An Overview of Renewable Smart District Heating and Cooling Applications with Thermal Storage in Europe

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Abstract: A series of transformations in heat and cold distribution systems is undergoing with the introduction of 4th generation District Heating and Cooling (DHC) technologies. At the center of this process is the integration of renewable technologies, such as solar heating, geothermal systems with large heat pumps and cooling from natural water formations. In this context, smart DHC systems are designed and early prototype implementations are demonstrated in sites across the world. The purpose of this paper is to trace the latest advancements in existing DHC networks and to identify early smart city technologies incorporated. A summary of basic components and characteristics is attempted with focus on thermal storage technologies coupled with renewable heating and cooling.

1 INTRODUCTION

The process of supplying district end users, for instance residential and commercial buildings, with thermal energy in order to cover heating and cooling demand, is in the scope of district heating and cooling networks (DHC) involving efficient heat distribution designs. Since their dawn, DHC network systems exploited a variety of energy resources, namely, geothermal, fossil fuel, waste and biomass incarceration. In the context of development, combinations of heat production methods and resources employed in DHC, underwent a series of transformations (Lund et al., 2014) with the latest, driven by the impact of climate change and fossil fuel shortage towards abundant solutions, pointing specifically to renewable energy resources. Table 1 summarizes the main DHC technologies generations along with distinguishing characteristics.

Historically, DHC technologies have been adopted in parts of Europe, North America and Asia**.** Only in Europe it accounts for 12% coverage of total heat demand (Euroheat & Power, 2015), with leading adopters Scandinavian, Central and Eastern European countries, which since the second half of the 20th century invest in large scale heat distribution infrastructure. Specifically, DHC infrastructure has claimed a principal role in thermal energy supply for urban areas in these countries. The setting in Western Europe appears more moderate, where countries such as Germany and Switzerland receive a stable contribution from these systems.

Table 1: Generations of district heating technologies and primary resources.

	Timespan	Production	Primary Resource
1st Generation	1880-1930	Steam Boilers	Coal
2nd Generation	1930-1980	CHP and Heat Boilers	Coal and Oil
3rd Generation	1980-Today	Large-scale CHP	Biomass, waste and fossil fuels
4th Generation	2020-2050	Heat Recycling	Renewable Sources

District cooling covers space cooling needs in residential and commercial instalments. In any case, location induced constraints towards the applicability of the technology can be surpassed, with working examples demonstrated in cities spanning from Sweden to United Arab Emirates.

This paper aims to provide an overview of innovative realizations of Smart district heating and cooling supply, with focus on projects combining

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distribution with thermal storage under a wide range of conditions. The second section describes the concept of smart DHC networks and related regulatory framework in Europe. Section III summarizes the available technologies according to early smart DHC networks with thermal storage deployed across Europe. A recently delivered case study at Rotterdam concentrating elements of a smart thermal grid, is presented in the fourth section. Finally, technology limitations and future prospects conclude the paper in section V.

2 RENEWABLE DHC IN EUROPE

2.1 Smart District Heating and Cooling

DHC covers the generation and distribution of thermal energy in districts. In the case of heating, the design consists of a pipe network, filled with hot water, and heat sources (centralized heat production plant). Hot water circulates in the piping network aided by pumps, from the heating plant to end-users and backwards (Wiltshire, 2015). The heat hub relies on heat exchangers placed at every end-user building, in order to transfer heat from network to residential node heating and hot water systems. Remaining water from heat exchangers returns through the pipe network and is pumped back to the heating plant, where it is processed in a new heating cycle.

District cooling follows similar principles as district heating. Indoor envelope temperatures can be decreased with cold water, which is distributed in the pipe network to end-user ventilation systems. Water temperature ranges can start from approximately 6 ºC at cooling site and return with approximately 16 ºC. Common methods developed for district cooling supply comprise of free cooling (cold water from lakes, seas or other waterways), absorption cooling (uses a heat source to produce cold) and heat pumps (produce heat and cold at the same time).

The vast majority of DHC networks operating nowadays provide heat and cold generated from centralized units (central plants) and are obliged to comply with air pollution regulations, via the enforcement of emission control methods, while, efficiency and generation output volume differ depending on the type of plant and energy resource utilized (Wang et al., 2015). Undesirable fluctuations in supply such as over-generation or under-generation may result in energy waste or unsatisfied demand, respectively. To this end, optimal management of the generation units is required to ensure sufficient energy distribution to end-users with maximized efficiency, cost and minimum emissions.

Smart DHC introduces innovative solutions in the domain of thermal energy management therefore aiming to improve the performance of systems (Mathiesen et al., 2015). Key technologies for this transition are expected to be a) heat metering (smart heat load meters, Gustafsson et al., 2016), b) monitoring and automated control of heat exchangers, triggering research in domains such as, Internet of Things, thermal energy modelling and optimization and power electronics and c) thermal storage with complementary control systems (Wong et al., 2017, Monti et al., 2016). Cogeneration and residual heat usage, enable improved allocation of network energy resources. From the end-user perspective, an upgrade in radiator control through variable speed radiator pumps is opted in order to facilitate network-balancing issues without thermal discomfort side effects. In a similar manner with smart power grids, smart thermal grids can be designed, as heat load consumers also contribute to heat production by installing generation or storage components, where besides participating solely in demand, they appear as suppliers in a hybrid demand supply driven network (van den Ende et al., 2015, Brand et al., 2014).

It is evident that major challenge for this transition is to tackle efficiency drawbacks sourcing from heat losses present in previous generation DHC networks and low energy performance buildings. In fact, when building refurbishment is considered as a parameter in sizing of DHC systems, results indicate additional economic and environmental benefits (Pavičević et al., 2017). Increase in building energy efficiency results in reduced heat demand, thus lower performances are required for supply. At the same time, heat losses in distribution pipes decrease in low temperature district heating systems.

2.2 Legislative Framework

According to directive 2012/27 of the European parliament, a common framework of actions has been adopted regionally targeting efficient district heating and cooling with high renewable energy shares for 2020'. The European directive defines efficient DHC systems as those using at least 50 % renewable energy, 50 % waste heat, 75 % cogenerated heat or 50 % of a combination of such energy and heat (European Parliament, 2012). In Fig. 1 and Fig. 2, current renewable heating shares and 2020 projections for European countries are illustrated (REN21, 2017).

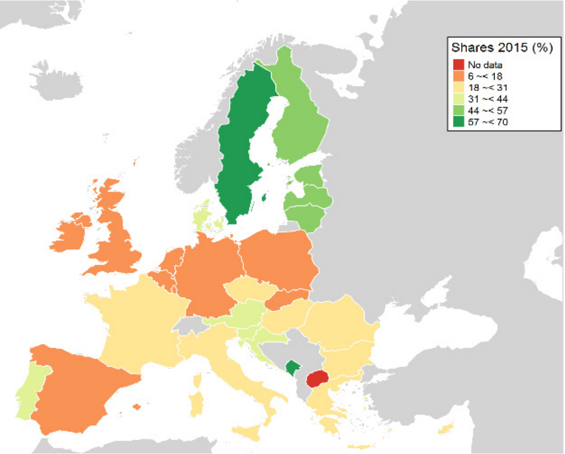

Figure 1: European heating and cooling from renewable sources shares in 2015.

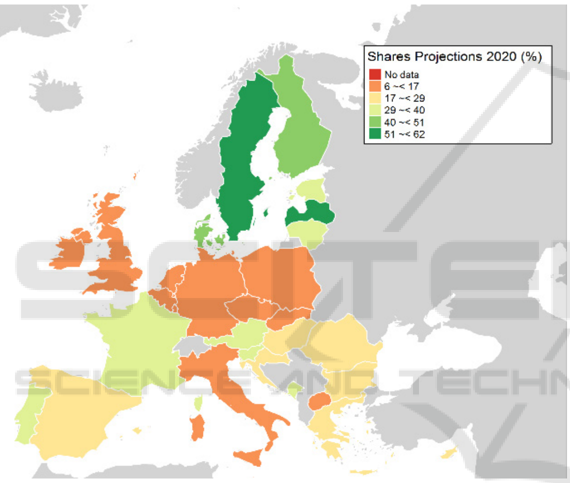

Figure 2: European Heating and Cooling from renewable sources projections for 2020.

It is important to mention that percentages mapped in the figures refer to renewable sources feeding all types of heating, not strictly DHC. It can be observed that, Scandinavian, Baltic and Central European countries have already achieved their 2020 targets, in contrast, Southern European countries, UK, France and Germany maintain low renewable penetration percentages for heating supply.

In national legislation level, Denmark and Germany present the most comprehensive policies related to DHC, providing details on federal support, clean energy targets, connection obligations (appears also in Poland) and end-user protection. In addition, support policies may include low interest loans (Japan), resource assessment subsidies (Switzerland), tax incentives (US), and explicit targets (UAE, Switzerland).

2.3 Potential Benefits

The widespread of renewable DHC systems is linked with a number of potential benefits that can be categorised into environmental, systemic, synergies with urban environment and increased energy security (IRENA, 2017).

In the first category, the following can be recognized; a) achievement of clean energy targets, higher renewable fractions are pursued, hence, ensuring sustainability of the developed infrastructures, b) improvement of urban air quality, as carbon dependent solutions lead to a series of negative externalities, especially in cities with dense populations where air pollution evidently has diminished, c) rapid and inexpensive green house gas emission reductions and d) water consumption abatement, relevant to the fact that natural water resources can be exploited for example in cooling applications.

In the context of systemic benefits, at first, the combination of technologies provides cross-sectoral benefits, for instance, CHP can be coupled with surplus from geothermal heat stating smart thermal grids flexible, capable of handling variations present in supply and demand, in short-, medium-, and long-term; load profile is smoothened thereby relieving the electricity grid. Moreover, utilization of local resources in biomass or waste to heat systems creates value in the financial chain and generates multi-scale business schemes.

As urbanisation is rapidly progressing, integration of renewable heat and cooling networks could free construction space that would be necessary in decentralized facilities (natural cooling). As a result, visual impact is reduced and land-use can be dedicated adaptively.

In countries recording major imports of fossil fuels, local renewable sources ensure availability and price securities. Similarly, using a mix of resources secures the resilience of the energy system and can achieve stable prices throughout operation.

3 TECHNOLOGIES

In this section main renewable technologies integrated in DHC applications are described. Depending on network size and complexity of the network, the distribution system per se can function as thermal storage or seasonal storage units may be required (Lake et al., 2017). In Table 2, notable renewable DHC applications across Europe are listed, according to integrated technology (SDH, 2017, GeoDH, 2017, Perez-Mora et al., 2017, Bailer et al., 2006, RES Chains, 2012, SIG, 2016)

3.1 Solar District Heating

Solar thermal systems transform solar radiation into heat. Their efficiency is negatively influenced by low irradiation and high temperature difference between output hot water and outdoor ambient, leading to poor efficiency during wintertime. Ensuring efficient use in DHC requires them to be coupled to a seasonal heat storage (to cope with the delay between efficient production and heat demand) or to an absorption chiller for cooling needs (alignment of efficient production and needs). During wintertime, when low temperature heat may be produced, they can be connected to technologies that will upgrade the temperature level (compression or sorption heat pumps), (Hennaut et al., 2014).

Although, solar collectors have been used for water heating in individual buildings, solar district heating applications are recently rising as a supplement for cogeneration (Joly et al., 2017). These systems consist of large-scale flat plate solar collectors deployed on landfill sites or on building roofs paired with seasonal storage methods. Specifically, large volume hot water storage tanks store the heating medium during summer for use in winter. Instead of tank thermal storage, underground stores can be employed as either underground pit thermal storage, gravel water underground storage or last borehole storage. Exceptionally, aquifer thermal storage is utilized, however, installation is more complex and it is the least preferred method in solar district heating systems. In borehole realizations, secondary tanks can serve as a temporary node in the network.

3.2 Geothermal District Heating

Geothermal district heating systems drain heat from natural formations (geothermic wells) with high underground temperatures and inject it to the distribution network via injection pumps and heat exchangers. A cool sink functions as a terminal for the cooled fluid, thus completing the heating loop. Surface features or shallow wells with temperatures between 40°C and 150°C (Nielsen et al., 2016) are suitable for hot water circulating in DHC systems, whereas higher temperatures are ideal for electricity generation. In shallow geothermal energy systems, recovery of thermal energy (low or medium temperature) is possible when paired with UTES methods, such as borehole or aquifer storage.

Extraction of geothermal heat has low spatial requirements. Nevertheless, installation works are challenging in urban settings. In some occasions, geothermal cooling has been demonstrated in conjunction with absorption chillers.

3.3 Heat Pumps

Compression and sorption heat pumps use low temperature heat sources in order to transform them into useable heat. Actual renewable contribution depends on their seasonal performance factor and/or on the way, the driving energy (electricity for compression HP and high temperature heat for sorption HP) is produced. Their seasonal performance is positively affected if heat is delivered at low temperature (low energy buildings equipped with low temperature heat emission systems) and if the low temperature heat source is at “high temperature”. Preheating the low temperature heat source with solar thermal panels is a way of boosting the seasonal performance factor. High temperature heat source for driving sorption heat pumps may be produced by biomass boilers, CHP or from medium to high enthalpy geothermal fluid.

3.4 Biomass District Heating

Biomass-fired heat-only boilers replace traditional fossil fuel combustion in CHP plants and simultaneously provide an efficient measure of cutting greenhouse gas emissions.

A wide variety of biomass fuels exist, dominated by wood fuels, mainly consisting of wood chips and sawdust. Biomass comprises a relatively reachable alternative, suitable for use within the present heating infrastructure, although heating capacities of biofuels are lower, raising the amount of required resources (Lund et al., 2014).

3.5 Solar District Cooling

The operation principle of solar cooling systems relies on passing the heat output of panels used in solar thermal systems to an absorption chiller for cooling. Absorption chillers are used in applications driven from excess heat from industrial processes or waste incineration plants. Usually, heat can be collected in plants and later on distributed to smaller units closer to end users (Perez-Mora et al., 2017).

Compared to solar heating systems, solar irradiation trend follows and contributes to cooling peak loads.

3.6 Natural Water Cooling

Water in low temperatures, originating from district water sources, such as rivers, the sea or lakes can be utilized for cooling purposes. In general, the former function as either the heat sink or a heat exchange for generating chilled water. Cold water is drained from the water source with an inlet pipe structure and, via plate heat exchangers, chilled water is generated and circulated to buildings at a higher temperature. There, the cold water is either injected directly into the district cooling system or coupled to a closed loop network via heat exchangers (Wiltshire, 2015).

Table 2: Demonstration sites for renewable DHC technologies in Europe.

Technology	Site	Capacity	Ren Frac %	Storage
SDH	Silkeborg, DK	80 000 MWh	20	4 Heat Tanks 64,000 m^3
GDH	Paray-Vieille-Poste, FR	12 MWth	30	Aquifer
HP	Katri Vala, Helsinki, FI	60 MWh	32	11,500 m^3 Cold Water tank
Biomass	Växjö, SE	90 MW	60	25MW Hot water tank
SDC	ParcBit, Mallorca, ES	3,000 MW_c	43.2	2 Cold Water Tanks 100 m^3
NWC	GeniLac, Geneva, CH	13,250MWh	30	Aquifer

4 CASE STUDY

Even though large-scale smart DHC networks have not been completed at the moment (Lund et al., 2014), a case study concentrating DHC technologies with seasonal storage and attributes in the domain of smart thermal grids has been selected in the context of this paper. Mainly, detailed information was retrieved from EU Smart Cities Information System (http://www.smartcities-infosystem.eu).

As a demonstration site for the EU funded CELSIUS project, Rotterdam participated on two interventions: a) development of an energy system supplying with under-floor heating and cooling in De Rotterdam (Rotterdam Vertical City), a mixed-use building with housing, commercial and recreational functionalities, containing a total floor area of 160 000 m^2; b) the creation of a heat hub aiming to increase the efficiency of the waste heat distribution in Warmtebedrijf, Rotterdam. Importantly, energy system planning in Rotterdam follows an Energy Approach Planning called REAP described in (Lenhart et al., 2015).

4.1 Waste Heat Distribution System

Residual heat is produced by a waste incinerator facility located in the Port of Rotterdam, thereby distributed to Rotterdam. Furthermore, the plant has a thermal exit capacity of 105 MW and the piping network consists of a double pipeline system (total length 26 km) connecting the plant with previous district heating infrastructure. The developed heat hub, started operation on the 4th quarter of 2013, was installed near the waste heat transportation infrastructure and the district heating system.

Tank thermal storage has been incorporated with the use of a well-insulated buffering tank. The capacity of the buffer is 185 MWh and the discharge capacity is 30 MWth. Instead of placing the tank in the surroundings of the waste incinerator facility, a central area of the distribution network was selected, aiming to increase buffering capacity efficiency, due to the fact that heat is delivered in close proximity to the end-user. Moreover, air quality is positively affected by substituting gas-fired boilers in the handling of peak load.

Optimal operation of the deployed infrastructure assists in increasing the total heat supply without investing in extra heat resources or upgrades in network resources (buffers, pumping). To this end, Smart technologies incorporated, include, buffering, heat balancing, automated control and forecasting. These elements offer more flexible control of the energy system, mitigating possible malfunctions or heating price volatility.

4.2 Renewable Energy System for De Rotterdam

De Rotterdam is one of the tallest buildings in the Netherlands (Zeiler, 2017). The major part of the heat demand is supplied from a 16 km-long pipeline connected to a waste-to-energy plant set on the island of Rozenburg. A CHP plant, located at Capelseweg, can serve as a reserve supply source in below zero temperatures.

A small CHP (capacity of 250 kW), running on biodiesel, was built-in the building, for renewable generation of heat and power. However, due to high fuel cost and difficulties in transportation, it is not preferred for frequent use.

High-temperature hot water supply is provisioned for residential sections and for a hotel based in one of the towers. According to Dutch water quality regulations, hot water systems for residential use must satisfy a minimum of 70 °C. Conversely, the office towers can be supplied with water of lower temperature. This difference in temperature demand was essential for designing a system, which reduces the temperature of the return line in the district heating loop, eventually connecting the offices to the return line (Fig. 3).

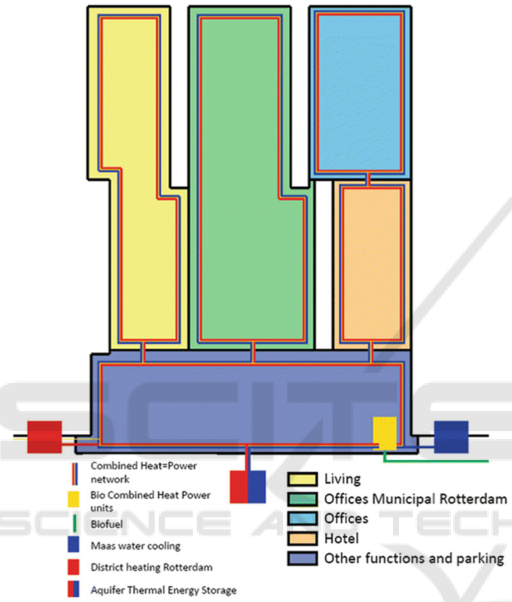

Figure 3: Layout of De Rotterdam’s energy system with building typology.

Taking advantage of De Rotterdam’s location, on the banks of river Maas, which maintains a low temperature during the year, a natural water cooling system was developed, as in the case of the Maastoren, a skyscraper also located on the peninsula (Molenaar, 2011). This centralized cooling facility generates cold, pumping water through intake pipes concluding in the river and passing it through three water-cooled compression chillers (Fig.4).

River water filters are necessary for ensuring water quality, supported by a compressed air system. Piping is extended for the distribution loop and end-users are provided through a metered connection, meanwhile thermostats enable control of interior temperature in rooms. Heat-reflective double-glazing and windows to let fresh air inside reduce the cooling demand.

Ambient temperatures are low throughout the year; therefore, cooling demand is low in general. In summer, where cooling demand rises, river temperatures are between 15 and 25 °C, stating it unsuitable for district cooling. Nevertheless, river water is injected directly to the condensers (through copper-nickel alloy pipes for anti-corrosion), where it can be utilized for extracting heat from the ventilators of the air conditioners, as lower condensation temperatures, reduce air resistance in the condensers and the amount of energy required for the cooling compressor. Thermal storage is available via an aquifer storage in the form of underground wells under the sand layers of the soil.

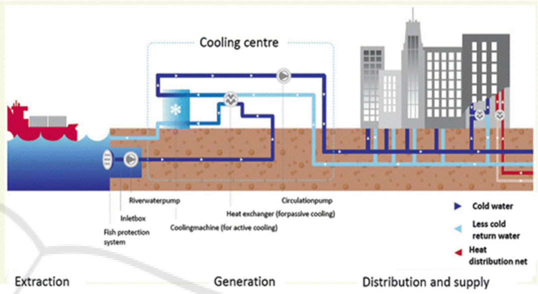

Figure 4: Design and functionalities of the deployed Maas river water cooling system in De Rotterdam.

The resulting system has a total cooling capacity of 6 MW, leading to 50% savings of energy for cooling. It functions in a modular way depending on river water temperature illustrated in Fig, 5, where: a) when the river water temperature is under 9° C: the buildings are cooled with free cooling only; b) between 9° C -15° C, a combination of free cooling supplemented with compression chillers is used; c) river temperatures over 15°C, only compression chillers are used to cover the cooling demand of the buildings.

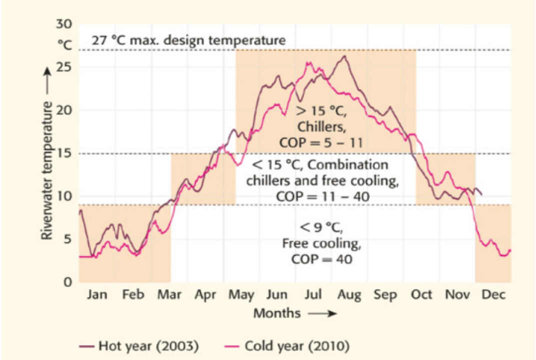

Figure 5: Modes of operation according to river water temperature.

Finally, the cooling system is installed in a spacious room, offering potential extension with more water-cooled chillers when demand rises, as further construction work is opted on the Maas peninsula. This will ensure that the systems built into The Rotterdam, such as the Maas water system, can be deployed as efficiently as possible while also saving space in the new buildings. Sustainability of the project may be enforced with the integration of solar panels, urban wind turbines, aquifer thermal energy storage (already widely available in the district heating system and used in the Maastoren energy system), extraction of thermal energy from the sewage water and more.

5 CONCLUSIONS

This paper presented an overview of options in implementing smart district heating and cooling systems in Europe with integrated thermal storage components. In this stage of DHC system design, main objective is to deliver efficient networks, utilizing renewable resources and technologies. Renewable energy-based heat production technologies offer a wide variety of coupling aiming at maximizing the system efficiency. These coupling may lead to complex system architectures appealing for smart management based on energy efficiency (mainly maximizing the renewable contribution), cost effectiveness and comfort.

Adding heat storage capacities offers degrees of freedom in managing such systems. Heat storage technologies may be envisaged for the following reasons: (i) technical operation (e.g. Biomass boiler) often need a heat storage to prevent from too many on-off when the heat demand is low compared to the installed thermal power, (ii) rising the solar contribution to heat demand, (iii) forcing the heat production of a unit when it offers good performances (e.g. compression air to water heat pump have better performances when outside air temperature is high), (iv) storing heat for dealing with variable electricity tariff and or maximizing green electricity use (when heat the production technology uses electricity (compression HP) or uses it (CHP)

Up to now storage technologies that were used in heating city districts are mainly based on the sensible heat storage principle (storage process results from a temperature lift of the storage material) whereas latent heat storage systems (storage process results from phase change of the storage material) and sorption heat storage systems (storage process results from a physical or chemical sorption of a vapour in a solid or a liquid) are still at the demonstration or R&D levels.

However, current technologies demonstrate limitations in applicability and aiming in satisfying 100% of heating demand from renewable energy systems remains a major challenge.

Concerning solar district heating, drawbacks include, space limitations in urban environments, and even with large storage tanks, compensating seasonal demand requires the use of cogeneration to serve the baseload. Moreover, solar irradiation is inversely correlated with heating demand peaks. Hence, the efficient performance of the system is heavily dependent on location. In Scandinavian countries where the heating season has a longer duration, it is possible to divert solar generated heat directly to end users. More energy will be fed into the system if the temperature difference between the collector input and output is maximised. In established systems, the high return temperatures create a barrier to the integration of solar heat

In the case of geothermal district heating, similarly with solar heating, greater amount of heat can be extracted due to lower water temperature in the network return line. Thus, produced heat is fittest for baseload satisfaction. A significant cost for design is the assessment of geothermal resources, which requires highly specialized personnel. Access to land, mineral and water rights accompanying geothermal projects involves complex administrative procedures.

Biomass adoption supports the conversion of coal power plants to biomass fuel combustion, depending on technologies, fuel availability and cost. This presents the advantage of utilizing existing infrastructure and procedures, as well as efficiently allocating space in dense urban environments.

The case study of Rotterdam exhibits how existing DHC infrastructure can benefit from the introduction of renewable technologies and thermal storage. Early attempts to integrate smart techno-logies in the energy system for balancing heating loads and optimising buffers, pumping and new nodes will ensure sustainability with high efficiency. Possible revenues from the operation of the more efficient and energy system can be returned to tenants and property owners. For new buildings connected to the district cooling system, an upgraded Energy Performance label is issued, whereas existing buildings lack an economic drive for replacing their existing compression chillers, as it is not cost efficient. This is a promising example, as more smart thermal grid realizations in Europe are expected in the coming years with countries adapting their regulatory frameworks in order to support the operation of such schemes.

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