

As stated above, previously smart energy systems have been studied widely, but nowadays a wider perspective is needed to link electricity with heat. In the other hand, the heat pumps in DH are linking the thermal and the electrical sectors and for that, they are seen as part of a flexible coupler to match the thermal and electrical demand. It will be necessary to combine research concentrating on power grids with combination to different energy systems to find the most energy-efficient solutions, especially the studies where the concentration is on the flexible part of thermal energy systems in the context of DH which has received less attention [5, 6].

4.2. Flexibility definition and measures in energy systems

Most analyses of the future European energy system conclude that in order to achieve energy and climate change policy goals it will be necessary to ramp up the use of renewable energy sources. The stochastic nature of those energies, together with other sources of short- and long-term uncertainty, have already significant impacts in energy systems planning and operation, and it is expected that future energy systems will be forced to become increasingly flexible in order to cope with these challenges.

An increase in wind and especially solar PV power plants might reduce peak times of conventional generation. Thus, the flexibility of the power system becomes more important. Key factors for a flexible system are the availability of flexible capacities on the generation side, high transmission capacities by balancing through the reserve market. With growing variable renewable energy (VRE) shares, all these mechanisms become increasingly important to integrate successfully renewable energies into the power system, when the flexibility is needed [7, 8].

Flexibility is a widely used term, in general, defined as the ability to change, to suit new conditions or situations. This definition can be transferred to the flexibility definition in the context of demand-side energy management. It is the ability to modify the energy generation or consumption of a system in response to external signals specified by markets or market members. Flexibility is defined in terms of the ability of a system to deploy its resources to respond to unexpected changes in supply and load.

Flexibility can be defined too as the ability of a system to adapt its operation to both predictable and unpredictable fluctuating conditions, either on the demand or generation side, at different time scales, within economical boundaries, or as the ability of a system to cope with the short-term uncertainty of energy system variables, or to deploy the systems' resources to respond to unexpected changes in supply and load [8–10].

Another possible definition of flexibility is the ability to speed up or delay the injection or extraction of energy into or from a system. Speeding up or delaying entails that a comparison with a reference energy use prole is made [11]. A complete overview of the concept of flexibility for electrical networks was given by Lund et al. [12]. Schuetz et al. [13] overviewed the flexibility definition of a residential heating system. Stinner et al. [14] discussed possible flexibility indicators for thermal applications. Arteconi et al.[15] provided an overview of the Active Demand Response (ADR) potential in systems with thermal storage. The researchers identified different types of flexibility and suggest ways in which the large flexibility potential can be unlocked.

While in the past a high share of thermal and power plants guaranteed sufficient flexibility in the energy system, the increasing share of volatile RESs changes this paradigm. Those RESs create a new source of the above mentioned short-term uncertainties, defined as uncertainties appearing on an hourly time level. Due to these development uncertainties requiring flexibility occur along the complete supply chain in energy systems. They most often turn up due to forecast deviations (end-use demand, demand-generation balancing, for different time-scales and all time-steps) of the energy system. To handle those deviations a range of technological options are available, (such as demand response, grid and storage expansion, excess capacity, curtailment of RES peak feed-in) which will be explained further.

Flexibility is a measure of the capability of power systems to maintain system stability. Demand-side flexibility can support energy system balancing especially for a short-term consideration. Peak-shaving and trading flexibilities at balancing power markets are two suitable applications.

Many technologies are able to provide flexibility, including centralised power plants, decentralised power supply, energy storages and demand-side devices. While a large energy supply or demand system can trade flexibility individually, smaller customers are not able to participate in flexibility markets because of high barriers or lack of expertise. Aggregation is a function of the market to trade the flexibility of many de-centralised customers, often referred to as a pool. Aggregators are intermediary market players and offer services to trade the flexibility of smaller customers. They play an important role in the complexity of energy markets.

4.3. Challenges of electricity system flexibility in the energy system

Most analyses of the future European energy system conclude that in order to achieve energy and climate change policy goals, a significant increase in renewable energy in the energy mix is required. As part of this the proportion of electricity generation from renewable energy is expected to increase from 20% in 2010 to 36% in 2020, and to 44% in 2030 and 52% in 2050 [16]. Hydro generation is the largest contributor to renewable electricity in Europe but its potential is for the most part already exploited. This means that a significant part of renewable electricity development in the future will be based on VRE generation such as wind and solar PV. However, for electricity demand, these renewable energies have a variable nature that is not perfectly predictable. As a consequence, short and long term variability and uncertainty in the electricity load generation balancing is likely to increase in the future, so the increasing share of solutions which link power and heat like heat pumps or power to heat (e.g., electrical boilers, large scale heat pumps, etc.) with their variability will have an additional influence on the operation efficiency of the thermal networks in the future.

To cope with the increasing variability and uncertainty, the electricity system will need to have sufficient flexibility to maintain the demand-generation balancing at all time. Therefore, energy and power system planning will need to address both the problem of capacity adequacy and flexibility, the adequacy can be defined as*: Adequacy is connected with the issues of investment decisions and is used as a measure of long term ability of a system to match* demand and supply with an accepted level of risk. This is a measure that internalizes the stochastic fluctuations of the aggregate demand and supply [5, 10, 17, 18].

So assessing the flexibility needs and adequacy will probably emerge as a new task in power and thermal energy systems planning. However, additional variability and uncertainty driven by RESs will increase the needs and the solicitation of power system flexibility. The development of RESs capacities is based first of all on the geographic distribution of wind and sun resources which involves a necessary adaptation of the existing electrical and thermal energy system (networks constraints) and drive additional costs [26].

In spite of the fact that flexibility is mostly required at the operational time scales from minutes to day-ahead, it needs to be considered from the planning stage. A system that has sufficient capacity to meet peak load is adequate but if this capacity is composed mostly by low flexible plants the system can experience problems for handling demand and generation variability. As a consequence, the representation of flexibility at the thermal energy and power systems planning stage will help to deliver a system that can handle this variability in a cost-effective fashion.

4.4. Holistic approaches to the flexibility of the energy system

Future energy systems will likely be a complex combination of centralized and decentralized energy production with a wide variety of energy resources and new VRE technologies. When VRE generation, especially from wind power and solar PV, with new technologies and market based solutions are required at all levels of the energy system to integrate economically with the increasing variability and uncertainty. Electricity consumers are becoming more important but harnessing the flexibility in the demand side is a complicated and multidisciplinary issue. To adequately analyse and mitigate the impact of increasing shares of variable generation in the existing energy system, analysis and modelling methodologies need to be improved at all levels including frequency and voltage stability studies, as well as unit commitment and economic dispatch tools, regional planning models and global integrated assessment models [10, 16].

A central question which needs to be analysed and modelled is the value of flexibility, i.e. what is the value of flexible generation, flexible demand, and other flexibility options, such as energy storages, and/or combination of these options. The value of flexibility should be considered in different operational time scales, in different geographic regions, and in different market regions. The distribution of the value of flexibility to the different participants in energy systems is also an important question. A more integrated view of future energy systems is enabled by integration of different simulation and optimization models operating at different time domains and with different sectoral and/or geographic coverage [25–27].

4.5. Thermal networks as a flexible part of a smart energy system

Flexibility in DH and cooling systems (thermal networks in general) is an important means to cope with the intermittent generation of heat and electricity as the share of RES increases. Important sources of flexibility are the thermal energy storages present in the DH and cooling networks, the thermal inertia of buildings, storage units and the thermal networks themselves. To unlock this flexibility in the thermal network and to use it effectively, a suitable control strategy and efficient technologies are required to quantify the flexibility needs [28].

In recent years, smart energy systems and smart cities have been under wide discussion. The term smart grids found in academic literature is used in many ways and is used differently by different authors depending on the parts of the energy system that are considered or depending on the authors' perspectives and focus of the study domain. Research of smart energy systems has concentrated on smart electricity grids, and few studies can be found in the area of smart thermal networks [30–32].

The drivers behind the development towards smart energy systems are varied and the approach to the future smart energy systems paradigm characterized by [29]:

- Growing penetration of intermittent and decentralised RESs (solar heating plants, geothermal plants and waste heat from an industrial process, biomass in energy systems, etc.).
- Fluctuating nature of renewable energy supply.
- The emergence of a very big number of buildings acting as local producers and consumers (prosumers) of the energy.
- Increased electrification in all energy sectors (from transport to buildings heating and cooling sectors and else).

These changes challenge the traditional power system which is designed for a small number of large power plants, operated to supply the demand at all times. Growing penetration of RESs such as solar and wind with their nature of intermittency and high fluctuation makes stable and profitable operation of the electric power system a challenging task. To accomplish this task, the energy infrastructure needs to be upgraded to accommodate higher flexibility, on both of the supply and the demand side. So the role of heat pumps and their contribution in the future smart energy system processes will be more essential [29].

Since energy systems are evolving and the thermal systems need to take advantage of such development. On the other hand, the environmental aspects are changing energy systems. Dependency on FF needs to be reduced. CO_2 emission targets are changing the fuel mix in many energy systems. These pretences will increase the share of RESs with their fluctuating characteristics. The expected energy systems based on decentralised production and various predicted renewable energy technologies need good management systems and information data and information communication technologies (ICT) to work more efficiently.

Flexibility in thermal networks (DH and cooling systems) is an important means to overcome with the intermittent generation of heat and electricity as increased penetration of RES [28] and to coordinate the provision of the heat-electricity interface in thermal networks.

Many advantages could be achieved with elimination of daily thermal requirement variations such as less use of the peak thermal load supplied by HOBs, which usually use more expensive fossil fuels, less need for electricity needs for pumping energy, easier optimisation of the DH system operation, and less need for maintenance because of the smoother use of heating plants [33]. It is necessary to mention that the start-up and maintenance costs of the HOBs are also additional significant cost items for DH companies [33].

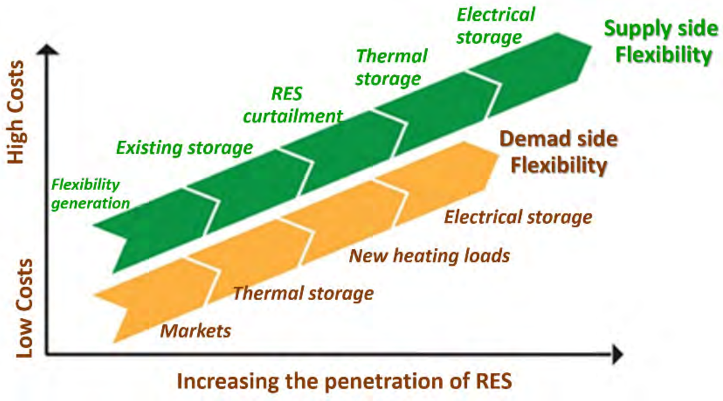


Fig. 4.1. General flexibility considerations of supply and demand sides

In another hand, the market studies are examinations into the causes of efficient functionality of particular thermal network markets, taking an overview of regulatory and other economic drivers in a market and patterns of consumer and business behaviour. In which the networks can be more exposed to competitive forces and can still afford to make a capital contribution to the developer, Fig. 4.1 shows some considerations of thermal network flexibility in the context of markets with relation to supply and demand sides. The thermal networks will be a flexible part of the smart energy system, this will bring adaptability in the short, medium, and long term [33–35].

Short-term adaptation means adapting energy supply and demand situations with different sizes of storage systems, demand-side management and thermal peak-load supplied by HOBs, all of which need to be integrated into the smart energy system.

Medium-term adaptation means adjusting the temperature level in existing networks and in the long-term, adapting by aligning the network development with urban planning. Smart thermal systems should also be flexible in size, which means they should bring wide possible solutions for neighbourhood-level or city-wide systems, according to their demands for heat and cold.

Also in the long-term, smart thermal systems should be flexible in the case of heat (and/or cold) demand decreases due to emission targets.

4.6. Flexibility in district heating–electricity interface

DH is centrally produced thermal system where the heat is distributed as steam or warm water to the consumers through network pipes. The DH with a natural monopoly structure, municipalities, cooperatives and other local organizations coordinate the provision of heat. The DH–electricity interface describes the area where DH and power systems are connected. CHP and power to heat technologies (electric boilers, large heat pumps) are identified as the most ideal technologies in the DH–electricity interface for increased flexibility. CHP can produce electricity and heat simultaneously, while the power to heat technologies consume electricity to produce heat. There are no direct policies for flexibility in the DH systems in European countries, which means that flexibility is mainly provided by market incentives and frugally by Energy Pol.

On the other hand, the need for flexibility varies throughout the countries under study. It might become most pronounced in the short term in some countries (like the Nordic countries) that have larger amounts of variable renewable electricity, while sufficient capacity and self-supply are goals of higher priority in other countries (like the Baltic countries). Hence, there is no one size fits all-solution for flexibility, which concerns DH–electricity interface [10, 17, 25, 36].

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

It is necessary to mention that since the DH markets differ between the European countries with regard to the energy technology mix and fuel distribution, so the presence of certain regulatory framework conditions has greater importance in some countries than in others. The observations show a large variation in regulation but at the same time, some similarities and patterns have emerged. General characteristics of DH flexibility, in general, is a concern with the current and future role of DH, infrastructure and regulations of DH. The flexibility resources related to DH–electricity interface are[36]:

- heat storage,
- CHP plants,
- electric boilers in DH,
- large heat pumps (HP),
- HOBs in DH (as a substitute to CHP),
- large field of solar PV panels,
- flexible DH network operation,
- consumers of DH as flexibility providers,
- individual HO generation (as a substitute to DH),
- feed-in to the DH network from industry, etc.

4.7. Addressing the operation flexibility in thermal networks

Reducing the primary energy demand in DH systems has to be undergone in three different sectors: the heat generation sector (conversion process efficiency, renewable heat and integrated energy), the heat distribution sector (better distribution thermal efficiency) and the consumers of the thermal demand sector (thermal loads reduction, smoothing the requirement profiles). 4GDH network with lower temperature levels and an increasing number of small scale generation plants, yielding both to a higher level of decentralization and demand for more flexibility and further a higher level of complexity as an author's own composition shown in Fig. 4.2 as a flexibility paradigm of heat pump based district networks. As a result, only holistic solutions taking into account all three sectors seem to be promising. These challenges can be addressed by the concept of smart thermal networks.

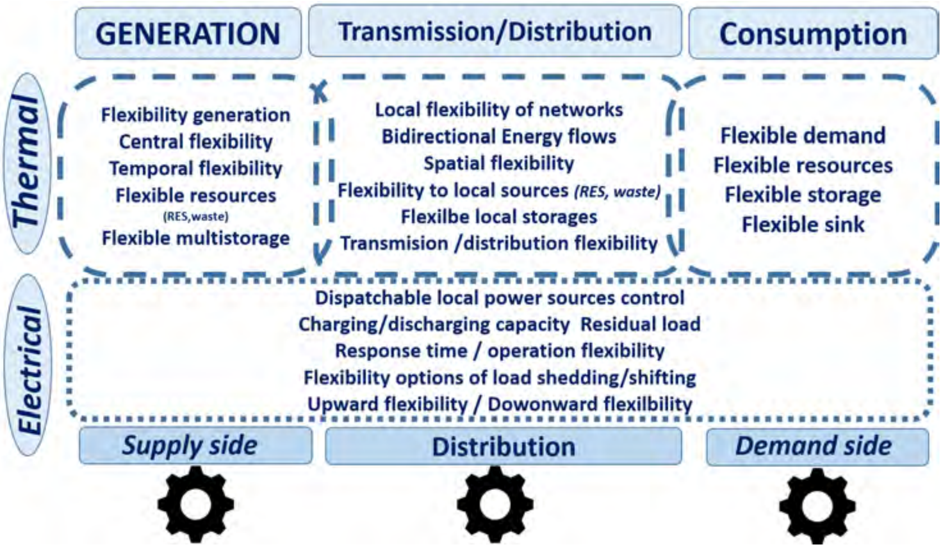


Fig. 4.2. Flexibility paradigm of thermal networks

Flexibility only requires that the system has inertia such that the energy balance can be respected at all times. In thermal networks, the thermal capacity serves as a source of thermal inertia. These capacities are found at different locations in the DH network.

The flexibility of operation. Flexibility is a characteristic of all energy systems, with higher levels of VRE shares (primarily, wind and solar) which can be connected to TES, so the flexibility of operation means the ability of a power /thermal system respond to the changes of the demand and supply sides requirements [37].

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

Flexible heat generation. Plants that can quickly and efficiently ramp up and down and run at low output levels (i.e., deep turn-downs).

Flexible heat distribution. In heat transmission networks with limited bottlenecks and sufficient capacity to access a broad range of balancing resources, including sharing between neighbouring systems (back up or auxiliary), and with smart network technologies that better optimize the heat distribution usage.

Flexible demand-side resources. Incorporation of smart grids to enable demand response, thermal storage, responsive distributed generation, and other means for customers to respond to the market signals or direct thermal load or the requirements control.

The usage type of thermal networks and thermal requirements and their demand profiles will largely impact on the flexibility potential of these networks, The following categories will be used to describe the major parts of the thermal system: local heating and cooling of buildings, DH and cooling, heat for industry, etc. [37, 38].

4.8. The flexibility of the thermal network and thermal storage

To increase the level of flexibility, the DH networks perform as small heat storage systems. In addition to this, many DH systems have separate heat storage capacity to even out the imbalance of the heat demand and production. In the energy systems with CHP production, heat storage units are also used to optimise the profits from electricity production.

As mentioned above thermal networks are a flexible part of the thermal energy system, with the capability of storing heat or cold in the short/long term. Heat storage systems have been studied widely in different scales and implemented to decrease thermal peak requirement capacity and investigate the effects on the whole energy system, and their role will increase in future energy systems with fluctuating renewable energy or VRE sources. Advanced thermal storage systems should be developed to be more efficient and applicable (such as seasonal storage for high temperatures, i.e., storing heat in summer to be used in winter) but they are not widespread in many DH systems since competitive technology does not yet exist [35, 39–43].

Heat storage systems have been suggested as one way of handling the thermal requirement variations. Short term energy storage in the form of batteries or thermal-electric systems connected to thermal storage can provide some of the needed flexibility.

As mentioned different sizes of heat storage units for DH systems have been studied [35, 41, 42, 45]. The use of building mass as heat storage has also been studied too [44]. For daily heat variations After having a functioning ICT system (smart heat meters), the exploitation of heat storage and DSM will make energy systems more efficient.

4.9. The interface of CHP and heat pumps in district heating

CHP generation is widely used in DH systems. CHP plants are an important source of heating energy in DH networks around the world. These plants are characterized by high efficiency due to the electricity produced alongside heat, this allows them to have lesser fuel consumption and smaller carbon footprint compared to when the two types of energy are produced separately [46].

The primary task of CHP plants connected to DH networks is supplying the heating energy, whereas electricity is often treated as a by-product. However, for worthwhile participation in electricity markets, more certainty is necessary regarding the heating demand. Although there are measures which allow more flexibility in the production of electrical energy by somewhat untying it from the heat demand, i.e., heat storage tanks, peak water boilers, improved cycling operation proper scheduling and operational control of CHP plants nevertheless heavily relies on heating demand forecasts. Accurate demand forecasting in DH networks is an essential and imperative task in the everyday operation of both, the network itself and the heating energy suppliers [46–48].

DH is a system for distributing heat that is generated in centralized units. DH has a high coverage especially in North, Central and Eastern Europe and it is primarily based on CHP production supported by HOBs [47, 48]. Currently, CHP is encouraged generally by the Energy Pol., not because of flexibility but to increase energy efficiency and security of supply.

Rapidly increasing penetration of intermittent renewable Energy production (i.e., wind, solar power) in the power system will remarkably increase the need for flexible and controllable power generation. As total heat production into the DH network needs to be balanced with the total heat consumption, this sets significant limitations to the long-term power production. However, the heat load and electric production can be decoupled temporarily by using the heat storage capacity of DH networks and heat accumulators, it is necessary to analyse the dynamic operability of interconnected CHP plants and DH networks. In cogeneration or CHP plants heat pumps will enable primary energy savings and higher energy efficiency in comparison to alternative heat and power generation technologies, thus the mitigation of GHG emissions [49, 50].

To date, the operation of CHP and HP is mostly heat-controlled: it consequently follows the demand for heat. With regard to energy systems with high VRE shares, a reorientation of these units towards power-controlled mode needs to be pursued [51–54]. This implies an adjustment of the operation to the current power demand and RE generation, and consequently a decoupling of production and consumption of heat by using TES. Furthermore, CHP supply systems can be complemented by the integration of an electric boiler or heat pump, which might be used to reduce or avoid VRE curtailments in times power generation exceeds demand, storage charging and grid capacity [55].

In CHP production, back-pressure turbo generators that produce electricity and heat at a fixed ratio are very common. As total heat production into the DH network needs to be balanced with the total heat consumption, this sets significant limitations to the power production. This issue is important, as CHP production and DH are seen as a future prospect to lower CO_2 emissions [56]. The momentary power increase in CHP production can be conducted in two ways when the steam turbine is not yet running at its full capacity. The first option to increase power production is to disconnect the fixed ratio of heat and power production in the unit, e.g., by controlling the bypassing reduction valves of turbines (by-pass), by reducing internal steam consumption (condensate stop) or other respective actions. The second option to increase the power production is to maintain the fixed ratio but increase the boiler power output and to store or waste the excess heat that is produced along with electricity. The storing can be conducted by utilizing heat accumulators [35, 57–60] and DH networks as heat buffers [61–63]. In practice, the solution can be a combination of these both options, depending on the required power change rate and capacity requirements [64].

The most effective exploitation of the flexibility potential of CHP plants takes place when the plant owners are able to take part in some market where the flexibility in electricity production can be tendered. The market structure defines the change rate and capacity requirements to enter the market. The attainment of the requirements depends on the CHP plant and DH network structures and their momentary operation regions. Therefore, it is useful to analyse the potential of different flexibility sources, to assess the possibility to take part in different markets and to analyse how the plant operates during a momentary change of power level driven by external control signal [64, 65]. However, the flexibility energy markets are still developing, it provides an indication of possible requirements and prospects in the future market structures [64–66].

The proportion of heat pump technology in the residential heating sector is growing and this trend will continue in further. The structure of CHP energy production in EU members determines the proportion of DH consumers with CHP and heat pump units. This advantage will facilitate and encourage the integration of renewable power generation. As it is known, managing heat and electricity demand is a core requirement when dealing with fluctuating energy generation sources, especially when linking RESs and TES [29].

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 a 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 DH 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 DH and cooling, they will be required to minimise the strain on the power grid in the future [67].

The development of DH networks and heat pump technologies demonstrates that heat pump technology can meet the needs of DH. Heat pump technology is able to feed DH effectively, by using both conventional and RESs as driving energy, which has never been used before on a large scale for DH [67, 68].

4.10. Energy flexible buildings and heat pumps

Energy flexibility of a building is the ability to manage its demand and generation according to local climate conditions, occupancies within these buildings or consumers' needs and power grid requirements. Flexibility can be understood as the margin in which the building can be operated while respecting its functional requirements, the flexibility will allow for demand-side management/requirement load control and demand response based on the requirements of the surrounding grids [69, 70].

Flexibility in buildings' energy use is needed to accommodate the further integration of varying renewable heat and power energy generation. The level of flexibility is strongly dependent on the thermal characteristics of the building, increased thermal mass and insulation levels have a positive effect on the switch-off times. The same is true for thermal energy storage, so the buildings have the ability to become energy flexible. Heat pumps can be used successfully to provide demand response, regarding the level of flexibility in relation to the different thermal characteristics of the building stocks [69–73]. Energy flexibility is represented as one of the main pillars governing the smartness of a building since the EC-study defines a smart building as a building that can manage itself, interact with its users and take part in demand response. In the proposed framework, the smart readiness level integrated with buildings is evaluated with a qualitative approach according to the number and type of services provided by its components.

Energy flexibility developed by IEA EBC Annexe 67 is based on quantitative and physical indicators, smart readiness indicator (SRI) defining a method for calculating affordably and easily an SRI, mainly rating different smart services integrated in buildings, SRI is evaluated with a qualitative approach according to the number and type of services provided by its components [73]. Energy flexibility indicators take into account respective individual building components and services, like occupant comfort, HVAC systems, and regional climate and energy system condition, rather than providing a qualitative rating of the implementation level of smart technologies. Annexe 67 is developing a methodology for obtaining quantitative energy flexibility indicators aiming at supporting design decisions on building and clusters of buildings' levels as well as quantifying the available energy flexibility in a building or neighbourhood during operation.

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

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

These properties generally follow from underlying definitions of energy flexibility as a change in power or energy compared to a reference scenario. In other words, the quantification methods formulate the energy flexibility of a building by assessing its ability [74]. In the context of integration of RESs, energy supply systems tend to become decentralized. The variability of these sources has a significant impact on the management of the power grid. To ensure grid balancing, several levels of action take place at different times. On the day-ahead electricity market, electricity suppliers have to nominate their electricity bids such that the forecast supply and demand are in balance. At the intraday-level, mismatches between the forecast and actual supply and demand can be compensated by using reserve capacity or by real-time demand response [75].

Smart grid energy ready buildings can help to minimize the cost of electricity supply at the distribution grid level in three different ways.

- A smart meter allows gathering information for better prediction of electricity demand profiles of local consumers.
- The electrical load of such buildings can be shifted based on time-of-use (ToU) variable electricity tariffs [76].
- Finally, imbalance costs resulting from mismatches between forecasted supply and demand can be tackled by real-time demand response.

In present energy systems, the flexibility of the heating requirement load associated to residential buildings with the use of heat pumps can be defined as the ability to shift the heat pump electric load from peak hours to off-peak hours in terms of electricity prices [77].

4.11. Heat pumps flexibility in a smart system

When the penetration of renewable electricity production in the electricity infrastructure increases, an increased part of the production follows a stochastic behaviour. In order to reduce power peak loads and to maintain the required balance between production and consumption at all times, two solutions can be envisaged: electricity storage and demand-side management (DSM) [78].

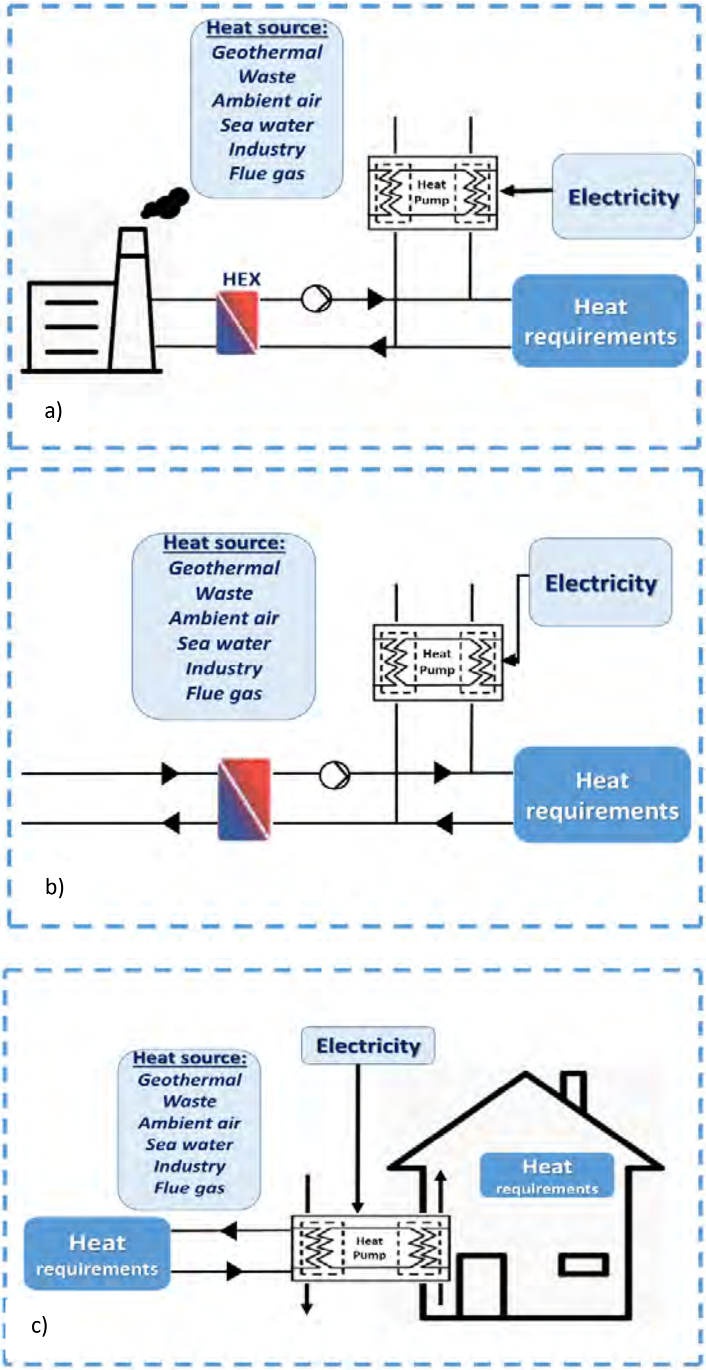


Fig. 4.3. Location features of heat pumps in the district heating network [95]

As explained in Chapter 3, the flexibility connection and operational modes of the heat pump into district heating networks due to the geographical location of the heat source, the type of heat pump technology, the required supplementary heat sources to cover the peak heating requirements of the buildings. Figure 4.3 presents the location features of heat pump driven by electricity in the district heating network; in Fig. 4.3a the location choice is as a main central heat source in addition to RESs for heat pump or local heat sources in Fig. 4.3b, or on optional location as an individual heat pump in Fig. 4.3c. Due to the connection and operational modes presented in Chapter 3, it can be defined as the operational role of the heat pump technology integration in the district heating network [68]. So due to the technical triangles and the case of heat pump application in the district heating network, the flexibility can be provided to the power system. It is evident that the technical and economic performance of the heat pump is closely related to the characteristics of the heat source.

Heat pumps link the thermal and the electric sector. Researches indicate that in the future the heat pump–district heating systems will play a pivotal role in the energy infrastructure due to the ability to modify their electric demand for a certain time and thereby providing flexibility to the power system [46, 68].

Besides lower carbon emissions compared to boilers fed by fossil fuels, the possibility to decouple heating demand from electricity consumption, and thereby offering flexibility to the power system, can be considered as the key benefit of heat pumps. This will facilitate the integration of distributed renewable power generation as managing electricity demand, which is a core requirement when dealing with fluctuating electricity generation sources from RES. The heat pump system not only provides a sustainable heating and cooling solution for the buildings but can also act as a linking and enabling technology in future energy systems.

The focus on consumer flexibility is a central point of demand response (DR) and DSM [79–86] as well as decentralized energy management [87, 88] approaches in the context of a smart grid, heat pumps are seen as a part of the demand side that can be actively managed to support the realization of a smart grid [80, 89–97]. Coupling heat pumps to thermal storage or actively using buildings' thermal inertia offers the possibility to decouple electricity consumption from heat demand, which brings flexibility in operation that can be used in a smart grid.

A wider, more holistic argumentation is stated in a reference where it is suggested to extend the focus of a smart power grid towards a whole energy system approach including not only electric demand and generation but as well thermal aspect and heat transportation sector. Some considerations and analyses are discussed through the heat pump flexibility in the smart system [26, 30].

Time scales and the need for flexibility in the power system. The need for flexibility in the power system is frequently motivated by an increase in RES [80, 97] and the resulting need for an ability to react or plan for safe and efficient power system operation. A transition towards a renewable electricity sector means that all services that are nowadays provided by conventional power plants will have to be provided by other devices [30, 32, 103].

For an individual device, the definition of flexibility provided by Eurelectric [97] highlights the important properties as seen from the electric point of view: *On an individual level flexibility is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The potential of heat pumps to provide flexibility to the power system depends on the case of application and the characteristics of the HP system*.

The dynamic properties of the heat pump unit are important for flexibility. The speed of response is limited by the maximum allowed change rate of compressor speed and thus power consumption over a certain time. A minimum run and pause-time requirement as implemented in most heat pumps further decreases flexibility. Since frequent switching events reduce the lifetime of the heat pump this should be avoided, which further reduces heat pump flexibility.

The annual performance of the heat pump systems is strongly influenced by how the heat pump capacity is regulated depending on the variable heat requirements or thermal demand. Fixed speed heat pump units are operated in an on-off manner, whereas variable speed heat pumps allow a continuous regulation of the compressor speed over large parts of the operation range. This allows control of the thermal output or electric demand. For applications with variable speed heat pumps can but do not necessarily improve system efficiency. For smart grid application, the possibility to increase or decrease electric consumption offers higher operational flexibility which is for example used in order to improve power quality or to increase local solar PV self-consumption [78, 86]. A smart grid can potentially manage peak electricity demands imposed by heat pumps and the heat pumps could help to reduce these peaks through DSM by:

- Thermal demand, which determines the amount of energy that can be shifted, and the time for recovery after a load shift (the time until storage is fully charged or discharged). This concerns with the heat pump size which determines if thermal load shifting is possible at a certain time and the power that can be ramped up or down.

• Dynamic properties of the system, which determines how a heat pump can be used respecting the minimum runtime in an operation point, the allowed number of switches and the allowed maximum gradients in heat pump operation [30]. Figure 4.4 shows an example which should be considered for smart systems as the main distinctive key features of residential heat pump systems [26, 30, 32, 103].

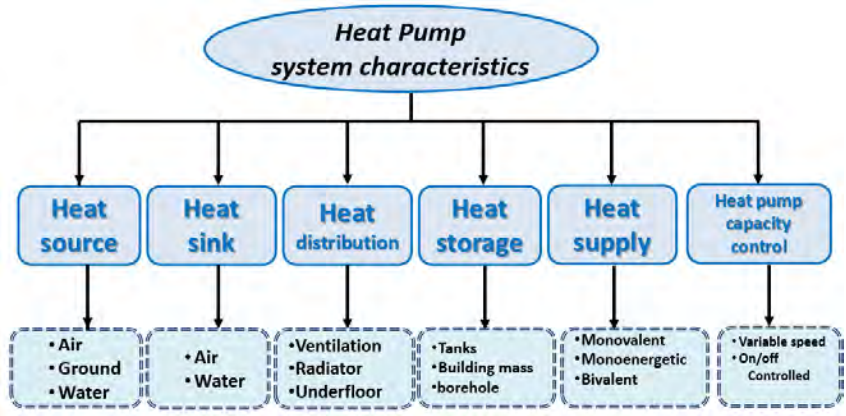


Fig. 4.4. Distinctive key features of residential heat pumps systems

Generally, a residential heat pump system can be characterized by the type of heat source and sink, the technical features of the subsystems such as compressor type, refrigerant cycle properties and controls, and the heating system of the building. In all application cases it should be noticed that a) the level of controls have a certain minimum autonomy to guarantee that the heat pump unit is operated within the allowed range and user thermal comfort is not sacrificed, b) the heat pump provides flexibility to the power system meanwhile providing efficient heating and cooling solutions to residential buildings.

Flexibility parameters. Adequate parameters for the determination of energy system flexibility are essential. These parameters which describe the flexibility must be defined individually for each energy system [3, 12, 53, 55, 98]. The literature review on heat pump flexibility showed that most of the literature assesses heat pump flexibility in special scenarios. These can be local, regional or national power grids with renewable energy penetration or the response to real price signals. Little research was done on generic approaches to determine the flexibility of heat pump pools as a response to different signal types in thermal networks. Widely used parameters of flexibility are shifted load or flexible power [99]. These flexibility values are often daily means dependent on the ambient temperature or average daily means per month. Other studies present the ability to balance intermittent power generation with self-defined indicators [12, 80]. The alteration offers flexibility for heat pump systems without storages and increases the flexibility of systems with storages.

4.12. Individual and pool heat pumps in smart system context

Heat pump units can be installed in individual buildings as a competitor to DH or in residential, commercial and industrial buildings. Heat pumps can be installed as a heat production units in DH networks, they can be placed as a central, local or individual heat source and can be connected to the DH network in serial or parallel connection modes [48, 98–102]. The integration of heat pump technology into DH considers at least placement, connection and operational mode of the heat pump unit. Heat pumps as individual units may be installed to join a thermal system as a hybrid solution or may be used as integrating temperature booster units. The installed heat pumps can be summarised in the following categories [100]:

- Small scale/individual heat pumps. Generally, the heat pumps have a capacity of 0–20 kW and a refrigerant charge of 0–5 kg.
- Medium scale/communal heat pumps. Generally, the heat pumps have a capacity of 20–170 kW and a refrigerant charge of 5–50 kg.
- Large scale/district heat pumps. Generally, the heat pumps have a capacity of more than 170 kW and a refrigerant charge of more than 50 kg.

The heat pump can be installed as an individual unit or single device in the thermal network for residential individual consumer or as a group of a large number or so-called pool heat pumps. A reason is sure that the single or individual heat pump units offer limited capacity.

Since individual heat pump units' electricity consumption is relatively small, pooling of a large number of heat pumps is required to satisfy the thermal requirements and in order to actively participate in electricity markets or to provide services through the grid, simultaneously the heat pumps are used to supply the consumers for space heating and DHW purposes, and working toward peak load shifting and system balancing and evaluate flexibility, which may be coupled to a thermal storage. Managing a pool of heat pumps requires fundamental managing and control knowledge about available power and thermal energy as well as the response expected when controlled externally. The availability of heat pump pool for load shifting has a strong seasonal dependency, showing negligible shifting potential during summer compared to winter and changing season due to simulation study for example by using a pool of 284 heat pumps which was conducted in Germany [100, 101].

Flexibility on the demand side will play an important role by installing a pool of heat pumps. In the other hand, the pooling of heat pump units is required to fulfil minimum requirements for market participation and allow for economies of scale. The pooling of heat pumps can be a combination of a single building or for a group of buildings. Hence, the technological approach used for integrating heat pumps must be cost-efficient, reliable and simple enough to be deployed to a large number of heat pump units. Aggregators are seen as potential players for a pool of a large number of heat pumps, to operate on markets or provide services to other actors in the power sector. For such aggregators, the question is how to operate and control the flexibility of a pool of residential or commercial heat pumps [80, 90, 100–104].

In order to offer the flexibility of heat pumps in the heating network and for the undisturbed operation of heat pump pool, the heat pumps sizing and backup heaters, bivalence temperature, building heating loads and charging-discharging of the thermal storage should be based on recommendations from the manufacturers. The sizing procedures should be adjusted by the parameters for HP efficiency, which lead to under-/oversizing of the heat pumps and the thermal storages. The pool of heat pumps is defined by three characteristics: building type, building age and the heat sources for the pumps. The simulation of the buildings must be in accordance with the available thermal characteristics of the building classes. Flexibility is the electric load deviation of the pool in response to the signals and determined for: a) flexible power, b) flexible energy, c) duration, and d) regeneration. Most significant is the flexibility assessment dependent on the ambient temperature. It should be mentioned that the socio-economic competitiveness of individual heat pumps is high in non-district heating areas.

The influence of the different signals on the performance in terms of heat pump efficiencies COP or SPF is required for the economic assessment of flexibility business models. A more detailed analysis of flexibility could define clusters beside the ambient temperature, for instance daily ambient temperature courses. These details could allow an additional identification of patterns for increased or reduced heat pump pool flexibility.

In the case of pool heat pumps, the system of heat pumps pool need to receive information about the current or expected state of the system to adapt their operation, or they could be directly controlled by an external body for the benefit of the power system. To remotely access and control heat pumps for the purposes of the power system. The smart grid ready (SG-Ready) communication interface has been developed, this interface enables an external body to access the heat pumps and use the flexibility [55, 99–102].

SG-Ready heat pumps are currently entering the European heat pump market. The SG-Ready functionality is intended to enable heat pumps to participate in a smart grid and to provide a standardised interface to third parties for using the heat pumps. In order to design business models or control strategies, an understanding of the potential flexibility in operation is essential [100–104]. Furthermore, basic knowledge about the behaviour of a heat pump pool in comparison to single or individual heat pump units is required.

4.13. Large scale heat pumps in district heating

The term high-temperature heat pump or large heat pumps is frequently used in connection with industrial heat pumps, mainly for waste heat recovery in process heat supply, there are high-temperature heat pumps with heat sink temperatures which range between 100 and 140 °C.

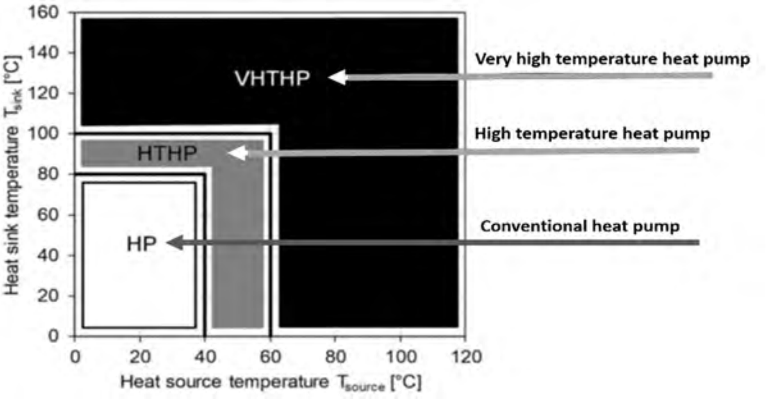


Fig. 4.5. High-temperature heat pump operating range [112]

Figure 4.5 shows the extent of temperature levels of the heat source and heat sink for conventional and industrial or high-temperature heat pumps [105–112]. High-temperature heat pumps can be used for heat recovery and heat upgrading in industrial processes. Apart from the industrial processes, they can also be used for heating, cooling and air-conditioning in industrial, commercial and multi-family residential buildings and increasingly often used in DH systems. Starting with a few 100 kW power, they can reach capacities of several megawatts (MW), which is sufficient to provide for European different countries, e.g., in Helsinki, Stockholm or Oslo for heating and cooling purposes. Currently, large heat pumps can generate more than 90 MW for heating and 60 MW for cooling services.

Industrial heat pumps are most often bespoke systems designed to cater to specific and large needs. DH companies have ambitious targets for lowering carbon emissions in heat production. Large heat pumps offer an interesting alternative heat production for DH allowing utilization of various heat sources that would otherwise be wasted [113, 114].

It must be remembered that the potential of large heat pumps and their role in DH systems are highly sensitive to electricity and fuel prices. The competitive conditions between large heat pumps and CHP plants depend on the market price of electricity and the magnitude of national electricity tax. If large variations of electricity price exist within a market, it is favourable to have both heat pumps and CHP plants as heat supply units [112].

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

Table 1 shows the typical role for different sized DH and cooling networks [113]. The largest potential for heat pumps is in small DH systems, where they reduce the use of fossil fuels. In medium and large DH systems with economical CHP production, the potential of heat pumps is smaller [113].

Lund et al. [115] and Lund and Mathiesen [116] predicted that the role of large heat pumps will increase in future energy systems, large heat pumps would produce 25–30% of the total DH heat production. Werner [117] claims that factors such as lower temperature levels in the DH network and more variable electricity production in energy systems will make excess heat with large heat pumps a more favourable source for DH.

Table 1. Typical role of heat pumps in different sized DH and cooling networks

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

The first case of large heat pumps being used within DH systems was in 1942 in Switzerland. This installation consisted of three units with a total heat capacity output of 5.9 MW [118]. Sweden has long experience in large heat pumps in DH systems. Several large heat pumps with an aggregated heat capacity of more than 1500 MW have been installed in Swedish DH systems since the 1980s [8, 111] and in 2013, Sweden had 73 large heat pump units still in operation with approximately 1220 MW heat capacity and producing almost 4 TWh heat energy (7.4% of total production) [112].

The analysis showed that there were several ways of how large heat pumps could increase the total profitability of existing DH systems. Heat pumps were regarded as devices bringing flexibility to a DH system, especially together with CHP production. Heat pumps start up quite quickly (usually in less than an hour), and starting-up costs are small, which brings flexibility in the case, where some other units are unavailable.

Heat pumps regarded also as diversifying the production mix in DH systems. The flexibility of the DH system and a versatile production mix were regarded as one way to manage market risks, which was raised as the third advantage. A versatile production mix protects the DH system from fluctuating electricity and fuel prices. Heat pumps also enable co-production of DH and district cooling and thus increasing the profitability of the heat pumps investment even further. In addition, the large heat pumps are favourable as they provide flexibility in the electricity system [112, 113].

The installations of large heat pumps initially created an important synergy for the introduction of district cooling because of installing cooling capacities and from the extensive operation and maintenance experiences. Further recent developments have been that many heat pumps have been installed in order to recover heat from local cooling devices and data centres to DH systems. Future operation of large heat pumps in district heating systems will probably be based on variable power generation with short term availability [111].

The environmental aspect and emissions of refrigerants from large heat pumps are one of the major issues concerning service and maintenance. These can be divided into three categories. The first category is emissions which occur during maintenance, the second is continuous emissions due to large non-hermetically sealed components, and the third is breakdowns, characterised by sudden and large emissions. However, statistics regarding these three leakage categories have not been collected in details. The primary concern has been emissions into the surrounding air. However, it is also important to consider emissions into the hydronic system, as refrigerants deteriorate into acids which cause corrosion on the DH system.

The previous chapter presented the environmental obstacles of heat pumps and the refrigerants in details. A comprehensive and detailed list of known complications with respect to emissions of refrigerants from the perspective of system design can be found in the literature [111, 112, 119].

4.14. Power to heat in district heating

Power to heat concept further will refer to conversion into heat from power and not to the combined generation of heat and power (CHP), simultaneously it will not consider another sector of coupling strategies, i.e., interactions between electric vehicle batteries and the power system [111] or conversion paths like power to gas or power to liquids, etc. [120–122].

The concept of power to heat with respect to buildings may be described as the use of heat pumps or electric boilers for covering heat demands in buildings. From a system perspective, there are two main ways to perceive this concept. It could either be large scale solutions at energy conversion plants or small scale solutions, i.e., individual heating systems at end-users. To be viable, large scale solutions require a DH system for heat distribution. Competitive advantages with large scale solutions are: a) fuel flexibility in heat supply, b) greater reception capability due to large heat storages, c) possibilities to integrate higher proportions of renewable energy due to power balancing capabilities, d) absorption of surplus electricity can be implemented at lower costs due to economy of size, and e) in the case of heat pumps, there is a potential to make use of strategically advantageous heat sources. Previously mentioned advantages are lost with small scale solutions, somewhat due to the size and static demand of end-users [111]. However, the possibility for small heat pumps with heat storage units, to be used for power balancing capacities at the location of the end-users has been analysed in other researches [123, 124].

To be viable, the power to heat relies heavily on the prevailing price of electricity; and since the price depends on supply and demand, a situation of surplus power is bound to increase the viability of power to heat due to lowered electricity prices. The main application area for large scale solutions would thus be in a system with a continuous surplus power situation, whether it be short term surpluses, i.e. wind and solar power, or a more long term surplus, i.e. hydro and nuclear power, and limited capabilities of power transmissions. Small scale solutions like individual heat pumps are generally best implemented in rural or suburban areas, where heat densities are lower and district heat distribution is not feasible [125, 126].

Flexibly using renewable electricity for heating purposes may help to decarbonize the heat sector, and contribute to the power system integration of VREs by providing additional flexibility. Power to heat technologies that have a large future flexibility potential also face large barriers today mainly due to Energy Pol.. The main cost drivers for these technologies are the energy taxes that with the present level are prohibitive for investing in large heat pumps or electric boilers.

As expected, the results are varying among the countries, but a common result is that operation on the power markets provides the best signal to DH for flexible operation. This may not be a sufficient incentive, since the gains of operating flexible on the power market have not brought sufficient business-economic incentive in all cases, to establish flexible equipment and operational procedures.

4.14.1. Flexibility of power to heat and interconnection strategies

The use of renewable energy sources will play a major role in the global response to the threat of climate change. In particular, increasing shares of VREs such as wind and solar power have to be integrated into different end-use sectors. In this context, the coupling of power and heat sectors receives increasing attention of researchers and policymakers alike. Compared to other flexibility options and sector coupling strategies, linking the power and heat sectors is often considered to be particularly promising because both the costs of generating heat from electricity and the costs of heat storage are relatively low [41]. Power to heat technologies are identified as the technologies in the heat-electricity interface providing the largest potential for supplying flexibility [127].

The integration of VRE sources requires additional flexibility in the power system as the feed-in patterns of wind and solar power are only partly correlated with electricity demand [128–130]. There are many ways of providing such flexibility, for example, flexible thermal generators, various forms of energy storage, demand-side measures, grid-connected electric vehicles, geographical balancing facilitated by transmission, as well as changes in design, siting, and dispatch of VREs [131]. While generating heat from electricity was traditionally not a preferred option in fossil fuel-based power systems, the flexible use of electricity for heating purposes, often combined with heat storage, has recently received increasing attention as another and particularly promising source of system flexibility [14, 127].

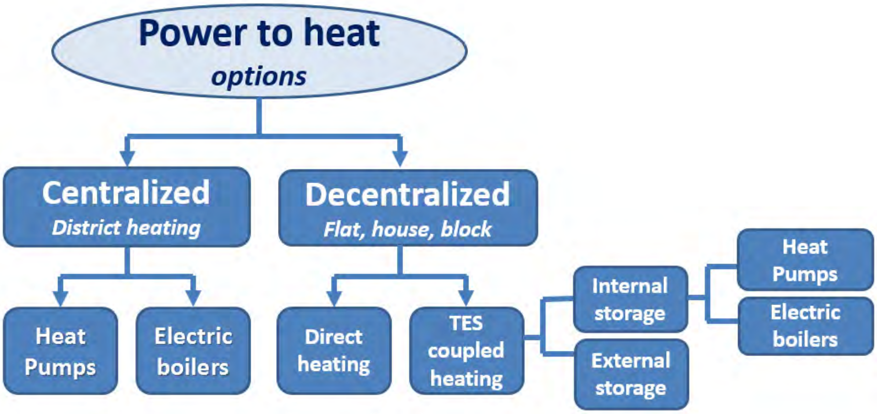


Fig. 4.6. Categorization of power to heat options [127]

There are different means to convert electricity into heat. Figure 4.6 categorizes the most important options of power to heat for the residential heating sector. Following the categorization provided in Fig. 4.6, we can first distinguish between centralized and decentralized power to heat options. Under the centralized approach, electricity is converted into heat at a location that may be distant to the point of actual heat demand, and DH networks are used to distribute the heat to where it is needed [127, 132].

In addition, Fig. 4.6 illustrates the interconnection of different power to heat options with the power grid and DH networks. Centralized power to heat technologies draw electricity from the grid to generate heat, using either large scale heat pumps or electric boilers. Heat energy is then transported to residential customers. In contrast, decentralized power to heat options do not make use of DH networks.

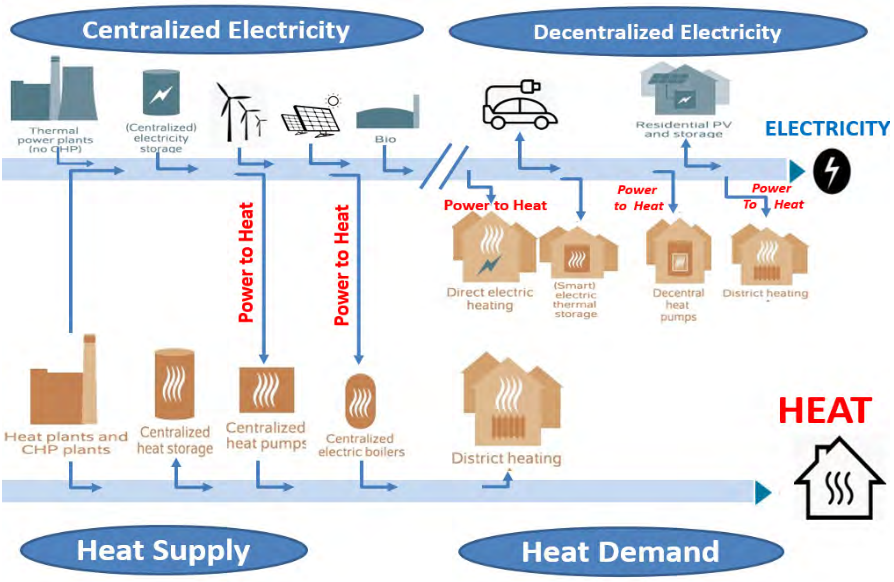


Fig. 4.7. Interconnection of power to heat strategies to DH [127]

Figure 4.7 also indicates that most power to heat options involve some energy storage capability in heat supply and demand sides. In terms of energy systems, interactions between different kinds of heat storage and electricity storage technologies are of particular interest.

4.14.2. Power to heat and decarbonisation

A flexible coupling of power and heat sectors can contribute to both renewable energy integration and decarbonisation. In many industrialized countries, decarbonizing the heating sector is a precondition for achieving ambitious climate policy targets; in particular, space heating accounts for substantial fractions of final energy demand and greenhouse gas emissions.

Power to heat solutions like heat pumps and electric boilers are foreseen to be possible future tools to stabilise international power markets with high proportions of variable power supply. Temporary low-cost electricity can be used for heat generation at times with high availability of wind and solar power through substitution of ordinary heat supply, hence contributing to increased energy system sustainability. Power to heat installations in DH systems are competitive due to the low specific investment and installation costs for large electric boilers, heat pumps, and heat storages [111].

Achieving medium and long-term climate targets calls for decarbonisation not only of electricity generation but also of the space heating sector. At the same time, the power system integration of variable wind and solar energy sources requires additional flexibility. A flexible coupling of power and heat sectors appears to be a promising strategy to address both of these challenges. Several power to heat technologies are available that may contribute to both decarbonizing heat supply and, if sufficiently flexible, integrating variable renewable electricity [1, 10].

4.15. Flexibility of heat requirement

Heat requirement or thermal load profiles for space heating and DHW in DH are determined by the weather, building thermal characteristics and consumers behaviour. Regardless of the method used, the heating demand profile of each user consists of three major parts, including physical and environmental characteristics of a building (i.e., building construction and the measure of thermal resistance per unit of a barrier’s exposed area or *R*-values, infiltration rate, ambient air temperature, solar radiation, humidity, etc.), human-related factors or social behaviour of the residential occupants and their comfort expectations, and random factors that account for uncertainties. Different techniques have been suggested in the literature in order to predict the demand profile of the users considering one or all of the above factors including historical approaches deterministic, and times series predictive methods, etc. [56, 58, 68].

Consequently, the daily heat requirement profiles can be quite diverse across countries. In DH systems, where sometimes heat is stored in the pipelines of DH network and also in the building envelopes resulting in a daily profile with little variation, they are mainly driven by ambient temperature variations [133].

According to the technical triangle presented in Fig. 4.2 in the previous chapter, the operational strategy for heat pump flexibility 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 of heat pump defines the flexibility role of the heat pump integration in the DH system.

On the other hand, the available RESs for heat pumps have a great influence on satisfactory fulfilment of the heating requirement, 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 sources to cover the peak heating requirement. The heat pump technology 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, i.e., heat sources, heating requirements and heat pump technology have bidirectional based dependencies [68, 134].

Heating and cooling offer a very large flexibility potential for power systems. Much of it could become cost-effective as the share of variable RES generation increases.

In the current energy systems, the majority of electricity and heat is produced in CHP plants. With increasing shares of intermittent RES power production, it becomes a challenging task to match power and heat production, as heat demand and production capacity constraints limit the power plants.

Efficient heat pumps can be used to decouple the constraints of electricity and heat production while maintaining the high energy efficiency needed to match the environmental policies and CO_2 emission goals. The requirements in terms of heat pump efficiency COP, location, capacity and economy were demonstrated in the literature, by using an energy system model which includes power plants, heat pumps and DH consumption profiles, as well as an evaluation of techno-economical characteristics of technologies [135, 136].

The heat requirement profile variations require a flexible heat production structure. When designing the production for a DH system, there are many strategies for managing the thermal load duration curve or the thermal requirement profile due to the combination of heat sources [68].

To cover the heat requirements profile, the simplest case includes one heat production unit as presented in Fig 3.8. in Chapter 3. The advanced case includes more than one sources of heat production, which means that the needed heat requirement can be generated by two divided sources, one for the base load and the other for peak load (which takes shorter time period) in the year scale as in Fig. 3.11 in Chapter 3. In the same chapter, similar multisource heat production cases can be found in Figs. 3.4, 3.9, and 3.11–3.14. Multi-source cases have more advantageous and better system reliability, it means that the needed power generated can be divided for the base load and for the peak load. The base load is typically produced in the CHP plants, but for the peak load demand separated HOBs are used [68, 137].

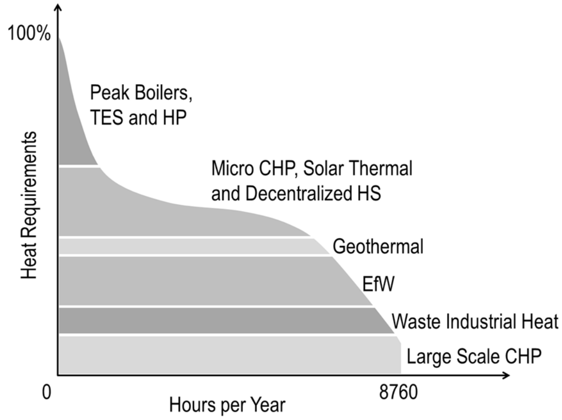


Fig. 4.8. Typical load duration curve for a multi-source DH network [137]

Managing heat requirements loads involves a comprehensive control strategy, based on the full load hours of the heat sources and their costs, a priority scheme can be derived, in order to actually realize the benefits of the installed physical DH network [138]. The most efficient and reliable source, i.e., CHP, or waste industrial heat sources are normally selected during base load hours while only back-up sources, i.e., large scale boilers or thermal storages are used to cover the peak load hours [139]. Figure 4.8 shows a typical heat requirement profile curve for multi-source even with energy from waste (EfW) in DH network. Usually, at times of peak heat demands, the electricity and heat production are decoupled in CHP plants to enhance operational flexibility [137].

By using long term thermal storage, the operational time of base heat equipment, the efficiency, costs and environmental benefits of the entire DH system can be enhanced substantially [140]. Several algorithms and control strategies have been formulated to define the operational strategy of heat storages and the functionality of the involved heat plants [141]. The best mechanism for operation can be achieved by accurately predicting future loads and applying DSM techniques to balance out the load curves. Several forecasting techniques have been developed with the most promising; using artificial intelligence methods, where the accuracy of 95% can be predicted [142].

In the future, the transmission of electricity and heat would be operated and studied simultaneously. This is because of the several interlinked technologies and the fact that excess electricity from intermittent RES technologies and TES, would be used for heat production [143, 144]. Excess electricity could be utilized by using electric boilers for peak requirements shaving, in a DH network and is thought to be a common strategy in the future. An extremely vital characteristic of DH is its flexibility in the sources of heat. Many different centralized and decentralized sources can be connected for reliable operation and flexibility to a DH network.

4.16. Flexibility in the power grid

Traditionally, power systems are operated on the basis that the supply is adjusted to follow the load in real-time, meaning that the flexibility to maintain a balance between the power supply and demand is mostly provided by the generation side, which is dominated by centralised, large-scale flexibly dispatchable (fossil fuel based) power plants. So in the past, power grids were following a demand-side design, consumer demand was followed by modifying the output of numerous central power plants, where the electricity was mainly flowing from the supply to the demand side [145–148].

Nowadays, the European power systems are evolving towards a generation mix that is more decentralised, less predictable and less flexible to operate due to the large-scale integration of distributed energy sources mainly by RES in order to meet the European environmental targets. In this context, additional flexibility is expected to be provided by the demand side [148–150]. Figure 4.9 represents the traditional and expected flexibility paths in future power system operation.

The power grid is changing with the ongoing "greening" of electricity production, many comparatively small and decentralised power producers are entering the power grid, making it more competitive and generating bidirectional flows of electricity. Therefore, an increasing share of RESs increases the difficulty to match supply and demand in the power system. This change makes the controlling of supply side more difficult, if not impossible, as RESs, namely solar PV and wind provide energy in variable amounts and at variable times.

In addition to previous changes, further strategies for stabilizing the electric grid like digital components of monitoring and measuring elements are becoming more needed criteria, so we have the possibility toward the smart grids. The new approach to grid stabilization requires a focus on adjusting demand to the given supply. New approaches providing demand-side flexibility are getting increasingly important, some of which include: storage (hydro, building core, ground, ice storage etc.), and batteries control strategies to modify electricity demand of devices and systems in response to capacity/price signals from the grid.

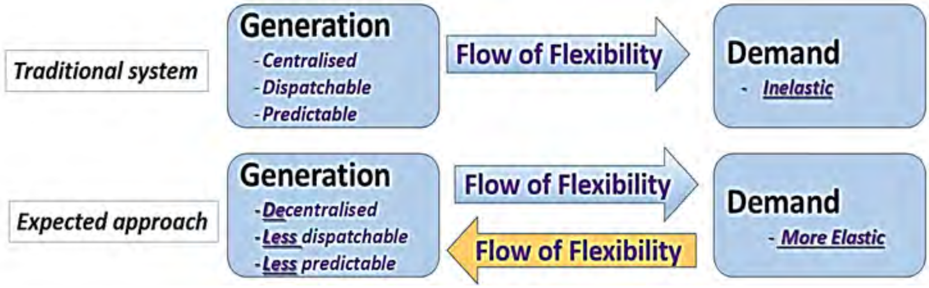


Fig. 4.9. Expected flexibility in future electric system operation [148]

So in future markets with increasing shares of RES, additional flexibility is needed to maintain system reliability. Therefore, the grid flexibility is a concept which has implications in a variety of components of an energy system. In general terms, flexibility is the ability to supply and absorb energy whenever required and ensure a supply and demand equilibrium, so flexibility options are required to balance residual load fluctuations. There is a trade-off between the technologies presented: some are complementary and others compete with and among a category.

4.16.1. Residual load curve

In response to the increasing share of intermittent electricity generation from VRE leads to several challenges in both of DH system and the power grid. The availability of most technologies depends on the weather, wind speeds and solar irradiation levels. In an energy system, the electricity generation is not necessarily available when needed, in the case with high RES capacity, some situations occur when the electricity generation from RES exceeds total demand as well as situations when RES production cannot fulfil total demand. The difference between electricity demand and the RES generation is defined as residual load, or the load that remains after the VRE generation is referred to as the residual load. The term residual load refers to the electricity demand that is not covered with intermittent renewable systems and therefore it must be met by dispatchable electricity generation units.

Thus, in a system with high RES capacity, times occur when electricity generation from these plants excesses the demand as well as times, when they produce not enough electricity to fulfil the demand profiles of requirements. Figure 4.10 illustrates the residual load and load duration curve and the deficit or surplus of VRE. Subsequently, the residual load should be analysed for different compositions of the power system to expose the flexibility requirements for different scenarios [148, 152, 153].

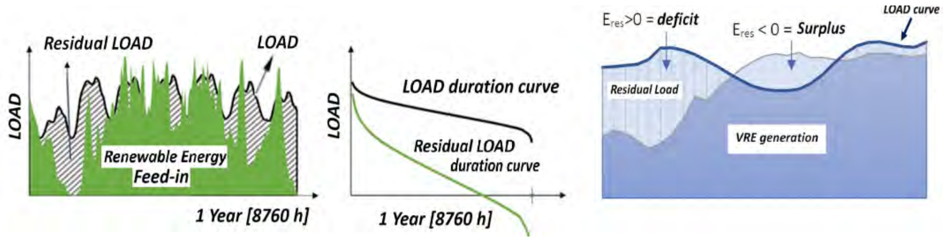


Fig. 4.10. Residual load and load duration curves [112, 153]

As visualised in Fig. 4.10, the positive residual load ($E_{\mathbf{res}} > 0$) indicates that additional energy is required to reach the demand, whereas a negative residual load ($E_{\mathbf{res}} < 0$) indicates a surplus of the added energy.

The residual load duration curve helps to estimate the impact of renewables on the electricity system. The amount and number of hours with excess generation will increase with the increasing number of RES plants. On the other hand, electricity generation from wind and PV or their hybrid plants cannot be available during times with high demand. In this case, the peak of the residual load is not significantly lower than the one of the total load curve. As a result, a high amount of back-up capacity would be needed to ensure the security of supply [151].

In addition, increasing the electricity generation from intermittent RES increases the gradient and volatility of the residual load. Miscellaneous technologies exist which can provide flexibility. However, they perform different technical and economic characteristics. The project REFLEX was developed as a systemically structured overview of flexibility options for a system integrated with RES [14, 151–153, 158].

4.16.2. Residual load and heat pumps

The flexible operation of the heat pump and its availability for seasonal load shifting has a positive effect on heat pump operation. There are many analyses for residual load-shifting by heat pump systems coupled to thermal storage, therefore the heat pump based systems can normalize the demand side requirement profile by providing load shaping and load shifting services. The shifting potential is required throughout the year (more in winter than in summer) and can be balanced by heat pumps in residential and office buildings [12].

The smoothing effects on the residual load curve and reducing feed-in peaks are a benefit that can be achieved by altering the heat pump operation. The integration of VRE electricity takes place on different levels. By using heat pumps for integration in larger VRE plants (such as solar PV arrays and wind) requires different strategies as for maximising the use of on-site solar PV power generation. To integrate large amounts of wind and solar PV, numerous heat pump units or pool of heat pumps have to be coordinated according to their availability and to the current production conditions. On the level of individual buildings, coordination of the heat pump with other technologies (i.e., battery systems) is required in case of on-site solar PV power generation [4].

The correlation between renewable power generation and heat demand award the ability of heat pumps to support the integration of renewable electricity in the power system. There are some inconveniences or limitations to integrate the heat pumps to solar PV power generation. The reason is, that for central and northern European climates the thermal demand is highest during winter whereas the electricity generation from solar PV is lower in this period.

In opposite, the electricity generation from solar PV in summer is higher, whereas the thermal demand is lowest during summer time [112, 155–157]. Figure 4.11 illustrates the principles and impacts of smoothing effects on demand response (DR) load shifting and load shedding. It is clear that the smoothing effects of the heat pump induce the flexibility on the demand side response curves [17, 112].

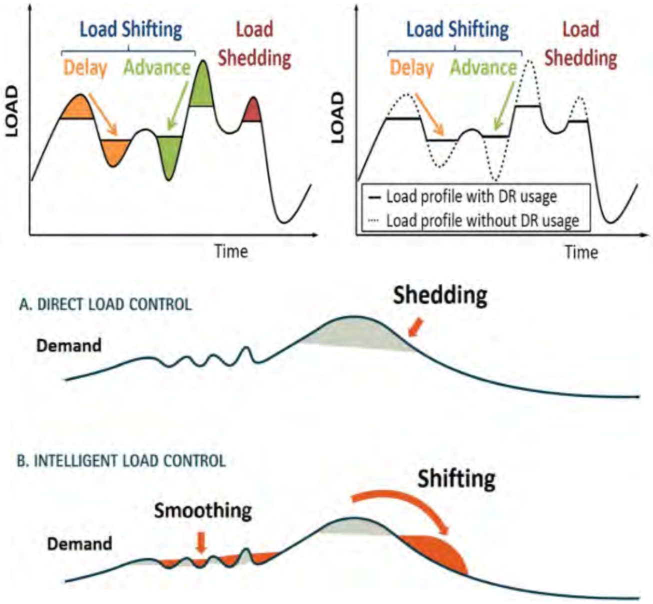


Fig. 4.11. Smoothing effects through load shedding and load shifting [54, 112]

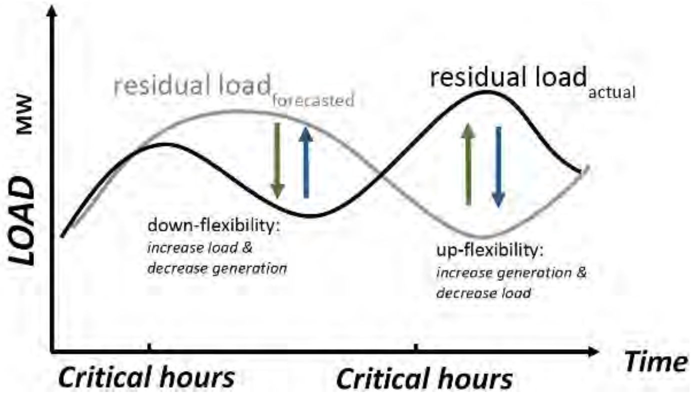


Fig. 4.12. Flexibility needs of the power system [8]

Two kinds of flexibility can be distinguished:

- Long-term flexibility to adjust conventional generation technologies to a residual demand which might be decreasing over time but with increasing scheduled ups and downs over hours. Figure 4.12 represents the flexibility options needed in a generation, transmission, market and operation in the power system, down and up flexibility in critical hours, note that residual load is the difference between power load and VRE generation [8].
- Short-term flexibility within one hour, which arises from short-term deviations between forecasted and actual outcomes. Thus, sudden changes in the supply-demand-balance, be it an unexpected decline or increase in VRE power generation, or changes in load, challenge the power system's flexibility [8].

4.16.3. Overview of flexibility options

Due to developed flexibility options by REFLEX project (as mentioned above , the residual load duration curve helps to determine the impact of renewables on the power system as shown in Fig. 4.4. To compensate the fluctuation of the intermittent RES feed-in, flexibility options are required. Situations with excess power generation from RES (negative residual load) as well as situations with RES deficit (positive residual load) need to be compensated in some way. A range of flexibility options exists to provide the necessary compensation in these situations [14, 151–153, 158].

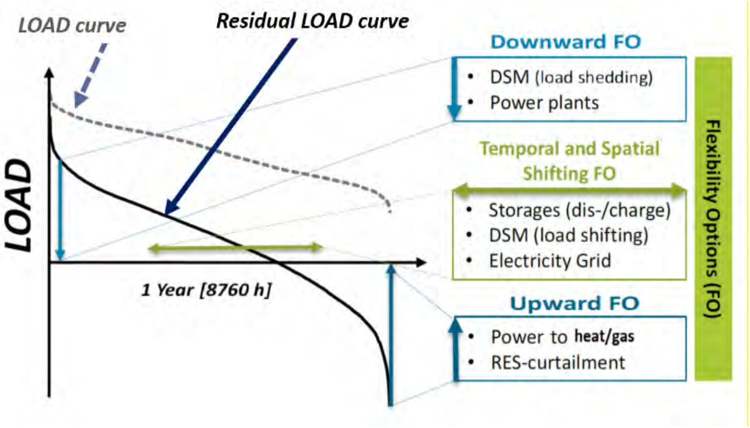


Fig. 4.13. Corresponding flexibility options
and the residual load and load duration curves [30, 153]

The future need for flexibility is mainly caused by the residual load. Both, times with excess power generation from RES plants (negative residual load) as well as times with RES deficit (positive residual load) need to be balanced. Miscellaneous flexibility options exist, which can either provide flexibility in one of these two situations or in both as shown in Fig. 4.13. Therefore, the way of flexibility provision can be categorized into three different types [151–153, 158]:

- Downward-flexibility: Reducing or supplying the positive residual load with power plants or load shedding (especially for peak load situations).
- Upward-flexibility: Reducing surplus RES feed-in from RESs by curtailing the excess amount or increasing the demand.
- Shifting-flexibility: Shifting surplus feed-in of RESs to other regions or time steps with the positive residual load as well as shifting positive load peaks to times with low or negative residual load.

4.16.4. Shedding and shifting flexibility applications and heat pumps

Each of the mentioned three types comprises different flexibility options. The thermal power plants with load shedding applications can provide downward flexibility by decreasing load peaks. Load shedding applications decrease their electricity demand without compensating their reduction at another time. Shifting flexibility options involve technologies which can be used for spatial and temporal shifting. Power grids balance the intermittent power generation in one region by transferring surplus electricity to another region (spatial shifting).

Demand-side management (DSM) is a broad concept encompassing a variety of tools aimed to manage the energy demand of consumers, which include residential and industrial users. Flexibility will thus allow demand-side management, load control and thereby DR based on the requirements of the surrounding power grid. Therefore a flexibility service that can help matching supply and demand is DR, so DR can be defined as changes in power usage implemented directly or indirectly by end-use customers/prosumers from their current normal consumption/injection patterns in response to certain signals [148, 159, 160].

DSM regarding load shifting applications and energy storage belong to the category of temporal shifting. Energy storage systems can be charged with excess electricity (negative residual load) and discharged in times with capacity deficits (positive residual load).

In particular, flexibility options belonging to the category shifting flexibility fulfil the categories downward and upward flexibility as well. To assess which of these technologies can provide better flexibility needs (in each of these mentioned three categories), it is essential to consider the technical and economic features too.

Flexibility can be obtained at the supply side or on the demand side of the power system. On the demand side, promising flexibility options are DR and storage. DR are the changes in the power consumption of the consumers relative to their normal consumption pattern in response to a certain signal. Multiple devices (e.g., electric vehicles, storage units and heat pumps) can be controlled with DR. DR with heat pumps is one of the options with a high potential to provide flexibility to the power system, because of the increasing penetration of heat pumps, and the capability of heat pumps to store energy close to demand. Aggregators can play an important role in leveraging the flexibility potential of heat pumps too [137, 161].

The value and necessity of DR as a flexibility means has been widely recognised among stakeholders and policy makers in Europe. The gradual roll-out of smart meters at residential level and the deployment of smart grids are expected to provide the hardware for DR. Also DR requires active participation of consumers, who are rather passive nowadays [148, 150, 162–165].

4.16.5. Demand response with heat pumps

The applications of DR with heat pumps which researched in academic references vary widely, but main generic applications can be distinguished as:

- to provide balancing services,
- to improve RES to electricity integration,
- to profit from variable electricity prices.

There are many factors mentioned in academic references which influence the flexibility of DR potential with heat pumps but the main three factors are determined by heat requirements or thermal load demand of building type, heat pump technology, and the type and size of the storage [153]. These main determinations can be described further as:

Heat requirements of a heat pump are the total thermal load demand for space heating (which is the largest share) and DHW, so heat requirements consequently determine the total amount of energy that can be shifted. There is a potential to shift load from the peak demand periods to the low demand periods that results in energy cost savings for the end-user.

The potential of shifting the demand for space heating was investigated for residential apartment blocks, the total potential of the shifted load was in the range of 30–47% of the original load [166, 167]. This potential can be used to shift load from high to low peak periods to minimize electricity costs, and also to minimize CO_2 emissions [168]. In other studies, the potential of DR by the usage of heat pump to raise the temperature of DHW in an ultra-low temperature in DH system was investigated too, which results in energy cost savings for the end-user [169]. The studies conclude that DR provides evident benefits for reducing CO_2-abatements costs. Both heat demand for space heating and DHW have the potential for DR with heat pumps [167, 169].

Building types: The studies concerning thermal demand profiles differ in terms of buildings and chosen climate, but they all focus on similar urban areas which are: residential areas. Overall the academic literature proves that DR with heat pumps has the economic potential in residential areas to serve as a flexibility resource, but an analysis that includes other urban areas besides residential areas is scarce. It is necessary to mention that different thermal load profiles related to the thermal demand of buildings are taken into account in current literature for different countries. Differences exist between the requirement load profiles of the residential sector and the service sector in terms of yearly, monthly, weekly, daily and hourly dynamics that affects the potential for DR with heat pumps [94, 137, 167, 169–172].

Heat pump technology: Concerns with heat pump size and technical properties. It determines the total amount of electricity consumption that can be increased or decreased by ramping the heat pump up or down [153, 158]. Both large heat pumps that provide heat for large or multiple consumers and smaller heat pumps that provide heat for individual households [167] can provide extra benefits through DR [168]. The analysis focused the smaller heat pumps which are providing heat for individual households. The heat pump type and properties determine the speed of response, the maximum ramping rate of electricity consumption and other extra requirements like minimum run and pause times [30, 158]. The technical characteristics of the heat pump differ for every heat pump type. In general two main types can be distinguished: air source coupled heat pumps and ground source coupled heat pumps [167]. Air source coupled heat pumps obtain external heat from the air and ground source coupled heat pumps obtain external heat from the ground. Air-coupled heat pumps as well as ground coupled heat pumps have flexibility potential for DR [170, 173]. Air source coupled heat pump system in combination with floor heating is the best cost-optimal option in terms of CO_2--abatement cost [137, 173].

The type and size of the storage determine how much energy can be shifted over a period of time. There are two common storage options for heat store from heat pumps, which are widely researched in the literature, they are storage in a water tank or storage in the thermal inertia of buildings [174]. Flexibility can- be increased by increasing the size of the storage tank. In addition adjusting storage tank size has a significant effect on flexibility potential in terms of load shifting and cost reduction, but that may increase the storage tank capacity and also leads to higher heat losses, which should be taken into account when determining the optimal size of storage tank [168, 169]. Thermal inertia of buildings as heat storage for individual households is used to balance electricity use and local electricity production with keeping in mind the thermal comfort for consumers [173]. The results show strong potential for short-term shifting of peak electricity demand for heating with heat pumps to off-peak hours. Furthermore, the interaction between the heat pump system and the thermal mass is very important. Physical characteristics of building strongly influence on the flexibility potential when the thermal inertia is used as storage. Well insulated buildings have more potential for load shifting than traditional buildings which are less insulated, due to the faster drop in temperature [167, 175–177].

4.16.6. Relevant technologies to provide flexibility

The technologies can be distinguished as technologies to downward flexibility and technologies to shifting flexibility.

Technologies to downward flexibility. The key options that are able to provide downward-flexibility are conventional power plants (with or without CHP) as well as load shedding applications, mainly in the energy-intensive industry.

Technologies to shifting flexibility. Various technologies are considered when analysing flexibility options for spatial or temporal shifting: technologies are related to different categories, such as energy storage, energy demand appliances with the potential for shifting the use of related equipment (for DSM) or power grids. Therefore, the comparison is made among technologies with different fields of application, e.g., demand management of products which need electricity (such as washing machines, dryers, freezers, etc.), options related to the electrification of other sectors (such as electric vehicles, heat pumps, water heating, etc.), or power storage technologies (such as batteries).

For demand flexibility, it is important within which timeframe the needed capacity is available for either decreasing or increasing the load.

To upward flexibility. Technologies that provide upward-flexibility are needed if electricity generation exceeds demand during times of high feed-in by VRE. In general, two concepts can be distinguished: either RES to turn down feed-in or to increase the power consumption. The corresponding technologies are wind power plants (on- and off-shore) and solar PV plants on the supply side and power to heat (electric boilers, heat pumps), as well as the power to gas (water electrolysis) concepts on the demand side curtailment of RES, provide upward flexibility.

One important criterion for flexibility options is the activation time. The feed-in of wind and solar photovoltaic plants can be regulated downwards or even curtailed within seconds or minutes. The same reaction time applies to power to heat (electric boilers, heat pumps) and power to gas (water electrolysis) can be turned on within seconds or minutes, depending on if it is a cold start or the plant was operated in standby before [158].

References

[1] Hvelplund F., Østergaard P., Möller B., Mathiesen B.V., Connolly D., Andersen A.N., *Analysis: Smart Energy Systems and Infrastructures*, H. Lund (Ed.), *Renewable Energy Systems*, Academic Press, Boston 2014.

[2] Lund H., Andersen A.N., Østergaard P.A., Mathiesen B.V., Connolly D., *From electricity smart grids to smart energy systems: A market operation based approach and understanding*. Energy, 8th World Energy System Conference, WESC 2010, 2012, 96–102.

[3] Lund H., Werner S., Wiltshire R., Svendsen S., Thorsen J.E., Hvelplund F., Mathiesen B.V., *4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems*, Energy, 2014, 68, 1–11.

[4] Fischer D., *Integrating Heat Pumps into Smart Grids*, PhD thesis, Royal Institute of Technology (KTH), Stockholm 2017.

[5] Cochran J., Miller M., Zinaman O., Milligan M., Arent D., Palmintier B., *Flexibility in 21st Century Power Systems*, Report of NREL (NREL/TP_6A20-61721), Berkeley 2018.

[6] Masy G., Georges E., Verhelst C., Lemort V., Andre P., *Smart grid energy flexible buildings through the use of heat pumps and building thermal mass as energy storage in the Belgian context*, Sci. Techn. Built Environ., 2015, 21, 800–811.

[7] Eurelectric, *Flexibility and aggregation: Requirements for their interaction in the market*, Tech. Rep., Brussels 2014, 13.

[8] Breitschopf B., Bäumann A., *Methodology Paper: Measuring the Flexibility of the Power System – Approach and Results*, Fraunhofer ISI, January 2018.

[9] Gracceva F, Zeniewski P., *A systematic approach to assessing energy security in a low-carbon EU energy system*, Appl. Energy, 2014, 123, 335–348.

[10] González I.H. et al., *Addressing flexibility in energy system models*, Joint Research Centre, Institute for Energy and Transport, European Commission, Brussels 2015.

[11] Vandermeulen A., van der Heijde B., Helsen L., *Controlling district heating and cooling networks to unlock flexibility: A review*, Energy, 2018, 151, 103–115.

[12] Lund P.D., Lindgren J., Mikkola J., Salpakari J., *Review of energy system flexibility measures to enable high levels of variable renewable electricity*, Ren. Sust. Energy Rev., 2015, 45, 785–807.

[13] Schuetz P., Gwerder D., Gasser L., Fischer L., Wellig B., Worlitschek J., *Thermal storage improves flexibility of residential heating systems for smart grids*, Proc. 12th IEA Heat Pump Conference, Rotterdam 2017, 1–9.

[14] Stinner S., Huchtemann K., Müller D., *Quantifying the operational flexibility of building energy systems with thermal energy storages*, Appl. Energy, 2016, 181, 140–154.

[15] Arteconi A., Hewitt N.J., Polonara F., *State of the art of thermal storage for demand-side management*, Appl. Energy, 2012, 93, 371–389.

[16] Directorate General for Energy, Directorate General for Climate Action and Directorate General for transport, *EU energy, transport and GHG emissions, trends to 2050, reference scenario 2013*, European Union, Brussels 2013.

[17] Silva V., Prime G., Hinchliffe T., Lafond D., Rehulka F., Lopez-Botet Zulueta M., *Challenges of the representation of near term electricity system flexibility in energy system models*, *addressing flexibility in energy system models*, European Commission, Joint Research Centre, Institute for Energy and Transport, Brussels 2015.

[18] Salazar G., Angel M., Trevor K., Prchlik L., *Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables*, Ren. Sust. Energy Rev., 2018, 82, 1497–1513.

[19] Bertsch J., Growitsch C., Lorenczik S., Nagl S., *Flexibility in Europe's power sector: An additional requirement or an automatic complement?*, Energy Econ., 2016, 53, 118–131.

[20] Cochran J., Bird L., Heeter J., Arent D.A., *Integrating Variable Renewable Energy in Electric Power Markets. Best Practices from International Experience*, online https://pdfs.semanticscholar.org/2d74/8fd65d293761f6f6a19da5eaff8ea5086846 (18.01.2018).

[21] Cochran J., Mackay M., Zinaman O., Milligan M., Arent D., Palmintier B., NREL, 2014, *Flexibility in 21st Century Power Systems*, Report of NREL (NREL/TP_6A20-61721), Berkeley 2018.

[22] Deason W., C*omparison of 100% renewable energy system scenarios with a focus on flexibility and cost*, Ren. Sust. Energy Rev., 2018, 82, 3168–3178.

[23] Denny E., O'Mahoney A., Eamonn L., *Modelling the impact of wind generation on electricity market prices in Ireland. An econometric versus unit commitment approach*, Ren. Energy, 2017, 104, 109–119.

[24] Didsayabutra P., Lee W.-J., Eua-Arporn B., *Defining the must-run and must-take units in a deregulated market*, IEEE Trans. Ind. Appl., 2002, 38, 596–601.

[25] Koljonen T., Kiviluoma J., Lehtilä A. et al., *Holistic approaches in addressing flexibility in energy system modelling, Addressing flexibility in energy system models*, European Commission, Joint Research Centre, Institute for Energy and Transport, Petten, The Netherlands, 2015.

[26] Fischer D., Lindberg K.B., Madani H., Wittwer C., *Impact of PV and variable prices on optimal system sizing for heat pumps and thermal storage*, Energy Build., 2016, 128, 723–733.

[27] Madani H., *Capacity controlled ground source heat pump systems in Swedish single family dwellings*, PhD dissertation, Department of Energy Technology, Royal Institute of Technology, (KTH), Stockholm 2012.

[28] van der Meulen A., van der Heijde B., Helsen L., *Controlling district heating and cooling networks to unlock flexibility: A review*, Energy, 2018, 151, 103–115.

[29] Madani H., Fischer D., Lundqvist P., *The role of heat pumps in future urban energy systems*, Heat Pump. Techn. Mag., 2017, 35 (1), 50–53.

[30] Fischer D., Madani H., *On heat pumps in smart grids: A review*, Ren. Sust. Energy Rev., 2017, 70, 342–357.

[31] Gunda M., *Economic analysis of air-water heat pump technologies with a screening method*, PhD dissertation, Department of Energy Technology, Royal Institute of Technology, Stockholm 2015.

[32] Mader G., Madani H., *Capacity control in air–water heat pumps: Total cost of ownership analysis*, J. Energy Build., 2014, 81, 296–304.

[33] Gadd H., Werner S., *Daily heat load variations in Swedish district heating systems*, Appl. Energy, 2013, 106, 47–55.

[34] Kontu K., *District heating and cooling as part of mart energy systems*, LSc thesis, AALTO University, Helsinki 2014.

[35] Nuytten T., Claessens B., Paredis K., van Bael J., Six D., *Flexibility of a combined heat and power system with thermal energy storage for district heating*, Appl. Energy, 2013, 104, 583–591.

[36] Sneum D.M., Sandberg E., Rosenlund Soysal E., Skytte K., Olesen O.J., *Framework conditions for flexibility in the district heating-electricity interface*, de Gruyter, Berlin 2016.

[37] Cocheran J. et al., *Flexibility in 21st Century Power Systems*, National Renewable Energy Laboratory, Texas, 2014.

[38] Lorenzen P. et al., *Design of a smart thermal grid in the Wilhelmsburg district of Hamburg: Challenges and approaches*, Book of abstracts 16th Int. Symp. District Heating and Cooling, Hamburg 2018.

[39] Arteconi A., Hewitt N.J., Polonara F., *State of the art of thermal storage for demand-side management*, Appl. Energy, 2012, 93, 371–389.

[40] Olsson-Ingvarson L.C., Werner S., *Building mass used as short term heat storage*, 11th Int. Symp. District Heating and Cooling, August 31–September 2, 2008.

[41] Østergaard P.A., *Comparing electricity, heat and biogas storages' impacts on renewable energy integration*, Energy, 2012, 37, 255–262.

[42] Sibbitt B., McClenahan D., Djebbar R., Thornton J., Wong B., Carriere J., Kokko J., *The performance of a high solar fraction seasonal storage district heating system: Five years of operation*, Energy Proc., 1st Int. Conf. Solar Heating and Cooling for Buildings and Industry 30, 856–865, 2012.

[43] Smith A.D., Mago P.J., Fumo N., *Benefits of thermal energy storage option combined with CHP system for different commercial building types*, Sustain. Energy Technol. Assess., 2013, 1, 3–12.

[44] Jokinen E., Kontu K., Rinne S., Lahdelma R., *Demand side management in the district heated buildings to optimize the heat production*, 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2014), Turku 2014.

[45] Schmidt R.-R., Pol O., Page J., *Smart cities: Challenges and opportunities for thermal networks*, 13th International Symposium on District Heating and Cooling, Copenhagen 2012.

[46] Sayegh M.A., Danielewicz J., Nannou T., Miniewicz M., Jadwiszczak P., Piekarska K., Jouhara H., *Trends of European research and development in district heating technologies*, Renew. Sustain. Energy Rev., 2017, 68, 1183–1192.

[47] Linkevics O., Ivanova P., Balodis M., *Electricity Market Liberalisation and Flexibility of Conventional Generation to Balance Intermittent Renewable Energy – Is It Possible to Stay Competitive?*, Latvian J. Phys. Tech. Sci., 2016, 53 (6), 47–56.

[48] Baltputnis K., Petrichenko R., Sobolevsky D., *Heating Demand Forecasting with Multiple Regression: Model Setup and Case Study Conference*, Proc. 6th IEEE Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE ’18), Vilnius 2018, 211.

[49] Luick P.J., Helsen L.M., D’Haeseleer W.D., *Influence of massive heat-pump introduction on the electricity-generation mix and the GHG effect: Comparison between Belgium, France, Germany and The Netherlands*, Ren. Sust. Energy Rev., 2008, 12, 2140–2158.

[50] Rosen M.A., Le M.N., Dincer I., *Efficiency analysis of a cogeneration and district energy system*, Appl. Thermal Eng., 2005, 25, 147–159.

[51] Blarke M.B., Dotzauer E., *Intermittency-friendly and high-efficiency cogeneration: Operational optimisation of cogeneration with compression heat pump, flue gas heat recovery, and intermediate cold storage*, Energy, 2011, 36, 6867–6878.

[52] Kusch W., Schmidla T., Stadler I., *Consequences for district heating and natural gas grids when aiming towards 100% electricity supply with renewables*, Energy, 2012, 48, 153–159.

[53] Lund H., Andersen A. N., Alberg Ostergaard P., Vad Mathiesen B., Connolly D., *From electricity smart grids to smart energy systems: A market operation based approach and understanding*. Energy, 2012, 42, 96–102.

[54] Gils H.C., *Balancing of Intermittent Renewable Power Generation by Demand Response and Thermal Energy Storage*, PhD dissertation, Institute of Energy Storage, University of Stuttgart, Stuttgart 2015.

[55] Hannon M.J., *Raising the temperature of the UK heat pump market: Learning lessons from Finland*, Energy Pol., 2015, 85, 369–375.

[56] Connolly D., Lund H., Mathiesen B.V., Werner S., Möller B., Persson U., Boermans T., Trier D., Østergaard P.A., Nielsen S., *Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system*, Energy Pol., 2014, 65, 475–489.

[57] Rinne S., Syri S., *The possibilities of combined heat and power production balancing large amounts of wind power in Finland*, Energy, 2015, 82, 1034–1046.

[58] Wang H., Yin W., Abdollahi E., Lahdelma R., Jiao W., *Modelling and optimization of CHP based district heating system with renewable energy production and energy storage*, Appl. Energy, 2015, 159, 401–421.

[59] Fang T., Lahdelma R., *Optimization of combined heat and power production with heat storage based on sliding time window method*, Appl. Energy, 2016, 162, 723–732.

[60] Noussan M., Cerino Abdin G., Poggio A., Roberto R., *Biomass-fired CHP and heat storage system simulations in existing district heating systems*, Appl. Therm. Eng., 2014, 71, 729–735.

[61] Li Z., Wu W., Shahidehpour M., Wang J., Zhang B., *Combined heat and power dispatch considering pipeline energy storage of district heating network*, IEEE Trans. Sust. Energy, 2016, 7, 12–22.

[62] Pini-Prato A., Strobino F., Broccardo M., Parodi-Giusino L., *Integrated management of cogeneration plants and district heating networks*, Appl. Energy, 2012, 97, 590–600.

[63] Sartor K., Quoilin S., Dewallef P., *Simulation and optimization of a CHP biomass plant and district heating network*, Appl. Energy, 2014, 130, 474–483.

[64] Frederiksen S., Werner S., *District Heating and Cooling*, Studentlitteratur Ab., Lund 2013.

[65] Stevanovic V.D., Zivkovic B., Prica S., Maslovaric B., Karamarkovic V., Trkulja V., *Prediction of thermal transients in district heating systems*, Energy Convers. Manage., 2009, 50, 2167–2173.

[66] Korpela T., Kaivosoja J., Majanne Y., Laakkonen L., Nurmoranta M., Vilkko M., *Utilization of District Heating Networks to Provide Flexibility in CHP Production*, Energy Proc., 2017, 116, 310–319.

[67] Connolly D., *Heat roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries*, Energy, 2017, 139, 580–593.

[68] Sayegh M.A., Jadwiszczak P., Axcell B.P., Niemierka E., Bryś K., Jouhara H., *Heat pump placement, connection and operational modes in European district heating*, Energy Build., 2018, 166, 122–144.

[69] d'Angiolella R. et al., *NZEB 2.0: interactive players in an evolving energy system*, REHVA Journal, May 2016.

[70] Jensen Søren Østergaard, *Energy Flexible Buildings IEA EBC Annex 67*, CLIMA, 2016.

[71] Jensen Søren Østergaard, IEA EBC Annex67 *Energy Flexible Buildings*, annex67.org/about-annex-67/

[72] Clauss J. et al., *Control strategies for building energy systems to unlock demand side flexibility: A review*, Proc. Conf. Building Simulation, San Francisco 2017.

[73] Østergaard J.S., Madsen H., Rui L., Rune J. et al., *Annex 67: Energy Flexible Buildings: Energy Flexibility as a key asset in a smart building future*, Technical University of Denmark, Copenhagen 2017.

[74] Masyi G., Georges E., Verhelst C., Lemort V., Andre P., *Smart grid energy flexible buildings through the use of heat pumps and building thermal mass as energy storage in the Belgian context*, Sci. Techn. Built Environ., 2015, 21, 800–811.

[75] Bruninx K., Patteeuw D., Delarue E., Helsen L., D'Haeseleer W., *Short-term demand response of flexible electric heating systems: The need for integrated simulations*, 10th Int. Conf. European Energy Market (EEM), Stockholm 2013, 1–10.

[76] Newsham G.R., Bowker B.G., *The effect of utility time-varying pricing and load control strategies on residential summer peak electricity use: A review*, Energy Pol., 2010, 38, 3289–3296.

[77] Kamgarpour M., *Modeling options for demand side participation of thermostatically controlled loads*, IREP Symposium Bulk Power System Dynamics and Control, Rethymnon, Greece, August 25–30, 2013.

[78] De Coninck R., Baetens R., Verbruggen B., Driesen J., Saelens D., Helsen L., *Modelling and simulation of a grid connected photovoltaic heat pump system with thermal energy storage using Modelica*, 8th Int. Conf. System Simulation in Buildings, Liege, December 13–15, 2010.

[79] Behrangrad M., *A review of demand side management business models in the electricity market*, Ren. Sust. Energy Rev., 2015, 47, 270–283.

[80] Wolf T., *Model-based Assessment of Heat Pump Flexibility*, Master thesis, Uppsala University, Uppsala 2016.

[81] O'Connell N., Pinson P., Madsen H., Omalley M., *Benefits and challenges of electrical demand response: A critical review*, Ren. Sust. Energy Rev., 2014, 39, 686–699.

[82] Meunier L., Vidalenc E., *Technical potential of smart grids: an assessment of load shifting actions in France*, Proc. Int. Energy Workshop, Stanford University, 2011, 1–10.

[83] Gellings C.W., *The concept of demand-side management for electric utilities*, Proc IEEE 1985, 73 (10), 1468–1470.

[84] Delgado R.M., *Demand-side management alternatives*, Proc IEEE 1985, 73 (10), 1471–1488.

[85] Thillainathan L., Dipti S., Zong S.T., *Demand side management in smart grid using heuristic optimization*, IEEE Trans. Smart Grid, 2012, 3 (3), 1244–1252.

[86] Farshid S., Paras M., Anurag K.S., *Demand response for sustainable energy systems: A review, application and implementation strategy*, Ren. Sust. Energy Rev., 2015, 45, 343–350.

[87] Timilehin L., Kennedy A., Gert B., Zeiler W., *On the application of multi-agent systems in buildings for improved building operations, performance and smart grid interaction: A survey*, Ren. Sust. Energy Rev., 2015, 50, 1405–1414.

[88] Kobayashi H., Asari M., Hatta H., *Integrated control techniques of supply and demand for Japanese style smart grid*, Proc. IEEE PES, 2010, 1–7.

[89] Arteconi A., Hewitt N.J., Polonara F., *Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems*, Appl. Therm. Eng., 2013, 51 (1–2), 155–165.

[90] Jae Y., Morgenstern K., Sager C., *Demand-side management with heat pumps for single family houses*, Proc. Conf. Sustainable Building, Fraunhofer IRB Verlag, Munich 2013, 1610–1617.

[91] Arteconi A., Hewitt N.J., Polonara F., *State of the art of thermal storage for demand side management*, Appl. Energy, 2012, 93, 371–389.

[92] Papaefthymiou G., Hasche B., Nabe C., *Potential of heat pumps for demand side management and wind power integration in the German electricity market*, IEEE Trans. Sust. Energy, 2012, 3 (4), 636–642.

[93] Salpakari J., Lund P., *Optimal and rule-based control strategies for energy flexibility in buildings with PV*, Appl. Energy, 2016,161, 425–436.

[94] Schibuola L., Scarpa M., Tambani C., *Demand response management by means of heat pumps controlled via real time pricing*, Energy Build., 2015, 90, 15–28.

[95] Stötzer M., Styczynski Z., *Demand side management potential in German power system for an optimized integration of renewable energies*, Proc. internationaler ETG-Kongress, Würzburg 2011, 7–12.

[96] Brunner M., Tenbohlen S., Braun M., *Heat pumps as important contributors to local demand-side management*, Proc. IEEE PowerTech Conference in Grenoble, Grenoble, June 2013, 1–7.

[97] *Flexibility and aggregation – requirements for their interaction in the market*, Technical Report, Eurelectric, Brussels 2014.

[98] Huber M., Dimkova D., Hamacher T., *Integration of wind and solar power in Europe: Assessment of flexibility requirements*, Energy, 2014, 69, 236–246.

[99] Fischer D., Wolf T., Triebel M.A., *Flexibility of heat pump pools: The use of SG-ready from an aggregator’s perspective*, 12th IEA Heat Pump Conference, Rotterdam 2017.

[100] *Low carbon heat: Heat pumps in London*, Etude September 2018 (Posted in 6th of December 2018), https://www.kensaheatpumps.com/the-technology/what-is-a-heat-pump/

[101] Miara M., Günther D., Leitner Z.L., Wapler J., *Simulation of an air-to-water heat pump system to evaluate the impact of demand-side-management measures on efficiency and load--shifting potential*, Energy Technol., 2014, 2, 90–99.

[102] Patteeuw D., Henze G.P., Helsen L., *Comparison of load shifting incentives for low-energy buildings with heat pumps to attain grid flexibility benefits*, Appl. Energy, 2016, 167, 80–92.

[103] Fischer D., Wolf T., Wapler J., Hollinger R., Madani H., *Model-based flexibility assessment of a residential heat pump pool*, Energy, 2017, 118, 853-864.

[104] Fischer D., Wolf T., Scherer J., Wille-Haussmann B., *A stochastic bottom-up model for space heating and domestic hot water load profiles for German households*, Energy Build., 2016, 124, 120–128.

[105] Jakobs R., Laue H.-J., *Application of industrial heat pumps*, The IEA HPP-IETS Annex 35/13, International Energy Agency (IEA), Heat Pump Programme, Industrial Energy-Related Technologies and Systems, Heat Pump Center, Workshop Application Industrial Heat Pumps, Aarhus 2015, 1–82.

[106] *Application of industrial heat pumps*: *Final report*, Annex 35 IEA, Part 1. Report No. HPP--AN35e1, Borås 2014.

[107] Peureux J.-L., Sicard F., Bobelin D., *French industrial heat pump developments applied to heat recovery*, 11th IEA Heat Pump Conference, Montreal, Canada, May 12, 2014.

[108] Bobelin D., Bourig A., Peureux J., *Experimental results of a newly developed very high temperature industrial heat pump (140_C) equipped with scroll compressors and working with a new blend refrigerant*, International Refrigeration and Air Conditioning Conference, Purdue, 2012, https://docs.lib.purdue.edu/iracc/1299

[109] Peureux J., Sapora E., Bobelin D., *Very high-temperature heat pumps applied to energy efficiency in industry*, ACHEMA 2012, Frankfurt, 21 June 2012, 1–23.

[110] Cordin-Arpagaus C., Bless F., Uhlmann M., Schiffmann J., Bertsch S.S., *High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials*, Energy, 2018, 152, 985–1010.

[111] Averfalka H., Ingvarssonb P., Perssona U., Gonga M., WerneraLarge S., *Large heat pumps in Swedish district heating systems*, Ren. Sust. Energy Rev., 2017, 79, 1275–1284.

[112] Nowak T., *Heat Pumps: Integrating technologies to decarbonise heating and cooling*, European Copper institute, Brussels 2018.

[113] Kontu K., Rinne S., Junnila S., *Introducing modern heat pumps to existing district heating systems: Global lessons from viable decarbonizing of district heating in Finland*, Energy, 2019, 166, 862–870.

[114] Frederiksen S., Werner S., *District heating and cooling*, Studentlitteratur AB, Lund 2013.

[115] Lund H., Østergaard P.A., Connolly D., Mathiesen B.V., *Smart energy and smart energy systems*, Energy, 2017, 137, 556–565.

[116] Lund H., Mathiesen B.V., *Energy system analysis of 100% renewable energy systems: The case of Denmark in years 2030 and 2050*, Energy, 2009, 34, 524–531.

[117] Werner S., *District heating and cooling in Sweden*, Energy, 2017, 126, 419–429.

[118] Zogg M., *History of heat pumps Swiss contributions and international milestones*, Proc. 9th International IEA Heat Pump Conference, Zürich 2008.

[119] Ingvarsson P., Lower emissions from heat pumps, Report No. 609, Värmeforsk 1997.

[120] Mathiesen B.V., Lund H., *Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources*, Institution of Engineering and Technology, Renewable Power Generation, 2009, 190–204.

[121] *Heating Calm JM District and cooling with heat pumps outside the United States*, paper DA--88-04-5, ASHRAE Trans., 1988, 94 (pt. 1), 754–762.

[122] Li Z., Lin D., Haiwen S., Shuang J., Yingxin Z., *District cooling and heating with seawater as heat source and sink in Dalian, China*, Ren. Energy, 2007, 32, 2603–2616.

[123] Hedegaard K., Mathiesen B.V., Lund H., Heiselberg P., *Wind power integration using individual heat pumps: Analysis of different heat storage options*, Energy, 2012, 47, 284–293.

[124] Hedegaard K., Münster M., *Influence of individual heat pumps on wind power integration: Energy system investments and operation*, Energy Conv. Manage., 2013, 75, 673–684.

[125] Nilsson S.F., Reidhav C., Lygnerud K., Werner S., *Sparse district-heating in Sweden*, Appl. Energy, 2008, 85, 555–564.

[126] Reidhav C., Werner S., *Profitability of sparse district heating*, Appl. Energy, 2008, 85, 867–877.

[127] Bloessa A., Schillb W.P., Zerrahn A., *Power-to-heat for renewable energy integration: A review of technologies, modelling approaches, and flexibility potentials*, Appl. Energy, 2018, 212, 1611–1626.

[128] Perez-Arriaga I.J., Batlle C., *Impacts of intermittent renewables on electricity generation system operation*, Econ. Energy Environ. Pol., 2012, 1 (2), 3–17.

[129] Lew D. et al., *The western wind and solar integration study phase 2*, National Renewable Energy Lab (NREL), Colorado, 2013, https://www.nrel.gov/docs/fy13osti/55588.pdf

[130] Schill W.-P., Pahle M., Gambardella C., *Start-up costs of thermal power plants in markets with increasing shares of variable renewable generation*, Nat. Energy, 2, 17050, https: //dx.doi.org /10.1038/nenergy.2017.50

[131] Kondziella H., Brückner T., *Flexibility requirements of renewable energy based electricity systems: A review of research results and methodologies*, Ren. Sust. Energy Rev., 2016, 53, 10–22.

[132] Olsthoorn D., Haghighat F., Mirzaei P.A., *Integration of storage and renewable energy into district heating systems: A review of modelling and optimization*, Solar Energy, 2016, 136, 49–64.

[133] Ommen T., Markussen W.B., Elmegaard B., *Heat pumps in district heating networks*, 2nd Symposium on Advances in Refrigeration and Heat Pump Technology, Odense, Denmark, 2013.

[134] Blarke M.B., *Towards an intermittency-friendly energy system. Comparing electric boilers and heat pumps in distributed cogeneration*, Appl. Energy, 2012, 91, 349–365.

[135] Banos R., Manzano Agugliaro F., Montoya F., Gil C., Alcayde A., Gomez J., *Optimization methods applied to renewable and sustainable energy: A review*. Ren. Sust. Energy Rev., 2011, 15, 1753–1766.

[136] Despres J., Hadjsaid N., Criqui P., Noirot I., *Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools*, Energy, 2015, 80, 486–495.

[137] Mazhar A.R., Liu S., Shukla A., *A state of art review on the district heating systems*, Ren. Sust. Energy Rev., 2018, 96, 420–439.

[138] Ahvenniemi H., Klobut K., *Future services for district heating solutions in residential districts*, J. Sust. Dev. Energy Water Environ. Syst., 2014, 2, 127–138.

[139] Djuric I.D., Trygg L., *Economic and environmental benefits of converting industrial processes to district heating*, Energy Conv. Manage., 2014, 87, 305–317.

[140] Fazlollahi S., Becker G., Marechal F., *Multi-objectives, multi-period optimization of district energy systems: II-daily thermal storage*, Comp. Chem. Eng., 2014, 71, 648–662.

[141] Christidis A., Koch C., Pottel L., Tsatsaronis G., *The contribution of heat storage to the profitable operation of combined heat and power plants in liberalized electricity markets*, Energy, 2012, 41, 75–82.

[142] Powell K.M., Sriprasad A., Cole W.J., Edgar T.F., *Heating, cooling, and electrical load forecasting for a large-scale district energy system*, Energy, 2014, 74, 877–885.

[143] Wu X., Lampietti J., Meyer A.S., *Coping with the cold: Space heating and the urban poor in developing countries*, Energy Econ., 2004, 26, 345–357.

[144] Bottger D., Gotz M., Theofilidi M., Brückner T., *Control power provision with power to-heat plants in systems with high shares of renewable energy sources. An illustrative analysis for Germany based on the use of electric boilers in district heating grids*, Energy, 2015, 82, 157–167.

[145] *Standardisation mandate to CEN, CENELEC and ETSI in the field of measuring instruments for the development of an open architecture for utility meters involving communication protocols enabling interoperability*, European Comission, Brussels 2009.

[146] EC, Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing, Directive 2003/54/EC, 2009.

[147] EC, Commission staff working paper: *An energy policy for consumers*, http//ec.europa.eu/energy/gas_electricity/forum_citizen_energy_en.htm, last accessed 3 June 2013.

[148] Hancher L., He H., Azevedo N., *Shift, not drift: Towards active demand response and beyond Topic 11*, European University Institute, San Domenico di Fiesole 2013.

[149] EC, Document by the services of the Commission: *European energy consumer checklist*, http//ec.europa.eu/energy/agathe_power/pdf/Energy_ Consumers_CheckList.pdf, 2010.

[150] EC, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: *Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage*, Brussels 2010.

[151] Michaelis J., Müller T., Reiter U., Fermi F., Wyrwa A., Zöphel C., Kronthaler N., Elsland R., *Comparison of the techno-economic characteristics of different flexibility options in the European energy system*, IEEE Xplore, 2017.

[152] Plötz P., Michaelis J., *The probability of long phases without wind power and their impact on an energy system with high share of renewable energies*, 9th Conference on Energy Economics and Technology, ENERDAY 2014, Dresden 2014.

[153] Müller T., Schreiber S., Herbst A., Klingler A. L., Wyrwa A., Fermi F., Reiter U.*, How to balance intermittent feed-in from renewable energies? – A techno-economic comparison of flexibility options 2017 REFLEX*, Brussels 2017.

[154] Klein K., Killinger S., Fischer D., Streuling C., Salom J., Cubi E., *Comparison of the future residual load in fifteen countries and requirements to grid-supportive building operation*, Eurosun, Palma de Mallorca 2016.

[155] Hedegaard K., *Wind Power Integration With Heat Pumps, Heat Storages, and Electric Vehicles*, Doctoral thesis, Technical University of Denmark, Roskilde 2013.

[156] Council of European Energy Regulators, *Regulatory and market aspects of demand-side flexibility*, Technical Report, 2013.

[157] Carmo C., Detlefsen N., Nielsen M., *Smart grid enabled heat pumps: An empirical platform for investigating how residential heat pumps can support large-scale integration of intermittent renewables*, Energy Proc., 2014, 61, 1695–1698.

[158] Müller T., *Overview of techno-economic characteristics of different options for system flexibility provision*, European Union, Analysis of the European energy system, October 2016.

[159] Jensen S.Ø., *IEA EBC Annex 67 Energy Flexible Buildings*, Energy Build., 2017, 155, 25–34.

[160] *Demand side flexibility in the Nordic electricity market: From a distribution system operator perspective*, TemaNord, Nordic Council of Ministers, Copenhagen 2017.

[161] van Etten M.J.J., *Simulating the flexibility potential of demand response with heat pumps in the Netherlands*, MSc thesis, Delft University of Technology, Delft 2017.

[162] EC Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions: *Making the internal market work*, Brussels 2012.

[163] Directive 2012/27/EU of the European parliament and of the Council of 25 October 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing directives 2004/8/EC and 2006/32/EC, EC 2012.

[164] Smart Grids Task Force, EG3 First Year Report: *Options on handling Smart Grids Data*. http//ec.europa.eu/energy/gas_electricity/smartgrids/taskforce_en.htm, accessed 3 June 2013.

[165] *ENTSO-E Network Code on Demand Connection*, ENTSO-E, 2012.

[166] Pedersen T.H., Hedegaard R.E., Petersen S., *Space heating demand response potential of retrofitted residential apartment blocks*, Energy Build., 2017, 141, 158–166.

[167] Patteeuw D., *CO_2-abatement cost of residential heat pumps with active demand response: Demand-and supply-side effects*, Appl. Energy, 2015, 156, 490–501.

[168] Knudsen M.D., Petersen S., *Demand response potential of model predictive control of space heating based on price and carbon dioxide intensity signals*, Energy Build., 2016, 125, 196–204.

[169] Knudsen M.D., Petersen S., *Model predictive control for demand response of domestic hot water preparation in ultra-low temperature district heating systems*, Energy Build., 2017, 146, 55–64.

[170] Alimohammadisagvand B., Jokisalo J., Kilpeläinen S., Ali M., Sirén K., *Cost-optimal thermal energy storage system for a residential building with heat pump heating and demand response control*, Appl. Energy, 2016, 174, 275–287.

[171] Sichilalu S., Mathaba T., Xia X., *Optimal control of a wind–PV-hybrid powered heat pump water heater*, Appl. Energy, 2017, 185, 1173–1184.

[172] Fischer D., Lindberg K. B., Mueller S., Wiemken E., Wille-Haussmann B., *Potential for balancing wind and solar power using heat pump heating and cooling systems*, Energynautics GmbH, 2014, retrieved from http//www.greenhp.eu/work-packages/wp10-smart-grid/?eID =dam_frontend_push&docID=2584

[173] Reynders G., Nuytten T., Saelens D., *Potential of structural thermal mass for demand-side management in dwellings*, Build. Environ., 2013, 64, 187–199.

[174] Baeten B., Rogiers F., Helsen L., *Reduction of heat pump induced peak electricity use and required generation capacity through thermal energy storage and demand response*, Appl. Energy, 2017, 195, 184–195.

[175] Cabrol L., Rowley P., *Towards low carbon homes: A simulation analysis of building-integrated air-source heat pump systems*, Energy Build., 2012, 48, 127–136.

[176] Hong J., Johnstone C., Torriti J., Leach M., *Discrete demand side control performance under dynamic building simulation: A heat pump application*, Ren. Energy, 2012, 39, 85–95.

[177] Prüggler N., *Economic potential of demand response at household level - Are Central-European market conditions sufficient?* Energy Pol., 2013, 60, 487–498, retrieved from http//ac.els-cdn.com/S0301421513002978/1-s2.0-S0301421513002978-main.pdf?_tid=192e6c02-979c-11e7-af4c-00000aacb360&acdnat=1505208415_1a712e1056c3497eca2a12c9d393d8f6

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