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Review

International review of district heating and cooling

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ABSTRACT

The purpose with this review is to provide a presentation of the background for the current position for district heating and cooling in the world, with some deeper insights into European conditions. The review structure considers the market, technical, supply, environmental, institutional, and future contexts. The main global conclusions are low utilisation of district heating in buildings, varying implementation rates with respect to countries, moderate commitment to the fundamental idea of district heating, low recognition of possible carbon dioxide emission reductions, and low awareness in general of the district heating and cooling benefits. The cold deliveries from district cooling systems are much smaller than heat deliveries from district heating systems. The European situation can be characterised by higher commitment to the fundamental idea of district heating, lower specific carbon dioxide emissions, and higher awareness of the district heating and cooling benefits. The conclusions obtained from the six contexts analysed show that district heating and cooling systems have strong potentials to be viable heat and cold supply options in a future world. However, more efforts are required for identification, assessment, and implementation of these potentials in order to harvest the global benefits with district heating and cooling.

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1. Introduction

According to [1], the fundamental idea of district heating is 'to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place'. Traditional excess heat resources are combined heat and power (CHP) plants, Waste-to-Energy (WtE) plants, and industrial processes. During recent decades, some renewable heat from geothermal wells, solar collectors, and biomass fuels have been introduced into the global district heating systems. Hereby, a combination of heat recycling and renewable heat is the current focus for district heating systems. This provides a substitution of ordinary primary energy supply for various societal heat demands, while achieving lower environmental impact. Hence, the district heating economy can be characterised as economy-of-scope instead of economy-of-size that characterise other parts of the energy system, giving a fundamentally different business situation for district heating.

Globally, district heating systems have been able to fulfil this fundamental idea to very different extents with respect to market penetration, use of local resources, size of heat distribution networks, and environmental impact. In countries with strong driving forces, district heating systems provide heat to about half of the national building stocks. In other countries, very few systems appear because of low awareness or competitiveness of district heating.

The primary merit of district heating is lower heating costs when international fuel prices are high and when lower environmental or climate impacts are valued by internalisation of external damage costs into national taxes or fees. The heat distribution costs are low in dense urban areas with concentrated heat demands. The shortcomings are lower competitiveness at low international fuel prices and high distribution costs in suburban and rural areas with less concentrated heat demands.

Established expertise of district heating has paved the way for introduction and deployment of district cooling systems, mainly for covering space cooling demands in buildings. However, this district cooling development has been more recent compared to the development of district heating. District cooling systems are therefore neither as common nor as extensive as district heating systems.

Assessments, reviews or surveys of district heating in the world have been available since the 1930s. The early surveys between the 1930s and 1970s contained information about the pioneering countries of USA, Germany, and Russia as presented by Refs. [2–8]. The two international oil crises in the 1970s, with considerable higher international fuel prices, created a higher interest in district heating and this renewed curiosity was reflected in Refs. [9–13]. More recent surveys have shown interest in the use of renewables in district heating systems [14,15]. An international review about district heating and cooling has never been published in a scientific energy journal.

European assessments, reviews or surveys of district heating have been available since the late 1940s. Early experiences from Germany, France, the Nordic countries, and Poland were reported in Refs. [16–20], while the first complete European survey was presented in 1974 in Ref. [21]. Further surveys in the aftermath of the international oil crises were provided in Refs. [22–24]. Only one review has been published in a scientific energy journal [25]. Two more recent surveys have focused on the possible expansion of district heating in Europe [26,27].

Russian surveys concerning the recent situation after deregulation of the Soviet planned economy have been provided by Refs. [28,29]. A current North American review perspective has been published in Ref. [30]. The current Chinese perspective is summarised in Ref. [31]. The situation for district heating systems in transition economies after the deregulation of the planned economies in East European countries around 1990 was the core theme in Refs. [32–34].

The first attempt concerning a global statistical survey was provided by Ref. [35]. The first complete international overview was published by a dedicated district heating committee of the World Power Conference in 1968 [36]. Nowadays, corresponding statistical information is easily available in the heat column of the world energy balances provided by the International Energy Agency (IEA) in Paris [37]. This compilation of international and national energy balances has been the main information source for the market, technical, and supply contexts in this article. These energy balances are not perfect, since discrepancies appear for some national district heating sectors. However, this database is currently the best available statistical information source concerning the global energy system.

Euroheat & Power, the European trade association for district heating and cooling (earlier called Unichal), have published statistical information about the status of district heating in European countries since 1978. This statistical information has been provided in special survey reports every second year since 1991. The most recent survey report is [38].

Fewer surveys and reviews are available about global district cooling installations and statistics. One technology review has recently been published in Ref. [39]. Some global information is also provided in two international district cooling books [40,41]. No appropriate worldwide statistical information is available for district cooling. Some European market information is available from two EU-projects in Refs. [42,43], while statistical information about district cooling is also available from Ref. [38].

The basic issues in this review are the market, technical, supply, environmental, institutional, and future contexts for district heating and cooling in the world with some deeper insights for Europe and the European Union. However, the review is heavily unbalanced with a more comprehensive description of district heating, since district cooling is still in its early days and publications about these systems are rare. An article with the same review structure has also been written concerning the national perspective of Sweden [44].

2. Market context

The market context considers the positions of district heating and cooling in the international heating and cooling markets with respect to introduction, expansion, current volumes, specific demands, market shares, and user categories.

2.1. District heating

District heating was first commercially introduced in cities as

Lockport and New York in the 1870s and 1880s [45]. However, a medieval pioneer system existed already in Chaude-Aigues, France in 1334, by distributing hot water from a geothermal source to some buildings in the village [46]. The first European commercial systems were introduced in Germany in the 1920s. The planned economies of Soviet Union and China introduced district heating in the 1930s and 1950s, respectively.

Nowadays, major district heating systems appear in cities as Moscow, St. Petersburg, Beijing, New York, Kiev, Seoul, Warsaw, Berlin, Hamburg, Helsinki, Stockholm, Copenhagen, Paris, Prague, Sofia, Bucharest, Vienna, and Milan. The total number of systems has been estimated to 80 000 systems [1], thereof about 6000 systems in Europe.

The main user categories of district heating are industries and buildings according to Fig. 1. During 2014, these customers bought 11,5 EJ of heat from district heating activities in the energy sector according to the IEA energy balances [37]. Russia, China, and the European Union were responsible for 85% of these heat deliveries. The user category proportions were 51% to buildings, 45% to industries, and 4% to others. However, the real heat deliveries in the USA are higher than the deliveries reported in the IEA energy balances, since many district heating systems are operated by end-user categories as universities, hospitals, and military camps.

The estimated heat use proportions for all buildings during 2014 are presented for the world and the European Union in Fig. 2. Total heat uses were 74 and 10 EJ, respectively. Combustible renewables as firewood etc. dominates the world situation with a market share of 36%, since this option is used in many developing countries and rural areas. In the European Union, natural gas dominates with a market share of 41%, since a high proportion of the population lives in urban areas and natural gas grids are present in most European urban areas. The direct use of fossil fuels had the proportions of 43% in the world and 60% within the European Union. The corresponding proportions of heat deliveries were 8% and 13%, respectively. Somewhat more heat is supplied by electricity than by district heating in both the world and the European Union. Hence, the utilisation of district heating in buildings is still low in average. However, high implementation rates around and above 50% appear in Iceland, Denmark, Sweden, Finland, Estonia, Latvia, Lithuania, Poland, Russia, and northern China.

For Europe, average national specific heat demands were presented in the Ecoheatcool project [47] and later updated in Ref. [48]. However, the variation of these heat demands among countries is smaller than normally expected. This smaller variation can be explained by the concept of degree days that has been used since the 1930s to describe the climate influence of space heating in buildings.

Degree-days are the integral of all positive daily differences during a year between effective indoor and outdoor temperatures creating space heating demands. Simply expressed, the number of degree days is a measure of the cold to counteract with space heating. In Europe, the degree days are about twelve times higher in the most northern parts compared the most southern parts. It becomes then more favourable to put more insulation into buildings located in cold regions with high degree day numbers. A simple optimisation analysis reveals that the optimal heat demand should be proportional to the square root of the degree days. The extreme variation in Europe shrinks therefore to a factor of 3.5 (equal to the square root of twelve). In order to show this small variation in Europe, the European Heating Index was introduced in Ref. [49]. From the European average, adding twenty percent represents the optimal heat demand in Stockholm, while a subtraction with twenty percent represents the corresponding conditions in Venice. Most people in Europe live within this variation. The conclusion is that the heat demands are high enough for establishing district heating systems in dense urban areas also in countries having less cold climates.

2.2. District cooling

Early district cooling systems were established in Hartford (USA) in 1962, Hamburg in 1967, and the La Defense district outside Paris in 1967. However, early precursors were the 'pipeline refrigeration' systems introduced in New York and other US cities in the 1890s [1]. These systems had decentralised evaporators and one central condenser, using the refrigerant as cold carrier. Major district cooling systems appear in cities such as Singapore, Tokyo, Stockholm, Paris, Dubai, Chicago, Toronto, Courbevoie outside Paris, Helsinki, Barcelona, Vienna, Berlin etc. The total number of district cooling systems in world is unknown, but around 150 European systems are in operation.

Current annual district cold deliveries can be estimated to be around 300 PJ per year, thereof around 200 PJ in the Middle East, 80 PJ in USA, 14 PJ in Japan, and 10 PJ in Europe. Hence, the volumes of district cold deliveries in the world are currently much smaller than district heat deliveries. Internationally, the dominating user category is service sector buildings, while residential buildings are more common in the Middle East, where district cooling systems provide about 7% of all cooling demands. Proportions of service sector buildings using district cooling are about 4% in USA and 0.7% in Europe.

Information about real space cooling demands is rare, since they are not measured regularly. However, they can be estimated from electricity use and standard coefficient of performances for chillers, but direct electricity use for chillers is also rarely measured. In order to estimate and understand the variations in European space cooling demands, the European Cooling Index was introduced in Ref. [42] and later further analysed in Ref. [50]. By combining information about the European Cooling Index and measured cold deliveries from twenty European district cooling systems, the European space cooling demands were estimated in Ref. [51]. The total annual cold demand was estimated to be about 4.2 EJ, thereof 2.6 EJ in the residential sector. However, only 16% of the total demand was met by cold deliveries. The corresponding proportions were 33% for the service sector and 7% for the residential sector. An estimation of the potential of the future European residential cold deliveries have been provided by Ref. [52]. The future annual cold use for residential space cooling was expected to increase to about 1 EJ from the current 0.2 EJ. A similar estimation for the service sector is not available.

3. Technical context

The technical context considers the technical methods used for heat supply, heat distribution, heat deliveries, and district cooling.

3.1. Heat supply methods

Annual volumes of heat supplied into district heating networks are presented by four different heat supply methods in Fig. 3 for the world and in Fig. 4 for the European Union. The information source has been the IEA energy balances [37] and considers only heat supplies from district heating activities in the energy sector. Heat supplies from district heating systems belonging to end-user categories are therefore excluded. An error in the IEA energy balances is that all heat supply in China is reported as coming from boilers, although the real proportion of heat supply from CHP plants was just below 50% during 2012 [53] and somewhat lower during earlier years. In order to repair this statistical error, the proportion of heat from Chinese CHP plants was assumed to be 40% in average

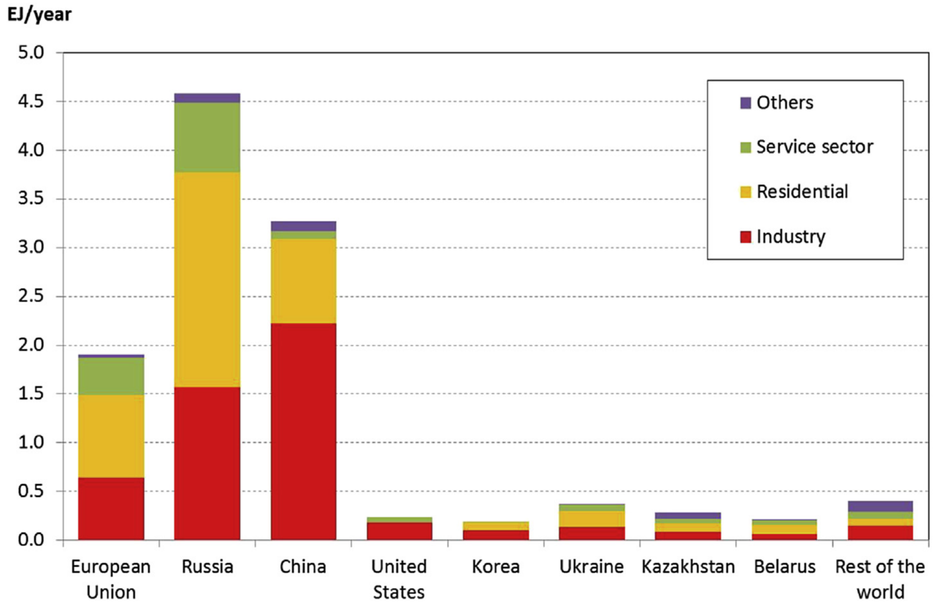

Fig. 1. Heat deliveries in various regions and countries during 2014 with respect to user categories according to [37].

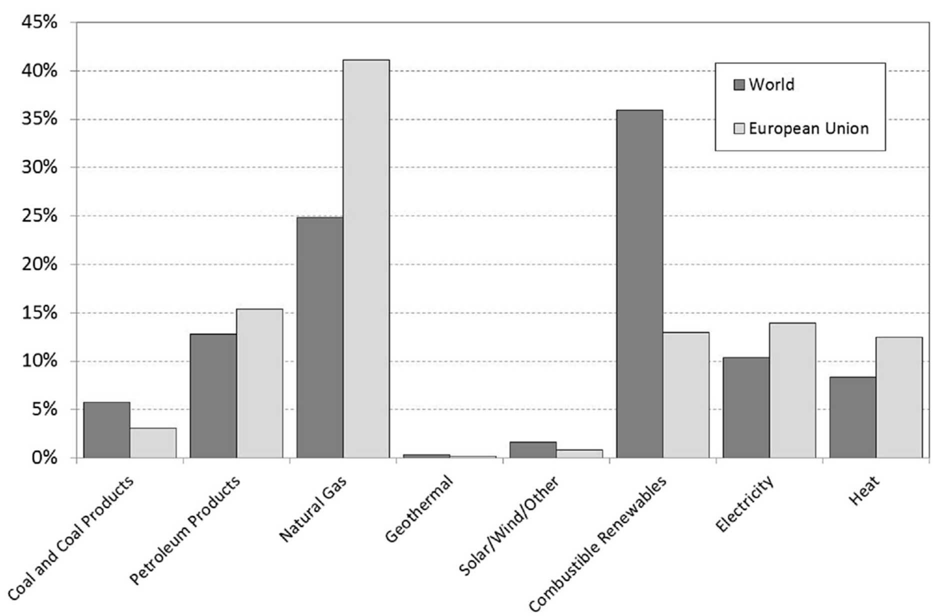

Fig. 2. Estimated proportions of all heat use in residential and service sector buildings in the world and in the current European Union during 2014 with respect to origin of energy supply group according to [37]. Heat denotes commercial heat deliveries (district heating) in these IEA energy balances.

between 1990 and 2014. The same error appears also for the United Kingdom, but has not been corrected, since this error has low influence on the world situation.

The total heat supply in the world was reduced in the mid-1990s since many industrial customers were disconnected in Russia after the deregulation of the planned economy. Since 2000, the annual heat deliveries have increased with low average growth rate of about one percent, mainly from the expansion of district heating in China. The total heat supply in the European Union has been almost constant since 1990. Disconnections of some customers in the former planned economies in Eastern Europe have been compensated by expansions in other countries. The conclusion is that the international district heating sector has rather stable heat deliveries. It has not the same expansion rate as the whole global energy system.

Internationally, the use of CHP plants has been the strongest argument for introducing district heating systems. Hereby, the inevitable heat losses from thermal power plants can be recycled for other heat purposes. Simply expressed, the heat should be used twice [54,55]. Small CHP plants can also be used [56,57]. These are not as efficient as large CHP plants, but do not need extensive heat distribution networks.

With respect to heat supply methods, the European Union has higher proportions of both recycled heat (72%) and renewable heat (27%) compared to the world situation with proportions of recycled heat of 56% and renewable heat of 9%. The proportion of CHP plants of only around 50% in both Russia and China influences this low world level of recycled heat. These low proportions of recycled heat

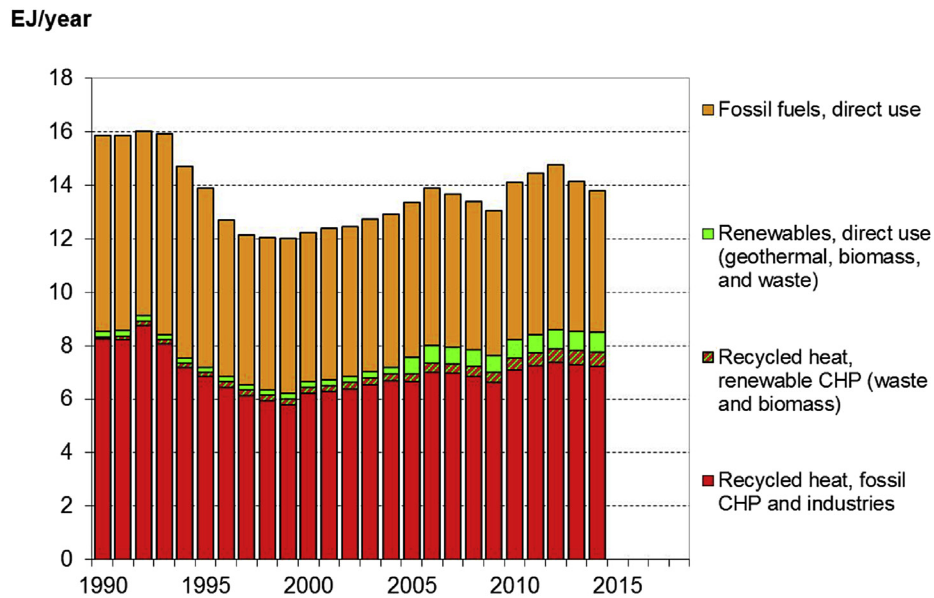

Fig. 3. Heat supplied into all district heating systems in the world 1990–2014 according to four different heat supply methods.

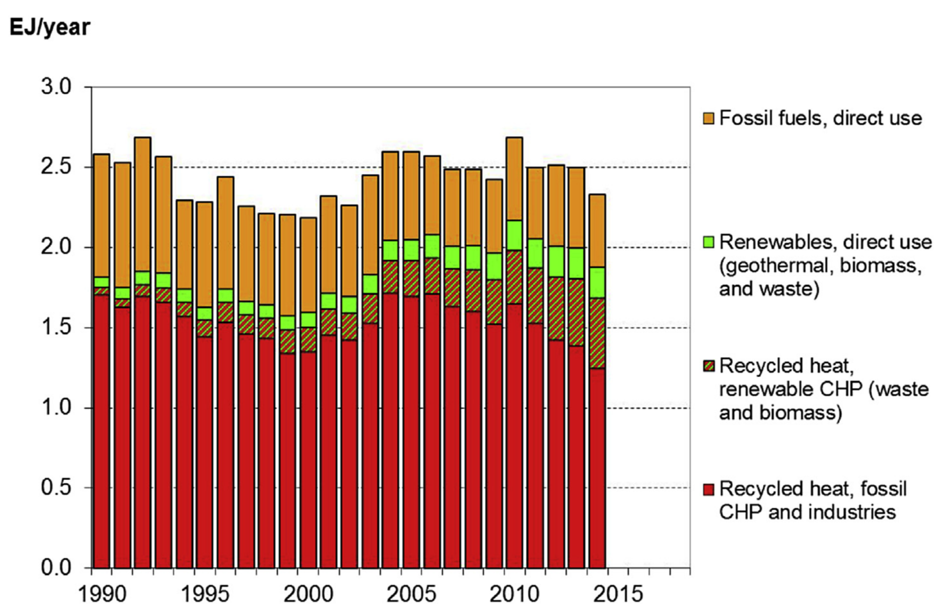

Fig. 4. Heat supplied into all district heating systems in the current European Union 1990–2014 according to four different heat supply methods.

indicate that the fundamental idea of district heating has not been fully implemented in these two largest district heating countries. The heat supply has therefore still very high proportions of direct use of fossil fuels in large boilers.

Heat storages are sometimes used to counteract daily heat load variations. Almost no seasonal heat storage has been installed until recently, when relatively large heat storages have been installed in conjunction with new solar district heating systems in small Danish towns and villages. A survey of various use of heat storages in the five Nordic countries in northern Europe has been provided by Ref. [58].

3.2. Heat distribution

The four generations of heat distribution have been defined in Ref. [59]. Steam was the heat carrier in the first generation, while water has been the heat carrier in the following generations. Carbon dioxide as future alternative energy carrier has been advocated by Ref. [60].

Most first generation systems have been converted to water systems or been closed, since steam is nowadays considered an inefficient heat carrier with respect to heat losses and maintenance costs. However, steam is still used as heat carrier in the Manhattan system in New York and in the central system in Paris. These two systems are still viable since their urban areas have very high population densities giving relatively short pipes and low proportion of distribution costs.

Second generation of district heating technology was introduced in the 1920s, when German engineers identified water as more efficient heat carrier. This technology generation was considered best available technology until the 1970s, when Danish, Swedish, and Finnish engineers started to expand the use of district heating. They reengineered the second generation into a third generation by introducing more lean technology with prefabricated pipes and substations together with lower distribution temperatures.

All these three generations were based on the use of fossil fuels and the connected building had high heat demands. A general transition into a new energy system with less fossil carbon dioxide emissions calls for an enhanced generation of district heating technology. This new energy system will have other supply and use conditions with more variable renewable energy sources, less thermal power plants, and customer buildings with lower heat demands. The five abilities for a fourth generation of district heating technology have been defined by Ref. [59]. A major feature of the fourth generation is that heat will be distributed with lower temperatures than applied in the third generation. An early research initiative has been taken by the Danish 4DH project [61].

Current district heating systems apply both second and third generation technologies with a wide variation of temperature levels used. Total route length of distribution pipelines can be estimated to about 600 000 km in the world and about 200 000 km in the European Union. Various applied temperature levels, insulation standards, and linear heat densities (heat sales per route length) create inevitable heat distribution losses between 5 and 35% [1].

In Europe, most customers are connected by substations to primary distribution networks supplying heat with the same supply temperature to all customers. However, secondary networks with lower distribution temperatures are sometimes connected to the primary network by a group substation. These secondary networks are more common in Russia and China.

System functioning is finally based on that heat is distributed by the product of flow and the temperature difference between the supply and return pipes. The corresponding overall control system is based on four different and independent control systems. The heat demand and flow control systems are located in each customer heating system and substation, while the heat supplier is responsible for the centralised differential pressure and supply temperature control systems [1]. However, the heat demand and flow controls are often missing in the Russian and Chinese secondary networks giving severe flow allocation problems with a large variation of indoor temperatures. This malfunctioning gives district heating a bad reputation in these two countries.

3.3. Heat deliveries

Substations deliver heat to buildings for space heating and hot water preparation with or without heat exchangers. Many Chinese systems just deliver heat for space heating purposes, neglecting the possibility to apply hot water preparation. The use of heat exchangers is motivated as responsibility and pressure divider in networks with considerable altitude variations. However, heat exchangers give somewhat higher temperature levels in the networks in order to provide temperature differences for obtaining heat transfer in the heat exchangers. Some Russian systems are called 'open' systems, since they use the district heating water directly for providing hot domestic water by blending with cold water. These systems must compensate this hot water supply with corresponding addition of make-up water to the distribution networks.

Industrial heat demands are connected to the networks in a similar manner. If the industrial customer is located close to the local heat supply plant, a special pipeline connection can provide another temperature level required.

Best available technology in Europe has been to use heat meters for measuring the heat delivery for each customer. They are now providing automatic readings and the measurements are transferred to the heat provider with wires or wire-less methods in order to generate invoices. However, the tradition in Russia and China has been to charge the heat delivery by an annual fixed fee related to the floor area utilised, why heat meters have not been used. The customers will then have no incentive to change their heat use.

3.4. District cooling

The cold supply is managed by using natural and excess cold resources (through heat exchangers), absorption chillers from excess heat resources, mechanical chillers (with or without heat recovery), and cold storages. No statistics is available in order to show the proportions of each cold supply method, neither for the world nor for the European Union.

Distribution of cold water is performed with a small design temperature difference between the cold supply temperature and the warmer return temperature. Hence, district cooling pipes are much wider than district heating pipes at the same capacity demand. Cold losses are very small in Europe where the annual average ground temperatures are almost equal to the distribution temperatures. Higher ground temperatures in the Middle East calls for more insulation of the pipes.

Cold deliveries are managed by substations in each connected building with or without heat exchangers. Since the temperature difference between supply and return pipes are very small, heat exchangers with long thermal lengths are used in the substations in order not to reduce the transfer capacity in the cold distribution networks. Shorter thermal lengths had given lower return temperatures and lower temperature difference in the distribution network.

4. Supply context

The supply context considers the original energy sources used in energy conversion plants and the corresponding proportions.

4.1. District heating

The original energy sources used for the heat supply are presented in Fig. 5 for the world and in Fig. 6 for the European Union without any reference to applied heat supply methods as described in Figs. 3 and 4. The information source has also been [37].

The proportion of heat supply from fossil fuels is still very high, both in the world (90%) and in the European Union (70%), since fossil fuels are still the main energy supply group for both CHP and boiler plants. This is very evident in Russia, with natural gas as main fuel, and in China, with coal as main fuel.

In order to reduce the future carbon dioxide emissions from these plants, new non-fossil heat sources must replace the current fossil-based plants. Examples of these expected new sources can be found in many of the existing district heating systems.

Heat recycling from waste incineration is applied in many countries in Waste-to-Energy (WtE) applications [62]. Major WtE installations in USA and Europe are listed in Ref. [63] with installed capacities, incinerated waste volumes, and useful energy outputs. Unfortunately, many of these lack heat recovery, since they only generate electricity. In Denmark and Sweden, all waste incineration plants are WtE installations and are connected to district heating systems for heat recycling. During 2014, 400 PJ heat was supplied from waste incineration plants in the world, thereof 208 PJ in the European Union [37]. The possibilities for more heat recycling in Europe have been further explored by Ref. [64]. Few WtE installations appear in Russia and China, but a growing interest exist [65].

Heat recycling from industrial processes is applied in some countries as Russia, Sweden, Germany etc. Suitable heat can be found from industrial processes having excess heat from high temperature processes [66]. A systematic heat cascading concept for an integrated industrial-urban system was presented in Ref. [67]. The current extent of this kind of heat recycling in the world is unknown, since the IEA energy balances do not report them properly. However, the Russian excess heat recovery from industrial processes of 331 PJ during 2014 was found in the Others column under the Solar/Wind/Others label. In Sweden, the corresponding heat recovery was 16 PJ during 2014. However, much research efforts have been spent for exploring these possibilities. Further use of industrial excess heat in district heating systems have been assessed for UK [68], Spain [69], Germany [70,71], Sweden [72], China [73–75], and the European Union [76]. The common denominator for these assessments is verified high potentials for heat recoveries, but the main barrier is the economic risk associated to these potential heat recoveries, if the primary industrial activities will close down.

Nuclear reactors with heat recovery to district heating systems were listed in Ref. [77] at 14 locations (six in Europe, one in China and seven in Russia). During 2014, 26 PJ heat was supplied in seven countries (Russia, Bulgaria, Czech and Slovak Republics, Hungary, Switzerland, and Ukraine), thereof 4 PJ within the European Union [37].

The possibilities for using large solar collector fields in conjunction with district heating have been explored in Sweden, Denmark, and Germany since the 1980s [78,79]. During recent years, a remarkable expansion has occurred in Denmark, reaching the milestone of one million square metres of solar collectors during 2016 [80]. In the end of the year, 1.3 million square metres corresponding to capacity of 900 MW was installed in 104 Danish district heating systems [81]. During 2014, 0.7 PJ heat was supplied from solar heat in the world with significant deliveries only in Denmark and Austria [37].

Geothermal heat resources have been used in district heating systems for many years in Iceland [82] and France [83]. Other installations appear in Germany, Hungary, Italy, Romania, Belgium, and United Kingdom. During 2014, 30 PJ heat was supplied from geothermal sources in the world, thereof 7.3 PJ in the European Union [37], but almost only European countries were reported. However, these supplies seem to be somewhat underrated, since the European GeoDH project recently reported deliveries of 47 PJ in Europe [84]. One quarter of the population in the European Union lives in urban areas that could be reached by geothermal heat through future district heating systems [85].

Biofuels in solid, liquid and gaseous states are used in countries as Sweden, Finland, Denmark, and Austria. The Swedish use is based on domestic wood waste from the strong national forestry sector [86]. Outside Europe, some use appears in USA, Russia, and China. Biofuels are relatively easy to use since they are suitable within the traditional combustion infrastructure established from the use of fossil fuels, although the heating values are lower. However, the available biomass resources in Europe are not large enough to substitute all current fossil fuel use [87]. During 2014, 524 PJ heat was supplied from biofuels in the world, thereof 405 PJ in the European Union [37]. Future use of biofuels will probably meet strong competition from other uses as transportation fuels and fossil-free feedstock for the petrochemical industry [88,89].

District heating systems are today already integrated with power generation in the electricity systems since CHP-plants are used for heat supply. A future electricity system with high proportion of variable power generation from wind and solar power will create both new opportunities and conditions for this integration. First, excess power generation can be absorbed in district heating systems through large electric boilers and heat pumps. These possibilities have been explored in Denmark [90–92], China [93], USA [94], and Russia [95]. Sweden have operation experiences of this kind of integration since some excess nuclear power generation during the 1980s initiated many installations of large electric boilers and heat pumps in district heating systems [96]. Second, CHP-plants need to be more flexible in order to compensate for variable power generation [97,98]. Third, some of the integration between electricity and district heating systems can be managed by large heat storages, since heat storages have much lower installation costs than electricity storages [99].

District heating systems can also utilise excess heat from large electricity users as large data centres that provide cloud services. The continuous electricity use can reach 100 MW in these large data centres. This kind of heat recycling is already in operation in

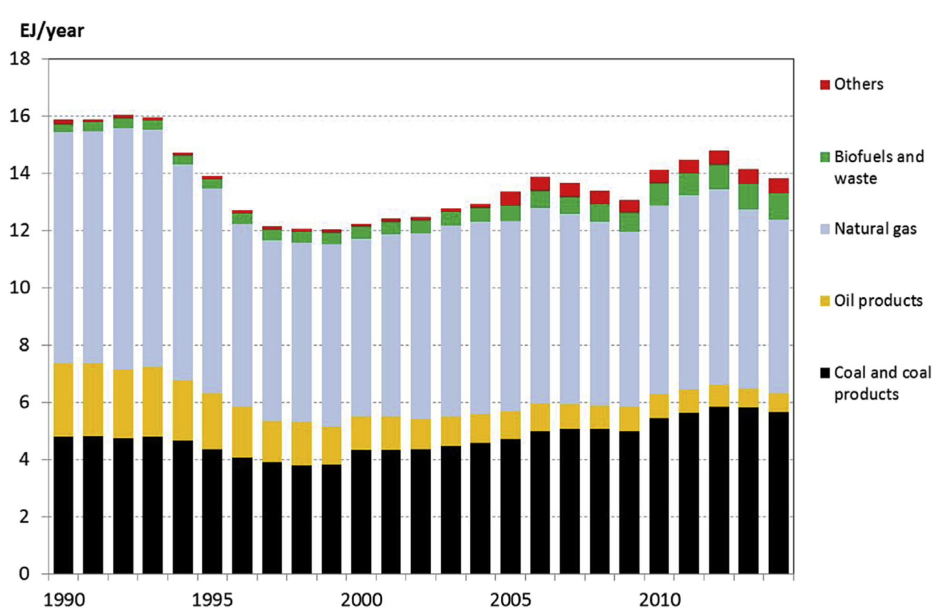

Fig. 5. Heat supplied into all district heating systems in the World 1990–2014 according to original energy supply sources used.

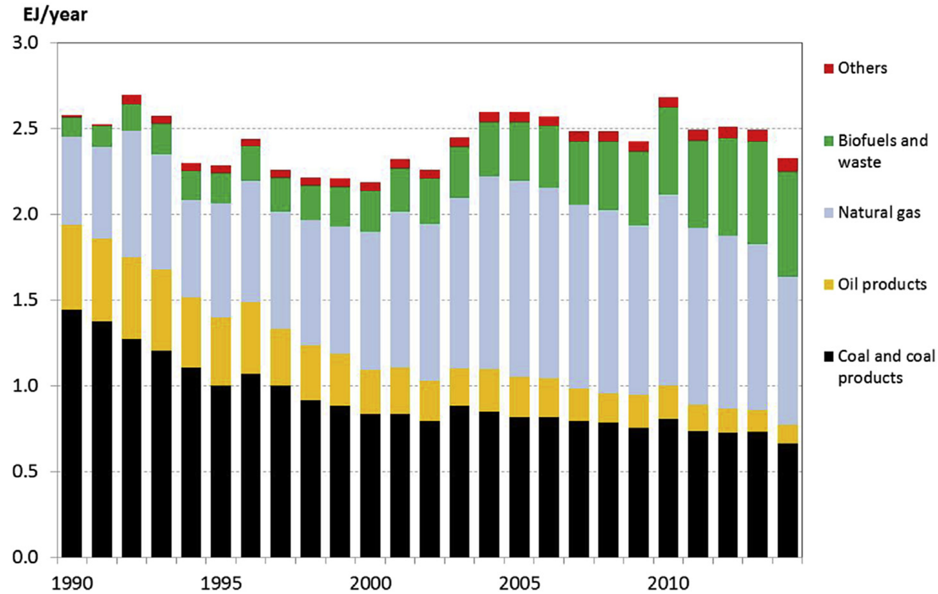

Fig. 6. Heat supplied into all district heating systems in the current European Union 1990–2014 according to original energy supply sources used.

Stockholm and Helsinki, where several large heat pumps are supplying heat to the district heating systems from cooling of large data centres. An assessment for the corresponding opportunities in London have been provided by Ref. [100]. A review of data centre cooling technology, operating conditions, and the corresponding excess heat recovery opportunities has been published in Ref. [101].

4.2. District cooling

Various cold supply resources, such as natural cold, excess cold, mechanical chillers, absorption chillers, and cold storages, can provide cold to district cooling systems. No international statistics is available to present the proportions of these various cold supply options.

The cold supply structure in district cooling systems can utilise the possibility to apply a logical merit order for available cold supply options. These logical merit orders reduce the cold supply costs compared to individual cold supply with local traditional mechanical chillers.

Natural cold resources are available in deep sea or lake waters in countries with cold winters. During warm summers, the stored cold waters from previous winters are utilised for district cooling, as in Toronto [102], Geneva, Stockholm, Amsterdam, and at Cornell University. The main cost advantage is that these systems have only variable costs for operating the distribution pumps.

Useful excess cold can come from processes that have cold as by-product. An example is the cold recovery from the LNG terminal in Barcelona to a local district cooling system.

Absorption chillers can use excess heat from industrial processes or waste incineration plants. This heat can be distributed by district heating systems and then facilitate the use of smaller units close to the customers. This cold supply option is utilised in Korea, Germany, Spain (Barcelona), Austria (Vienna), and Sweden (Göteborg and Linköping).

Traditional mechanical compressor chillers can be used for cold supply since larger units have better efficiency ratios than smaller individual units. These units can be equipped with or without heat recovery from the condenser. In case of heat recovery, heated return waters in district cooling systems are used as heat source in large heat pumps supplying heat into district heating systems. Hence, the same heat pump supplies both heat and cold to the two different supply systems. Hereby, both absorption chillers and heat pumps create valuable synergies between district heating and cooling systems.

Cold storages are important for meeting peak cold loads during warm summer days, since these days are characterised by a large variation between daytime and nighttime cold loads.

5. Environmental context

The environmental context considers the environmental problems addressed in national legislation and the corresponding actions taken. An early recognition of the environmental benefits with district heating was presented by Ref. [103] focusing on the higher air quality when some large combustion plants replace many small local boilers. A vital health aim with all global heating and cooling systems is to reduce the mortality risk from very low and high ambient temperatures [104].

Heat recycling according to the fundamental idea of district heating generates no or small marginal carbon dioxide emissions. Hereby, considerable lower carbon dioxide emissions are obtained when traditional fossil primary energy supply is substituted with recycled heat that otherwise had been wasted. These international possibilities for lower carbon dioxide emissions were initially explored in Ref. [105] and further communicated in Refs. [106,107].

The annual specific carbon dioxide emissions have been estimated since 1990 and are presented in Fig. 7 from all district heating systems in the world and in the current European Union. The use of fossil fuels was estimated from the heat supply by fuel origin in Ref. [37] and typical conversion efficiencies. The corresponding carbon dioxide emissions were estimated by default emission factors of 95, 76, and 56 g per MJ heating value from table 1.4 in Ref. [108] for coal, fuel oil, and natural gas, respectively. However, when estimating these emissions, an allocation problem arises, since the fundamental idea of district heating is based on synergies from joint production with other societal activities. The estimations in Fig. 7 are based on two basic allocation rules.

The first allocation rule was used because some electricity is lost from steam power processes when heat is recovered. This additional fuel use have been allocated to the recycled heat and estimated by the virtual heat pump analogy for CHP plants according to [109]. The corresponding coefficient of performance of 10 was used in this estimation. The second allocation rule was that no carbon dioxide emissions was allocated to heat recycling from waste incineration, industrial processes, and fuel refineries. This second rule was used in order not to violate the polluter pays principle, keeping the environmental incentives for actions for improving or substituting the primary processes.

Two conclusions can be drawn from Fig. 7. First, the current global specific carbon dioxide emissions have been almost constant on a level of 55 g per MJ heat delivered since 1990. The total carbon dioxide emission during 2014 was 604 million tons. This is about 15% lower than corresponding combustion of natural gas for heat supply. However, this high level is influenced by the low proportion of CHP plants of around 50% in both Russian and China. Expansion of coal-based district heating in China has also counteracted lower emissions in other countries during recent years. No plan exist in the Russian energy strategy to increase the future proportion of CHP plants in the heat supply [110].

Second, the specific emission in the European Union is now about 40% lower than the specific emission in the world. The average specific carbon dioxide emission during 2014 was 31 g per MJ heat delivered, corresponding to total emissions of 59 million tons. The European specific emissions have been reduced by 35% since 1990. The explanation for this change is higher proportions of CHP plants and renewables in the heat supply. This short analysis reveals that the European Union fulfils the fundamental idea of district heating to higher degree than rest of the world.

In Fig. 8, the combinations of the specific carbon dioxide emissions and the total proportions of recycled and non-fossil heat supply are presented for the 2 regions studied and 47 countries with significant heat deliveries above one PJ per year. The input information comes also from Ref. [37]. The high specific carbon dioxide emission for China can be explained by the strong commitment to coal as fuel and the low proportion of CHP plants. As an example, an in-depth analysis of the current and future carbon dioxide emissions for the Beijing urban area has been provided by Ref. [111].

In Europe, Poland has high specific emissions because of high commitment to coal as fuel. The ideal position is taken by Iceland having no carbon dioxide emissions from their dominating use of geothermal heat. Both Sweden and Norway are also very close to this ideal position. The main conclusion is that neither the global nor the European Union district heating systems have yet exploited the real opportunities for lower carbon dioxide emissions achieved by these three European countries.

The ability to deliver lower carbon dioxide emissions with heat recycling into district heating systems is underrated in contemporary assessments of mitigation of climate change. This favourable ability was just briefly mentioned twice in Ref. [112], but without any further analysis of the real opportunities. The same is valid for the recent IPCC assessment reports of IPCC [113–115]. The label ‘district heating’ was only used 10, 37, and 39 times in the mitigation parts in the third, fourth and fifth assessment reports, respectively. However, they only acknowledged the possibilities to use renewables in district heating systems and omitted the heat recycling possibilities.

6. Institutional context

The institutional context consider the basic driving forces, awareness about district heating and cooling benefits, ownership, legal frameworks, pricing, and knowledge development. Reviews of the major institutional issues have been provided by Ref. [116] for thirteen countries outside the European Union and the Ecoheat4EU project [117] for fourteen member countries of the European Union.

6.1. Driving forces

The basic driving force for introducing district heating systems is strongly linked to the fundamental idea defined in the introduction. The traditional focus of heat recycling and the corresponding reduction of primary energy supply have been essential in both market and planned economies with respect to the heat supply side. On the customer side, consumer convenience with no own responsibility for boilers and fuel purchases has also been a driving force.

In market economies, the expected cash flow of lower fuel costs from the synergy of CHP have motivated the introduction of district heating systems [9,11,13,54,118]. Hereby, district heating systems have been less competitive in times of low fossil fuel prices. An interesting observation is that the number of articles in scientific energy journals about district heating have been proportional to the international crude oil price [1]. More energy researchers have

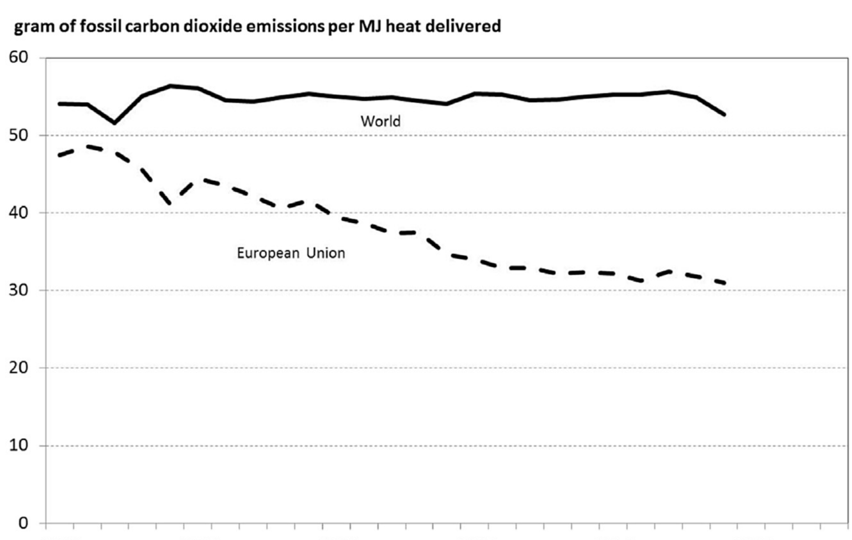

Fig. 7. Estimated specific carbon dioxide emissions 1990–2014 from all district heating systems in the world and in the current European Union.

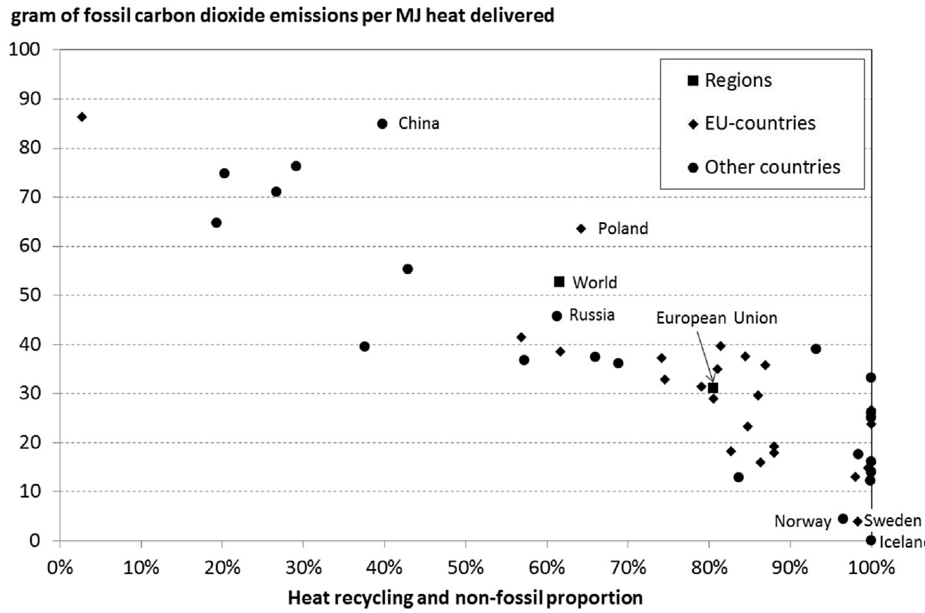

Fig. 8. Estimated specific carbon dioxide emissions during 2014 from all district heating systems in the two regions presented in Fig. 7, 24 EU-countries, and 23 other countries.

assessed the possibilities for more district heating and less primary energy supply, when the international fuel prices have been high. Less research efforts have been spent when the fuel prices have been low.

In the former planned economies of the Soviet Union and Eastern Europe, the focus was on the amount of fuel saved by district heating. This strong planning focus was not always so viable in a market economy context, when these countries became transition economies in the 1990s and the existing district heating systems had to be refurbished [32–34].

Some countries have introduced further driving forces by applying favourable legislative incentives as national heat planning and high fossil fuel taxes as in Denmark [119] or just high fossil fuel taxes as in Sweden [120]. The lack of corresponding national incentives in UK have been analysed and discussed in Refs. [121–125].

In order to obtain low distribution costs, short distribution pipes giving high linear heat densities are preferred [1]. This focus was not always considered in the former planned economies of the Soviet Union and Eastern Europe. A new more market-oriented Russian approach has been proposed by Ref. [126].

An analysis of 83 major European cities in four different countries revealed that these cities have high population densities giving low distribution costs [127]. Normally, few single-family houses are connected to district heating systems, since these areas are associated with low linear densities and high distribution costs. Only 1–2% of the European single-family houses are connected. Exceptions in this respect are Denmark and Iceland that have connected high proportions of single-family houses.

6.2. Awareness

Internationally, a publication showing high awareness of the district heating and cooling benefits is [128]. However, the proportion of documents lacking awareness is very high. Many international energy textbooks or anthologies neglect the synergies of district heating and cooling. Two North American examples are [129], and [130]. The possibilities with district heating and cooling are very briefly mentioned in Ref. [131] having the ambition to assess ‘city-integrated renewable energy for urban sustainability’. An exception is [132] that contains a chapter about district energy systems, although from a limited Canadian perspective.

Definitions of urban energy system indicators for identifying sustainable cities have been provided in Refs. [133,134], but both have no indicator for the presence of district heating systems. The label of ‘district heating’ does not appear at all in these two indicator documents. The major benefits with district heating is not easily recognised in international energy statistics having an energy allocation view based on the first law of thermodynamics [135]. Hereby, the main benefit of district heating with lower primary energy supply is directly neglected.

An early example of initial awareness in Europe was presented in Ref. [136] that stated that ‘Governments should study on the international as well as the national level the results of experiments in district heating and its possible extension taking in account all the factors involved’. Recent European Union documents showing high awareness are the 2012 energy efficiency directive [137] and the 2016 heating and cooling strategy [138]. In general, the use of primary energy factors is proposed in order to translate heat deliveries into corresponding primary energy supply. According to [139], most European countries apply high default values primary energy factors for district heating systems. Hence, they neglect the true benefits of district heating with respect to low primary energy supply.

Netherlands is an example of an European country that has moved from low to high awareness about district heating [140]. Several Dutch cities have now plans for more extensive heat distribution networks including transmission pipelines between major cities.

6.3. Ownership

Ownership of district heating and cooling systems varies by region and country. Municipal ownership has been common in Europe, especially at the implementation stage. This commitment can be explained by the strong local business opportunities of district heating and cooling. However, poor financial status and lacking energy experience of the municipalities have often prevented further development and proper utilisation of existing infrastructures [116]. Strong municipal commitment appeared in Denmark, Sweden, and Finland, since they by tradition apply designated municipality taxes for financing municipal responsibilities. The same magnitude of financial resources has not been available for municipalities in other countries.

State or federal ownership was applied for the heat supply part of district heating systems in both the former Soviet Union and China. Primary networks were also included in these state ownerships, while local and municipal organisations were responsible for the secondary heat distribution networks. Korea initiated also district heating systems by a state-owned company.

Private ownerships initiated originally the district heating systems in USA. These private commitments have also become more important in other parts of the world, either in full ownership or in cooperation with shared ownerships with local municipalities. In Ref. [141], eleven different European ownership models were identified. Eight different versions of mixed ownership models between private and public owners were presented together with the three pure models of cooperative, municipal, or private ownerships.

6.4. Legal frameworks

The legal frameworks for designing market conditions for district heating and cooling activities vary also very much by region and country [142]. Some countries (such as Denmark, Sweden, Norway, and Lithuania) apply very distinct legal frameworks in special district heating laws, while other countries (such as Finland, United Kingdom, France, and USA) just apply ordinary energy and competition laws for the district heating and cooling activities.

Third party access have not been implemented to the same extent as for electricity and gas networks, since these networks are both national and international, while heat networks are only local or regional. The legislative contexts and various supporting instruments have been reviewed in Ref. [117] for fourteen EU countries. One legislative barrier is that some countries do not consider district heating and cooling as energy efficiency measures [116].

6.5. Pricing

The basic pricing principles for district heating have been either market-based or cost-oriented. Private owners prefer prices close to prices for the competitive heat supply alternatives in order to capture the full benefits of district heating. Municipal owners have had a tradition of applying cost-oriented prices in order to share the benefits of district heating with the final customers [143].

Aggregated information is lacking about district heating prices in traditional energy price reports as [144], since statistical authorities do not gather this information properly. Therefore, long national time series of average national district heating prices in Europe have been compiled in Ref. [145] in order to increase the transparency of district heating prices.

District heating prices are often regulated in countries where district heating have high proportion in the heat supply for buildings. In market economies, most heat deliveries are invoiced based on measurements performed by heat meters. In former and existing planned economies, heat deliveries are still invoiced by lump sum tariffs. They motivate neither the heating company nor the customers to implement energy efficiency measures [116]. During recent years, the discussion has been intense in China about introducing heat meters for heat deliveries [146,147].

6.6. Knowledge development

The IEA-DHC technology collaboration programme is the only international research cooperation concerning district heating and cooling. It has generated about 80 research reports with various topics, since the start in 1983. A recent anthology of the district heating and cooling knowledge base is provided in Ref. [148], while [149] presents a review of current district heating research.

European research programs have traditionally had few projects concerning district heating and cooling that was addressed in Ref. [150]. A compilation of relevant research issues were compiled in Ref. [151]. However, the presence of European projects has been more evident during recent years according to Fig. 9.

The former SAVE and IEE research programmes have supported market projects as DHCAN, Ecoheatcool, Ecoheat4EU, and Ecoheat4Cities, while the current framework programme (Horizon 2020) have financed larger projects as Storm, Opti, Flexynets, and Heat Roadmap Europe. Germany and Sweden have had special national research programmes for many years. The Danish 4DH research centre has become the pilot project for developing the fourth generation of district heating systems [61] in the context of smart energy systems. This integration of district heating and cooling systems into the concept of smart energy systems was first mentioned, defined, and further communicated in Refs. [152–154].

Chinese district heating researchers have become very active in scientific energy journals during recent years [155]. A recent important Chinese innovation has been to introduce large absorption heat pumps in both CHP plants and group substations in order to increase both efficiencies and capacities in existing infrastructures [156–158].

Russian researchers have low attendance at international conferences and seem prefer to publish their findings in domestic journals. Some translated articles about district heating conditions and research in Russia can be found in the Thermal Engineering journal. Some of these articles are used as references in this review.

7. Future context

The future context considers the future challenges for the district heating and cooling sector. The future prospects for district heating and cooling systems in the world should be promising, since they can deliver higher security of supply, lower costs, and lower carbon dioxide emissions. However, further deployment of the international and the European heat deliveries have not taken place during the last two decades, despite that energy policymakers are searching for energy technologies having these favourable characteristics. New methods have to be applied in order to increase the awareness of the possibilities with district heating and cooling systems.

The challenge is that district heating and cooling systems are associated to local conditions as urban demands and local heat and cold resources. This is a strong contrast to the fossil fuel society, where generic solutions have been applied all over the world. The relevant local conditions must be aggregated and quantified to regional, national, and international levels, since they are unknown in current energy statistics. It is a scientific challenge to provide these aggregations and quantifications. An early attempt to aggregate the European possibilities was made in the Ecoheatcool project [159,160]. The corresponding quantifications of cost benefits and lower environmental impact for the European Union was provided for the first time in Ref. [161]. Corresponding quantitative analyses are not available for the world situation.

The solutions to obtain these aggregations have been to gather information about heat demands with high resolutions (city districts, square kilometres, or hectares) and join this information with thousands of possible heat sources. These aggregations have been performed with modern GIS-tools concerning Europe [76,162], Germany [163], UK [164], China [165], and USA [166]. All these

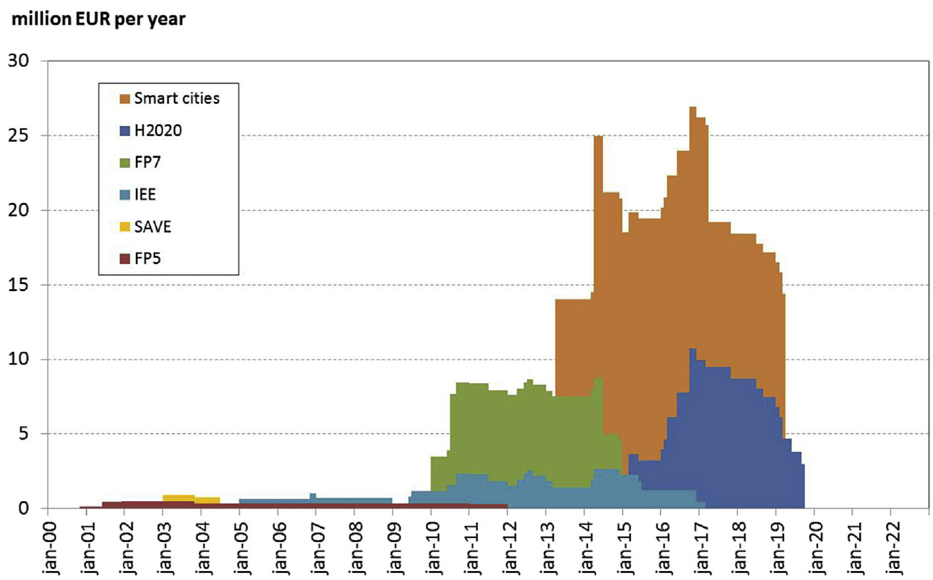

Fig. 9. Annual average financial resources spent in district heating and cooling research projects performed within various EU research programmes since 2000.

studies imply that district heating and cooling systems have the potential to be viable heat and cold supply options in the future.

Although the future conditions for district heating may look promising, the current district heating technology must also be enhanced in order to handle future competition. Current third generation of district heating technology was developed for fossil fuels and buildings with high heat demands. The next fourth generation technology must consider other feature characteristics of renewables and buildings with low heat demands [59]. New systems should be built according to this new district heating technology and existing systems should be transformed during the coming decades. A major challenge will be to provide heat with low temperatures in existing buildings [167].

The future prospects for more district cooling systems in the world should also be promising, since a low proportion of the current cooling demands are not met by actual cold deliveries. Higher standards of living in the future will increase this proportion.

However, an international vision and assessment for the future for existing and new district heating and cooling systems is still missing. A Heat Roadmap World project is really needed.

8. Conclusions

The market context presented low utilisation of district heating in buildings at the magnitude of ten percent in the world as well in the European Union, but implementation rates vary with respect to countries. Some countries has almost no district heating systems, while other countries have implementation rates over fifty percent. The proportions of heat deliveries to industries vary also much. The volumes of district cold deliveries in the world are currently much smaller than district heat deliveries.

The technical context showed moderate commitment to the fundamental idea of district heating, since direct use of fossil fuels in boilers is still high, especially in Russia and China. The use of heat recycling and renewable heat is higher in the European Union compared to the rest of the world. Current technology use is committed to the second and third generation of district heating technologies.

The supply context revealed high dependence on fossil fuels in the world, but this dependence is lower in the European Union. The corresponding environmental context presented lower specific carbon dioxide emissions in European district heating systems. Possible carbon dioxide emission reductions with district heating and cooling systems have not been recognised in international mitigation assessments.

The institutional context identified the different driving forces in market and planned economies. Some countries internalise external costs from climate change by adding fossil fuel taxes to the market fuel prices. This addition creates more favourable market conditions for heat recycling and renewables in district heating systems. In general, low awareness of the district heating and cooling benefits was identified in many international documents, but higher awareness was recognised in some recent documents from the UN environmental programme and the European Union. Initial public ownership has been strong, but proportion of private sector commitments is increasing in established systems. Legal frameworks and pricing principles vary among regions and countries. The knowledge development by research exists, but has low extent compared to other energy system research.

The future context foresees promising possibilities for district heating and cooling, but strong efforts are required in order to realise them. One important effort is to enhance the current district heating technology to align with future conditions associated to renewables and buildings with low heat demands. These new conditions should be met by introduction of the fourth generation of district heating technology. However, a common vision and assessment for the future for district heating and cooling in the world is still missing.

The conclusions obtained from the six contexts analysed show that district heating and cooling systems have strong potentials to be viable heat and cold supply options in a future world. However, more efforts are required for identification, assessment, and implementation of these potentials in order to harvest the global benefits with district heating and cooling.

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