Thermal Storage Integration in a Smart Thermal Grid

Ottawa Case Study with ENGIE

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A mio papà Sante che con la sua forza e positività
mi ha insegnato che nulla è impossibile. A mamma Serena,
per avermi sempre spronata, mano nella mano, a seguire i miei sogni.
A mio Fratello Mirko per esserci sempre con il suo sorriso contagioso,
ai miei nipotini Arya, Yara e Mirek che mi ricordano tutti i giorni
Quanto sia importante godersi,
alla mia migliore Amica Elena che, nonostante la distanza,
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Infine a me stessa, per aver affrontato questa salita
con onestà, testardaggine, resilienza e sacrificio
"come so fare io".

A special thank you to Marta for always supporting and
Pushing me in the redaction of this dissertation.

Abstract: Future urbanization is expected to reach 80% in 2050 with an increment in cold demand of 300%. One possible solution to reduce the effect of urban heat island, while reducing CO_2 emission are district energy systems such as district cooling network. New generation of district cooling can operate at higher temperature (supply 8 °C, return 15 °C) compared to old generation (supply 4°, return 12°C) integrating in a more efficient way renewable decentralize energy sources and thermal energy storage systems. In particular, this study aims to validate the flexibility effort of a thermal storage application in an existing district cooling network. Operational conditions of cold water storage and iced storage applications were simulated using two tools developed by ENGIE: 1) a cloud platform called NEMO which is able to simulate the entire network behavior hourly; 2) an AI algorithm for TES simulated different storage models directly comparing different technologies. As secondary objective the study explored the feasibility of operating cooling network at higher temperature while assuring a global network coefficient of performance (COP) above the contractual terms. The results demonstrated that, under the right conditions, thermal storage can play a valuable role as flexibility actor contributing to increase the global COP by 4 with annual savings between 30 and 40% in OPEX. In addition, it has been demonstrated that the utilization of higher temperature networks can increase the use of free cooling up to 50%, reducing potentially the electricity consumptions.

Keywords: Smart Grids, Smart Cities, District Cooling, Energy Transition, Energy Efficiency, Thermal Storage.

Resumo: Em 2050 espera-se que o nível de urbanização atinja 80% com um incremento na procura de frio de 300%. Uma solução possível para reduzir o efeito de ilha de calor urbano enquanto se reduz a emissão de CO2, são as redes urbanas de frio. A nova geração de redes urbanas de frio pode funcionar a temperaturas mais elevadas (alimentação 8 °C, retorno 15 °C) em comparação com a geração antiga (alimentação 4°, retorno 12 °C) integrando de forma mais eficiente fontes de energia renováveis descentralizadas e sistemas de armazenamento de energia térmica. Este estudo visa validar a aplicação de armazenamento térmico numa rede urbana de frio já existente. As condições operacionais das aplicações do armazenamento de água fria e de gelo foram simuladas utilizando duas ferramentas desenvolvidas pela ENGIE: 1) uma plataforma na nuvem designada NEMO que é capaz de simular o comportamento global da rede; 2) um algoritmo de inteligência artificial para armazenamento de energia térmica que simulou diferentes modelos de armazenamento comparando diferentes tecnologias. Como objectivo secundário, o estudo explorou também a viabilidade de operar uma rede de frio a temperaturas mais elevadas, assegurando simultaneamente um COP global acima dos valores contratuais. Os resultados demonstraram que, nas condições certas, o armazenamento térmico pode desempenhar um papel valioso como agente de flexibilidade contribuindo para aumentar o COP global em 4%, com uma poupança anual de cerca de 30 a 40% em OPEX. Além disso, foi demonstrado que a utilização de redes de temperatura mais elevada pode aumentar a utilização de refrigeração livre até 50%, reduzindo potencialmente os consumos de electricidade.

Palavras-chave: Redes Inteligentes, Cidades Inteligentes, Redes Urbanas de Frio, Transição Energética, Eficiência Energética, Armazenamento de Energia.

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Abbreviation	Unit	Desctription
1P	[-]	Single pipe (1 Pipe)
2P	[-]	Twin/ Double Pipe (2 Pipe)
2P	[-]	Three Pipe
3GDHC/ 3DHC	[-]	3rd Generation District Heating and Cooling system
4GDHC/ 4DHC	[-]	4th Generation District Heating and Cooling system
5GDHC/ 5DHC	[-]	5th Generation District Heating and Cooling system
C	[-]	Circulation pipe
CC	[-]	Creative Common
CC-BY	[-]	Attribution
CC-BY NC	[-]	Attribution-NonCommercial
CC BY-NC-ND	[-]	Attribution-NonCommercial-NoDerivs
CC BY-NC-SA	[-]	Attribution-NonCommercial-ShareAlike
CHP	[-]	Combine Heat and Power
CO	[-]	Carbone Monoxide
CO_2	[-]	Carbon Dioxine
COP	[-]	Coefficient of Performance
D	[Kg m^{-3}]	Density
DC	[-]	District Cooling
DCS	[-]	District Cooling System
DEN	[-]	District Energy Network
DER	[-]	Distributed Energy Resources
DH	[-]	District Heating
DHC	[-]	District Heating and Cooling
DHS	[-]	District Heating System
DHW	[-]	Domestic Hot Water
EE	[-]	Energy Efficiency
EU	[-]	European Union
EV	[-]	Electrical Vehicle
GS	[-]	Group Substation
H	[-]	Domestic Hot Water
HEX	[-]	Heat Exchanger
HP	[-]	Heat Pump
HVAC	[-]	heating ventilation and air conditioning systems
LTDH	[-]	Lox Temperature District Heating
m	[kg]	mass
n-ZEB	[-]	Near Zero Building
P	[bar]	Pressure

P2G	[-]	Power to Grid
PCM	[-]	Phase Change Material
PE	[-]	Polyethylene
PEX	[-]	Cross-linked high-density polyethylene
PP-R	[-]	Polypropylene random copolymer
PUR	[-]	Rigid polyurethane foam
PV	[-]	Solar Photovoltaics
Q	[J]	Energy in the form of heat for phase change
R	[-]	Return pipe
RE	[-]	Renewable Energy
RES	[-]	Renewable Energy Systems
S	[-]	Supply pipe
T	[°C]	Temperature
TES	[-]	Thermal Energy Storage
Tg	[°C]	Ground Temperature
Tr	[°C]	Return Temperature
TRL	[-]	Technology readiness level
Ts	[°C]	Supply Temperature
ULTDH	[-]	Ultra Low Temperature District Heating
V	[m^3]	Volume
WTE	[-]	Waste to Energy
ΔT	[°C]	Temperature Difference
Cp	[$Kg^{-1}K^{-1}$]	Specific heat capacity
L	[$KJ\ Kg^{-1}$]	Latent heat
OPEX	[-]	Operating expenses (OPEX)
CAPEX	[-]	Capital expenditures (CAPEX)
CAD	[-]	Canadian Dollar

1. Introduction

In the last 40 years, Europe and the entire World have been engaged in a "silent" war against greenhouse gasses and pollution: many national and international organizations, scientists, think tanks, and working groups have started raising their voice against the problem. One example is the Intergovernmental Panel on Climate Change, a body of United Nation with the aim of assessing the science related to climate change (ipcc, 2018). In 2019, more than 11 000 scientists have signed a letter warning on climate emergency (Ripple, Wolf, Newso, Barnard, & Moomaw , 2020). Moreover, recent studies and market researchers have identified in younger generation the most active and sensible actors when it comes to climate and sustainability (Deloitte, 2020). A great recognition in the effort of mainstreaming the topic goes to Greta Thunberg, the 17 years old Swedish girl who moved the entire world to take part in climate strikes under the motto "*Skolstrejk för klimatet"*. Thanks to the power of millions of voices gathered together, an always higher number of governments, countries and companies have been obliged to face once for all the "elephant of the room". This is the case of many countries part of the OECD, among them two great examples are European Union countries and Canada: while the Canadian House of Commons declared climate emergency in June 2019 (House of Commons, 2019), the European Parliament declared it in November 2019 (European Parliament, 2019). Since then, from different sides of the Atlantic Ocean the two realities have started to develop a strategic decarbonization roadmap towards 2050. The European Union and Canada, have made their first steps under the names of European Green Deal (European Commission, 2019) on one side, and under a Climate Lens approach in the other (Li et al., 2019). While Europe is trying to push the sustainable transition as a whole entity, Canada follows the overseas cousin's example by leading the Americas. In their efforts are touching very different topics: from electrification to energy poverty, passing through decarbonization of heavy industry, transport, heating and cooling biodiversity and smart cities. Among many targets Europe has: 55% carbon emission reduction by 2030 to become climate neutral by 2050, 32% increasing share in renewables energies, and 32.5% increase in energy efficiency (European Commission, 2030 Climate & Energy Framework, 2018). Canada has similar ambitious pushing the phasing out from fossil fuel by 2030, the electric vehicles uptake and a better energy use (Energy Generation, 2018).

In such a context this dissertation will explore the interconnected context of smart cities and smart grids with a focus on district energy systems as a possible global solution actors in the decarbonization of the heating and cooling sector. The dissertation will be focused on OECD countries best practices taking European Union as main referent for district heating systems with more than 500 networks in operations, while the use case for storage application will be based in Canada, as worldwide leader in the development of smart cities. Due to a higher number of publications linked to heating network in comparison with cooling network, for which almost no data is available in the literature, some example will be taken and adapted from heating studies under the belief that the logic under low energy thermal networks is the same for high energy cooling networks as it will be explained in future chapters.

1.1 District heating and cooling systems

One of the most difficult sectors to decarbonize is buildings, which is now responsible of almost 50% of final energy consumption. This sector in particular is very difficult to tackle due to feeble policies and lack of structured interventions (Saheb et al., 2018). In order to reduce carbon emissions, the focus on energy efficiency and energy savings has increased all around the World. The pathway toward heating and cooling decarbonization is not unique, as unique are not the usable technologies. There are three main pathways to decarbonize residential heat (Coker, 2019):

- Electrification, where households use heat pumps or direct electric heating;
- Green gas, which involves switching the gas grid to biogas, biomethane and/or hydrogen;
- District heating, which are mini grids that supply hot water around networks for households to use in both space heating and hot water.

The three solutions are all positively aiming to zero carbon emission. Therefore, they can easily be integrated with each other in order to supply different geographical areas. Policies, though, should give some indications since an electrical system is characterized by different equipment compared to a hydraulic one.

Since the level of urbanization in the European Union is expected to grow from 75% in 2020 to almost 84% in 2050 (UNEP, 2015), district energy has the potential to be a leading technology in urban areas where the heat and cold demand will further increase in the next 30 years. The following chapters will investigate the potential of district heating and cooling systems in the energy transition. However, two are the main challenges of such a technology:

1) Due to high investment cost, the integration of renewable energies and waste heat in the networks to substitute fossil fuels, mainly use in combined heat & power (CHP), is expected to be a great challenge. However, the projection towards 2050 are positive, as described in figure 1.
2) Since EU is pushing energy efficiency and energy savings policies, buildings are switching towards nearly zero-energy building (n-ZEB), thus the energy demand of such buildings will decline bringing to the need of a new low energy design of the entire system.

Since district heating networks have been historically already under thousands of studies, this dissertation will start analyzing innovations linked to such a technology with the aim of translating in future work the same logic towards district cooling networks. Up to today the material on cooling plants is limited, therefore, there is interest in developing more studies in this area.

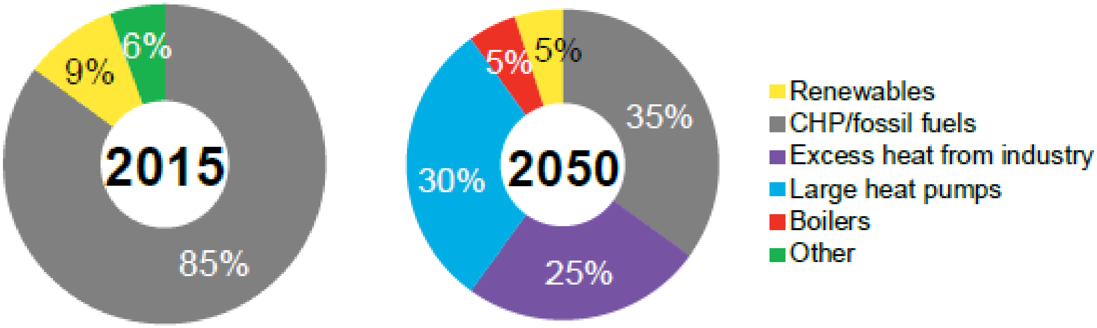

Figure 1 District heating fuel mix in Europe in 2015 compared to future projection in 2050. Reproduced according to (Heat Roadmap Europe, 2019). CC BY-NC-ND

1.1.1 District heating network

By definition district heating system (DHS or DH) is a localized system configuration that supplies heat to the residential and commercial buildings. Contrary to a typical individual heating system, most commonly a gas boiler, district heating distributes the heat from a central plant to the supporting buildings through a network of buried pipes. As shown in figure 2, DH usually comprises: a heat source (boiler, geothermal energy or waste heat from another system), a thermal energy storage system, a control and distribution system and finally the user. In Europe, the district heating network is already well established especially in northern Europe: Denmark, Sweden, Germany, and Poland. In southern Europe it has still a high exploitable potential, Italy and Spain, *in primis* (figure 3). The main challenges implementing such solutions comes from different points:

- The need of involving and on boarding different stakeholders ;
- The installed infrastructure requires hard work which in some case could suspend the viability of a city;
- The implementation of a district system require a strategic organization also in terms of renovation wave, which in southern countries plays a higher role due to the higher number of building suffering from energy poverty.
- Required investments sometimes are too high.

As a consequence, utilities or companies working both in northern countries and in southern countries had first started investing and operating in the north where they found an environment more open and helpful to accept district systems as a global decarbonization solution for the city. As a conclusion, in general, countries with stronger policies, typically in the north, are the one more developed and experienced in district heating or cooling. Going further, in the following paragraphs some of the challenges related to heating network optimization will be discussed. A network for low-energy houses cannot be made exactly the traditional way, because this will result in relatively large network heat losses. Hence, the first challenge would be to lower the heat losses and it can be accomplished through the following parameters: smaller pipe dimensions, larger insulation thickness, highly-efficient polyurethane insulation, cell gas diffusion barrier, diffusion-tight flexible carrier pipe, twin pipes (double pipes) or reduced pipe lengths. (Olsen et al., 2008)

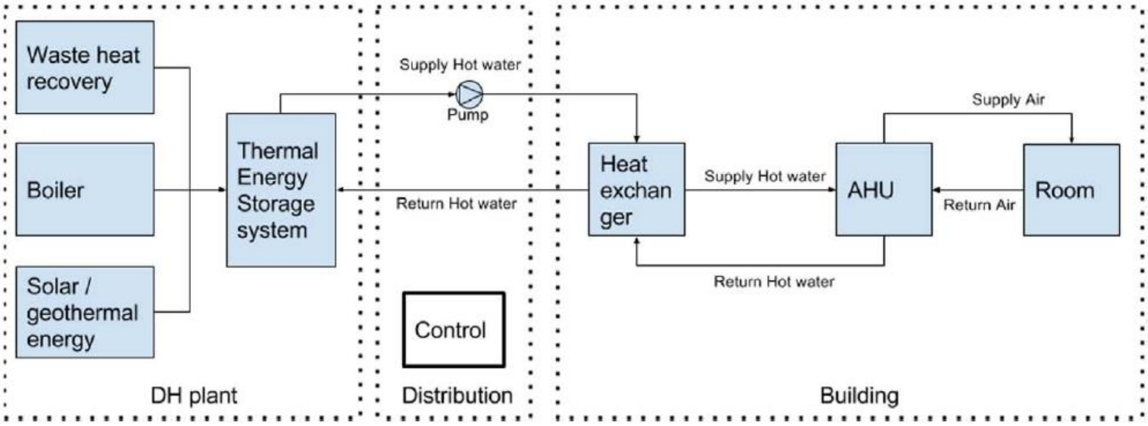

Figure 2 System components of a district heating (DH) system. Reproduced according to (Rismanchi, 2016). CC BY-NC-ND

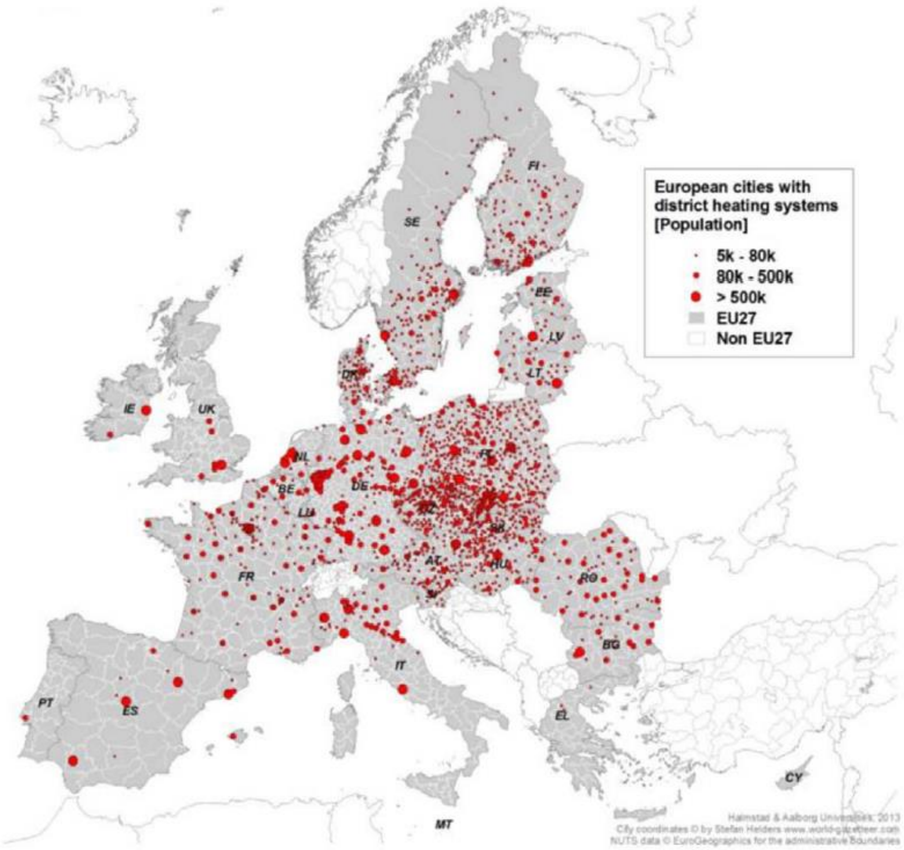

Figure 3 European networks of DHS. Reproduced according to (Rismanchi, 2016). CC BY-NC-ND

1.1.2 History and classification of district heating generations

Historically, district heating is a well-known technology it is possible to find its roots in Romans' application of hot-water distribution for baths and greenhouses. The first examples of commercially successful district heating are from the end of 1800 in famous cities such as New York and Paris, which are still partially running with the original design. Since the end of the XIX century the technology configuration of DH evolved and changed (figure 4).Up to today, it is possible to divide the time frame in five generations as following (Lund , et al., 2014):

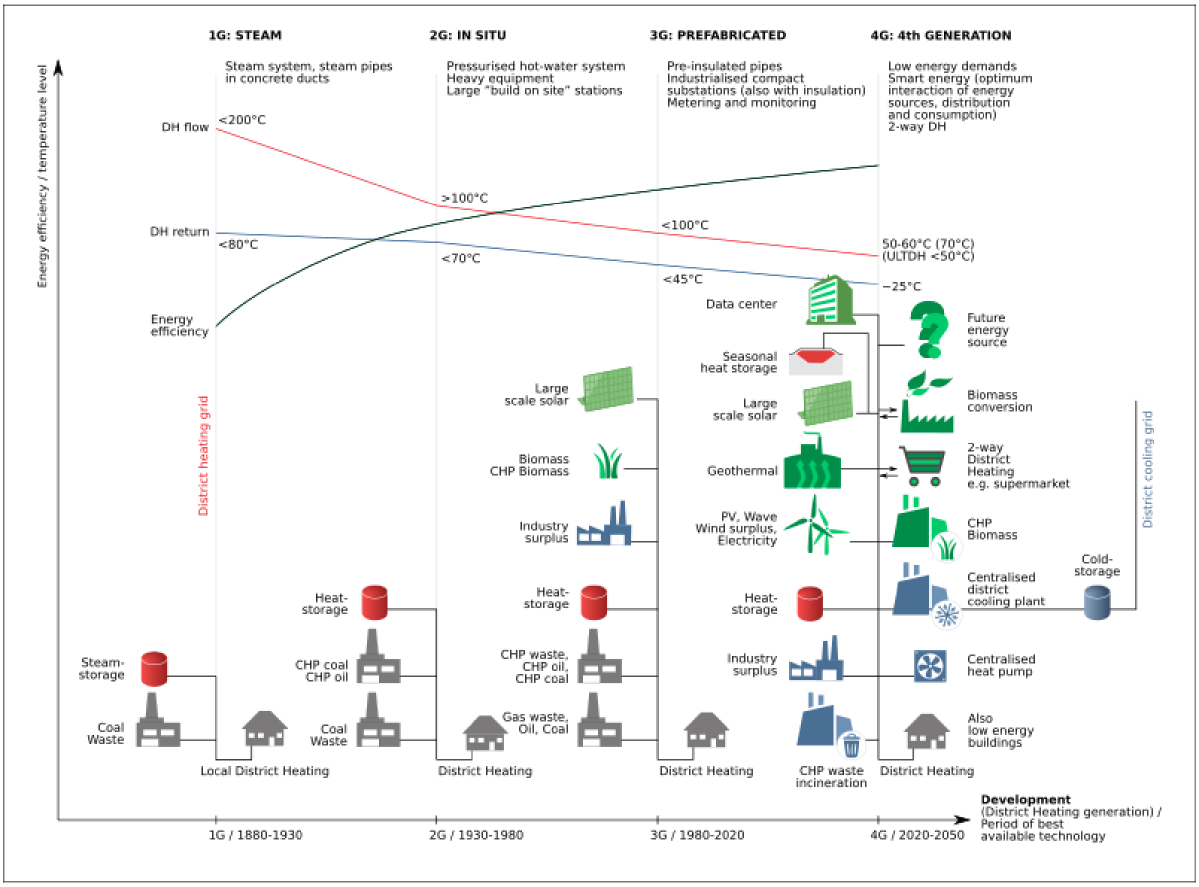

Figure 4 District heating and cooling evolution. Reproduced according to (Vad Mathiesen, et al., 2020). CC BY-NC

- First generation (1GDHC: 1880s – 1930s): established in USA, the first generation of district heating systems rely on steam as energy carrier. Initially, such systems were introduced to substitute individual heating, which at that time were extremely armful. Unfortunately, due to the high temperature of steam (>200 °C), critical explosions used to happened causing the deaths of many pedestrians. Moreover, the operating conditions often brought the return network to corrosion causing a rapid flow drop, and though an overall decrease of the efficiency. The conversion of such systems was possible in some cities, however. In New York and Paris they are still working.

- Second generation (2DHC: 1930s – 1980s): once steam has been classified as dangerous in such application, the new energy carried adopted has been hot water (supply temperature > 100 °C). Such systems were mainly developed in the Soviet Union, some of the components used were water pipes in concrete ducts, large tube and shell heat exchangers and material intensive, large and heavy valves due to the operational condition linked to the high temperatures. The main objective of district heating was to achieve fuel savings and better house comfort using CHP.

- Third generation (3DHC: 1970s – 2020s): traditional centralized production, still based on pressurized water as energy carrier. However, in this case the supply temperature is lower (T<100 °C), same for the return temperature which is around 50 – 40 °C. This technology developed fast in the Northern Europe: Denmark and Sweden are two leaders of this generation. Generally the components are prefabricated, pre-insulated pipes directly buried in the ground, centralized heat thermal storage, and plate steel heat exchanger in the substation. This one, among all, is the most dominant technology used nowadays, not only in Europe but also in China, Korea, Canada and USA. Even though policies and regulations are different country by country, 3rd generation is mainly used to provide supply security in relation with oil crises and increasing attention toward the efficient use of CHP.

- Fourth generation (4DHC: 2020s – 2050): the future of district heating is moving towards the concept of smart thermal grid. According to this definition, the infrastructure network will have to evolve towards a low temperature network, supplying at 50 – 60 °C and return around 25 – 15 °C aiming to increase the overall efficiency (figure 5). This will also bring to a higher grade of renewable integration as well as the opportunity of increasing the use of assembly-oriented components and more flexible pipe materials. At the same time, it is also integrating separate cooling systems, as well as centralized cooling storage systems and smart digital tools to optimize operation and maintenance. The integration of all these technologies will permit to cover the heating and cooling demand of the residential sector with a global view. According to this new concept, the design is becoming more flexible towards the integration of decentralized energy production sites. However, this does not have any impact on final consumers who maintain their traditional role. 4DHC is a 4-pipe (supply and return for heating and supply and return for cooling) solution and has to be designed to the lowest common denominator buildings i.e. at the highest heating temperatures.
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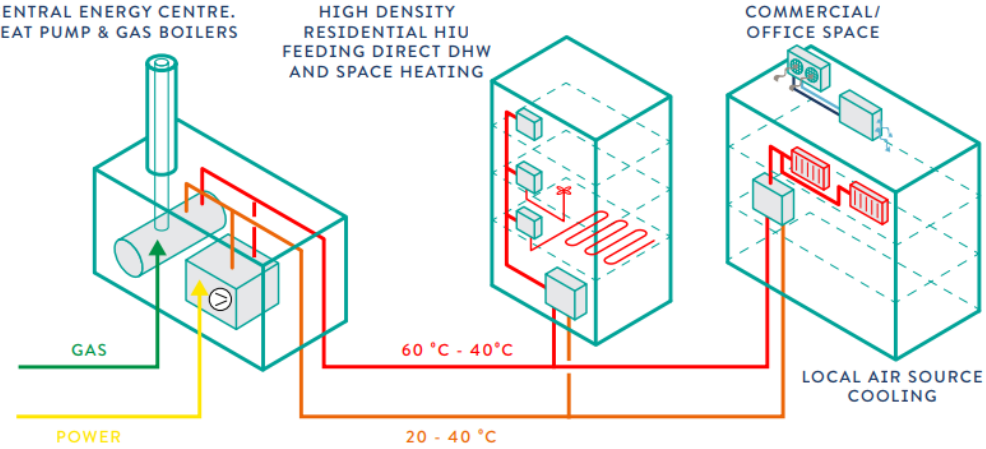


Figure 5 Example of a 4DHC. Reproduced according to (HeatNet NWE, 2019). CC BY-NC-ND.

- Fifth generation (5GDHC: 2050 - ?): in the following years the network as well as the consumer behavior is expected to change. Most probably, the heating and cooling network will evolve in a non-tradition topology with decentralized plants of different size and technologies (mainly heat pumps) supplying heat along ultra-low temperature headers in the network. The ΔT is less relevant with a supply < 45 °C and a return around 25 – 15 °C (ambient loops may also be possible in smaller systems). 5DHC often consists of un-insulated plastic pipework with very low heat losses and longer pipe runs. 5DHC usually includes seasonal thermal storage to balance the spine temperatures and perhaps some short term localized thermal storage. 5DHC will always need supplementary boosting to supply DHW temperatures. 5DHC has built-in cooling supply and can interchange heating/cooling between buildings. 5DHC provides a single integrated ‘plug-and-play’ heating and cooling system allowing buildings to be ‘prosumers’ across the network. 5DHC are sometimes also defined as DEN (District Energy Network) for its ability of providing heating, cooling but also electricity. Unlike other technology; this type of network is able to expand as the city grows, also permitting the integration of battery storage systems, increasing the overall efficiency as well as helping the demand management while ensuring a great penetration of renewable energies (HeatNet NWE, 2019). 5DHC is a good solution where the demands are both heating and cooling. In this case, cooling would be provided in the same spine system, a 2-pipe system to achieve full 5DHC rather than a 4-pipe 4DHC system. This allows interchange of energy between heating and cooling demands in different buildings (figure 6).

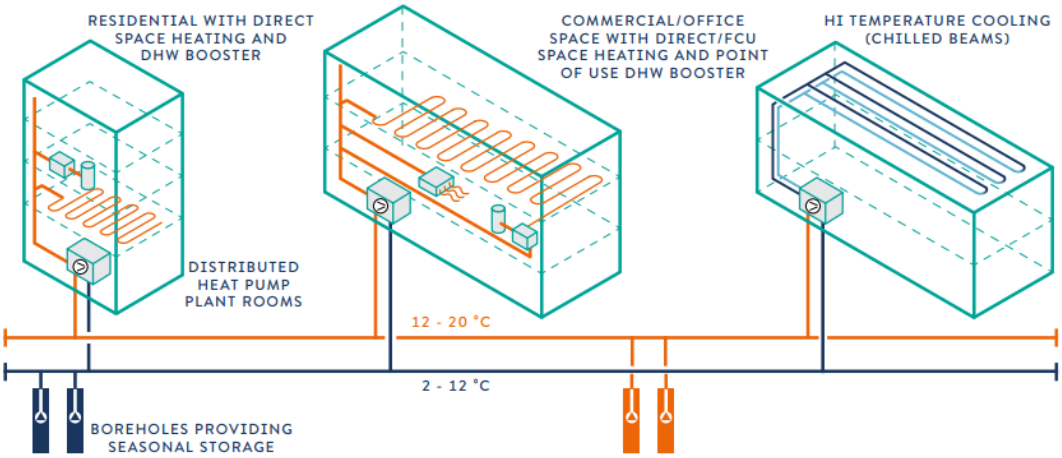


Figure 6 Example of a 5DHC. Reproduced according to (HeatNet NWE, 2019). CC BY-NC-ND

1.1.3 District cooling network

As district heating, district cooling (DC) is based on the same principle: building a network of infrastructure highly efficient in order to substitute, where possible and mainly in high demand area, individual electrical chillers or heat pumps. Its main function is to integrate and distribute cold energy to support the cooling load of a group of connected buildings. The chilled water running through the network of pipes delivers the cooling load to the building and the return cold water would then go back to the plant room. Some of the advantages of such a system are: better efficiency, less leakage and longer life cycle in a controlled environment. As shown in figure 7 the basic structure of a DC network includes a chiller plant room, thermal energy storage systems, control and distribution system and user at the end. Differently from DH, DC has not yet reached a great market penetration, mostly because the demand of cooling increased mostly in the last couple of years linked to an increase in some countries living standards. However, market projection forecast a 300% increase of cold demand worldwide, resulting in a theoretical increase of related carbon emissions (IEA, 2018). A good enough reason to widespread the concept of district cooling globally. To sustain this need, some studies have extensively demonstrated the efficiency of district cooling systems compared to individual heating, ventilation and air conditioning systems (HVAC), with overall 15% savings of energy used in subtropical climate. (Rismanchi, 2016). From figure 8 it is possible to see operational cooling networks in Europe. In comparison with the same map for heating, now the networks pipeline are not as much develop. This is translated in a less comprehension of such networks.

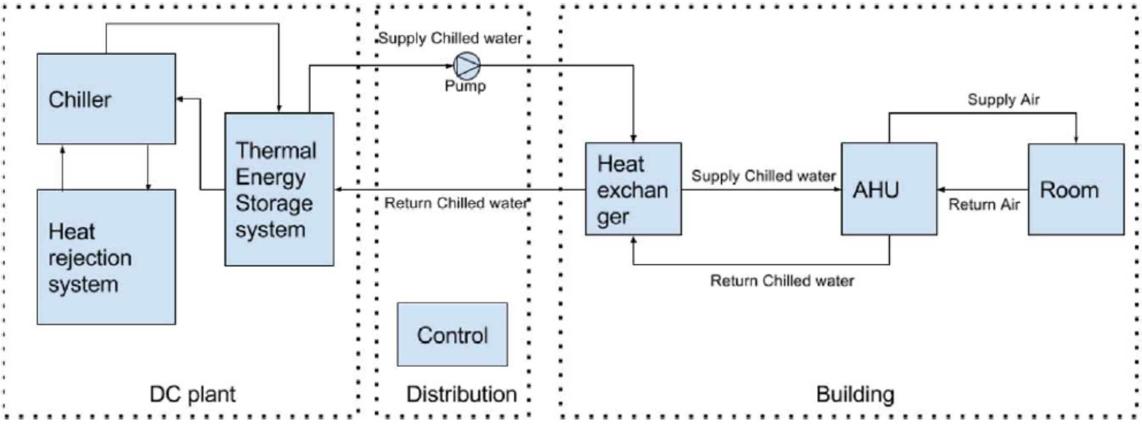


Figure 7 System components of a district cooling (DC) system. Reproduced according to (Rismanchi, 2016). CC BY-NC-ND

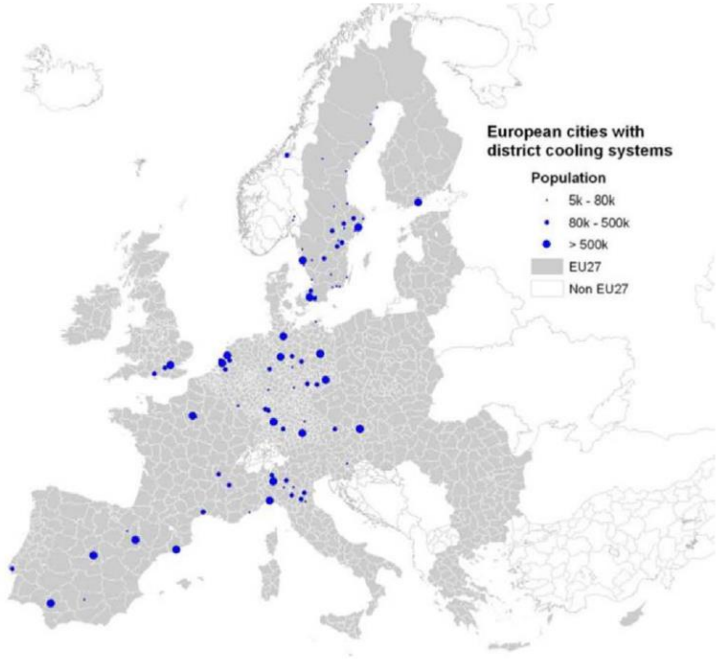


Figure 8 European networks of DCS. Reproduced according to (Rismanchi, 2016). CC BY-NC-ND

1.1.4 History of district cooling network

The first working district cooling system (DCS or DC) was in Colorado, at Denver's Automatic Refrigerator Company, installed in 1889 (Gang et al., 2015). A second larger system was installed, in 1930, in the Rockefeller Centre of New York city. USA was by far the leading County: by 1996, 20 cities have already adopted DCS. In Europe the first installation appeared in Paris during 1960s, the cooling plant was using the cold water of river Seine. Afterwards, it begin to be largely used in Germany, Italy, Sweden, Finland, etc.. Starting from 1970 also Japan started using DCS, after that it has been developing very fast especially from the Japanese government which believed in its high efficiency as well as the potential of reducing pollution emissions, resulting in 154 district cooling system installation by 1995 in Japan. In 1999 DCS made its appearance in United Arab Emirates where now it counts 10% of the cooling market. Finally, in China DCS is a quite new system, the first installation is in

Bejing and began to work only in 2004, after that a high number of network have been constructed (Gang et al., 2015).

1.2 Overall energy efficiency along the value chain

As introduced briefly in the previous paragraphs, an added value of DHC system is its overall energy efficiency compared to individual installation. However, in order to have a holistic approach to energy savings and energy efficiency, it is important to always think with a systematic perspective, thus, the whole energy value chain should be considered. Such an approach is deeply important when comparing different solutions. For example, a CHP plants coupled with district heating systems will increase the plants' conversion efficiency significantly because of the reuse of heat which otherwise would be lost; however, distribution losses in the network will then appear in comparison to a system installed on site.

The increase of energy efficiency can be achieved in different ways (Vad Mathiesen, et al., 2020):

1) reducing the amount of energy needed to fulfil the (useful) demands of an energy system (for example, through a higher thermal energy performance of buildings or optimization of control systems);
2) minimizing the energy loss in transport and distribution;
3) reducing and recovering as much as possible the energy lost in the transformation phase;
4) improving the fit between production and distribution (role of smart control in a decentralized system using multiple sources of production).

Energy efficiency is an important and trustable metric when analyzing well-defined systems; however, when the system becomes more complex, it gets more difficult to quantify it through energy efficiency. For example: in case of combined heat and power plants, losses are difficult to attribute: are they linked to electricity, heating production or both? Another question could be how to quantify the production efficiency of excess heat resources. Often when deploying a sector-specific approach, the synergies and system effects are not captured, which clearly becomes a problem when dealing with smart grid integration. The solution is to analyze the primary energy consumption of the whole energy system. In this case, the synergies and the different impacts on the system will be included (Vad Mathiesen, et al., 2020). In figure 9, the process of energy conversion from primary energy to useful energy is shown. The energy efficiency value chain can be defined as the conversion process from primary energy through final and delivered energy to useful energy.

Energy process is a type of conversion, transmission or distribution where the fuel or energy content is processed in one form or another. *Energy amount* is thus the amount delivered or received from the process.

The efficiency of a process can be found by the ratio of the input and output amounts. Thanks to this overall approach it is possible to compare district heating with individual installation in a total objective way.

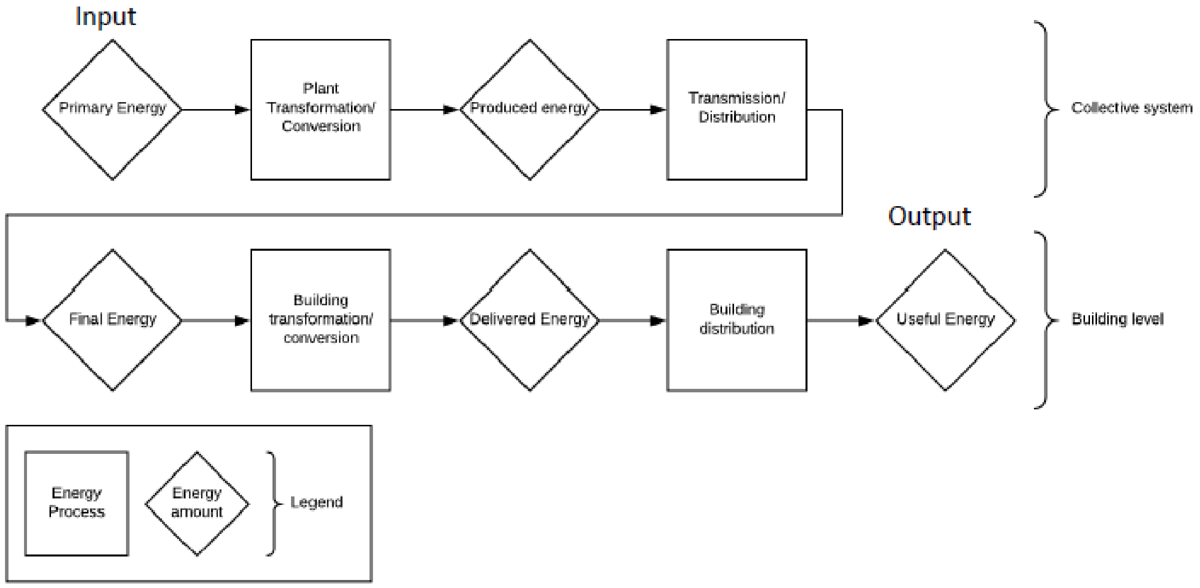


Figure 9 Energy efficiency value chain from primary energy to useful energy. Reproduced according to (Vad Mathiesen, et al., 2020). CC BY-NC-ND

2. Smart thermal grids

The following chapter will study and analyze in depth the characteristics of future 4th and 5th generation district heating and cooling systems, the so called smart thermal grids. By definition, a smart thermal grid is a system designed to balance the supply and demand for heat and cold within a network with intelligent control. It aims to increase efficiency, reduce carbon emissions and reduce demands on the environment while providing an overall high level comfort reducing costs. As shown in figure 10, smart cities and smart grids are closely connected. In particular smart thermal grids include an innovative decentralized design integrated with new technologies. On the design part there is a shift from a demand driven network to a combination of demand and supply driven network, which includes: lower energy consumption buildings, low temperature heating and high temperature cooling networks coupled with distributed renewable energy sources (i.e. residual heat, geothermal, solar), thermal storage systems also coupled with the electrical grid (UNEP, 2015).

Benefits and challenges of smart thermal grids will be listed and analyzed in the following paragraphs in order to discover what opportunities are there to explore. To be noted that on the literature there are many more publications and studies related to heating but very few regarding cooling, for this reason to explain the logic behind district cooling this chapter will flex the attention to the proved concept in district heating.

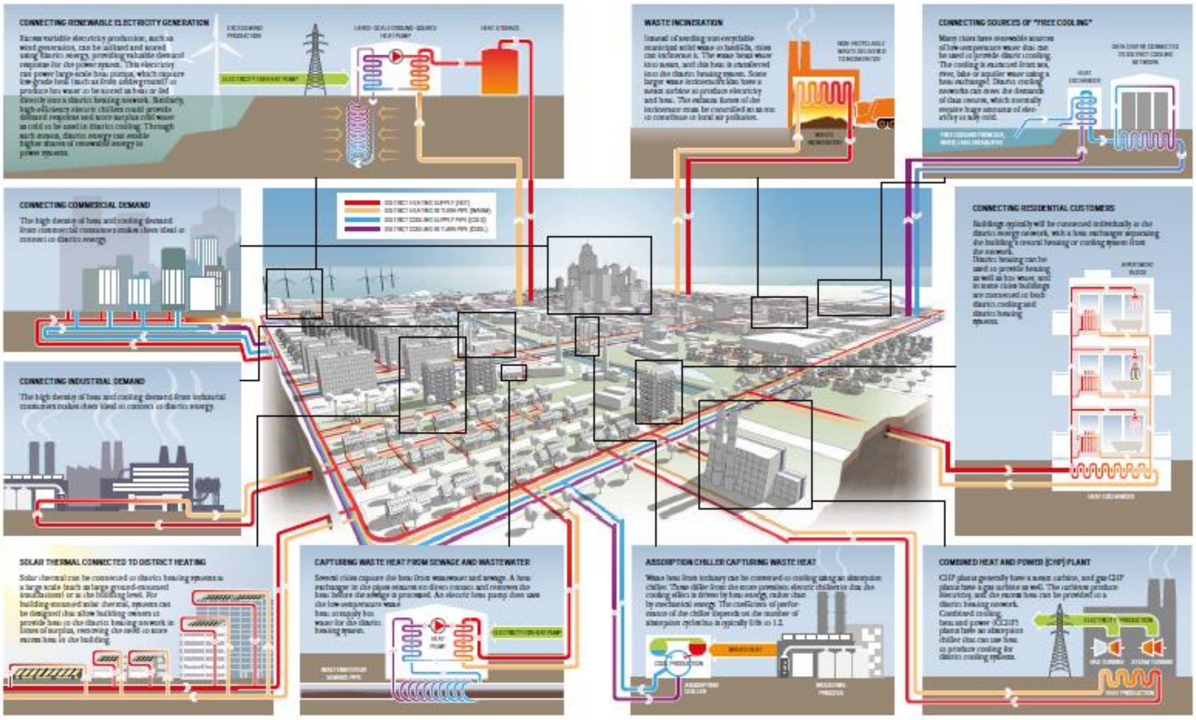


Figure 10 Smart thermal network. Reproduced according to (UNEP, 2015)) CC BY-NC-SA – see Annex for details.

2.1 Low energy networks

Moving towards low energy networks, is essential to easily integrate decentralized renewable energies sources such as solar, wind, geothermal or heat waste. However this is not the main purpose of low energy network. In fact, by lowering the supply network temperature towards 30 – 70 °C (generally 45 – 55 °C), the grid heat losses would consequently follow a great decrease, improving efficiency. In fact, decreasing the network temperature from T > 100 °C to 60 °C, the delta T between the ground temperature and the network temperature would strongly decrease leading to a lower heat exchange between the two materials.

The research of a global high efficient system pushes the integration of storage units within the heating and cooling network, increasing therefore its sustainability impact. The residential sector is under deep changes due to the ambition of reaching high efficient buildings. This trend will lower overall buildings' energy demand require the supply systems also to follow the trend. Not to forget, is that the development of low energy infrastructure has the potential to lower by 80% CO_2 emissions for domestic heating and cooling by reducing the amount of fossil fuels, thus reducing from combustion (Vad Mathiesen, et al., 2020)

2.2 4th generation DHC Vs 5th generation DHC

A good point would be to identify where and how it is more suitable the implementation of 5th rather than 4th generation. The different essence of the two networks is not the only factor: the building typologies linked to the network is another important parameter to take in consideration (Gartland & Codema, 2018). In this sense, new buildings would be a relatively easy fit with 4/5DHC since their design can be optimize in advance to meet low temperature heating system's needs; similarly, deep-retrofit buildings can be converted to match 4/5DHC requirements (HeatNet NWE, 2019). In the context of low energy network, with supply temperature less than 55 °C, both new and deep-retrofitted buildings on one hand would have installed the right heating equipment for low temperature (i.e. underfloor heating), on the other hand they would still require some systems to boost domestic hot water (DHW) temperatures at an individual dwelling level or at a more centralized building level. On the contrary, existing buildings and undergoing retrofit-lite would still require higher temperatures (80/70ºC) for heating due to the mix between poor insulation and old heating equipment, therefore, switching towards 4/5DHC would be more of a challenge. However, it is true that a combination of district heating and heat pumps could also be implemented: higher temperature heat pumps could be used to boost to 80/70 °C in order to supply higher temperature heating systems but it could require an extremely high amount of electricity, which could make the investment meaningful. As shown in figure 11, 4DHC is a good solution where the demands are mainly heating, while 5DHC is a good solution where the demands are both heating and cooling. In this case, cooling would be provided in the same spine system allowing interchange of energy between heating and cooling demands in different buildings.

A key part of a more decentralized 5DHC approach is that the scheme operator needs to take control of the distributed plant rooms to allow full scheme optimization and encourage prosuming across the network. The operator can then optimize heat pump performance through good control and maintenance. Whilst also promoting greater exchange of energy between buildings. The more prosuming between buildings the lower the overall operating costs (and carbon savings). An essential part of 5DHC is therefore that the scheme operator must take full responsibility for the whole scheme including the decentralized heat pump plant rooms in order to allow management of the buildings as prosumers and balancing of the 5DHC headers/boreholes. Without this, prosuming is less likely and the benefits of 5DHC begin to fall away. According to what said above, 5DHC changes the lines of responsibility for the operator and consumer (HeatNet NWE, 2019). This opens up opportunities for new ways of selling heating and cooling, which might be better described as ‘selling comfort not heat’. Consumers could then be offered a temperature based service without having to worry about maintenance and replacement. Although these new business models are possible with 4DHC, they are less likely. Whereas a comfort based service is almost built-in to the 5DHC approach. Despite some consumer might have problems with less independence, it is potentially a huge step forward for new business model for heat networks. Finally, since the cooling demand is increasing both due to climate changes and consumer expectation, 5DHC offers a better solution than 4DHC, compared to single system, to supply both heating and cooling. (HeatNet NWE, 2019)

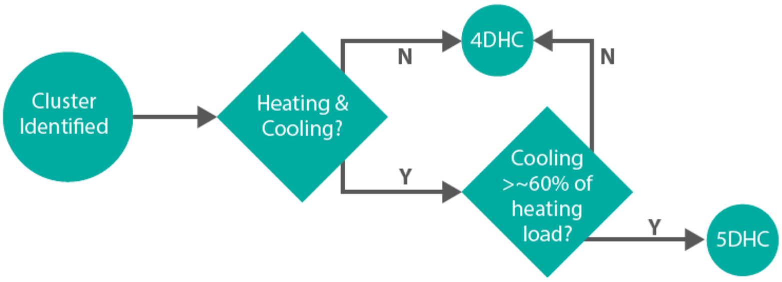


Figure 11 4DHC Vs 5DHC. Adapted from (HeatNet NWE, 2019) CC BY-NC-ND

Table 1 describes the evolution trend of district heating system with a focus on characteristics of the two latest generations. Efficiency curve is increasing according to new generations, while temperature decreased.

Table 1 Comparison of 4DHC and 5DHC against 3DHC. Adapted from (HeatNet NWE, 2019)

Definition	4DHC	5DHC
Topology	Traditional single energy center supply heat outwards	Decentralized plant supplying spine/cluster/buildings, supplying heat along a spine/backbone, low temperature headers
Temperature	- Supply at: 55-45 °C, - wider ΔT, - Return temperature: 25-15 °C, - no weather compensation	- Supply at: <45 °C, - ΔT less relevant (10°C still needed) - Return temperature: 25-15 °C, - no weather compensation
Pipework	- Highly insulated, - pre-insulated pipework - Plastic pipework	- very low losses, longer runs (to be verified) - Plastic un-insulated pipework (in theory due to low T insulation is not needed. It is probably true for return pipe, since the objective is to reach the lowest T possible to reach a greater ΔT, however experts estimate that supply should still be insulated)
Storage	- Very large thermal storage (larger than 3DHC due to lower temperatures, so lower energy density)	- Seasonal thermal storage - Some short thermal storage
Domestic Hot Water (DHW)	- Supplementary boost to supply DHW needed	- Supplementary boost to supply DHW needed, avoiding a secondary circuit (legionella risk)
Cooling	- Separate system (4 pipe system)	- Built-in cooling in a 2-pipe system
Heat interchanges	- No interchange of heat between buildings	- Interchange of heating/cooling with balancing mechanism, - Buildings become prosumers
Advantages	- operating costs and carbon emissions still quite high, - lower heat losses compared to 3DHC – longer pipe runs due to lower pressure losses - Greater plant efficiency than 3DHC but less than 5DHC - New opportunities for heat pumps - New opportunities to use waste/renewable heat sources but not much exploited - More opportunity for simultaneous heating & cooling in separate systems	- Even lower operating costs and carbon emissions, - supplying both heating and cooling, - heat recovery between buildings, - buildings pick-off/inject so less load dependent (to be verified), - can add buildings more easily, - heat losses become almost irrelevant, - longer pipes runs covering wider areas, even greater plant efficiency, particularly heat pumps, - more opportunities to use waste/renewable heat sources
Disadvantages	- Larger pipework than 3DHC, - greater pumping costs due to longer pipes, - requires DHW boost, - less storage density (compared to 3DHC) - No opportunity for energy exchange between buildings across the network	- Larger pipework than 4DHC, - greater pumping costs, - requires DHW boost, - less storage density
Application	- **Mainly a new-build technology integrable with specific solutions for existing buildings where necessary** - New build (relatively easy) - Deep retrofit (straightforward) - Existing buildings & retrofit lite - Boost to 80/70 °C with high temperature HPs - Less opportunity for simultaneous heating & cooling compared to 5DHC	- **More flexible/connectable plug and play LAN approach with built-in cooling and interchange of energy between buildings** - New build (easy) - Deep retrofit (easy) - Retrofit lite (relatively easy) - Boost with conventional temperature HPs - Existing buildings (straightforward) - Boost with high temperature HPs

		- Built-in simultaneous heat & cooling (using conventional HPs) - Seasonal storage using boreholes

2.3 Benefits and challenges of the transition to 4th and 5th generation DHC

Compared to individual installation, one of the main advantages of district heating and cooling systems is the high potential of reducing carbon emissions. According to the historical period of energy and ecology transition in which we are, the reduction of carbon emission is the first and probably one of the most relevant criteria which brings people to explore such a technology. However, this is not the only advantage that DHC could bring. In fact, it has also the power and the structure to bring a strong effect of economy of scale which might translate in lower final tariffs for consumers.

Some other benefits of a low-energy DH system can be summarized in three main blocks: environment, community and buildings owners/tenants (Rismanchi, 2016):

- For environment: it will provide a platform for a flexible choice for an energy resource that is ideal for utilizing renewable energies where possible. They have overall better efficiencies that lead to a reduction in using fossil fuels and therefore reduction in harmful emissions productions such as CO, CO_2. The centralized system would make it easier to have control over maintenance and keep the efficiency on the designed condition.
- For communities: they will enhance the potential for energy management. Also, they will provide a platform for an increase in penetration of local energy resources and recover the waste energy sources. The system would expand based on the community's demand. Also, it would generate job opportunities.
- For building owners and tenants: it will reduce the overall cost of heating and cooling. More importantly, will reduce or eliminate the operational, maintenance cost and its complexity.

On the opposite side of the medal, in order to be able to fulfil its role in future sustainable energy systems, DHCs will have to meet the following challenges (Lund , et al., 2014):

- Ability to supply low-temperature district heating for space heating and domestic hot water (DHW) to existing buildings, energy-renovated existing buildings and new low-energy buildings;
- Ability to distribute heat in networks with low grid losses;
- Ability to recycle heat from low-temperature sources and integrate renewable heat sources 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 4th Generation 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.

2.4 New design of supply and return pipes in a loop layout

An important aspect of low temperature network is their easy and in some case necessary integration with old district systems. In particular, it is not that common to implement a district heating in a fully new residential district. Only in this ideal case, low temperature network will not have any problem supplying new n-ZEB (nearly zero energy building or passive building), in reality, a district heating system is most commonly applied to a multi-tipology of buildings with old, retrofitted and new building all in one. Such an application could be problematic for 4/5DHC since they can supply heating temperature less than 50 °C, which might not be enough for high consuming old buildings. In this situation one solution could be using locally installed heat pumps in order to boost the temperature at the building level, however where it is possible, a more efficient solution would be the integration of old district systems in a cascade loop with new generation one, as shown in figure 12 (Gartland & Codema, 2018). This would imply: a reduction of supply temperature (thus a reduction in heat losses in distribution pipes and operating costs); a reduction of heat load resulting in smaller equipment, smaller pipes, and cheaper investment; a reduction of temperatures enabling the use of low grade waste heat, thus lowering cost of heat. These optimizations can make high efficiency buildings connected to 4DHC viable, even when heat density in the territory is quite low.

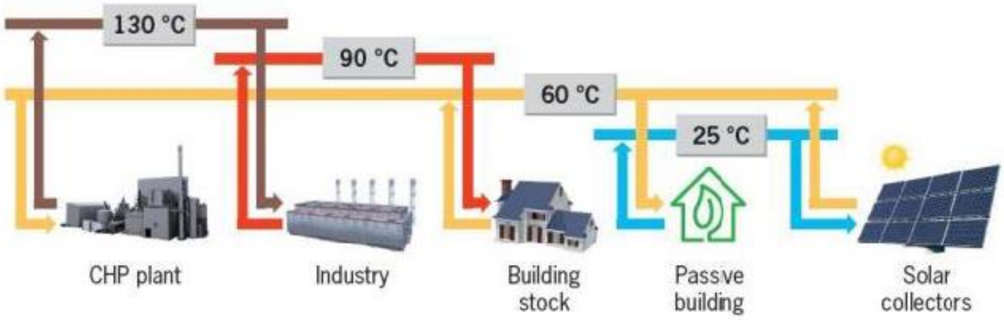


Figure 12 A passive building supplied by the return of a 3rd generation district heating network. Reproduced according to (Gartland & Codema, 2018). CC BY-NC-ND

2.5 Low energy networks requiring buildings wave renovation

As it was shown in previous paragraphs, low energy network have demonstrated to be a performant energy solution for both heating and cooling of new buildings or deep retrofitted one where the energy dispersion is very low thanks to good isolation. However, low temperature DHC, in some case, can be implemented also in old buildings using heat pumps to boost the temperature of the secondary circuit, but the risk is to get a lower overall efficiency. According to these findings, a well-structured decarbonized strategy would need to push at the same time the investments in DHC infrastructure while implementing a strong renovation wave of old buildings. Such approach would permit to save money and give guideline to building renovation, which sometimes results a bit chaotic (Gartland & Codema, 2018). According to the Green Deal, the next 30 years will be critical in order to tackle the residential sector in terms of heating and cooling with a high focus in the fight against energy poverty (European Commission, 2019). Energy efficiency in buildings is one of the main targets, thus a renovation wave has been requested. As shown in figure 13, the scenario “business as usual” on the left with the current renovation rate of 1%; on the right, the scenario with a doubled retrofit rate, as suggested on the Green Deal to reach the targets of energy efficiency in buildings. It is evident that such an effort would lead to an increase in opportunity, therefore, it is crucial to identify the right policies in order to take advantage of this window as much as possible. In fact, nowadays a lot of different means of heating are available on the market: gas or biomass boilers, mainly based on a water circuit at building level, electrical systems, or district heating. Those technologies differ in the type of equipment installed, thus, renovating the house according to one mean of heating rather than the other could prevent the implementation of DHC systems if financing method are not expected. The following paragraphs will clarify the role of centralized district heating against individual systems.

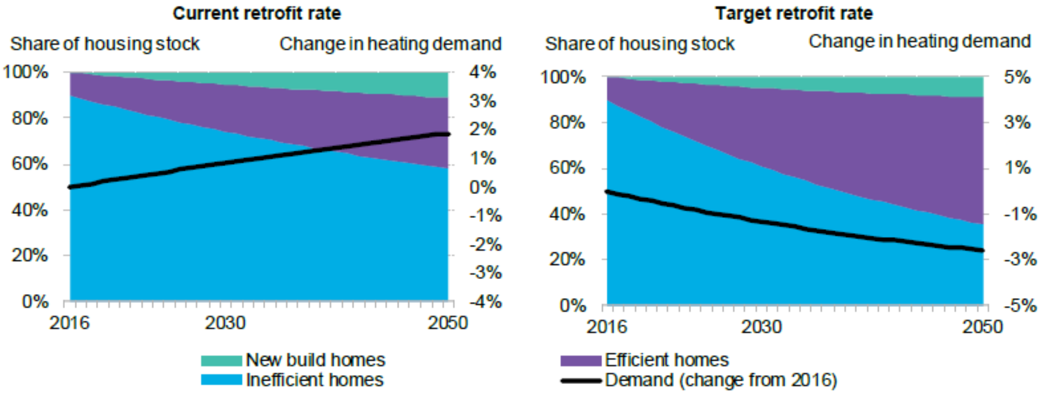


Figure 13 Change in housing stock and energy consumption for homes heating demand by 2050. Reproduced according to (Coker, 2019) CC BY-NC-ND

2.5.1 State of art of individual heating systems

Historically building heating has been dominated by individual heating systems. The first underfloor heating systems, appeared in Turkey in 1300 B.C., The Romans than brought the technology to high art. Thanks to Romans, first heated walls appeared as well as design of early warm-air heating systems. The first heating systems have been implemented in 2500 B.C. in the Greek period, and they were forms of fixed central hearths. The first crude fireplace heating was used at the 800s A.D. and widespread in Europe by the 13th Century. The first good records of a warm-air system date to the 1200s. These records indicate that the city hall in Luneberg, Germany had a central warm-air system using three furnaces. After the 14th Century, chimney and stoves of different design and material have been installed and continued evolving throughout the 1800s. The Industrial Revolution provided the catalyst for more advanced warm-air systems and with it also steam application. In the same period hydronic systems started to be develop in France using hot water boilers. Radiators and boilers followed then becoming the main heating source of late 1800s. Finally, in 1900s forced-air systems were used in UK and US (The News, 2011). Until contemporary days, and still now, individual heating systems have dominated the landscape in different form and application. Only around the second industrial revolution, first forms of centralize district heating took place and restricted to city’s areas. Moreover, individual systems were able to give a high grade of independency to families even in remote areas. However, according to the rate of growth of urbanization, are individual systems still the best choice available on the market?

A brief state of art of the main individual heating technology available nowadays will be introduced to better understand the context.

2.5.1.1 Boilers

Based on solid fuels (biomass), liquid oil or gas, boilers use such fuels to increase the temperature of a circular water system at the building level. Such water system, coupled with a domestic hot water (DHW) system, is used to supply rooms’ radiators which are responsible for heating. Most efficient boiler systems are the condensing boiler, which can reach 98% of thermal efficiency. The supply temperatures can be two, one at 63 °C with full condensation and one at 84 °C with partial condensation. When coupled with DHW, which requires temperature at 60 °C, boilers supply at 84 °C because three degrees difference would be too low to provide hot domestic water. The return temperature is around 55 °C; the lower the return temperature to the boiler the more likely it will be in condensing mode. If the return temperature is kept below approximately 55°C, the boiler should still be in condensing mode making low temperature applications such as radiant floors and even old cast iron radiators a good match for the technology. A scheme of an in-house boiler installation is shown in figure 14.

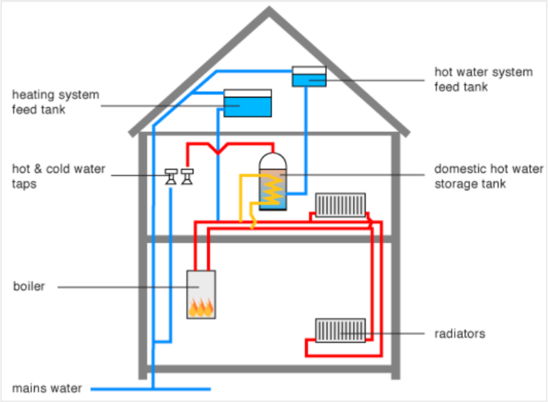
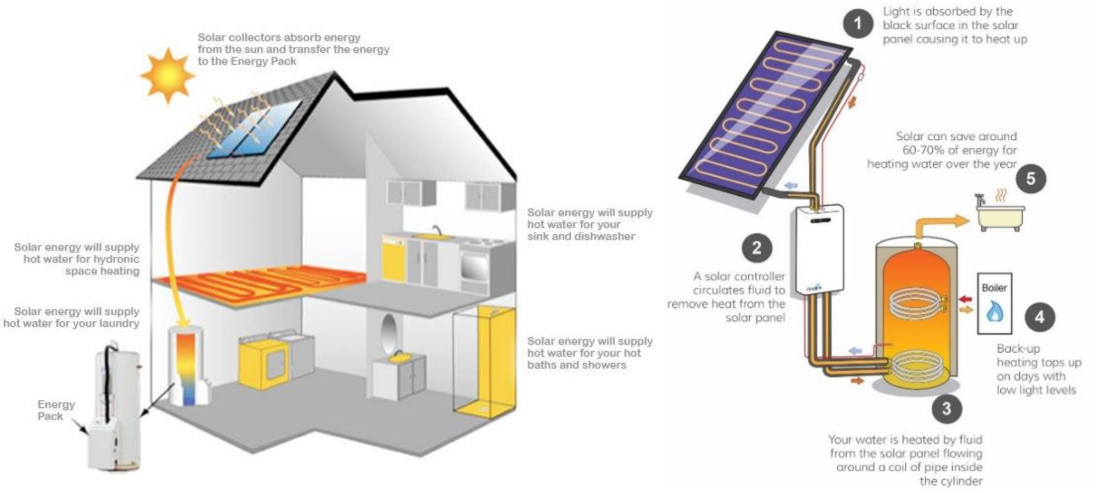


Figure 14 Conventional boiler schema. Reproduced according to (Affordable Warmth Scheme, 2018). CC-BY

2.5.1.2 Thermal solar

The concept of thermal solar is very similar as traditional boiler systems. In fact, solar energy will supply hot water for hydronic space heating as well as DHW. These systems are primarily low-temperature systems with heating medium with temperature within 20–60 °C range, suitable for underfloor heating systems, as shown in figure 15.



(a) (b)

Figure 15 a) solar thermal heating adapted from Pinterest EnviSolarEnergy; (b) zoom on thermal solar DHW. Adapted from (Pinterest Viridian Solar,2019). CC-BY

2.5.1.3 Heat pumps

A heat pump comprises a thermodynamic cycle in which a refrigerant circulates. Energy is captured in the cold reservoir by an evaporator in which a low-pressure and low-temperature (lower than the temperature of the cold reservoir) refrigerant circulates. Heat is therefore transferred from the cold reservoir to the refrigerant, which changes from a diphasic state (simultaneous gaseous and liquid state) to gas state. The compressor then channels this gas to high-pressure and high-temperature to deliver the energy drawn from the cold reservoir at the temperature desired. The heat transfer process takes place inside the condenser, where the fluid delivers its energy to the hot reservoir by changing from gas to liquid. Finally, the refrigerant travels through the expansion valve, which lowers its pressure and temperature and thereby makes the refrigerant turn into a low pressure diphasic state (liquid/gas) (figure 16). This cycle is beneficial in terms of energy consumption when the energy is drawn from a free and renewable cold reservoir. The electricity used by the compressor represents the only cost for the user. The thermal energy supplied to the building is several times greater than the electrical energy used by the system, as shown by the heat pump’s Coefficient of Performance (COP = 5). This process therefore allows any source of renewable energy that is available in the vicinity of a building to be used, even if its temperature is far lower than that of the building’s inside air. However, the higher the reservoir’s temperature, the higher the system’s COP. It is for this reason that a ground -or water- based heat pump, which runs at around 12°C throughout the heating season, will perform better than a heat pump that uses outside air whose temperature can fall below -20°C. Both radiators and underfloor heating are feasible.

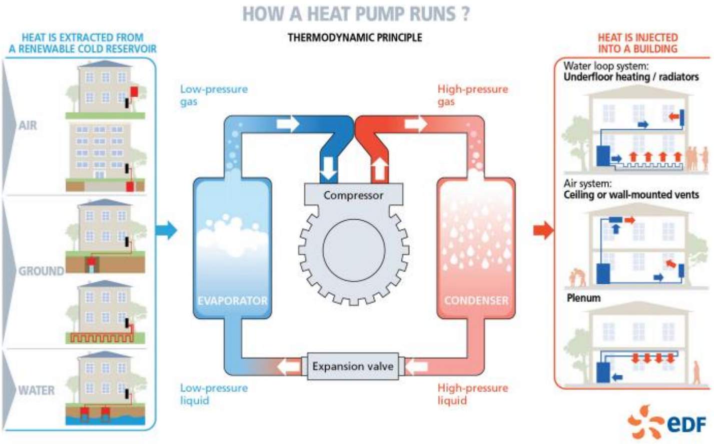


Figure 16 Heat pump functional scheme. Reproduced according to (R&D EDF, 2015). CC-BY-NC-ND

2.5.1.4 Electrical heating

The heating element inside every electric heater is an electrical resistor, and works on the principle of Joule heating: an electric current passing through a resistor will convert that electrical energy into heat energy with will heat an energy medium circulating inside the radiator (figure 17). The efficiency of any system depends on the definition of the boundaries of the system. For an electrical energy customer the efficiency of electric space heating is almost 100% because almost all purchased energy is converted to building heat. However, if a power plant supplying electricity is included, the overall efficiency drops drastically. For example, a fossil-fuel power station may only deliver 3 units of electrical energy for every 10 units of fuel energy released. Even though the electric heater is 100% efficient, the amount of fuel needed to produce the heat is more than if the fuel were burned in a furnace or boiler at the building being heated. If the same fuel could be used for space heating by a consumer, it would be more efficient overall to burn the fuel at the end user's building. On the other hand, replacing electric heating with fossil fuel burning heaters, isn't necessarily good as it removes the ability to have renewable electric heating, this can be achieved by sourcing the electricity from a renewable source. Therefore, the cleanliness and efficiency of electricity are dependent on the source.

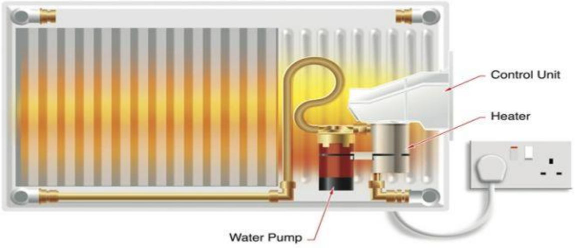


Figure 17 Electrical radiator. Reproduced according to (Elite Heaters Ltd., 2018) CC-BY

2.5.1.5 *Comparison of different heating systems*

Table 2 Comparison of different heating systems. Adapted from: (Gartland & Codema, 2018)

	Gas Boiler	Thermal Solar	Heat pumps	Electrical Heating	District Systems
		Individual systems			
Source	Gas/biomass/mini cogeneration	Solar energy	Ambient air, water or ground	Electricity (Grid)	Central generation (CHP or renewables)
Distribution	Water pipes	Water pipes	Water pipes	Wiring	Water pipes
Exchange	Radiators	Radiators or underfloor heating	Splits/ radiators/ underfloor heating	Electrical radiators	Underfloor heating or large radiators
Heat quality	Good	Good	Good	Bad	Good
Efficiency	Good	Good	Very Good	Bad	Very good
Renewable Energy	Only if biomass	Yes	Yes	Grid related, depends on the source	Yes (if 4th and 5th gen)

The optimal share of district heating might vary according to the specific region, and availability resources in the territory. For example in Europe the optimal shares of district heating versus individual heating solutions is 66% for Italy and Spain, 50% for the Netherlands and Germany, and between 27% and 43% for most other EU countries (Connolly et al., 2014). While for district heating a lot of cities have been used for such a comparison, in district cooling still there are no many studies. One common study on the city of Singapore is demonstrating that for the specific characteristics of this city, the optimal share of district cooling would be 30% due to specific restriction of the city in terms of available space for PV installation on the ground or poor wind availability (Krajacic, 2019). Moreover, warmer regions that have very high cooling density demands usually correlate with high global insolation, having a large potential for solar energy development. Consequently, a combination of solar energy and efficient heat pumps can be more cost-effective than having very large shares of district cooling based on waste heat utilization in absorption chillers.

2.5.2 Individual heating Vs centralized heating

In the previous paragraph it was clearly shown the need of different equipment linked to the dissimilar individual technologies. This becomes particular important when considering a wave renovation. Policies could push a technology rather than the other. In particular, DHC systems work with hydraulic systems, as boilers and heat pumps. On the contrary, electrical heating is based on electrical equipment plug and play in each room. As a result a conversion from electrical system to DHC would be more expensive and would require a deeper retrofit than traditional boilers (Euroheat & Power, 2020).

For this reason a well-conceived strategy for renovation wave should take in consideration at the same time the implementation of district heating, pushing it were the implementation of such systems is more profitable. At the same time, as demonstrated in the previous paragraphs, new generation DHC compared to old generation needs different equipment at building level, typically underfloor heating or wider radiators in order to have a greater exchange heating surface. Thus, even in this case, the source of heat influence the type of retrofit required.

At this point, of high interest could be the impact analysis of district heating in comparison with individual systems. Therefore, based on a global efficiency study of the entire value chain, in figure 18 and 19 it has been visually shown the comparison between district systems and individual installation in terms of CO_2 emissions and costs (EuroHeat & Power, 2007).

From these graphs, the positive effects of economy of scale it is not only related to cost but also to the technology's carbon footprints. In figure 18, for example, district heating produces four times less CO_2 emissions per kWh than electric heating which is highly dependent on the type of primary energy used to produce such electricity. In fact the PRF factors represents the primary resource factors measure the combined effect of efficiency and the use of renewable and surplus heat resources. The lower the PRF of a technology (in operation), the greater its contribution to reduce the use of fossil primary energy. The projection towards 2050, in figure 19, shows that heat pumps would be the only direct competitor of district systems in terms of cost per kWh (Hansen et al., 2016). As a result what is clear for the future decarbonization strategy is that district systems can play a great role in the decarbonization roadmap but not alone. In fact, they can easily be integrated and sustained by heat pumps: while district heating and cooling results as the best option for cities and high energy demand areas, heat pumps can be used in low energy demand areas such as rural areas with a great competitive role.

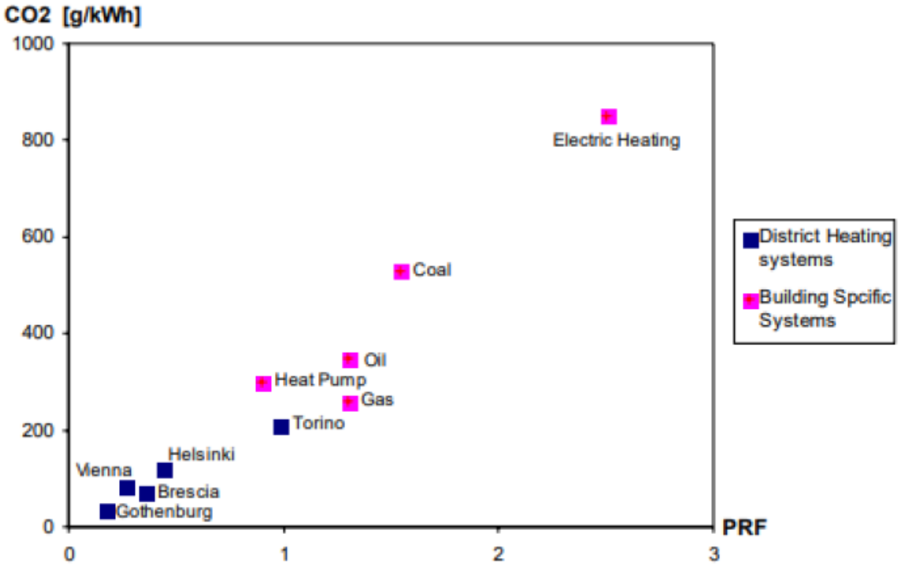


Figure 18 Comparisons of different heating systems: relations between primary resource factors and CO_2. Reproduced according to (EuroHeat & Power, 2007) CC BY-NC-ND

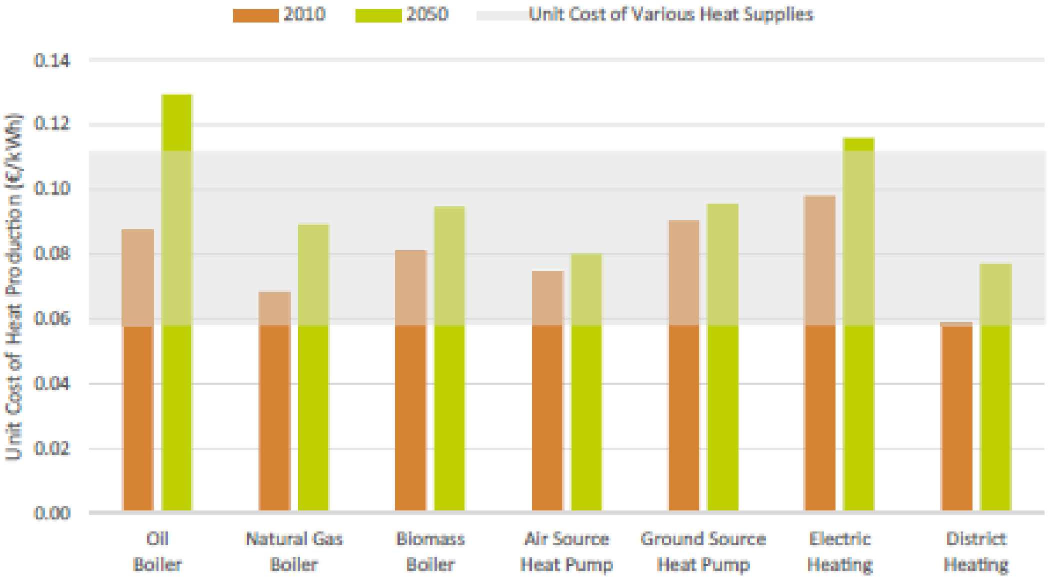


Figure 19 Unit cost of heating production for various technologies. Reproduced according to (Hansen et al., 2016) CC BY-NC-ND

2.6 District cooling network overview

As district heating, district cooling aims of using a network of pipes to cover cooling demand increasing the overall efficiency of the system. A typical district cooling is formed by a cold production plant, a re-cooling plant, cooling distribution network, seasonal and daily storage, as discussed in 1.1.3. A complete scheme of equipment of a cooling plant is reported in figure 20.

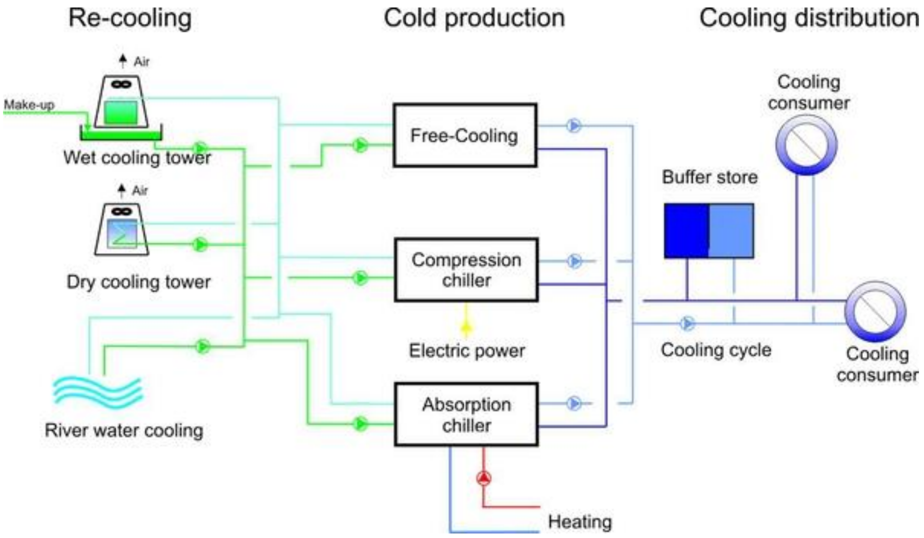


Figure 20 Simple design of a centralized cooling plant. Reproduced according (Bios Bioenergiesysteme GmbH, 2018) CC-BY-NC

2.6.1 Basic design of a centralized cooling plant

The production of cooling energy is based on three different energy sources:

Electric power: A compressor (piston, screw or turbo compressor)driven by electric energy compresses the refrigerant (e.g. ammonia, R134a etc.) which then condenses due to the re-cooling of the refrigerant. Thereafter, the refrigerant is expanded in an expansion valve causing a temperature drop and thus allowing the cooling of the secondary cooling cycle (e.g. water, ammonia or glycol). Thereby the refrigerant is evaporated and fed into the compressor. A different variety of electric driven chillers exist already on the market. To summarize it is possible to divide them in three different categories: screw, centrifugal and magnetic bearing chillers. The operational concept behind them are the same, the main difference are in performances at different current loads. In particular, in figure 21 it is possible to show the development of the energy efficient ratio (EER) at according to the chiller capacity load, where EER indicates the electrical performance of a chiller.

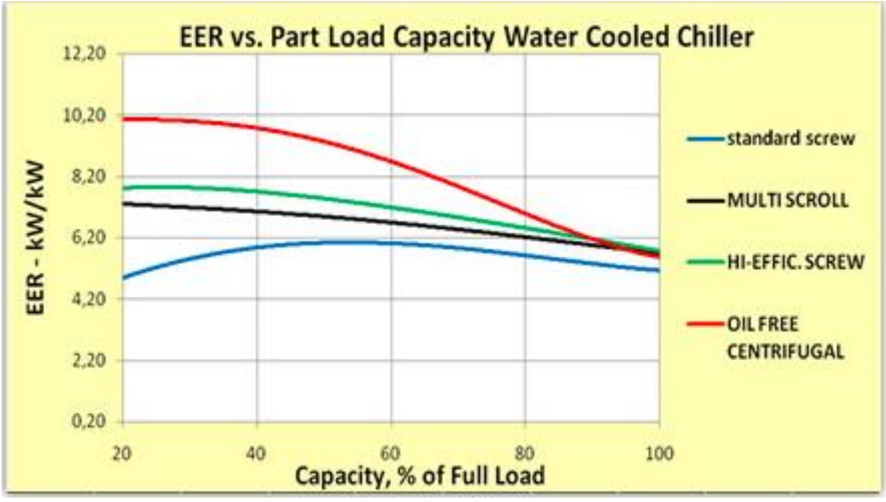


Figure 21 Energy Efficiency Ratio Vs Part Load.. Reproduced according to (Frigel Firenze SpA , 2020) Frigel Firenze SpA CC-BY

In figure 22, a similar analysis is done but taking in consideration centrifugal chillers against magnetic bearing ones. It is clear, in this case, following the coefficient of performances how the magnetic chiller is drastically working better at partial load in comparison with a centrifugal chiller.

These differences have to be taken in consideration in the design phase of the project according to the network demand and operational conditions.

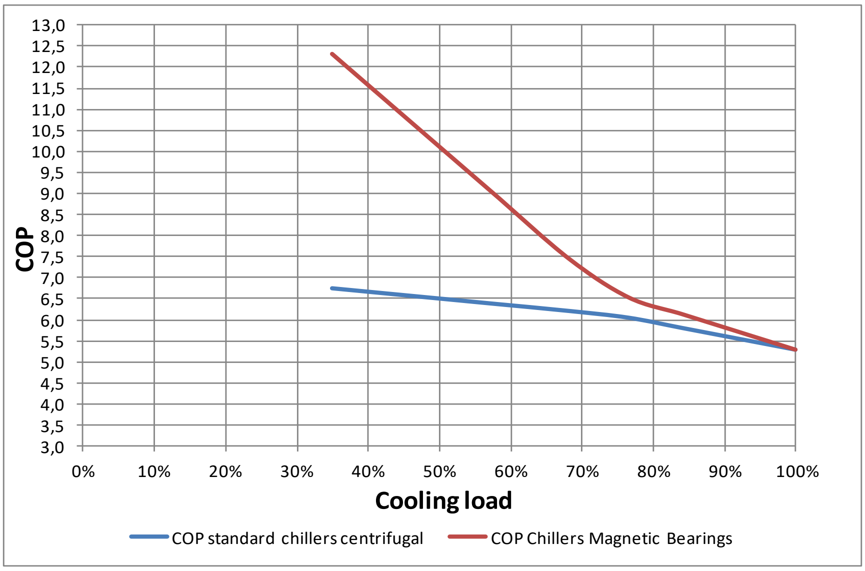


Figure 22 Centrifugal chillers performance Vs magnetic bearing chillers Reproduced according to (ENGIE Axima, 2020). CC-BY-NC-ND

Heat: Absorption chillers utilize heat in form of hot water or steam in a thermodynamic cycle for the cold production. Possible heat sources are district heating plants based on fossil or renewable fuel, waste heat or solar heat. The thermodynamic cycle of absorption chillers is based on a refrigerant and a solvent. The refrigerant must be totally soluble in the solvent. Absorption chillers based on lithium bromide and water achieve cold water temperatures of 3°C while the minimum temperature of the heat source needs to be 80°C. In order to achieve lower temperatures with absorption chillers the application of ammonia as refrigerant and water as solvent and higher temperatures of the heat source are required. Other technologies such as adsorption chillers or diffusion chillers are also suitable for cooling based on heat. Absorption chillers are used with form of waste heat such as incinerators. In order to compare different chillers efficiency a coefficient of performance need to be calculated as in equation 1.

$$COP = \left(\frac{Net\ Useful\ Refrigerating\ Effect}{Energy\ Supplied\ from\ External\ \ Sources}\right) \tag{1}$$

Free-Cooling: A heat exchanger connects the cooling cycle with the re-cooling cycle and allows a direct cooling of the cooling cycle by the re-cooling unit. Therefore, no chillers and no additional energy for the cold production are necessary. Free-cooling applications are depending on the re-cooling technology applied and the climatic conditions and are mainly applicable during the winter season. When surrounding conditions, such as river or lake temperature is below 8 °C, free cooling technology are implemented so cold water is directly used to cool down the network bypassing chillers and reducing the energy consumption (figure 23). This is the case of a DCS in Paris: seven chillers are installed in the plant, of which four use cooling towers and the other three use water from Seine to produce cooling thanks to heat exchangers. When the Seine’s temperature is below 8 °C, the three free cooling technologies are used to cooled down the network (Gang et al., 2015)

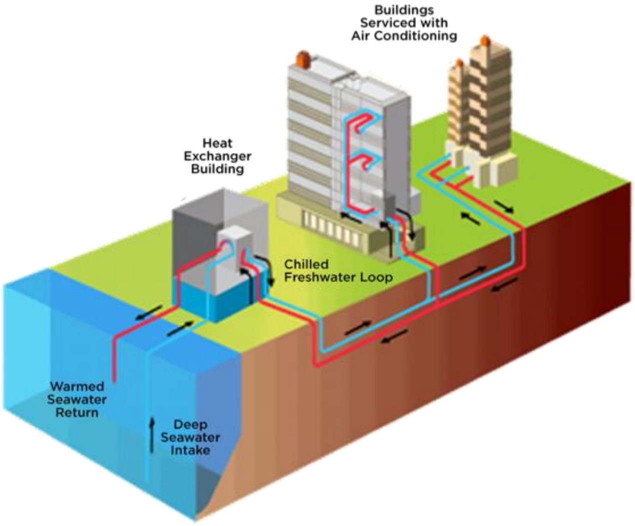


Figure 23 Free Cooling Scheme example. Reproduced according to (Angel Andreu et al., 2019) CC BY-NC-ND

The second part of cooling plant is the re-cooling plant in which the thermal energy transferred from the cooling cycle to the chiller and the electric or thermal energy input needs to be re-cooled. Generally, the following cooling systems are available:

- River water cooling
- Dry cooling towers
- Wet cooling towers
- Hybrid cooling towers

The selection of the re-cooling technology depends on site constraints such as the climate, the availability of cooling water and the required space. The re-cooling demand of adsorption and absorption chillers is significantly higher than the one of compression chillers and has to be considered appropriately.

Finally the distribution of cooling energy comes in place: the achievable temperature difference between supply and return flow of a district cooling system is considerably lower compared to the one of district heating systems. The air conditioning of buildings, which is the most relevant cooling application, requires feed temperatures of approximately 6 to 12°C. Hence, the flow rate in district cooling systems increases and larger pipe diameters are required compared to district heating networks. Furthermore, the investment costs and the operation related costs increase due to pipe size and increased pumping. The trend of the daily cooling demand of a district cooling system typically shows rather high short term peak loads. The integration of storage tanks is a feasible option in order to provide the cooling energy needed during such peak loads. This way, the cooling capacity of the compression chillers installed can be reduced and the cooling energy provided by absorption chillers can be increased (Gang et al., 2015).

2.6.2 Cooling design optimization

One aspect that highly influences the optimization of the network is the load profile of such network: a well performing DCS is not only positioned in a high-density energy area but also with an uniform distribution of buildings type, with an overall uniform cold demand, therefore minimizing the start and stop counts of chillers and ensure the system to work with a high stability (global COP optimization) (Gang et al., 2015). Another important aspect for the performance of the network is its design. The optimal combination of these two aspects should aim to lower at minimum DCS's energy consumption which are mostly related to chillers and pumps electricity consumption.

Most existing studies on DCS optimization are tackling the chilled water distribution networks (Chan et al., 2007). Such connection as in the case of heating can be direct or indirect using heat exchanger. The main differences are that in direct connection the installation costs and CAPEX are lower due to less needs of equipment, but the risks of cross contamination are way higher; in the case of indirect connection the efficiency is lower and the capital cost is increased because of the heat exchangers. Usually indirect connection is chosen since it is safer and more reliable for the stability of the network. The chilled water network can be organized in radial or tree shaped networks. Genetic algorithm (GA) is frequently used to get the optimal layout and size of the chilled water network as shown by (Chan et al., 2007). It is a probability searching algorithm, which is based on simulating mechanisms of creature genetics and the evolution in the nature environment (Xiang-li et al., 2010). The objective of the optimization could be the piping cost plus pumping energy cost, or in general an optimization of the annual equivalent cost of operation and maintenance.

Another way to reach a more efficient network is to use energy efficiency measures to improve the benefits. Some good practices to reach higher efficiency and lowering electricity consumption are:

- to circulate the chilled water with a large differential temperature, allowing free cooling to act more efficiently and for a longer period through the year;
- to use the outdoor air directly for free cooling when the outdoor temperature is even lower;
- to reduce the outdoor air intake based on ventilation demand, reducing the amount of work required to cool down indoors temperatures;
- to reset the indoor temperature set-point. For example, The One Degree project in Canada has demonstrated that adjusting indoor temperature closer to external temperatures for businesses can save 1.8 million tonnes of CO_2 emissions and more than 800 million CAD (One Degree, 2019).

From an operational point of view, it is possible to (Gang et al., 2015):

- Reduce the resistance of the pipelines reducing the friction, thus the losses;
- Increase the thermal capacity of the fluid in the chilled water network by adding a volume of pentadecane into the chilled water. With a larger thermal capacity, the flow rate and pump energy consumption can be decreased;
- Limit the pipe distance and enlarge the difference between the supply and return chilled water temperatures. The difference between the supply and return chilled water temperatures should be 8-10 °C (worst case not less than 5°C) for the system with thermal storage. The radius of the network should be 1-2 km considering the heat transportation loss.

2.6.3 High Temperature Cooling Network

As encountered in previous paragraphs for low temperature heating networks against old high temperature ones, the same principle could be applied to cooling networks. In fact, recent publications have demonstrated the possibility of rethinking and redesigning existing cooling networks in order to achieve an overall higher efficiency (M. Jangsten et al., 2020). In particular, the study proposes a high temperature district cooling (HTDC) characterized by design temperatures of 12/14 °C supply and 20/22 °C return. This study demonstrated the benefit of fighting low delta-T syndrome in order to reach higher temperatures and thus greater performances. Low delta-T syndrome is an effect of cooling networks due to a decreased return temperature from the substations, with a consequently additional usage of chillers as well as a higher water flow rate to supply the same cooling load. This behavior leads to an increased energy demand and a reduced amount of free cooling available which explains the needs to erase such effect. The problem of low delta-T syndrome is that it is closely linked to the customers assets, therefore there is not a unique solution to the problem. Eliminating low delta-T syndrome requires a high effort, and thus case by case should be study. Once again, as previously seen, renovations are needed in order to adjust assets to operational strategies, not only in terms of low delta-T syndrome but also to have the right equipment at the customer site. In particular, high temperature DC systems, request the decoupling of sensible and latent cooling loads which will be independently controlled by temperature and humidity (Xiaohua Liu et al., 2013). For example, in a typical customer installation, a high temperature water based cooling system, such as radiant panels, handles the sensible cooling load at a chilled water supply temperatures of 16 °C compared to conventional systems at 6/8 °C. The dehumidification is managed by a separate ventilation system.

Even if the implementation strategy of HTDC is quite demanding, the outcomes are quite relevant. In fact, eliminating low delta-T syndrome, the network is able to reach a supply temperature of 6° and a return temperature of 16 °C, which yields to multiples benefits, such as:

- Chillers are able to increase 50% their COP at a chilled water temperature of 16 °C, lowering the temperature between refrigerants’ condensing and evaporating temperature;
- Water flow rates are decreased thanks to high return temperature,;
- Usage of free cooling from natural resources can be increased, almost doubled for return temperature in the range 12/20 °C against 6/12 °C;
- Easier Integration of renewable sources.

At both local and regulatory scale, some work is needed in order to create a strong bone infrastructure for such systems to be widely developed. Moreover cooling networks needs to be better studied especially since the demand of cooling will strongly increase in future years.

2.7 4th and 5th generation DHC as integrated part of smart energy systems

As seen in previous paragraphs, the new generations of district network can and will change the usual way of thinking a centralized source. In fact, lower temperature for district heating and higher temperature for district cooling not only will provide an overall better efficiency in the system but also will enable more and more the integration of renewable energies in the network, drastically reducing though the apport of cities’ CO_2 emissions. Additionally, new generation district networks will be a key factor in the design of the innovative concept of smart energy grid where multiple energy sources come together to act in a whole system bounded by different types of synergies. As shown in figure 24, DHC will assure new possibilities to exploit energies which before were lost, such as waste heat or recovered heat of industries as well as pushing co-generation technologies with direct coupling with the electrical grid. On top of this, new business models and new strategies will be enabled such as the use of thermal storage systems coupled with district networks. Finally, it is possible to think about a whole integral system where electric grid meets and cooperate with thermal grid supported by new digital means.

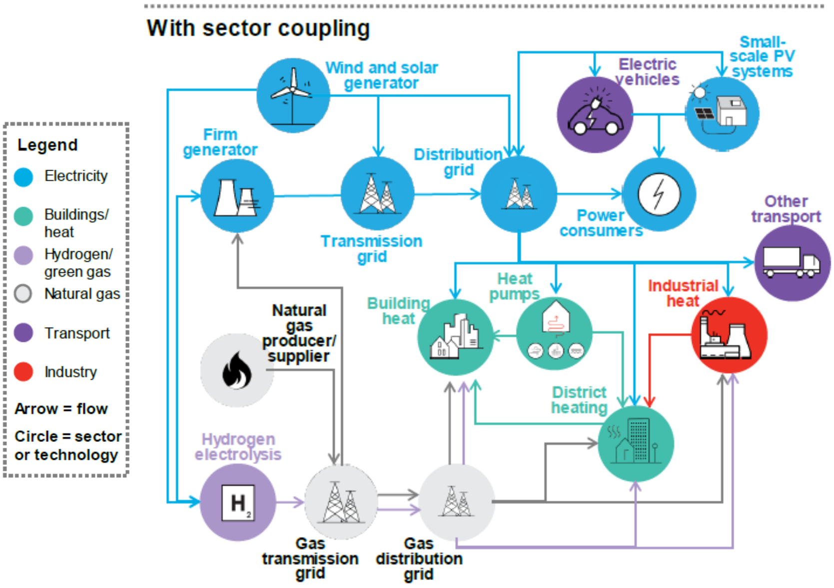


Figure 24 Sector Coupling Scheme. Reproduced according to (Coker, 2019) CC BY-NC-ND

3. Thermal energy storage

Thermal energy storage are units of different size which can retain thermal energy (heat or cold) thanks to their physical properties. Such characteristics are linked to the type of material used, named storage medium. The application of large scale thermal energy storage (TES) units in district heating networks has the power to better manage the coupling of demand and supply of both heating and cooling. One of the main advantages of storage is its ability of flattening the demand curve by filling the gap between demand and supply. The demand curve, in fact, is dependent of several parameters: people consuming behaviors, external temperature, hour of the day, period of the year, etc… All of them contribute to peaks during different time of the day or of the year, as shown in figure 25 (Guelpa & Verda, 2019).

In very few words, TES coupled with DHC provides more flexibility to the grid and a higher overall performance of the network enhancing the smart integration of renewables in the thermal network. Enlarging the network, including more buildings, will push down costs and global emissions. The application of TES systems in industrial and building sectors is expected to provide an annual energy saving up to 7.8% in the European Union (Arce et al., 2011). As for the environmental impact, the utilization of these systems can reduce CO_2 emissions by 5.5% (IEA-ETSAP, 2013). More in general, the use of TES in Europe allows to save annually about 1.4 million GWh (IEA-ETSAP, 2013).

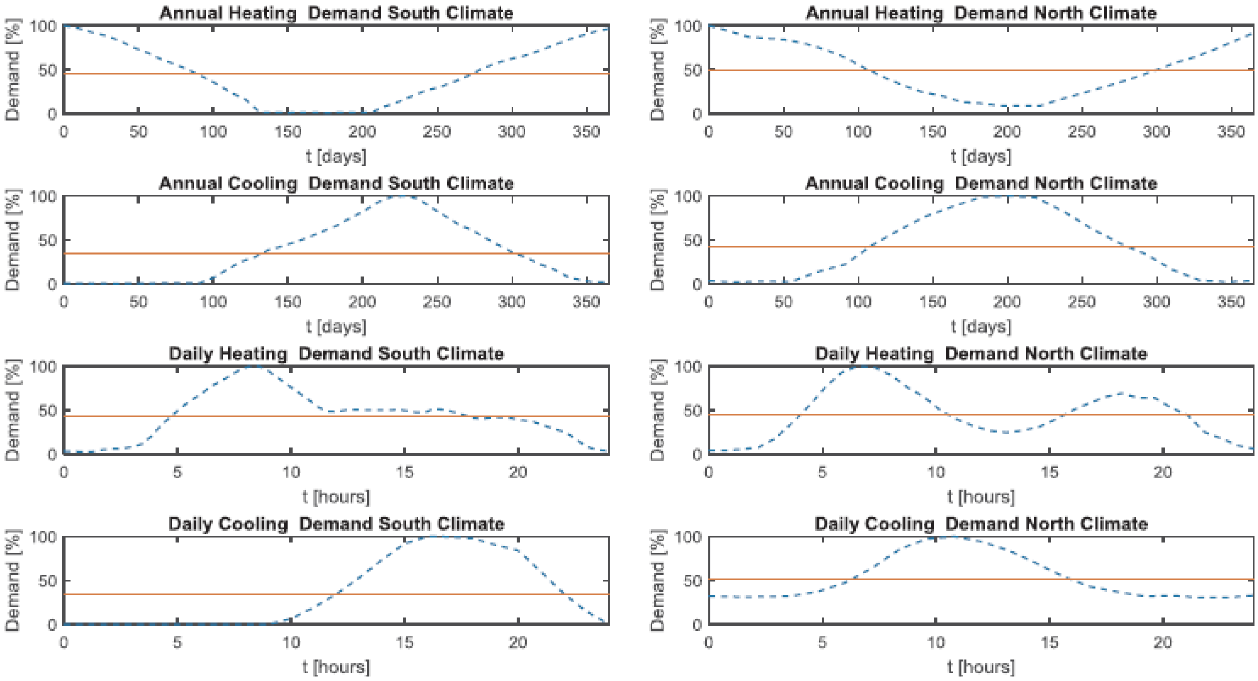


Figure 25 Thermal demand evolution. Reproduced according to (Guelpa & Verda, 2019) CC BY-NC-ND

3.1 TES Benefits

Some of the benefits of thermal energy storage are (Guelpa & Verda, 2019):

1) The increasingly flexibility due to storage system installation should influence the conception and design of CHP plants. In particular, it allows reducing generation units increasing the equivalent operating hours and reaching the needs for supplementary generating capacity;

2) When they are connected to the primary line of DHC networks, they allow a smaller pipe size in the distribution network;

3) Minor use of boiler and chillers as the available heat stored allows tackling rapid demand changes;

4) Increase the overall performances by means of time-varying management;

5) Thermal storage installed in DHS connected to cogeneration plants allows a better management of CHP plants, making it possible to shift the production of electricity to hours when electricity unit price are higher. This allows maximizing profits by making more flexible the combined generation of electricity and heat;

6) Relieving the intermittent feature of energy generated from renewable energy sources. This allows DH to become a platform for the flexible selection of various energy sources;

7) Storage allows reducing operational cost, such as the cost due to pumping systems, by reducing mass flow rates in some area of the network during the peak request. Pumping costs are not negligible, especially in large DH networks when primary energy consumption is around 1% ;

8) When installed on the primary line of an existing DH network, TES allows overcoming the limitations in circulating mass flow rate. It allows increasing the number of users connected without modifying the network design. It can be combined with a model for the optimal connection of further buildings;

9) In the user perspective, large scale TES at DHC level does not require large annual maintenance comparing to individual systems;

10) Cold TES is particularly suitable for DHC technology since:

- During summer, peaks in the electricity demand usually occur when the cooling load is large. Due to the large (and increasing) cooling demand, simultaneous peaks in the cooling demand and electricity demand take place.
- Tackling peak load is more expensive in case of district cooling. This is mainly related with the installation costs of centralized cooling systems, which are not often available in residential buildings.
- Cooling daily demand varies more than heating demand, as the cooling demand is significantly affected by the solar radiation.

3.2 TES drawbacks

Few main drawbacks related to thermal energy storage are the following:

1) The investment costs of the installation are non-negligible. Costs vary totally depending on the type of TES considered.

2) A dedicated space has to be reserved for the installation. This is a typical problem of all the storages, at various levels (distributed, concentrated). The issue becomes more demanding when long-term storage is considered.

3) Thermal losses that occur during all the phases of the storage process can be significant. The problem of thermal losses is particularly important for long-term storages. Research should be further intensified in this direction.

4) The design of the system and the connection planning can be challenging.

5) The lack of suitable supportive legislation could create problem in the design and approval stages. (Guelpa & Verda, 2019)

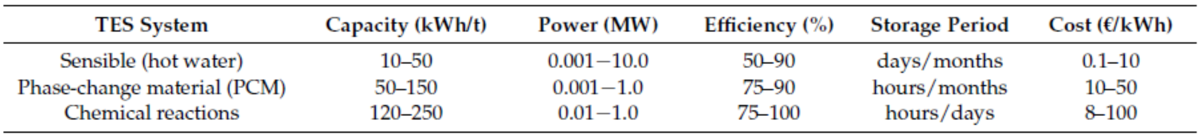
3.3 Main technical characteristics of an energy storage system

An energy storage system can be described in terms of the following characteristics (IEA-ETSAP, 2013):

- Capacity defines the energy stored in the system and depends on the storage process, the medium, and the size of the system;
- Power defines how fast the energy stored in the system can be discharged (and charged);
- Charge and discharge time defines how much time is needed to charge/discharge the system;
- Efficiency is the ratio of the energy provided to the user to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging/discharging cycle;
- Storage period defines how long the energy is stored and lasts hours to months (i.e., hours, days, weeks, and months for seasonal storage);

The main parameters for different storage typologies are reported in table 3. Clearly sensible storage is the less performant of the three, however thanks to its low costs it is widely applied in a high number of projects.

Table 3 Typical parameter of TES systems. Adapted from (Sarbu & Sebarchievici, 2018)



TES System	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage Period	Cost (€/kWh)
Sensible (hot water)	10–50	0.001 − 10.0	50–90	days/months	0.1–10
Phase-change material (PCM)	50–150	0.001 − 1.0	75–90	hours/months	10–50
Chemical reactions	120–250	0.01 − 1.0	75–100	hours/days	8–100

3.4 Classification of TES

Thermal Energy Storage units can be classified according to different criteria as shown in figures 26 and 27:

1) Physical: sensible, latent and chemical storage;
2) Storage duration: short term storage, long term storage;
3) Storage location and dimension: distributed, localized, mobilized;

Sensible storage is the most common and implemented type when it comes to hot water, mostly because it is the most mature technologically. On the contrary, latent and chemical storage are less technologically ready. However, they have shown to have a great potential for reducing thermal losses and storage volume.

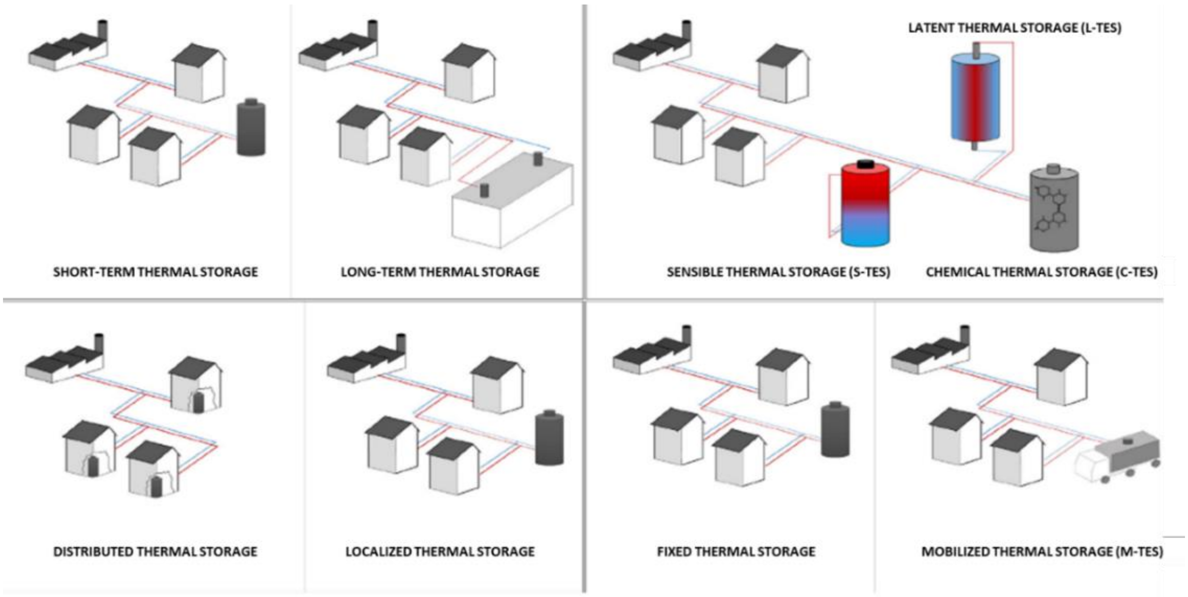


Figure 26 Classification of TES connected to DHC systems. Adapted from (Guelpa & Verda, 2019)

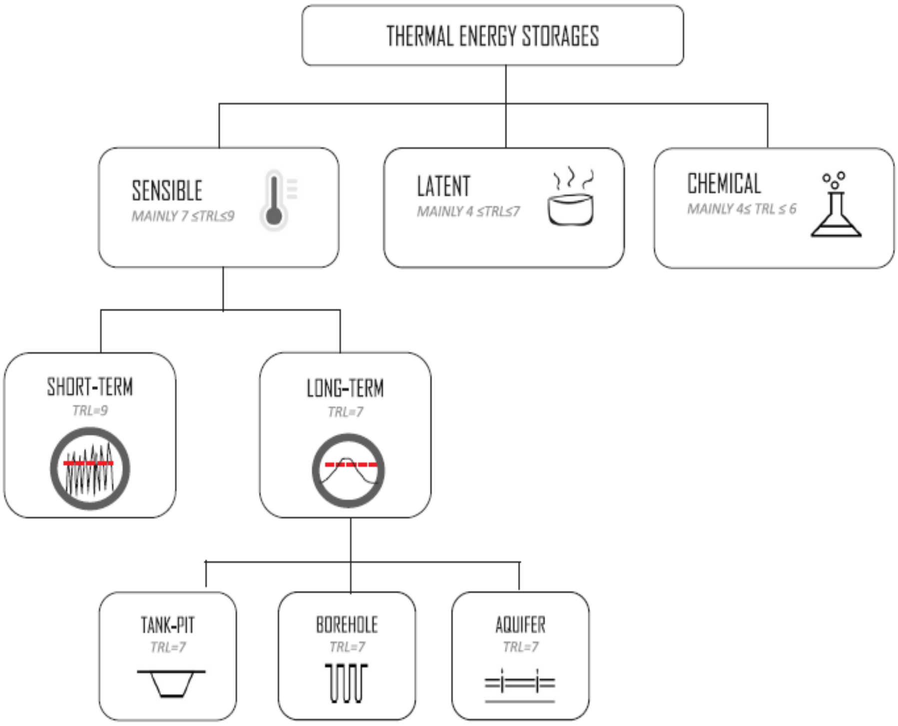


Figure 27 TES classification and Technology readiness level (TRL). Adapted from (Guelpa & Verda, 2019)

3.5 Short term thermal storage for district cooling application

Thermal storage technologies can be used for both heating and cooling network. So far, for massive district application, water is the most common used carrier because it is less expensive compared to other materials and it does not require the use of toxic materials. During previous chapters, heating networks have been used as a starting point for the study of cooling networks since specific publication on cooling networks are not that many yet. The concepts of district heating can be applied in the same way, with some adjustment, in district cooling. Therefore, from now on the study will be focused only on cooling networks preparing the reader to the case study.

When it comes to short term, the objective is to dimension a tank to cover a daily or weekly demand. Water tanks have been widely used for large applications; however, as shown in table 4, their CAPEX is strictly linked to the required land surface which could lead to a great impact on initial investment. For this reason, new forms of alternative storage applications have been studied, namely, passing from cold water to iced water, to ice. In other terms from sensible to latent thermal storage.

Water has the following characteristics:

- Specific heat capacity, Cp = 4,18 kJ kg^{-1}K^{-1} (1,16 kWh m^{-3}K^{-1});
- Latent heat of ice fusion, L = 335 kJkg^{-1} (93 kWh m^{-3}),
- Density, d = 1000 kg m^{-3}.

$$L = \frac{Q}{m} \tag{2}$$

$$Q = mL \tag{3}$$

$$m = d\,V \tag{4}$$

$$Q = (d\,V)L \tag{5}$$

$$V = \frac{Q}{d\,L} \tag{6}$$

Where V is the volume, Q is the amount of energy in the form of heat required to completely effect a phase change, m is the mass.

Therefore, applying equation 16, a 100 KWh cold storage needs:

- with water cooled from 14 to 4 ° C, a volume of about 8,5 m^3, which is a ratio of about 12 kWh / m^3,
- with ice, a volume of about 1,1 m^3 meaning a ratio of about 100 kWh / m^3.

In this example, for the same amount of energy stored, the storage volume is divided by 8 (or with the same volume, 8 times more energy is stored) when using the latent heat of water. An example is shown in table 4. Nevertheless, even if latent storage has been demonstrated to be more performant than sensible storage, at current state the majority of application are still represented by cold water tanks because of their relative small investment. However iced storage is taking over especially in situation where a lot of constrains are present. The following paragraphs will present the two technologies.

Table 4 Influence of the compactness of the tank on the cost of storage by stratification; Adapted from (Cylergie Lab. ENGIE, 2011)

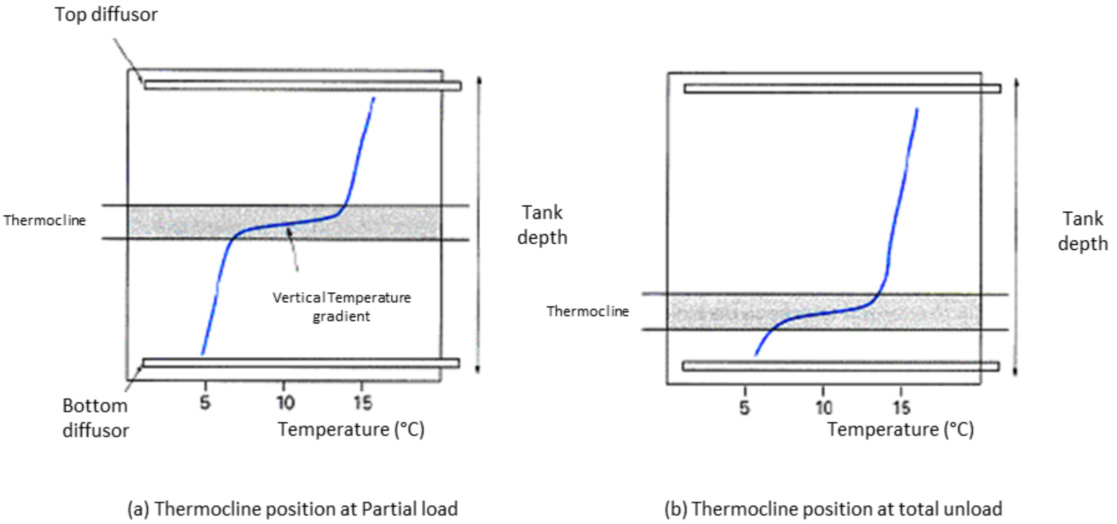
Energy Stored (kWh)	5000		
Volume necessary (m3)	500	500	500
Height (m)	27	20	10
Floor area (m2)	18,5	25	50
Cost tank + foundations (€/kWh)	**115 000**	**100 000**	**90 000**
Land (€ based on 10000 €/m2)	185 000	250 000	500 000
Total storage cost with land (€/kWh)	**300 000**	**350 000**	**590 000**
Part of the land (%)	**62**	**71**	**85**

3.5.1 Cold water storage

The sensible heat storage is performed by cooling a volume of water on a temperature gradient suited to the intended use. Water remains in the liquid state. Generally temperatures are between 4 and 13 ° C. For air conditioning applications these temperatures correspond to departure and return network. The gradient is about 9 ° C. With a gradient of less than 5 ° C, the sensible heat storage is no longer considered economic because of excessive volumes that would result. The amount of stored energy is directly related to the temperature gradient and to the storage volume. A major problem is the mixture between water cooled at +4 ° C and return water at 13 ° C. It's very important to avoid this mixture to keep a significant temperature gradient. Different technologies have been developed. Storage compartments, tanks series, parallel and membrane tanks are listed for information but are not installed anymore. Only natural stratification storage is currently relevant. This method, the most interesting in ice water storage systems use the principle of natural stratification in vertical tanks (Cylergie Lab. ENGIE, 2011).

This technique is predominant in sensible heat storage technologies due to its simplicity and efficiency and remains the most economical. Indeed, much cheaper, it requires only one tank and avoids the presence of physical interfaces. In the bottom of the tank is withdrawn or introduced water to the lower temperature, and in the top part to the return water at 13 ° C. As shown in figure 28, thermal stratification is carried out by difference in density of the water as a function of its temperature. Separation takes place naturally by a layer of water acting as a stopper called "thermocline". The "thermocline" in this application, plays the role of a membrane. The height of the tank depends on the amount of energy that is to be stored and available space. Tanks typically found 15 to 25 meters high (Cylergie Lab. ENGIE, 2011).

The life time of a cold water storage is around 30 years and according to studies on real-word example, for chilled water storage technologies, CAPEX is in the range of 265€ to 1060 €/kW, for 6 hours discharging even if it varies based on the specific type (John S. Andrepont, 2016).



(a) Thermocline position at Partial load

(b) Thermocline position at total unload

Figure 28 Natural Stratification Storage. Reproduced according to (Cylergie Lab. ENGIE, 2011) CC BY-NC-ND

3.5.2 Iced water storage

As previously demonstrated, iced water storage can play a critical role in reducing storage volume. The phenomenon of phase change taking place at constant temperature, it is easier to keep constant the starting temperature of iced water. Unlike the heat sensitive storage, where the power is available at any time, the latent heat storage has a time lag due to the phenomenon of phase change. To minimize and optimize this time, various technologies have been developed. There are two forms of iced storage, dynamic and static. In dynamic storage, the water that is in contact with the ice formation is used directly by the user. Discharging capacities are very important (very good exchange coefficient) and the temperature obtained very low (close to 0 ° C), which is more for industrial applications. Some examples of dynamic storage are: ice melting on external tube, ice harvested and process «mud or ice slurry». On the contrary, in static storage, water is used to make the ice and thus the stocked energy remains in the cold tank, energy is transferred thanks to intermediate cooling pipes. Ice melting on internal tube and encapsulated ice are two of the main used applications (Cylergie Lab. ENGIE, 2011).

Cold storage systems with phase-change material have a CAPEX of 1500 €/kW and 250 €/kWh and their efficiency is around 90% (ENEA Consulting, 2012).

3.5.2.1 Ice melting on internal tube

Under load, brine is brought to a negative temperature by the chiller's evaporator and allows the formation of an ice layer on the tubes of the heat exchanger immersed in the tray. In discharge mode, the same brine goes to the user, returns heated in the tray and allows the ice melt from the inside to the outside of the tubes. In these systems, 10% of the volume is provided for expansion of the water during the phase change. The remaining volume is devoted to crystallize. The level in the tank is variable and measurable, allowing the determination of the amount of ice formed and therefore the storage capacity (300 to 5000 kWh) (Cylergie Lab. ENGIE, 2011). The heat exchanger tubes, arranged horizontally and regularly spaced, are most usually made of steel and may have a cylindrical or elliptical form. The exchange surface is around 0.15 to 0.20 m² / kWh. The ice tray can be made of plastic, steel or concrete. Then it must be insulated and sealed. For storage capacity for less than 2000 kWh (corresponding to a 40 m3 tank), the tank can be made directly at the factory. Beyond this capacity, a design of several tanks in parallel or built with prefabricated modules should be considered. In figure 29 it is illustrated the process of brine making in the exchanger. During the charging period, from the injection of negative glycol (EG) in the tube, a layer of ice "G" forms around the pipe. In the discharging phase, the glycol water returns from the user in the exchanger internal pipes at a positive temperature melting the ice around the tube.

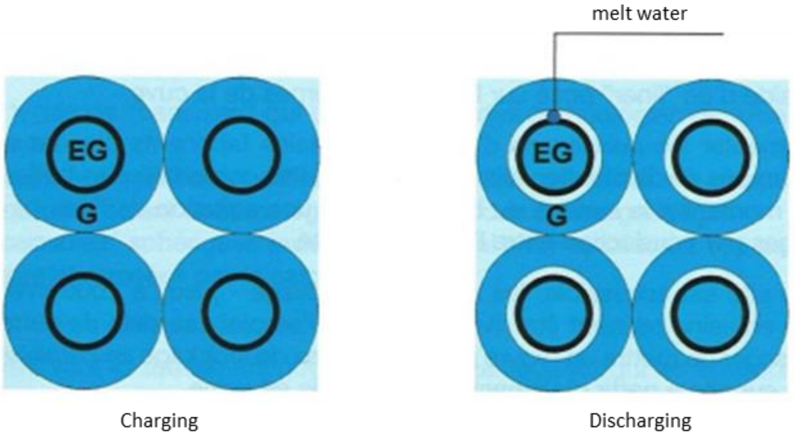


Figure 29 Ice melting on internal tube - formation and melting of ice on the heat exchanger. Reproduced according to (Cylergie Lab. ENGIE, 2011) CC BY-NC-ND

3.5.2.2 Encapsulated Ice

Encapsulated ice is one of the most recent but also one of the most reliable. A storage tank is filled with spheres containing the storage material, usually water for tertiary air conditioning. All these spheres with a diameter of 10 cm form the heat exchanger store. The tanks are usually cylindrical (vertical or horizontal depending on the configuration of the site) but can also be rectangular. The number of tanks can be multiplicated depending on the desired storage capacity. The typical ratio to be used for this technology is about 50 kWh/m^3 for air conditioning applications and the use of ice as a material storekeeper. This ratio is lower than the intrinsic latent heat water to 93 kWh/m^3 and takes into account the volume of brine required (approximately 40% of tank volume). For example, for a stored energy of 7.8 MWh, three tanks with a volume of 56 m^3 each can be installed (Cristopia Energy Systems, 2019). The spheres are made of plastic (polyolefin blend), material capable of being deformed and withstand the mechanical stresses caused by cycling, and the pressurization of the vessel. A pocket of expansion must be designed to absorb the increase in volume due to the crystallization of the water. Filling the tank with the plastic spheres is extremely easy also on site (Cylergie Lab. ENGIE, 2011). In fact, thanks to their spherical shape the spheres are displacing themselves even without human intervention. In addition, the diameter of 10 cm spheres allows large exchange surface, which are around 0.6 to 1 m²/kWh. In charging mode (figure 30), after passing through the chiller evaporator, the brine in the primary circuit enters into the tank from the bottom allowing the crystallization of the water within the spheres.

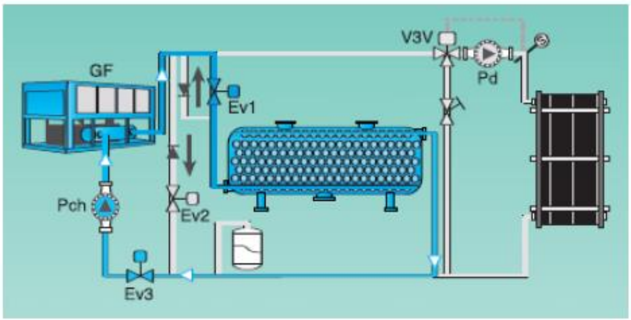


Figure 30 Encapsulated Ice - charging mode. Reproduced according to (Cylergie Lab. ENGIE, 2011) CC BY-NC-ND

In discharging mode (figure 31), the brine of the primary circuit enters the tank from the top and melts the ice encapsulated. The primary circuit gives these kilocalories in the secondary circuit thanks to a heat exchanger. The temperatures across the heat exchanger are typically 5 ° C / 10 ° C on the primary side and7 ° C / 12 ° C on the secondary side (Cylergie Lab. ENGIE, 2011).

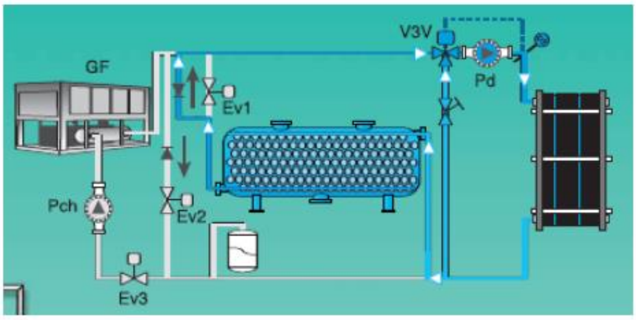


Figure 31 Encapsulated Ice - discharging mode. Reproduced according to (Cylergie Lab. ENGIE, 2011) CC BY-NC-ND

As shown in figure 32, compared to ice melting on internal tubes, encapsulated ice is able to manage the cooling needs simultaneously by the storage tank and the chiller, reaching a great flexibility compared to other models. Moreover, a damaged sphere has no impact on system performance due to the large number of them in the tank (40 spheres are needed to store 1 kWh). The advantage of the encapsulation is the possibility of replacing the water in the interior of the sphere by another phase change materials. Eutectic salts are part of phase change materials typically used for applications other than air conditioning. In particular, some industrial applications require lower temperatures and thus PCM with a negative melting temperature (pharmaceutical industries, slaughterhouses, breweries, ice rinks ...).

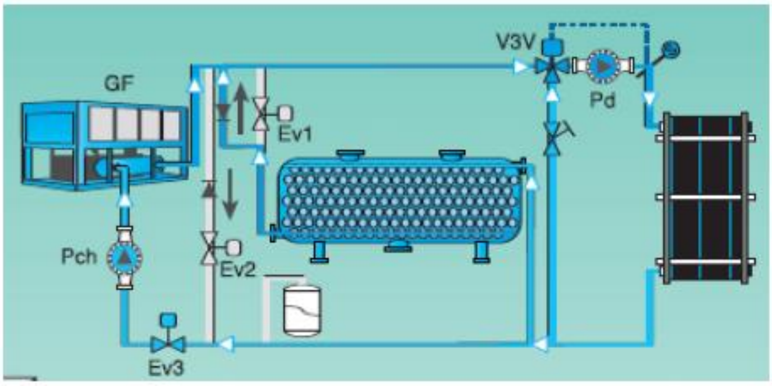


Figure 32 Storage of encapsulated ice – direct production and discharge. Reproduced according to (Cylergie Lab. ENGIE, 2011) CC BY-NC-ND

The installed cost for ice-on-coil and encapsulated ice storage is about $70/ton-hour (Federal Energy Management Program, 2000). According to principle manufacturers, although there could be economies-of-scale associated with the tank or containment vessel, most ice-on-coil systems come in preassembled tank and coil packages of moderate individual capacity with larger capacity needs met via multiple tanks.

3.5.3 Comparison of main characteristics of used technologies for cold storage

Table 5 shows a summary comparison of the main characteristics of the cold storage.

Table 5 Sensitive Storage Vs Latent Storage. Adapted from (Cylergie Lab. ENGIE, 2011)

	Characteristics	**Sensitive Storage**	**Latent Storage**
Cooling	Operating temperature	5 °C	-6 °C for ice
	Coolant	water or water with glycol	Water with glycol
	Investment cost	Normal	Slightly more expensive
Storage	Volume	Important, large area associated	Smaller and compact (volume reduced by 2 or 3 times compared to a sensitive storage)
	Flow temperature	Variable	Stable
	Power availability	Immediate	With delay
Distribution	Separation primary/ secondary	Not necessary	Heat exchanger required
	Maintenance	Simple	More complex
	Application	Air conditioning	Air conditioning
CAPEX	€/kW	265 - 1060	1500

3.6 Energy storage as a key component against CO_2 emissions

Beyond technical and economic interests, energy storage is part of an overall strategy to achieve a low-carbon energy mix (ENEA Consulting, 2012). The large-scale deployment of intermittent energy cannot be achieved without the development of compensatory solutions. At current state, peaking power plants overcome the hazards of renewable energy scarifying, on the other hand, the overall performance in terms of CO_2 emissions. In the long term, an approach more integrant coupling renewable energies with energy storage technologies could achieve great benefits under the environmental policies. The use of storage systems coupled with combustion plants actually represents a double benefit, first for the CHP plant which lowers its emissions, secondly, storage has an indirect impact in renewables lifetime and operation, especially wind, by reducing their loads and thus the frequency of starts and stops. An example, shown in figure 33, highlights the correlation between electricity demand and CO_2 emissions. In fact, electricity carbon content is strongly related to the type of sources used. When directly or indirectly the peak demand is covered by combustion plants it is natural that the carbon content increases drastically. If this happens and thus at peak power plants emits more CO_2 than their baseloads counterparts, energy storage can play a fundamental role lowering the emission from electricity production: low carbon energy is stored off-peak and released at peak period as a substitute of higher emitting plants.

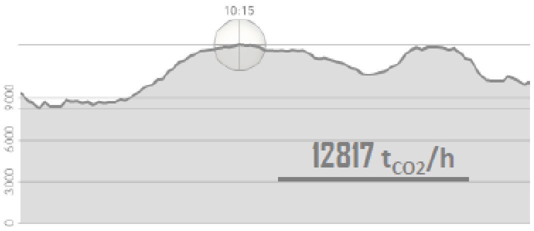


Figure 33 French electricity carbon content during the 8th of February 2012. Reproduced according to (ENEA Consulting, 2012) CC BY-NC

4. Case study

This chapter will analyze and discuss a specific case study of application: the district cooling network of the Canadian city of Ottawa will be chosen as an example of modernization of an existing network of 2nd generation DHC to 4th generation DHC. A digital platform, called NEMO, will be used in addition to an artificial intelligence algorithm applied directly to storage systems.

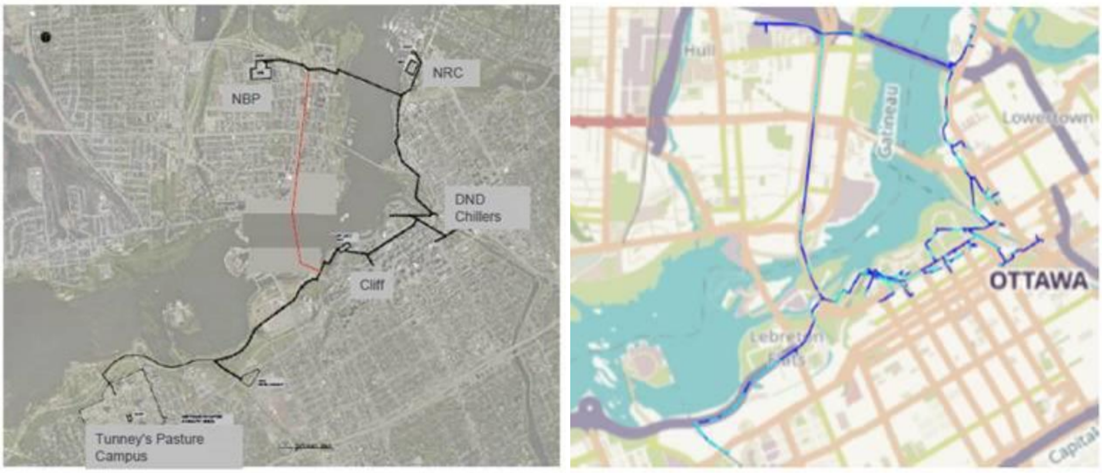
4.1 Network definition

For this specific case study, a district heating and cooling network operated by Engie in the city of Ottawa, Ontario, and Gatineau, Quebec, Canada, was considered. This specific site has been chosen as a pioneer example of conversion of an old 2rd generation district heating and cooling network running on steam to a more innovative 4th generation network (ENGIE Services Inc, 2019). As shown in figure 34, in the city of Ottawa, before Engie intervention, there were already four distinct networks: National Printing Bureau (NPB) on the Gatineau side under the jurisdiction of Quebec State, Cliff, Tunney’s Pasture (TP) and Confederation Heights on Ottawa side, Ontario State. All of them were composed by a steam heating network coupled with a cooling network. The four networks are independent from each other.

Figure 34 Map of Ottawa city highlighting the already existing generation sites. Adapted from (Google Maps, 2019)

In 2019 Engie signed a 35 year public-private partnership contract to modernize, maintain and operate the National District Energy System (DES) composed of 4 Power plants totaling 140 MW Heating and 100 MW of Cooling that heats 80 buildings and chills 67 buildings, including the Parliament Buildings, in Canada's Capital Region. Part of the deal includes the interconnection between the generation point of NPB, Cliff and TP (figure 35) through a low temperature network exploiting the recourse of River Water free cooling, while renovating the equipment on one side with heat pumps and in the other with chillers working with next-generation refrigerant (in this case R1233ZD) characterized by a Global Warming Potential of one and an Ozone Depleting Value of zero. The global warming potential (GWP) is the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide (CO2); GWP for CO_2 is 1, The comparable medium-pressure machine uses a refrigerant with a GWP of 573. The ozone depletion potential (ODP) of a chemical compound is the relative amount of degradation to the ozone layer it can cause. An ozone depleting value of zero means that the ozone layer is not touched.

Thanks to these changes the project will achieve several key objectives, such as: reducing carbon footprint pollution by 63% and improving the overall District Energy System efficiency while improving resiliency and working safety conditions. Such a solution was aligned with the Government of Canada's environmental policy, which had set itself a first objective of reducing its energy consumption and greenhouse gas emissions from operations by 40% by 2030 (ENGIE Services Inc, 2019). As a pioneer of energy transition, once the first objective will be achieved, Canadian Government aims to recourse to more renewables converting the base load to carbon neutral fuels.



(a) (b)

Figure 35 (a) Final Network Design after Engie intervention, (b) Network design simulation using Engie's NEMO platform. Adapted from (ENGIE NEMO,2019)

The interconnection work cited above will take place in the cooling network between NPB and Cliff, while Tuneey’s Pasture will keep a standalone network. Confederation Heights is kept out of the picture because it is not taken into consideration in the interconnection. It will remain a standalone heating and cooling network.

4.2 Previous feasibility study and work definition

As a possible call to innovation, a first preliminary feasibility study of a thermal storage technology application in the Ottawa network has been done by Engie in 2019 (ENGIE Digital, Internal Report Innovation Technologies Ottawa Case, 2019). Such a study aimed to explore the benefit of a storage system in the network according to the current and future operational boundaries, namely: production and usage rates. To do so an in house platform called NEMO has been used (ENGIE Digital, NEMO, 2020). NEMO is an internal digital platform of ENGIE and it is able to optimize the behavior of a cooling district network as well as a cold production plant simulating the best operational scenario in terms of costs. In this specific case, the tool has been used to optimize charging and discharging rate of an extremely large size thermal energy storage tank (above 45000 m^3) installed at Cliff. In this way, after the simulation, according to the maximum percentage of charging, it is possible to dimension the storage system. Taking in consideration the future load, for which both sites of NPB and Cliff will most probably be operating, Cliff has been selected as the best location for storage application because of Ontario’s higher price of electricity, which is 2.4 times higher than in Quebec. A second reason is depending on the available power in NPB: since NPB at current load is already running almost at its maximum capacity, there is not left much space for storage demand. The interconnection between the two sites anyway allows both sites of covering the storage demand if available, this is why at current load even if Cliff is not used, NPB is able to cover the storage demand. The use of NPB at its maximum capacity is a natural consequence of the lower price of electricity in Quebec compared to Ontario, as shown in table 6.

Table 6 Average electricity price according to contractual conditions

Plant name	**NPB**	**Cliff**
States	Quebec	Ontario
Electricity Price [ct/kWh]	6,81	16,41

A preliminary simulation (table 7), made for the linked network of NPB+Cliff, showed that at current load peak (60MW, figure 36), TES would barely be used since NPB at maximum capacity meets quite easily the system demand year-round. A different conclusion for the simulation of the future peak load represented in figure 37 (160 MW) (ENGIE Digital, Internal Report Innovation Technologies Ottawa Case, 2019).

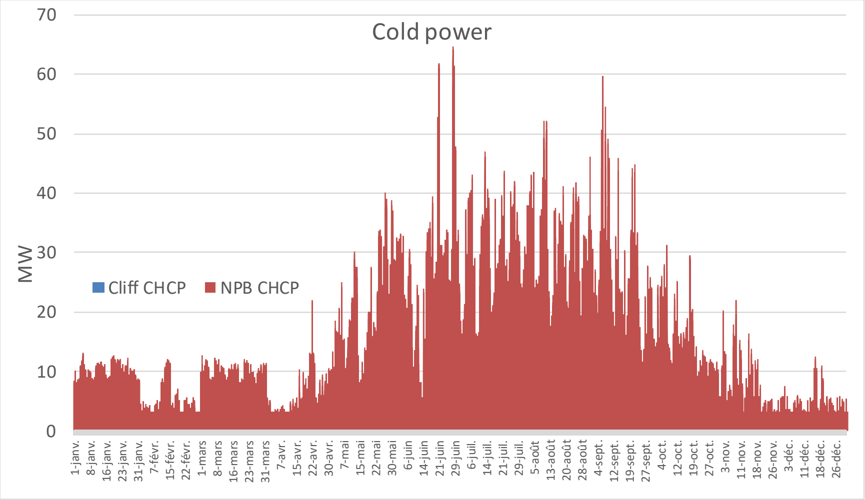


Figure 36 Cold Power at current load - peak at 60 MW

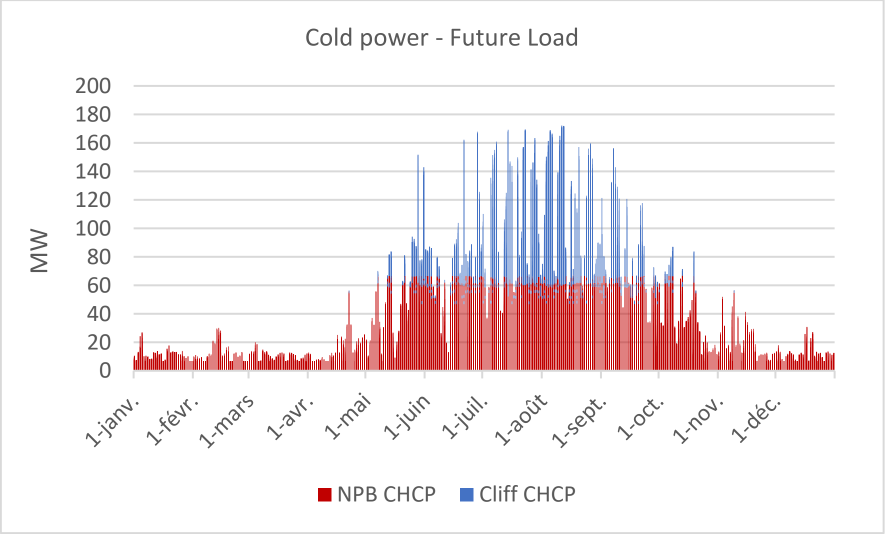


Figure 37 Cold Power - Future Load (peak at 160 MW)

In this case, TES would cover part of the demand however, it would not significantly reduce Cliff production requirement and charging would be limited by two factors: an almost full capacity usage of NPB in summer time, with not enough available charging at night on one side, and a small percentage of operational hours for Cliff which is active only during peak demands (less than 20% yearly hours).

According to this rough simulation and optimization, following the future load, TES would have an annual cost saving around 33k CAD which is not enough to justify the initial investment (around 5 M CAD). A detailed table of this preliminary study is reported in annex 2, A.2. However, such a study did not take in consideration real electricity tariff price. The usage of an average daily value is by default limiting the benefits of a possible TES application. Therefore, the present study will focus on a more detailed study of possible network innovation. In particular, as represented in table 8, five different scenario will be implemented on NEMO taking in consideration both current load network and future load network. The objectives are:

1) proving that thermal storage can bring great benefits coupled with existing networks;
2) demonstrating the feasibility of operating cooling network at medium/ high temperature (supply 8 °C, return 15 °C)
3) assuring that the proposed innovation will reinforce global plant COP at a value higher than the contractual one (for confidentiality purpose see Annex2 for reference), which is the contractual value signed by Engie.

Table 7 Simulation Scenarios for NEMO

	Description of the network
Scenario 1	Without TES
Scenario 2	Cold Water Storage
Scenario 3	Iced Storage
Scenario 4	Without TES HTCD (supply 8°C, return 15 °C)
Scenario 5	Cold Water Storage HTCD (supply 8°C, return 15 °C)
Scenario 6	Iced Storage HTCD (supply 8°C, return 15 °C)

The presented six scenarios follow a matrix electricity tariff according to Hydro Ottawa’s tariff prices for Business (figure 38 and table 9). The electricity cost will be the only different hypothesis compared to previous studies; the remaining hypothesis will be kept the same, namely: free cooling using Gatineau river will be consider available from mid-November to mid-April (figure 39); as shown in table 10, the cold production sites of NPB and Cliff will have a total capacity of 170 MW of which 46 MW in NPB (including free cooling); finally, historical data will be taken for substations’ consumption and Gatineau river temperature water. Scenario 1,2,3 will run to provide a supply temperature of 4,4°C (return 13°C) all year round, on the contrary, scenario 4, 5 and 6 will provide chilled water at 8 °C (return 15°C) in winter and at 4.4 (return 13°C) in summer following the curves of figure 40. Winter and summer seasons will follow the same rule of the electricity matrix tariff which considers summer lasting from May to October.

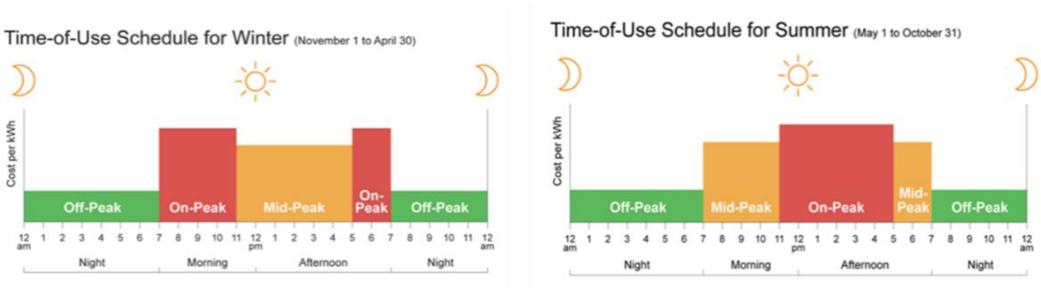


Figure 38 Hydro Ottawa Electricity tariff for NPB. Adapted from (Hydro Ottawa, 2020)

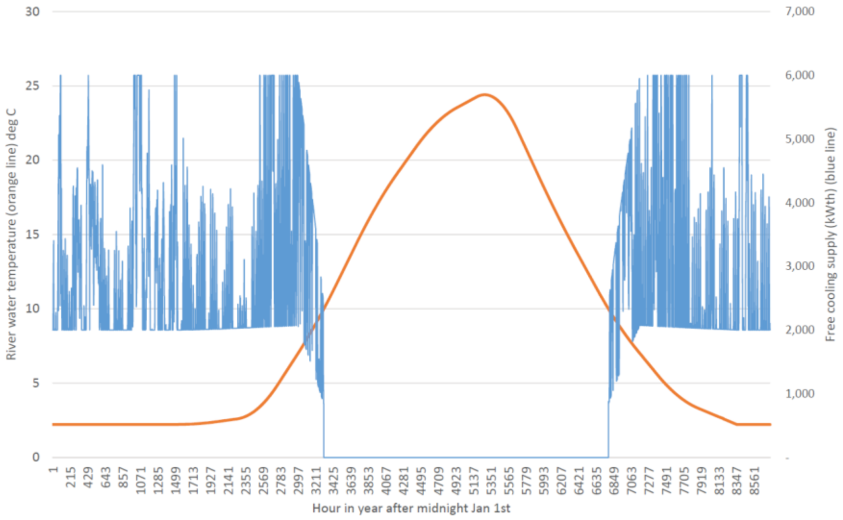


Figure 39 Free Cooling Supply and River Water Temperatures. Adapted from (ENGIE, 2019)

Table 8 Electricity Matrix Tariff NPB for Summer months in CAD/MWh

August							
	M	T	W	T	F	S	S
0	42	42	42	42	42	42	42
1	42	42	42	42	42	42	42
2	42	42	42	42	42	42	42
3	42	42	42	42	42	42	42
4	42	42	42	42	42	42	42
5	42	42	42	42	42	42	42
6	42	42	42	42	42	42	42
7	60	60	60	60	60	42	42
8	60	60	60	60	60	42	42
9	60	60	60	60	60	42	42
10	60	60	60	60	60	42	42
11	87	87	87	87	87	42	42
12	87	87	87	87	87	42	42
13	87	87	87	87	87	42	42
14	87	87	87	87	87	42	42
15	87	87	87	87	87	42	42
16	87	87	87	87	87	42	42
17	60	60	60	60	60	42	42
18	60	60	60	60	60	42	42

19	42	42	42	42	42	42	42
20	42	42	42	42	42	42	42
21	42	42	42	42	42	42	42
22	42	42	42	42	42	42	42
23	42	42	42	42	42	42	42

Table 9 NPB-Cliff Network Installed Capacity. Adapted from (ENGIE, 2019)

	Initial Cooling Capacity (Including N+1)			**Future Cooling Capacity (Including N+1)**		
	Numbers of Chillers	Capacity Per Unit (MW)	Total Output (MW)	Numbers of Chillers	Capacity Per Unit (MW)	Total Output (MW)
NPB	2	14	28	2	14	28
	1	10	10	1	10	10
				1	2	2
	*Free Cooling	6	6	*Free Cooling	6	6
	Total		**38**	**Total**		**40**
Cliff	3	14	42	3	14	42
	1	4	4	1	4	4
				6	14	84
	Total		**46**	**Total**		**130**

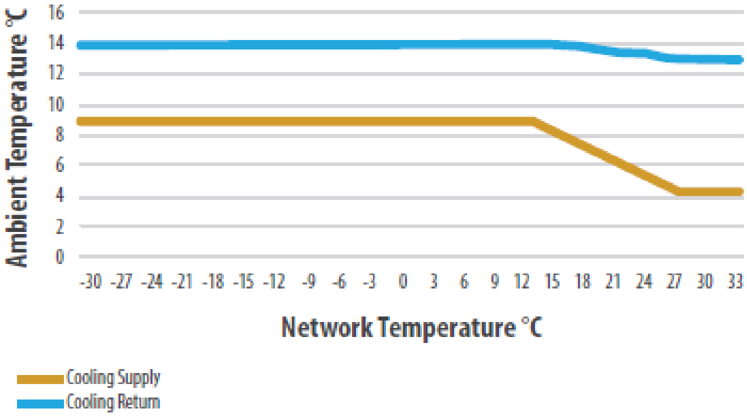


Figure 40 Modelled Network Temperature in scenarios 4,5 and 6 with supply at 8 °C and return at 15 °C in Winter. Adapted from (ENGIE, 2019). CC-BY

The study will be performed using two different tools which will provide insights on TES behavior as well as on the production plants. The first tool used is NEMO. It is an online digital platform developed by ENGIE Digital with the aim of supporting and helping engineers in complex technical studies of district network. NEMO is able to simulate on a 2D or 3D map the entire network from the production plant to the clients' buildings. Easily integrable with others platforms, it has the power to forecast demand based on external air temperature or historical consumption files to adapt to real case simulation and optimize the operations. The optimization can run according to best pressure distribution in the network or according to optimal operational costs, depending on the phase of design and its objective. Even if the tool is quite powerful and complete, it is still under development. Thus, a second tool has been developed for the final part of the study with the aim of focusing on storage behavior. This tool is an artificial intelligence algorithm which in the future will be integrated directly into NEMO.

4.3 Tools description

The majority of the simulations is based on NEMO which optimizes the cold production plants according to an optimal cost scenario. Using this tool is possible to study in details the network's characteristics simulating a set of operational constrains.

4.3.1 NEMO Platform

Using NEMO, the creation of an entire network can be done in less than 30 minutes for small networks. The configuration phase includes the pipes design, substation and cooling plants (pumps, chillers and storage). Once the model is set, some optimization and forecast can be run for a better understanding of the network. It has been demonstrated that using digital tools and data will prevent oversizing of the network, a problem always encountered in the past, especially in the first generations heating networks (UpGrade DH, 2019). According to the amount of input data, NEMO will be able to simulate a yearly production in a couple of hours. Each simulation is run on a monthly base according to real consumption and river water temperature for the specific month x. Each simulation lasts for some hours and the calculation are solved on the cloud environment; at the end of the process, NEMO will be able to provide a very detailed database of information in support to the study phase. The main groups of output information can be divided in the following main groups: cold production plant, subsystems, cost, departures, chillers, water storage and substations. For each simulation NEMO provides as output a zip file containing 90 ".csv" files, which represent hourly values of performance, temperature, pressure, consumption, production, storage levels, flow rates and costs for the groups mentioned above. The high number of information allows the user to have a clear global overview on the entire network. The logic of Nemo follows studies and formulas presented in the literature, for a better understanding on the tool it is possible to consult Annex 2.

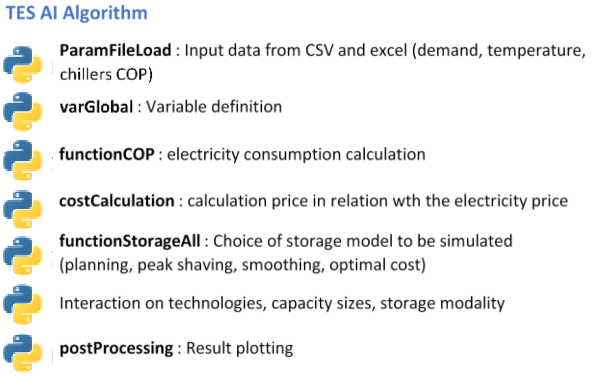
Even if NEMO is a very powerful tool, it is still under development. Thus, it faces some limitations and constrains in possible scenarios. For this reason, an artificial intelligence algorithm for thermal storage application will be also used. The tool has been developed in Python and adapted to NEMO for future integration, but at this stage is not integrated yet so it will be run separately.

4.3.2 TES optimization using an artificial intelligence algorithm

As introduced in the previous paragraph, in order to better study Ottawa case, and a possible implementation of a cold storage technology, a second tool had been used in integration to NEMO. The tool is used to have a deeper focus on storage application and behavior; it is designed in a very smart and flexible way. In opposition to NEMO, it does not require in advance the design of a network which leads to a wider use of this tool in pre-study phase. In fact, the AI algorithm for TES is able to quickly compare different scenarios using multiple storage models developed according to a specific given set of data, such as substations cold demand and chillers COP. In other words, given a storage technology X of size S and a storage usage model of M during a period of time T, the algorithm will return the electricity consumption C and the operational cost Y of the cooling production plant.

Historical data from substations installed in the operating cooling network of Ottawa associated with weather data from local station have been used for the implementation of the algorithm.
As expressed in the summary (figure 41), the flow of the application will consequently follow the following steps:

- input global variables from the excel file;
    - loop for technologies
        - loop for capacity sizes
            - loop for storage models
                - loop on 24h of the day to fill in the result file
    - loop of storage models
        - calculation of electricity consumption of each storage model starting from cold demand
    - Calculation of electricity consumption costs based on given data set of electricity price



TES AI Algorithm

ParamFileLoad : Input data from CSV and excel (demand, temperature, chillers COP)

varGlobal : Variable definition

functionCOP : electricity consumption calculation

costCalculation : calculation price in relation wth the electricity price

functionStorageAll : Choice of storage model to be simulated (planning, peak shaving, smoothing, optimal cost)

Interaction on technologies, capacity sizes, storage modality

postProcessing : Result plotting

Figure 41 Python TES AI algorithm working scheme

In this case, the calculations will be run in a personal computer with a processor Intel®Core™ i5-8350U CPU @1.70GHz 1.90GHz x64. Simulations can last from 30 minutes without optimization until hours in case of optimal cost and optimal energy specific calculations

4.3.2.1 Storage models

- ***Without storage*:** this function evaluates the interest of having a storage technology, it works on the base of a daily dataset for cold demand;
- **Smoothing:** average of the total production of the day to have the most constant production possible;
- ***Peak shaving***: based on the excel file where the user has set the hours authorized to store, for every hour not authorized to store, the algorithm push the discharging lowering the peaks;
- ***Planning***: Controlled by a schedule of hours of storage, hours of destocking and hours without storage or destocking. The algorithm stores the maximum of these capacities during storage hours and withdraws the maximum physical capacity of the installation during the authorized withdrawal hours
- ***Optimal***: A command that seeks to minimize a criterion by means of an optimization function. The criterion can be: electricity consumption for each day of operation, cost of electricity for each day of operation, maximum electricity consumption on one day of operation, maximum electricity consumption for a certain price range on an operating day.

To simplify the discussion for the reader, from now on the explanation will only be referred to cooling schemes; however, the same approach could be develop and performed for hot storage and heating networks.

4.3.2.2 Tool dimensioning

In the case of the AI algorithm, since the focus is only on the production site, it is important to well dimension it. The right dimensioning will simulate closer to reality the operational behavior of chillers and thus the amount of electricity required to produce the required chilled water to cover the substation's demand. In this sense, it is important to represent the chillers workload in terms of electricity consumption, function of different parameters such as: power demand, production groups, pumps, external conditions, cooling towers etc. To do so, it is requested to switch from the cold demand of the network (KWh of cold) to the electricity demand of the chillers (KWh of electricity) in relation with their COP. Particular attention in defining the chillers COP matrix is required since the delivery temperature influences the COP. For example, for iced storage, chillers have a different setpoint temperature depending on where the cold water is delivered ($T_1 \neq T_2$, where T_1 is the temperature when cold water goes to the network; T_2 is the temperature to storage). To simulate the different behavior of chillers, two Boolean variables are used. The first indicates whether the production groups affiliated to storage have the capacity to send chilled water to the storage and to the network at the same time. The second gives the capacity of the cooling plant to use the chillers, linked with storage, to produce directly for the network in parallel with the destocking. Another parameter to take in consideration is the storage pump power consumption linked to discharging process. The recovery of stored cold requires the use of a pump that consumes electricity. For the time being, the electricity consumption of this pump is considered proportional to the storage power.

Once all the technical parameters are defined, the last steps are to assume storage behavior (planning the storage when demand is low and or cheap) and understanding the geographical and operational constrains (i.e. electricity price, contractual power, set tariff, etc..).

4.4 Data collection for the study

The first step required for an accurate simulation of a district cooling TES is the collection of data referred to the network such us: generation plant configuration, network design, plant's working hours, electricity prices, profile loads for different type of buildings (retail, office, hotel, residence, central utility plant as datacenter, mass rapid transit as stations or auditorium, etc..), which can be summarized in the total cooling demand. Secondly, information on the characteristics of the production systems and on the hypothetical or realistic behavior of the storage is required (i.e. storage charging power, discharging power, chillers power, storage capacity, etc...). In Ottawa, for example, since the network is divided between two States where two different regulations are followed concerning electricity price, the main cooling facility used will be NPB because of its electricity cost 2,4 times lower than in Ontario where Cliff is based. At current demand, for example, Cliff plant is active only 94 hours per year, mainly during peak demand, resulting in a total of 21 days. In NPB there are currently 2 chillers with 14 MW capacity, 1 with 10 MW and 6MW dedicated to free cooling using the river water when the water temperature is below 8 °C. In Cliff there are 3 chillers of 14 MW and 1 of 4 MW. The plan is to expand the capacity of the two sites adding 1 chiller of 2 MW in NPB and 6 chillers of 14.8 MW in Cliff.

4.5 Results and Discussion

Simulated and run on NEMO on an hourly base, the six scenarios of table 8 will be presented according to yearly summaries in paragraph 4.5.1 (for monthly references see Annex A.1.2 for more information). Concerning the specific study on thermal storage, June and October have been chosen as reference for Summer and Autumn. In this case, August has not been chosen because of coherence: since the AI algorithm is not able to take in consideration the two different matrix tariff of Ontario and Quebec, June as reference of Summer months has been chosen, avoiding July and August for which the demand is asking full capacity in NPB, thus implying a possible utilization of Cliff if prices are convenient. June with a lower cold demand, avoids this complication which the AI tool could not take in consideration. In the initial plan, March and December were supposed to be studied for Spring and Winter Season, however due to some rigid constrains of the tool, coupled with a very articulate case, those months were not possible to be covered but they could be included in future studies.

4.5.1 NEMO Results

A year round simulation has been made on the NEMO platform. This tool aims to optimize the operational condition of the cooling network, production site and storage system according to some variable such as: total costs, network pressure, electricity consumption, water flow rate.

From a first simulation, for which the results are reported in table 11, it is possible to see straight away a great difference in terms of results compared to previous studies conducted by ENGIE (discussed in paragraph 4.2). This result is aligned with what was expected: the main difference for both scenarios, without and with TES, is mainly due to the application of a tariff matrix for electricity price. Clearly a unique daily value price for electricity of 68,1 CAD/MWh (6,81 ct/kWh) will bring to a different results if compared to a matrix price which is varying between 42, 60 and 87 CAD/MWh during the day. In addition to it, the lower price at night of the electricity matrix price enables a wider range of application for storage as a flexibility mean.

To simplify the output, the total cost will be considered as the sum of the cost of NPB and Cliff. In this case, at current load, Cliff plant is not used at all. As a result, all data comes from the unique site of NPB. The total cost are including the Gatineau water cost used for cooling, the total consumed electricity and where applicable the storage cost. In order to compare the different scenarios a coefficient of performance (COP) is introduced, which follows the equation:

$$COP = \frac{\text{Site Cold Production from chillers}}{(\text{Total Electricity Production } + \text{total electricity cooling } + \text{total electricity distribution})} \tag{7}$$

To summarize the results some tables with detailed references representing each scenario has been developed for current load and future load. For a matter of confidentiality, in the current dissertation the outcomes of the simulations will be normalized in percentage compared to scenario 1, without TES (100%). Meaning that for values higher than 100% the value would be increased from starting conditions, in case of values below 100% there is a decrease. For storage results, when it is not possible to compare the values with scenario 1, each scenario will be compared per type confronting directly scenario 2, TES, with scenario 5, TES S8R15 and scenario 3, ICE, with scenario 6, ICE S8R15. Savings in terms of cost will show directly the rate compared to the scenario 1. For the integral list of results please, revise Annex 2 - A.2, table will be represented with the same caption of this document.

The tool will optimize each scenario according to the most cost effective solution. In other words, it will try to use as much as possible the site of NPB reducing the utilization of Cliff as far as the demand can be covered by NPB. The same result can be obtain from a more detailed study of the storage application: for both cold water and ice storage, when it comes to the choice of the most profitable solution at high peaks (July and August) storage will not be used at current load (detailed references in Annex 2 – A.3). This choice is due to the fact that the utilization of storage during those months would require switching on some chillers in Cliff increasing drastically the total cost. In other words, during July and August the remaining Capacity in NPB is not enough to cover the storage cold demand. The results are confirming the assumption for which NPB will be chosen over Cliff due to the cheaper electricity price.

A yearly summary is disclose in table 11:

Table 10 Summary Yearly Cost – Current load

	NO TES	**TES**	**ICE**	**NO TES S8R15**	**TES S8R15**	**ICES8R15**
	scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Total Cost (electricity + storage)	100%	61%	62%	104%	59%	62%
Savings [CAD]	/	-39%	-38%	4%	-41%	-38%
Network COP (chillers unit)	100%	103%	102%	104%	104%	103%

From a very first analysis of the proposed results, focusing only on the savings, all scenarios but number 4 are reducing the linked OPEX (figure 42). In these cases, the savings are defined as the difference between each scenario and scenario 1, without storage. At the same time the coefficient of performance of all scenarios have been demonstrated to be higher than the case without TES, confirming the benefit of using higher temperature network or storage systems. Going further in the analysis, it is possible to explore more data provided in table 12.

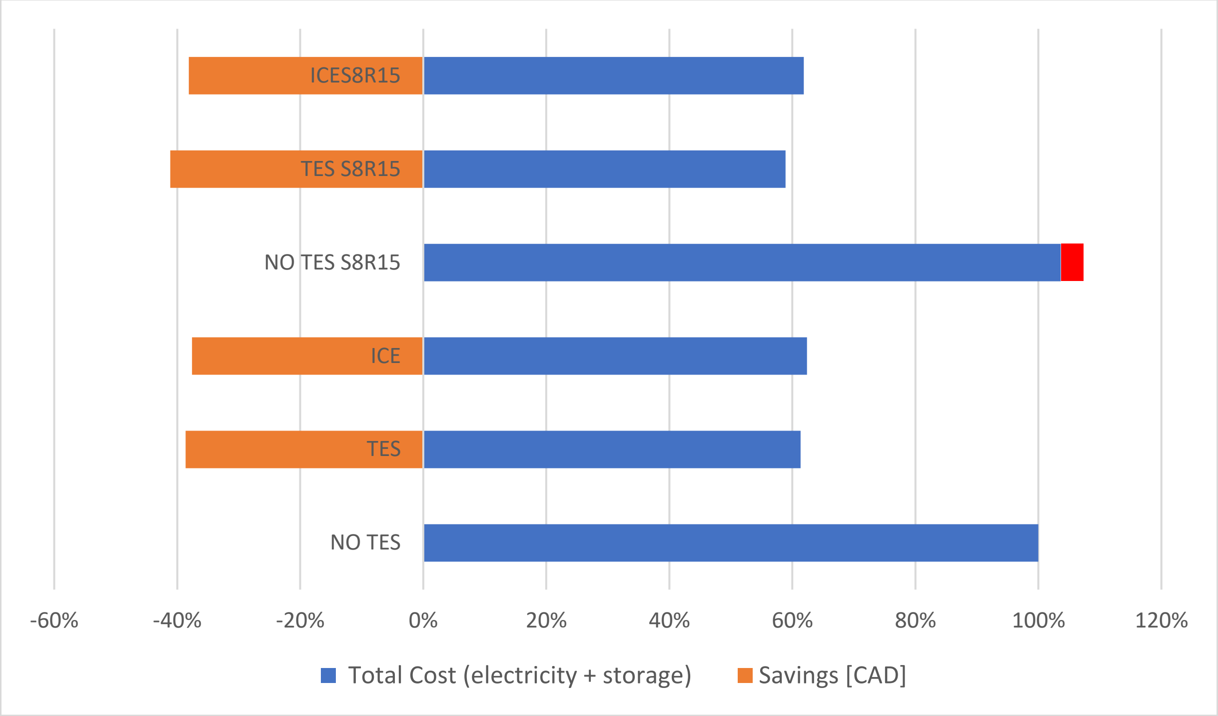


Figure 42 Total Cost and savings in CAD at Current Load

In general, as expected, cold power decreases in scenarios 2, 4 and 5 for higher temperature network without storage and for storage application. All three situations are requiring less effort from the chillers: from 19% to 10% less cold produced to answer the same network cold demand. As a consequence of the decrease in partial load, chillers are consuming a slightly lower electricity which overall brings to a higher network performance with COPs gains from 2% to 4%. On the contrary, in the case of ice storage the cold produced and the electricity consumption are higher. In fact, Cliff's iced storage is loaded thanks to a negative chiller (chiller number 1) placed in NPB thanks to the interconnection between the two sites. Chilled water at -5°C is injected outwards NPB and is flowing into the connection until Cliff.

Table 11 Scenarios Summary at Current Load

	NO TES	**TES**	**ICE**	**NO TES S8R15**	**TESS8R15**	**ICES8R15**
	scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Cold power for production NPB	100%	86%	104%	90%	81%	103%
Cold power for production CLIFF	-	-	-	-	-	-
Site cold production [MW]	**100%**	**86%**	**104%**	**90%**	**81%**	**103%**
Site electric consumption from chillers Group	100%	84%	105%	85%	78%	103%
Electric power for cooling NPB	100%	77%	95%	94%	74%	94%
El power for cooling Cliff	-	-	-	-	-	-
total elec cooling [MW]	100%	77%	95%	94%	74%	94%
Electric power for distribution NPB	100%	87%	91%	91%	87%	91%
Electric power for distribution Cliff	-	-	-	-	-	-
total elec distribution [MW]	100%	87%	91%	91%	87%	91%
TOTAL ELEC CONS (site elec cons from chillers group+elec cooling + elec distr) [MW]	**100%**	**83%**	**102%**	**87%**	**78%**	**100%**
COP (plant_cold_prod/(elec_prod (group unit+elec cooling +elec distrib)	100%	103%	102%	104%	104%	103%

Cold Storage Load Power [MW]	-	100%	-	-	97%	-
Ice Storage Load Power [MW]	-	-	100%	-	-	108%
Cold Storag Unload Power [MW]	-	100%	/	-	103%	/
Storage Distribution pump [MW]	-	100%	-	-	103%	-
Electricity power for Ice Storage [MW]	-	100%	-	-	97%	-
COSTS						
Electricity_NPB	100%	51%	62%	104%	49%	62%
Electricity_Cliff	-	-	-	-	-	-
TOTAL elec cost	**100%**	**51%**	**62%**	**104%**	**49%**	**62%**
Savigns	-	-49%	-38%	4%	-51%	-38%
Cold Water Storage Cost	-	100%	-	-	93%	-
Ice Storage Cost	-	-	100%	-	-	110%
TOTAL Cost (elec+storage)	**100%**	**61%**	**62%**	**104%**	**59%**	**62%**
Savings	/	-39%	-38%	4%	**-41%**	-38%

Though, during this path, heat losses occurs in the pipes. According to the literature such losses can be between 5 and 10 % according to the pipe's length and ground temperature. In this case, for the interconnection pipes, a 2 km length explains the increase in cold production of 3,5% to balance the heat losses. In terms of electricity consumption cooling is not requiring a lot of energy since most of the time a free cooling exchange using Gatineau's river water is used. At the same time electricity consumption for network distribution pumps and storage distribution pumps are very low compared to the chillers' electricity consumption. Last point to be noted in term of costs is in scenario 4, which is the only one that is losing in terms of costs while the overall performance is increasing. This result can be conducted to a constrain of the network. In absence of a thermal storage the network is missing a strong component in term of flexibility, resulting in higher operational costs even if the performances are quite increased. In fact as soon as a thermal storage is added into the network, scenario 5 automatically becomes the best solutions out of the six for both costs and performances with the highest storage utilization. Once again the thermal application results critical in this situation as a mean to manage the different electricity price during the day.

Once the current study has been concluded, it could also be very interesting to study the future development of the network performances linked to the cold demand growth. In fact in future scenarios the cold demand will be characterized by doubled values, which will lead also to an increase in electricity consumption related to chillers and pumps. In future stages, for a hourly peak demand of 160 MW, Cliff will be more active, especially during Summer months. Consequently, with an increased utilization of Cliff, cold water storage perceives an improvement in its application during the peak months of July and August, which brings a greater apport in terms of cost savings. As before, it is possible to start from a quick analysis in table 13.

Table 12 Summary Yearly Cost –Future load

	NO TES	**TES**	**ICE**	**NO TES S8R15**	**TESS8R15**	**ICES8R15**
	scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Total Cost (elec+water+storage) [CAD]	100%	73%	82%	100%	72%	82%
Savings	/	-27%	-18%	0%	-28%	-18%
Tot Cost Vs Current load	202%	239%	265%	195%	245%	266%
Cold produced Fut load Vs Current load	185%	220%	192%	207%	227%	192%
Network COP	100%	102%	103%	101%	102%	104%
Network COP at Fut load Vs Current load	94%	93%	96%	92%	92%	95%

This time, the simulations at future load return total costs doubled in comparison with current load, the trend is well correlated to the cold production which is also doubled. Once again, almost all scenarios are reducing OPEX costs compared to scenario 1, with the only exception of scenario 4. The coefficient of performance at future load are lower than previous simulations, however they are above the contract limit signed by Engie which makes all scenarios technologically applicable. For a visualization comparison of costs and savings, figure 43 can be observed. Once again the scenario with storage application results the most flexible to manage the electricity tariff, providing also a higher COP. Even if cold storage does not reach the same gain in term of COP compared to ice storage, it brings a higher OPEX savings resulting by far the best choice between the two (table 14).

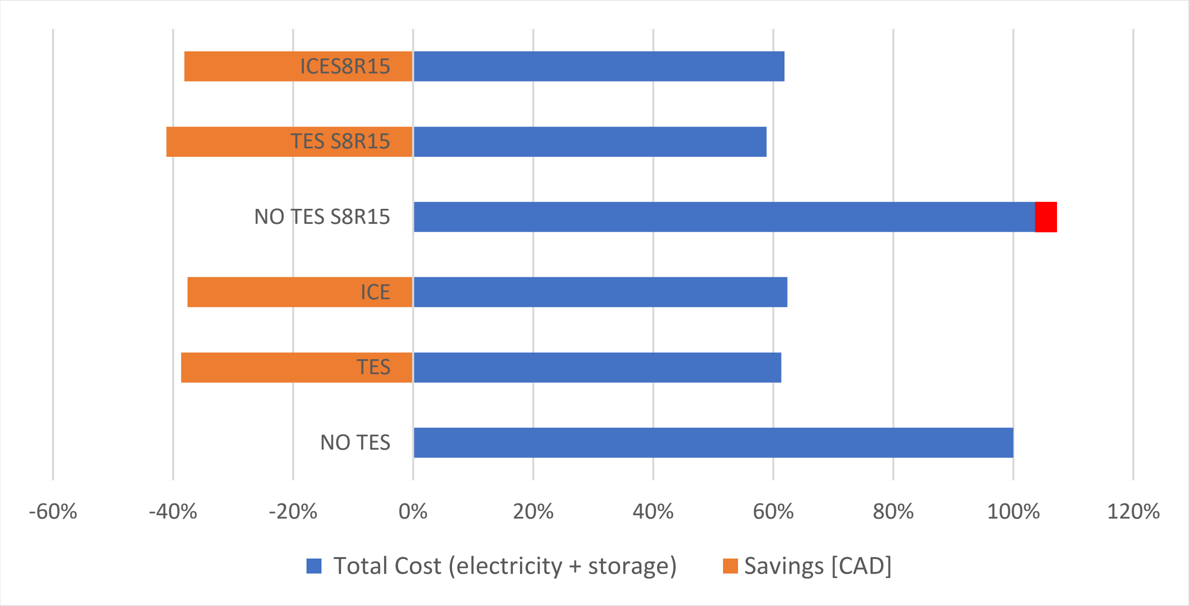


Figure 43 Total Cost and savings in CAD at Future Load

Table 13 Scenarios Summary at Future Load

	NO TES	TES	ICE	NO TES S8R15	TESS8R15	ICES8R15
	scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Cold power for production NPB	100%	109%	107%	101%	106%	107%
Cold power for production CLIFF	100%	56%	107%	100%	56%	107%
Site cold production [MW]	**100%**	**102%**	**107%**	**101%**	**100%**	**107%**
Site electric consumption from chillers Group	100%	102%	106%	99%	99%	104%
Electric power for cooling NPB	100%	99%	100%	101%	97%	100%
El power for cooling Cliff	100%	58%	107%	100%	58%	107%
total elec cooling [MW]	100%	94%	101%	101%	92%	101%
Electric power for distribution NPB	100%	105%	97%	101%	104%	97%
Electric power for distribution Cliff	100%	53%	102%	100%	53%	102%
total elec distribution [MW]	100%	97%	98%	101%	97%	98%
TOTAL ELEC CONS (site elec cons from chillers group+elec cooling + elec distr)	**100%**	**100%**	**104%**	**100%**	**98%**	**103%**
COP (plant_cold_prod/(elec_prod (group unit+elec cooling +elec distrib)	100%	102%	103%	101%	102%	104%
Cold Storage Load Power [MW]	-	100%	-	-	94%	-
Cold Storage Load Power Fut load Vs Current load	-	148%	-	-	145%	-

Ice Storage Load Power [MW]	-	-	100%	-	-	109%
Ice Storage Load Power [MW] Fut load Vs Current load	-	-	93%	-	-	93%
Cold Storage Unload Power [MW]	-	100%	/	-	102%	/
Storage Distribution pump [MW]	-	100%	-	-	101%	-
Electricity power for Ice Storage [MW]	-	-	100%	-	-	110%
Electricity power for Ice Storage [MW] Fut load Vs Current load	-	-	90%	-	-	91%
COST						
Electricity_NPB	100%	70%	75%	100%	68%	74%
Electricity_Cliff	100%	45%	105%	100%	45%	105%
TOTAL elec cost	**100%**	**64%**	**82%**	**100%**	**63%**	**82%**
Savigns	-	-36%	-18%	0%	-37%	-18%
Cold Water Storage Cost	-	100%	-	-	101%	-
Ice Storage Cost	-	-	100%	-	-	30%
TOTAL Cost (elec+storage)	100%	73%	82%	100%	72%	82%
Savings	/	-27%	-18%	0%	-28%	-18%

The results of future load are very much aligned with previous simulation when it comes to the scenario with and without cold storage. Some ambiguity can be seen in scenario 3 and 6 for iced storage. In particular, comparing the storage systems at current load against future load: while in the case of cold storage, the technology is used at a double rate in future load compare to current load; for the case of ice storage this is not happening. On the contrary, the load power and the electricity power for ice storage are more or less in the same range or lower. A first understanding of such data could lead to the conclusion that ice storage is used less at future load than current load. An explanation of it, it could be linked to costs added to a limitation in chillers negative capacities. In fact, in scenario 3 and 6 only one chiller in NPB and one chiller in Cliff are set as negative chiller with a frigorific power of 14 MW each. However, in both current and future load only the negative chiller in NPB results active. Since the full capacity of the iced storage has not been reached in any case, a direct conclusion would lead to a cost motivation: a negative working chiller in Cliff would not be cost effective, thus it has never been used. A focus on cold power and power demand per type (and per date) for June are reported in figure 44 for current load and in figure 45 for future load.

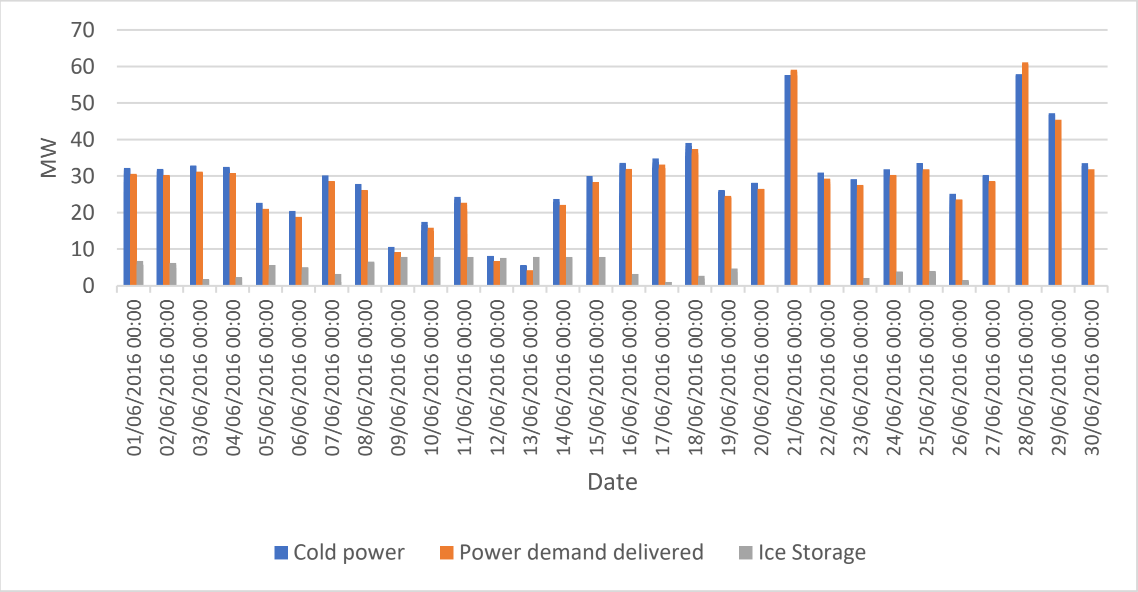


Figure 44 Cold power and power demand (MW) per type per hours in June at current load.

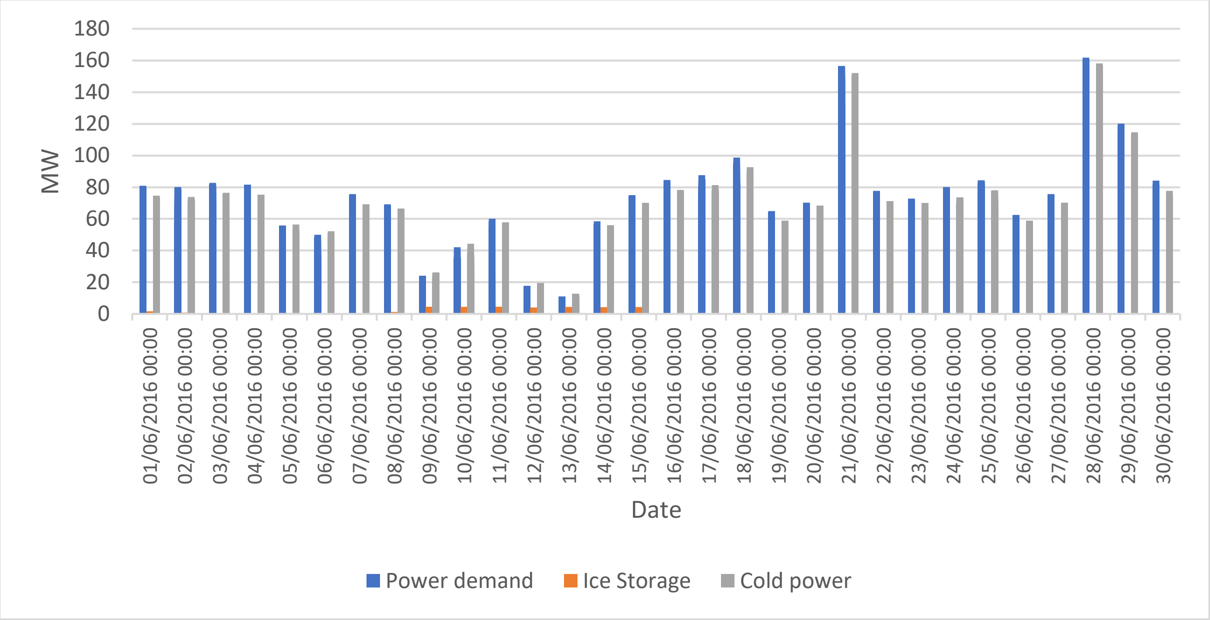


Figure 45 Cold power and power demand per type per hours in June at future load

To better understand the iced scenario, further studies would be required however at this point of the tool development the analysis is still quite limited. Such a study could be performed in later phases with also a more precise simulation of different storage technologies.

At this point, in order to have a clear view of the implication behind a higher temperature network, a comparison between the first three and the last three scenarios is developed. In particular, the focus will be into the study of free cooling. The simulation of free cooling has been implemented by using a chiller with a higher nominal COP as approximation (reference in Annex 2 – A.2), therefore it is not expected an extreme precise result; however an increasing trend is attended for the cases with higher temperatures. In table 15 and 16 a summary of chillers shares production are reported (more details in Annex 2 – A.2).

Table 14 Yearly Cold Production per Chiller without thermal storage

W/o TES future		**W/o TES future S8R15**	
Chiller description	%	Chiller description	%
Free Cooling	9,8	Free Cooling	11,5
NPB Chiller 1	17,6	NPB Chiller 1	17,5
NPB Chiller 2	14,8	NPB Chiller 2	14,4
NPB Chiller 3	20,6	NPB Chiller 3	20,7
NPB Chiller 4	2,7	NPB Chiller 4	2,1
NPB Chiller 5	12,3	NPB Chiller 5	11,6
NPB Chiller 6	9,4	NPB Chiller 6	9,79
Cliff Chiller 1	2,2	Cliff Chiller 1	2,24
Cliff Chiller 2	2,3	Cliff Chiller 2	2,37
Cliff Chiller 3	0,8	Cliff Chiller 3	0,85
Cliff Chiller 4	0,4	Cliff Chiller 4	0,38
Cliff Chiller 5	1,4	Cliff Chiller 5	1,46
Cliff Chiller 6	1,2	Cliff Chiller 6	1,22

Cliff Chiller 7	1	Cliff Chiller 7	1,03
Cliff Chiller 8	0,7	Cliff Chiller 8	0,75
Cliff Chiller 9	0,4	Cliff Chiller 9	0,4
Cliff Chiller 10	2,4	Cliff Chiller 10	2,46
TOTAL	100	TOTAL	100

Table 15 Yearly Cold Production per Chiller with thermal storage and ice storage

TES Future		ICE Future		TES S8R15 future load		ICE S8R15 future load	
Chiller description	%	Chiller description	%	Chiller description	%	Chiller description	%
Free Cooling	5,8	Free Cooling	8,2	Free Cooling	11,2	Free Cooling	10,51
NPB Chiller 1	18,9	NPB Chiller 1	8,9	NPB Chiller 1	13,7	NPB Chiller 1	11,04
NPB Chiller 2	16,7	NPB Chiller 2	18	NPB Chiller 2	16,6	NPB Chiller 2	17,01
NPB Chiller 3	25,6	NPB Chiller 3	22	NPB Chiller 3	23,5	NPB Chiller 3	20,21
NPB Chiller4	1,7	NPB Chiller 4	2,7	NPB Chiller 4	1,8	NPB Chiller 4	2,41
NPB Chiller 5	13,6	NPB Chiller 5	15,1	NPB Chiller 5	15,2	NPB Chiller 5	13,92
NPB Chiller 6	10,7	NPB Chiller 6	12,5	NPB Chiller 6	11	NPB Chiller 6	11,2
Cliff Chiller1	1,1	Cliff Chiller 1	2,3	Cliff Chiller 1	1,2	Cliff Chiller 1	2,5
Cliff Chiller2	1,4	Cliff Chiller 2	2,5	Cliff Chiller 2	1,4	Cliff Chiller 2	2,68
Cliff Chiller 3	0,4	Cliff Chiller 3	0,9	Cliff Chiller 3	0,4	Cliff Chiller 3	0,96
Cliff Chiller 4	0,3	Cliff Chiller 4	0,4	Cliff Chiller 4	0,3	Cliff Chiller 4	0,4
Cliff Chiller 5	0,9	Cliff Chiller 5	1,4	Cliff Chiller 5	0,9	Cliff Chiller 5	1,56
Cliff Chiller 6	0,4	Cliff Chiller 6	1,1	Cliff Chiller 6	0,4	Cliff Chiller 6	1,21
Cliff Chiller 7	0,2	Cliff Chiller 7	1	Cliff Chiller 7	0,3	Cliff Chiller 7	1,05
Cliff Chiller 8	0,1	Cliff Chiller 8	0,7	Cliff Chiller 8	0,1	Cliff Chiller 8	0,75
Cliff Chiller 9	0	Cliff Chiller 9	0	Cliff Chiller 9	0	Cliff Chiller 9	0
Cliff Chiller 10	2,2	Cliff Chiller10	2,4	Cliff Chiller10	2,2	Cliff Chiller 10	2,6
TOTAL	100	TOTAL	100	TOTAL	100	TOTAL	100

In the three cases examined, the increasing trend of cooling is sustained. In particular the growth rates are available in table 17:

Table 16 Free Cooling Scenarios Comparison

	Free Cooling growth
Scenario 1 (w/o TES) Vs scenario 4 (w/o TES S8R15)	+23%
Scenario 2 (TES) Vs scenario 5 (TES S8R15)	+50%
Scenario 3 (ICE) Vs scenario 6 (ICE S8R15)	+18%

Such growth rates are in the range encountered in the literature, as seen in paragraph 2.6.3 for which higher temperature networks can bring up to an increase of double utilization of free cooling (M. Jangsten et al., 2020).

All the simulations have demonstrated that it is possible to reach a higher global COP by stressing the use of free cooling as much as possible. In fact, because of the very low consumption of electricity in the case of free cooling, the overall network would profit from it.

As a last point of the analysis, from figure 46, it is possible to proceed the study of chillers behavior studying the application of each chiller during the year. In this case, the scenario 6 at future load has been used. The graph highlights how the yearly baseload is mainly covered by NPB and most precisely by free cooling, followed by Chiller 3 (20%) and chiller 2 (17%). Chiller 1 in NPB and chiller 1 in Cliff are the two negative chillers of the network, meaning that they are the only two able to supply water at -5 °C to fill up the ice storage. In this specific case those two chillers do not provide direct cooling in the network, meaning that the 11% of cold production will entirely cover iced storage demand.

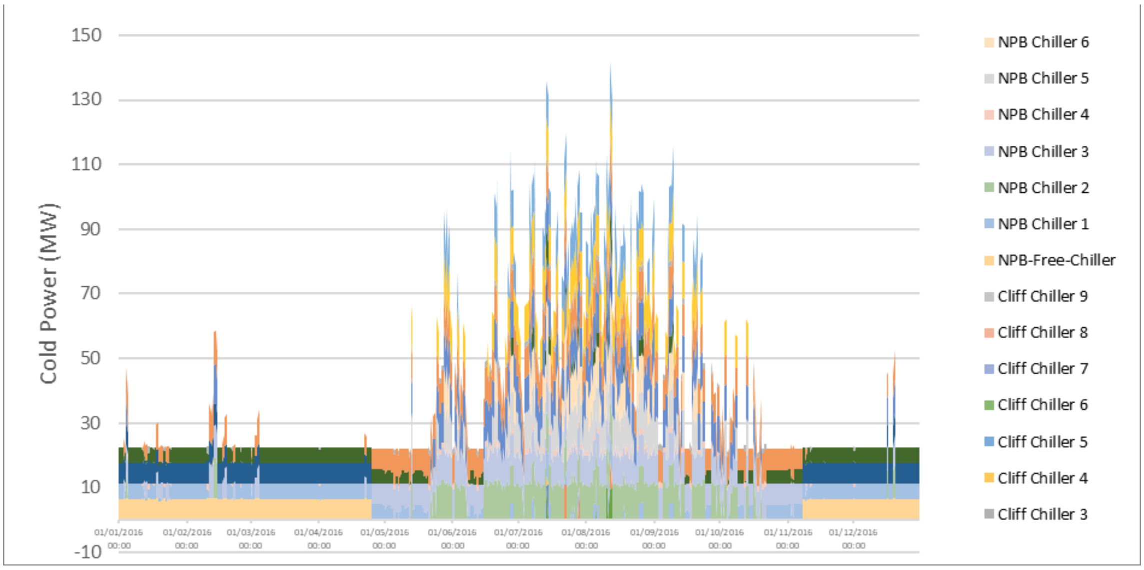


Figure 46 Chillers monotone in scenario 5 - Ice Storage S8R15, future load

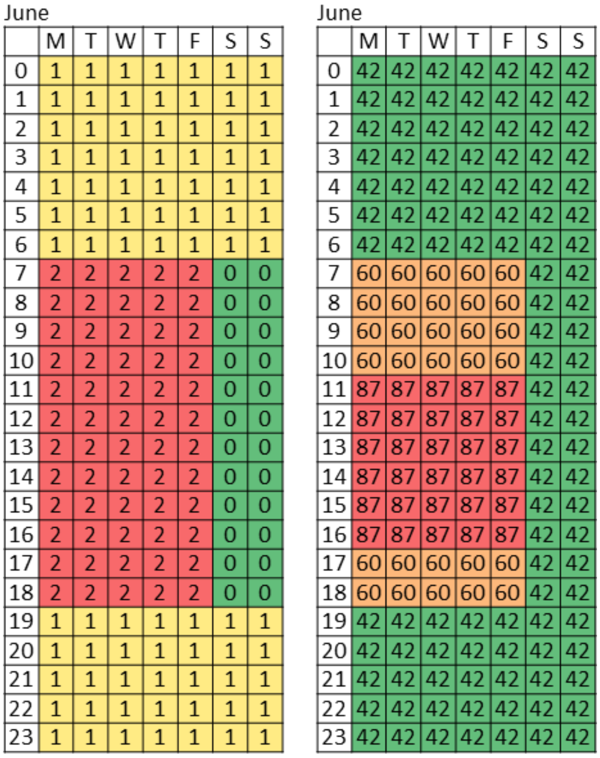
4.5.2 Deep dive in storage behavior using an AI algorithm

In order to have a deeper understanding of different storage models, a second artificial intelligence algorithm for storage systems has been used. As explained above, the tool aims to simulate and compare different scenarios in one time. More specifically, the objective is to validate the benefits of storage and its behavior rather in terms of cost, electricity consumption or in terms of flexibility over a period of time. The “plug and play” tool applied to this study has been created with the aim of being integrated directly into NEMO in future developments.

During the initial phase of the study, some constrains have been analyzed. In particular, at the moment, it has been recognized that the tool is not able to manage two different matrix prices, therefore, current load has been chosen for the following study, for which the only site of NPB is able to cover the entire demand. Since this kind of optimization over one or multiple months would require an extensive time of calculation (more than 24h), only the months of June has been chosen and more specifically the week between the 18th and the 24th of 2016: from Saturday at 00:00 to Friday at 23:00. According to the electricity matrix tariff, the ideal solution would be to implement a weekly storage where could be possible to take advantage of the lower electricity prices to store cold water or ice at a lower electricity price over the weekend, resulting in a greater flexibility during the week (table

18 b) In this way it is possible to use week-ends at their maximum potential to store cold water or ice (the same logic could be applied to longer period if applicable in relation to local conditions).

Table 17 (a) Storage planning. (b) Electricity matrix tariff for NPB
(1: charging mode, 2: decharging mode, 0: neither charging nor discharging)



June

	M	T	W	T	F	S	S
0	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1
7	2	2	2	2	2	0	0
8	2	2	2	2	2	0	0
9	2	2	2	2	2	0	0
10	2	2	2	2	2	0	0
11	2	2	2	2	2	0	0
12	2	2	2	2	2	0	0
13	2	2	2	2	2	0	0
14	2	2	2	2	2	0	0
15	2	2	2	2	2	0	0
16	2	2	2	2	2	0	0
17	2	2	2	2	2	0	0
18	2	2	2	2	2	0	0
19	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1

(a)

June

	M	T	W	T	F	S	S
0	42	42	42	42	42	42	42
1	42	42	42	42	42	42	42
2	42	42	42	42	42	42	42
3	42	42	42	42	42	42	42
4	42	42	42	42	42	42	42
5	42	42	42	42	42	42	42
6	42	42	42	42	42	42	42
7	60	60	60	60	60	42	42
8	60	60	60	60	60	42	42
9	60	60	60	60	60	42	42
10	60	60	60	60	60	42	42
11	87	87	87	87	87	42	42
12	87	87	87	87	87	42	42
13	87	87	87	87	87	42	42
14	87	87	87	87	87	42	42
15	87	87	87	87	87	42	42
16	87	87	87	87	87	42	42
17	60	60	60	60	60	42	42
18	60	60	60	60	60	42	42
19	42	42	42	42	42	42	42
20	42	42	42	42	42	42	42
21	42	42	42	42	42	42	42
22	42	42	42	42	42	42	42
23	42	42	42	42	42	42	42

(b)

A first storage dimensioning in term of capacity is done following the average hourly cold demand over the year which is obtained from the cold demand curves of figures 47 and 48. August has been chosen for this study since it is the month with higher hourly peak demand around 74000 kW/h. The average cold demand for August is 32199 kWh. One best practice to quickly dimension a storage systems is to take 4 times the average cold demand for 6 hours discharging (Energy Plan, 2019), which would lead to (130 000 KWh). Adapting the result to an average discharging period of 8 hours, it would become a storage capacity around 140 000 kWh.

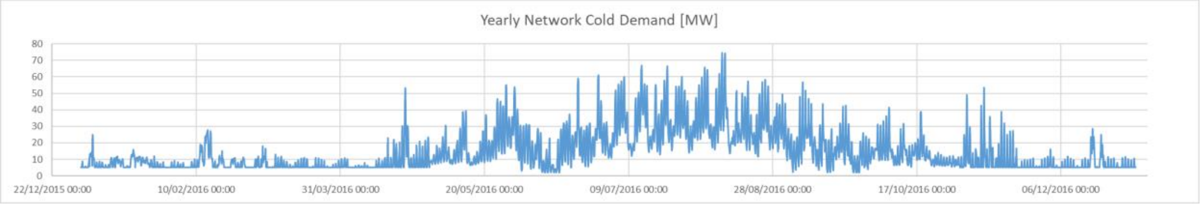


Figure 47 Yearly network cold demand

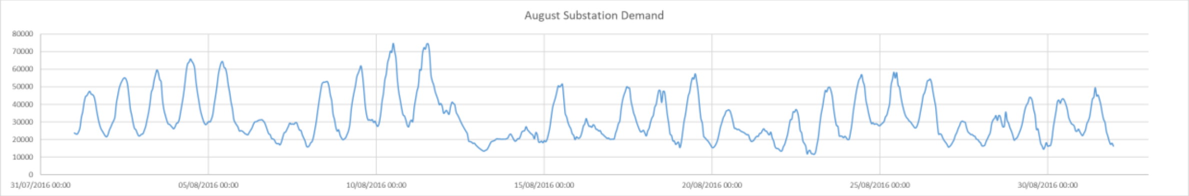


Figure 48 August network cold demand [kW]

The winter demand is quite lower compared to Summer and it mainly comes from public buildings such as hospitals or malls, however the investment results convenient in any case (see reference in annex 2).

In the following figures, it is possible to better highlight different trends over the seasons. In particular, in summer the demand is quite often, if not always, higher than 20 MW while in winter months it happens only few times per month. For this reason, two different discharging models have been picked: in summer months, a charging power of 10000 kW and discharging of 12000 kW has been chosen, while in winter a halved power would be sufficient. The different values between charging and discharging power is due to the fact that during a week period of time, counting also weekends, the available charging time is higher than the required discharging time; a lower charging power allows to run chillers at partial load reaching a greater global COP. Once the tool is fed by demand data, electricity price, storage planning and COP matrix, the tool is able to simulate the behavior of different technologies in a given range of capacities, providing in few minutes a true comparison in terms of cost and electricity consumption. In this case cold water storage will be compared to ice storage. Both technologies will deliver into the network at 4 °C, however, ice storage will have an operational temperature of -5 °C, therefore, the linked chiller group will run at negative power.

As a result of these simulation graphs of figure 49, 50, 51 and 52 are obtained for each seasonal reference month.

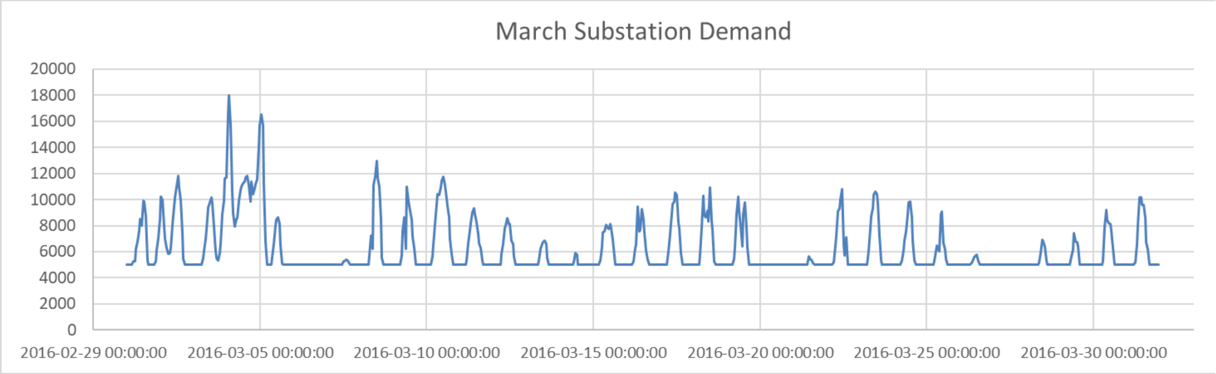


Figure 49 Network cold demand [kW] – March

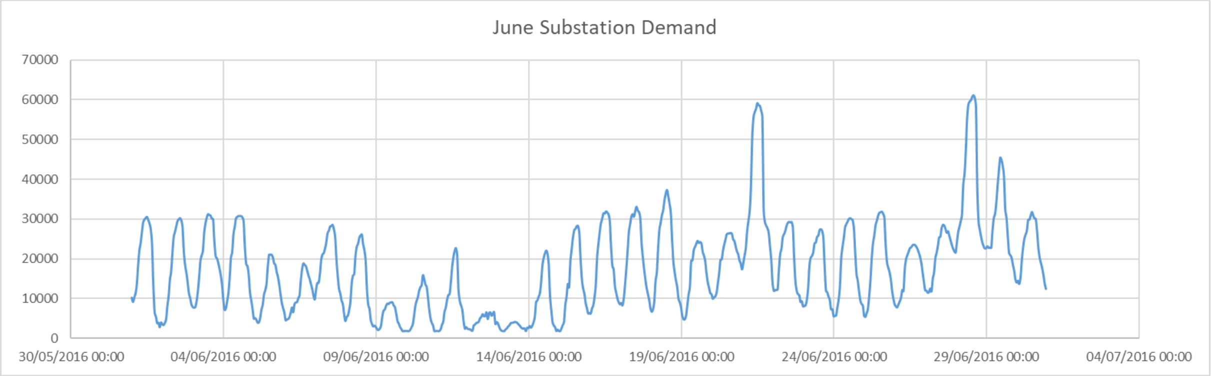


Figure 50 Network cold demand [kW] - June

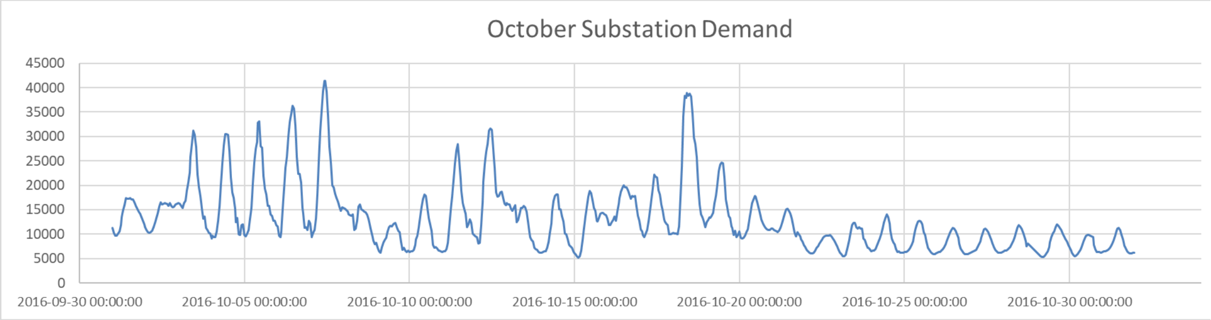


Figure 51 Network cold demand [kW] – October

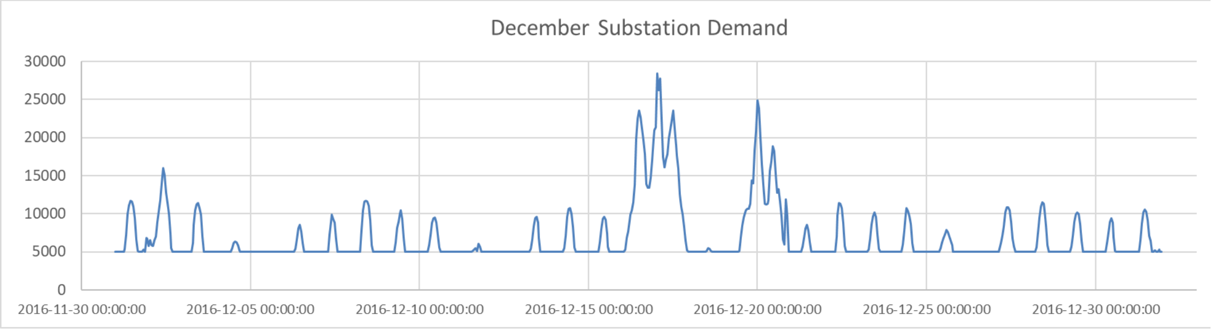


Figure 52 Network cold demand [kW] - December

The peaks that are shown in those figures are mainly due to higher external temperatures as well as a higher exposure to sun lights, which is leading to higher indoor temperatures and an increase in conditioning demand.

Analyzing figure 53, for the technologies comparison, it comes quick to eye how all storage models are bringing an advantage in terms of costs and most of the time in electricity consumption, planning and peak shaving can play a critical row in both reducing cost and electricity consumption, especially in the case of peak shaving for cold water storage. The savings on costs are up to 11% and around 6% in electricity consumption for cold water storage, while for ice storage savings on costs are 10% max but it is generally consuming the same or more energy than the case without storage. From this comparison it has been demonstrated that storage is totally able to play a critical role in the network. A reduction in electricity consumption with the same or a higher cold production will lead to an overall increase of global COP bringing straight forward a better efficiency. In this case, the difference in term of cost saving between the two technologies is not much relevant, with better results for cold water rather than ice storage. The current simulation for cold water storage using the control model of peak shaving compared to NEMO results gives an error of 4%. Considering that the calculated cost and consumption using the AI tool do not take in consideration distribution pumps which are considered in the NEMO simulation, it is understandable that the cost results lower. Therefore, the AI tool for cold storage can be considered aligned with NEMO results in term of TES. When it comes to ICE the error is higher (20%), however it is possible to denote a problem in the results for ice storage for which the optimal costs and energy are higher than the peak shaving case. Such an error is due to a mislead input configuration of the optimal case. In order to revise this error future debugging will be required, as well as further development of the tool.

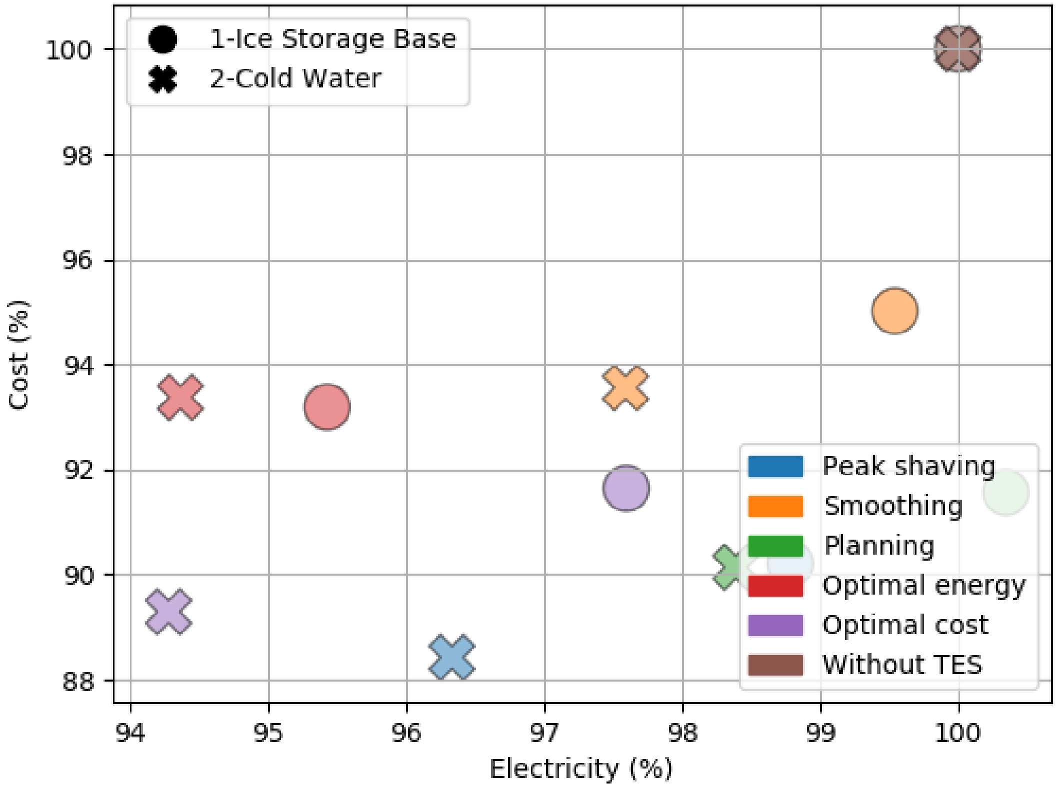


Figure 53 One Week simulation June

A summary of the simulation results are reported in table 19. A necessary consideration to be done is the following: at current developments the tool has been developed for a daily storage optimization scenario. As a result, the hypothesis of taking a weekly optimization period, even if correct could bring to mislead results. as a consequence, for future studies it could have a great impact to develop the tool for optimization on longer period of time. Said so, it is still possible to consider the simulation valid but on a daily base instead of weekly (more details in annex 2 – A.4).

Table 18 Total cost and electricity consumption. Capacity 140000 kW (more details in annex 2)

Techno	control	Total Cost [%]	Total Electricity [%]
Cold Water Storage	*Without storage*	100,00	100,00
	Smoothing	93,55	97,59
	Peak Shaving	88,42	96,33
	Planning	90,14	98,39
	Optimal Energy	93,37	94,37
	Optimal Cost	89,29	94,28
Ice Storage	*Without storage*	100,00	100,00
	Smoothing	95,01	99,54
	Peak Shaving	90,21	98,79
	Planning	91,56	100,35
	Optimal Energy	99	100
	Optimal Cost	102	102

For such a reason, the storage behavior in figure 54, 55 and 56,57 will show some overestimation in terms of storage load. The graphs are showing the charging and discharging phases applied to different models and how storage state is changing according to its usage.

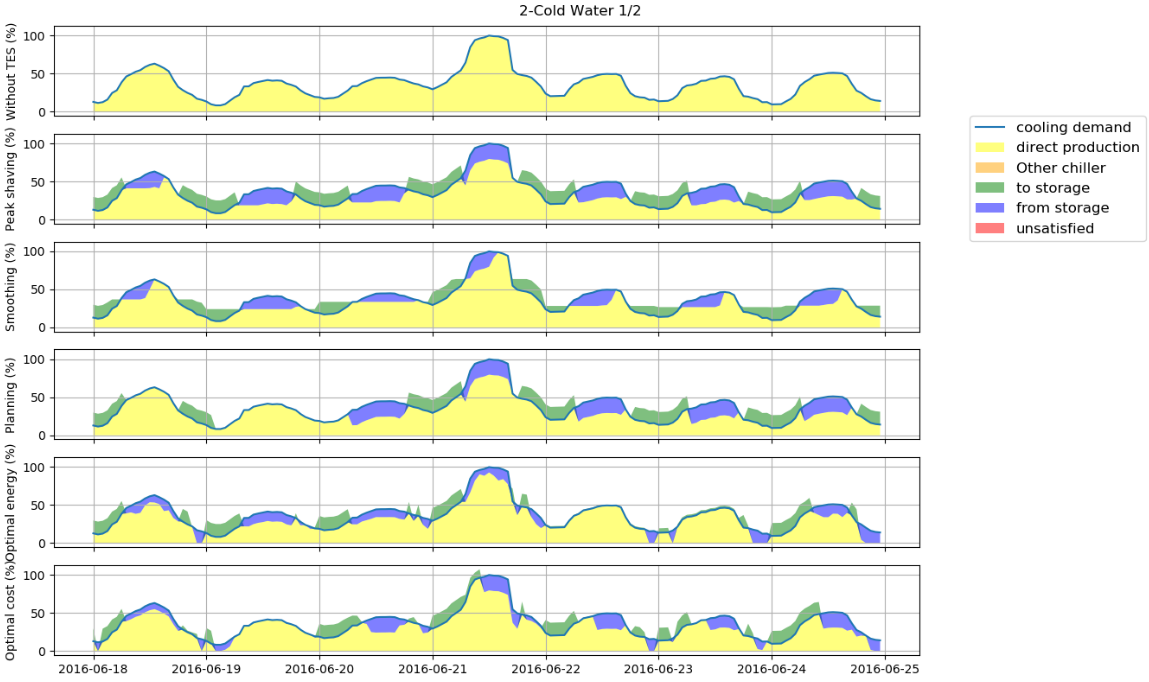


Figure 54 Storage behavior, and models detail for cold water storage

Figure 55 Storage state at different models for cold water storage

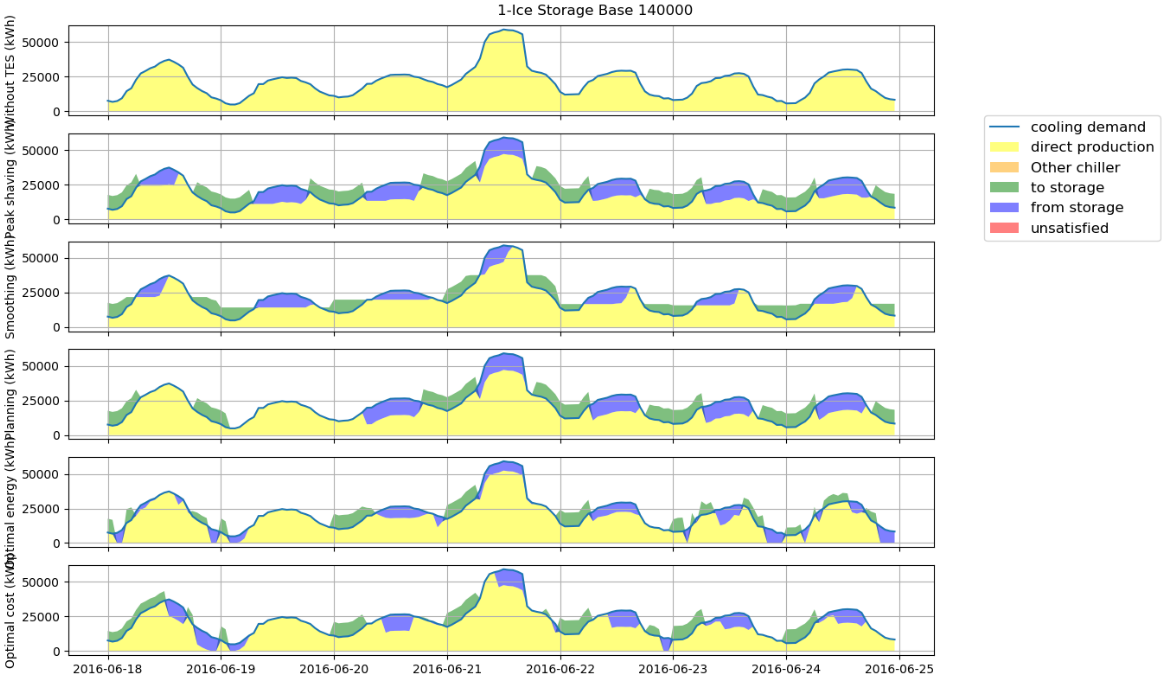


Figure 56 Storage behavior, and models detail for iced storage)

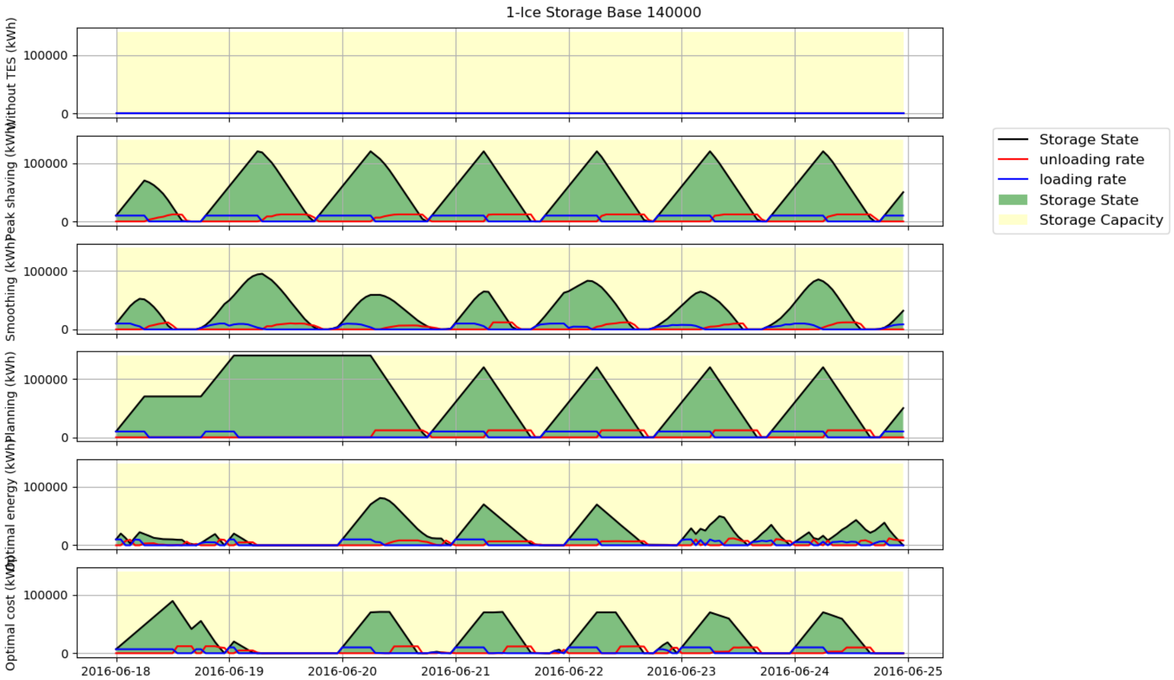


Figure 57 Storage state at different models for iced storage

Of course, then, the choice of storage size depends on other factors such as: the available surface, and the type of investment which the client is willing to pay. When it comes to decision making in terms of investment, it is good practice to explain the investment taking in consideration other external positive factors which are adding value to technical and cost one. Few of these argument could be for example, a better utilization of public and private space such us rooftops or basements, a lower costs for end users therefore an increase in network customers, or a decrease in carbon footprints. In general, more studies of this type need to be done. In this case, the 180000 kW has been chosen due to the limit in the surface required. In table 20 a summary of CAPEX value of cold water and ice storage as reported in previous paragraphs from the literature are reported.

Table 19 Summary CAPEX storage technologies

Techno	CAPEX
Cold Water Storage	265 ÷ 1060 €/kW, 10 €/kWh
	405 ÷ 1618 CAD/kW, 16 CAD/kWh
Ice Storage	≈1500 €/kW, 100 ÷ 250 €/kWh
	2290 CAD/kW, 165 ÷ 388 CAD/kWh

According to literature, considering a capacity of 140000 kWh, a very rough estimation of initial capital investment would be around 2,3 MCAD for water storage and between 20MCAD and 50MCAD for ice storage (without considering land cost). Clearly it is possible to see that the range changes drastically according to the type of technology. Considering the minimum values around 2M CAD and 20 M CAD, and taking annual savings between 700 kCAD and 1 MCAD, the return in investment would be between 2 and 20 years according to the specific case.

Since a typical district cooling contract between public-private entities is usually lasting 30 or more years, the investment seems quite feasible. However, since CAPEX data references for storage systems are quite difficult to be find in the literature, further study in this sense would be required to assure the feasibility of the investment.

Operational experts of ENGIE confirmed the result obtained as realistic one and aligned also with other studies performed in the networks of Barcelona and Paris (ENGIE, 2020).

In conclusion, a last reflection is raised. All the proposed study demonstrate the added values of both cold water storage and iced storage. With cold storage up to now quite prevalent in terms of CAPEX and OPEX savings but with a limitation linked to its intrinsic energy, which in some situation such as limited surface availability may be problematic. Iced storage thus can be a feasible alternative characterized by high performances but also high investment costs. However, if the design network trend will lead to higher temperature cooling networks, ice storage would still be a feasible choice or heat losses would overcome savings? A certain outcome of this dissertation is the need of further studies both for cooling networks but also cold storage systems. Such a challenge will be left “a posteri”.

This case study has demonstrated that bringing forward innovation will not only influence cost but also operations, bringing improvements in performances and better efficiency. In these applications, storage results also a mean to reduce electricity consumption, especially during peaks. As a result, thanks to storage application, there will be a direct and indirect reduction of carbon footprint which could also be an interesting argument of study for future developments, especially when it comes to cities or territories which have to become carbon neutral in the upcoming years. Carbon footprint could highly influence the decision making process of those clients.

5. Conclusion

This dissertation was a starting point for a reflection on the state of art and innovative perspective of heating and cooling district networks. Fourth and fifth generation district heating and cooling systems have been proven to be a key bone for the 2050 decarbonization strategy which requires a great infrastructure to sustain the energy transition. The clear output of this study is that district networks can be crucial when it comes to building a resilient smart grid: low temperature district heating and high temperature district cooling can be easily coupled with multiple renewable sources as well as thermal storage technology, adding an extra layer of flexibility to the existing infrastructure. Storage systems have been proven to be a great application to cut carbon emission, reducing costs and shifting the electricity demand over the day. However, it is true that both storage systems and DHC would require some ad hoc policies in order to have a smoother development process. A clear example was the case study developed in chapter 4, where the role of electricity matrix tariff played a critical role in the different proposed scenarios. From an initial point where a storage application was totally useless, the different scenarios with cold water and ice storage demonstrated that under the right conditions storage is able to provide multiple benefits in term of performances and overall COP, which can be increased up to 4%. In the same perspective, free cooling can be pushed by using a higher temperature network: in the proposed case with a supply of 8 °C and a return of 15 °C, free cooling has been increased between 20% and 50%. Moreover, while reaching a better efficiency, thermal storage can act as a strong flexibility mean, shavings the peaks while reducing drastically the costs optimizing the planning to electricity tariffs. In this case annual savings between 30% and 40% can be reach. In conclusion, the greatest outcome of this study has also been understanding that regulation can be the true gamechanger in terms of future change both in terms of technologies adoptions and operational deployment. Therefore, it is important to push them at local and global scale building a great network of stakeholders interested in the energy transition first and secondly in building green, resilient and smart territories. This study finally demonstrated that for pushing smart grids and the up taking of storage systems it is not only a matter of cost reduction but many more factors, such as: carbon footprint reduction, better management of loads end energy etc.. which need to be highlighted and bring forward at every level.

6. Future Studies

It has been demonstrated that district cooling will cover a great role in the decarbonization actions of cities. Even if, as a technology, it is not well deployed yet, a lot of projects are already in the pipeline from China to Canada.
In order to sustain and push it in an efficient fossil fuels phasing out strategy, more publication and studies would be required. In fact, a problem related to missing available data have been encountered. International organizations and policies networks such as United Nations, IRENA, IEA, EuroHeat and Power, European Commission, IPCC etc.. are already trying to highlight the attention on this point in order to include district systems in the global discussion, however also operational responsible should higher the awareness on this thematic. To better understand the future role of smart thermal grids, some suggestion have been gathered, especially since changing

the network temperatures could create new scenarios. For example, what it could be interesting to understand is the role of pipe and insulation at higher network cooling temperature and relative delta P and heat losses in relation also to ice storage and negative temperatures, since at the moment it is not yet clear the role of insulation for fifth generation district heating and cooling systems; this typology of study has already been well estimated for heating network but it is not possible to find any reference for cooling one. The up taking of higher temperature network might also influence the type of thermal systems required. It has been demonstrated that the integration of ice storage in a high temperature cooling network would be translated in a great performance, however, what is missing in such a study is the role of heat losses at a delta temperature around 10 °C between the storage system and the temperature network. Going further more studies are required for the integration of heating and cooling in the same pipes, with loops layout, as well as a sector coupling approach including electrical grids. When it comes to storage systems, apart from further regulation at local and international level, data on initial capital cost are very difficult to find, making it difficult to provide feasible estimation. More in general, in order to have strong scientific based position against individual installation, the level of knowledge of cooling networks need to equivalate, if not overtake, the one of heating network.

Finally in the specific case of Ottawa, next steps to be developed are studies regarding the influence of an even higher network temperature in relation to free cooling and global performances. Storage application, especially in terms of iced storage would be also important according to future development of NEMO. In the end, a more precise study of market available technologies and relative capital investment are needed in order to study the feasibility of installation against OPEX savings and find the best techno-economical solution for a given temperature network.

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Annex 1

A.1.1 Benefits and challenges of the energy transition

Compared to individual installation, one of the main advantages of district heating and cooling systems is the high potential of reducing carbon emissions. According to the historical period of energy and ecology transition in which we are, the reduction of carbon emission is the first and probably one of the most relevant criteria which brings people to explore such a technology. However, this is not the only advantage that DHC could bring. In fact, it has also the power and the structure to bring a strong effect of economy of scale which might translate in lower final tariffs for consumers.

Some other benefits of a low-energy DH system can be summarized in three main blocks: environment, community and buildings owners/tenants (Rismanchi, District energy network (DEN), current global status and future development, 2016):

- For environment: it will provide a platform for a flexible choice for an energy resource that is ideal for utilizing renewable energies where possible. They have overall better efficiencies that lead to a reduction in using fossil fuels and therefore reduction in harmful emissions productions such as CO, CO_2. The centralized system would make it easier to have control over maintenance and keep the efficiency on the designed condition.
- For communities: they will enhance the potential for energy management. Also, they will provide a platform for an increase in penetration of local energy resources and recover the waste energy sources. The system would expand based on the community's demand. Also, it would generate job opportunities.
- For building owners and tenants: it will reduce the overall cost of heating and cooling. More importantly, will reduce or eliminate the operational, maintenance cost and its complexity.

On the opposite side of the medal, in order to be able to fulfil its role in future sustainable energy systems, DHCs will have to meet the following challenges (Lund , et al., 4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems, 2014):

- Ability to supply low-temperature district heating for space heating and domestic hot water (DHW) to existing buildings, energy-renovated existing buildings and new low-energy buildings;
- Ability to distribute heat in networks with low grid losses;
- Ability to recycle heat from low-temperature sources and integrate renewable heat sources 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 4th Generation 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

A.1.2 Distribution and transmission heating network

In the following paragraph the evolution of the distribution system will be analyzed for different generations of DHC. To simplify the analysis, the cases of first and second generation will be avoided since their operational conditions (high T and high P steam) would require very different configuration of networks such as the use of very large pipes with nominal diameter over 200 mm (N200 or higher), technical gallery buried in the ground, etc..

The comparison will focus on third, fourth and future fifth generations systems, for supply temperatures in the range between 100 °C and 45 °C.

A.1.3 Optimal design network

The right dimensioning of district heating network is important in order to lower as much as possible installation and operational costs. The use of dimensioning algorithm allows the optimization of the selected pipe especially when it comes to complex systems. Size-searching algorithm look for the lowest pipe diameter possible, defined in accordance with the maximum velocity and/or with the maximum pressure gradient. The aim is to avoid the installation of an over-dimensioned and unnecessarily costly DH network (Tol & Svendsen, Improving the Dimensioning of Piping Networks and Network Layouts in Low-Energy District Heating Systems Connected to Low-Energy Buildings: A Case Study in Roskilde, Denmark, 2011).

An additional extremely important factor is the heat loss, which is affected by the diameter of the pipes and the insulation material employed, as well as by the temperature of the supply and by the return heat carrier medium. For these reasons, special attention needs to be directed at the dimensions of the DH piping network so as to take advantage of DH in the best possible way. A good model of demand heat for the winter season is also needed in order to better design the system, such demands needs to be adjusted by a simultaneity factor which counts the fact that consumers will not use the same amount of heat at the same time.

As shown in figure. 18 the pipes network can be distinguished in transmission system (also called primary circuit) and distribution system (secondary circuit). The connection with the consumer could be direct or indirect. Indirect connections are the most commonly used, where the primary and secondary heating fluids are separated by means of a heat exchanger. In indirect networks the primary side has the flexibility to operate at any pressure or temperature without a concern of the buildings network; In direct connections, the primary and the secondary sides are the same, and the DH water comes into direct contact with the central heating system of the building (Mazhar, Liu, & Shukla, A state of art review on the district heating systems, 2018).

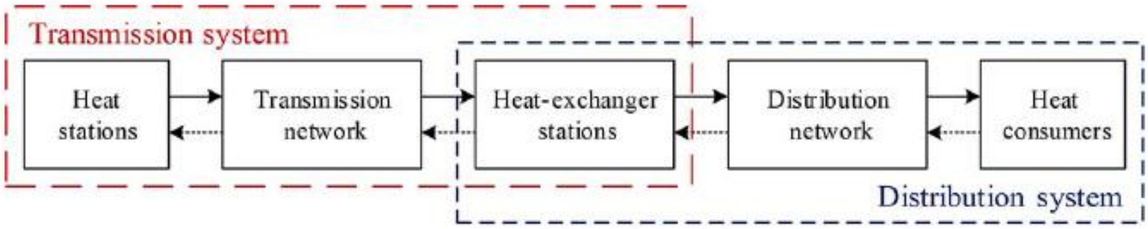


Figure 58: DHS Network Structure. Adapted from ?

A.1.4 Piping state of art

This paragraph will try to summarize all the existing type of pipes on the market with respect to their benefits:

- single pipe (1P): DHC systems up to third generation used to design the network with single buried steel pipe systems to distribute hot steam or hot water from the generation point to the final consumption. However, such pipes have been demonstrated to have very high heat losses. Moreover, due to the high supply temperature, such pipes were deep buried or for the case of steam inserted in technical galleries, which requires high investment; the majority of the district heating network still use this kind of pipe typically in steel or copper material. In order to lower the heat losses, thus increase efficiency, insulation is needed. In order to make the installation faster, manufacturer started creating pre-insulated pipes ready to install, as shown in figure. 19.

Figure 59: Single pre-insulated steel pipe. Adapted from (Logstor, Design manual, Version 2019.02)

- twin pipe (2P): by definition, twin pipes are two pipes in the same pre-insulated casing. One pipe for supply and one for return. They are available in the market and have started being used in multiple district heating projects in place of single pipe for transmission networks. The most famous manufacturers count a list of different dimension per material, mostly steel and plastics. The most common commercially available twin pipes are in the range of {10, 11.6, 15, 20, 26} for AluFlex set of inner diameter (TPD) and of {37.2, 43.1, 54.5, 70.3, 82.5} for Steel TPD (Logstor, Design with TwinPipes, Version 2016.08).

An ulterior development of twin pipes are the so called double pipes. They consist of a pair of media pipes of dissimilar size, co-insulated in the same casing. In service networks, (Dalla Rosa, Li, & Svendsen, Method for optimal design of pipes for low-energy district heating, with focus on, 2011) have demonstrated that this evolution of design can halve the heat losses in the case of operation during low heating load periods such as summer, where the only demand requested is for bathrooms.

Some benefits of one or the other will be evaluated in the following paragraphs.

Figure 60: left: Pre-insulated twin pipe design; centre: plastic twin pipe on reels. Adapted from (Logstor, Design with TwinPipes, Version 2016.08); right: cross-section detail of a double pipe with dissimilar size. Adapted from (Dalla Rosa, Li, & Svendsen, Method for optimal design of pipes for low-energy district heating, with focus on, 2011)

- three pipe (3P): this pipe design has been studied by (Averfalk & Werner, Novel low temperature heat distribution technology, 2018) with the objectives of lowering the heat losses of the distribution system and avoiding temperature degradation especially common in service pipe of low temperature network (LTDH). Such design counts of three pipes in the same insulated casing: typically one for supply, one for return and one for recirculation. The aim of recirculation is to avoid the increase in return temperature in the service pipe during summer period. This kind of pipe is not yet on the market, however it has already been installed in some low energy demo projects inside Engie group (example of a geothermic based mini-grid in Arcueil-Cachan in Paris) but also, such as in some bio-energy villages in Germany based on biomass (Lohrengel, Jühnde Bio-Energy Village in Germany - Presentation about renewable energy Jühnde, 2013).

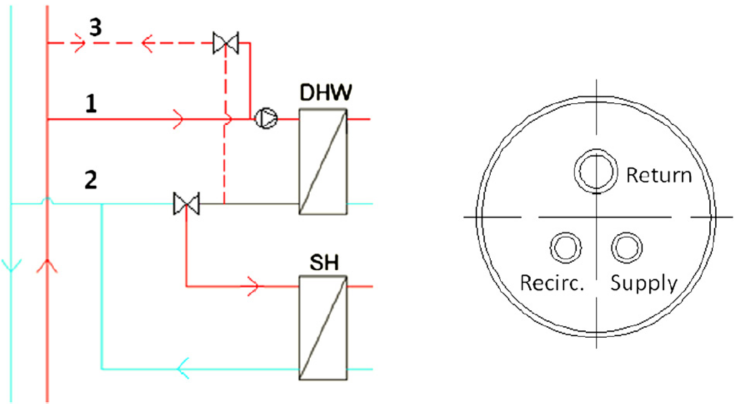


Figure 61: in the left connection with heat exchangers (HEX) ; in the right a cross section of a triple pipe configuration. Adapted from (Dalla Rosa, Li, & Svendsen, Method for optimal design of pipes for low-energy district heating, with focus on, 2011)

- Quadruple pipe: new studies carried out by (Teleszewski, Krawczyk, & Rodero, Reduction of Heat Losses Using Quadruple Heating Pre-Insulated Networks: A Case Study, 2019) have also explored the option of using quadruple pipes in the same insulated cage for service pipe. In this case there is one pipe for supply, one for return, one for circulation and one for domestic hot water (DHW). This kind of pipe, as the three pipe, finds high benefits in low temperature network because of its ability to lower the heat losses while reducing the cross-sectional area of thermal insulation. This kind of pipe i not extensively used yet, however they have started to be tested.

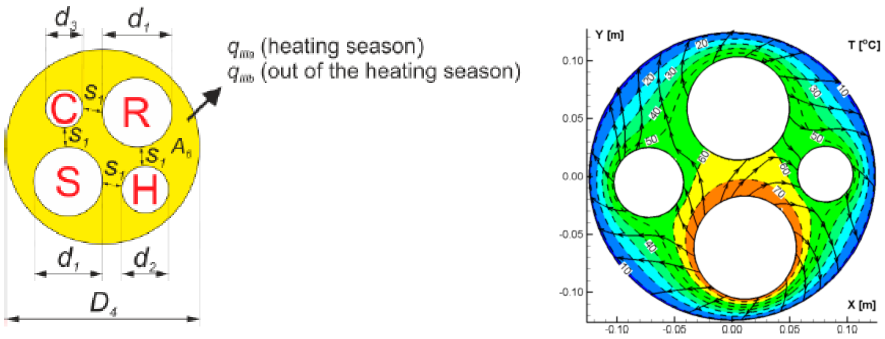


Figure 62: Quadruple pipe cross section. Adapted from (Teleszewski, Krawczyk, & Rodero, Reduction of Heat Losses Using Quadruple Heating Pre-Insulated Networks: A Case Study, 2019)

A.1.5 Benefit of low temperature heating network

The implementation of low temperature network will open new scenarios in the design of transmission and distribution network of district heating, not only because it will open up to the use of plastic materials but also because it brings a number of different benefits. Following a list of the already proved benefits:

Low heat losses network

Different studies carried out by (Vad Mathiesen, et al., Towards a decarbonised heating and cooling sector in Europe, unlocking the potential of energy efficiency and district energy, 2020) have demonstrated that the classical pipe design is not good enough when it comes to low energy networks. This kind of pipes, in fact, suffers of high heat losses. Thus, high investments would be needed for insulation. The optimal design for low heat networks consist of a twin pipe system for the primary transmission network, while few different option have been studied for secondary or service circuits based on double pipes, triple pipes and quadruple designs. Moreover, for low energy network, plastic material had shown multiple benefits not only in the reduction of heat losses but also in the reduction of installation costs, insulation material, and operational costs.

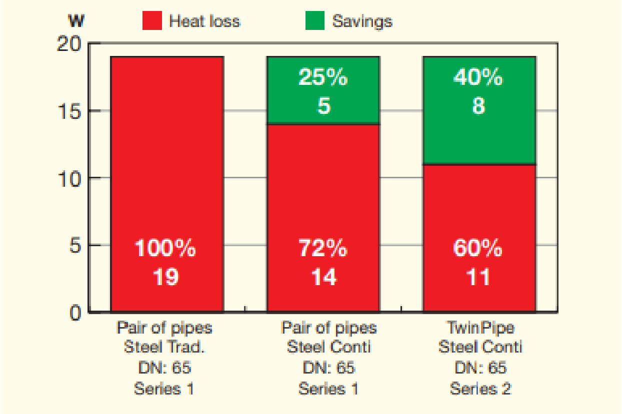


Figure 63: Savings in twin steel pipes Vs pairs of single steel pipes with lower heat loss. Adapted from (Logstor, Reduced operating costs and CO2 emissions by as much as 50 %)

Smaller pipe dimensions – plastics over steel

Thanks to the low temperature running in the network, new type of material has been investigated to lower the installation and operational costs of the network. Some type of plastics in particular resulted to have great impacts in the initial investment such as: Aluflex, PEX, PP-R and PE-R only available up to 300 mm diameter while steel pipes cover a greater range of diameters from DN20 to DN1200.

AluFlex will be the plastic pipe used in further examples, thus a brief description will follow: built on a multi-layer design containing aluminium and PEX (cross-linked polyethylene), this type of plastic is combining the advantages of the smooth surface of the plastic pipe with the durability and tightness of the welded aluminium pipe. The composition is a sandwich construction, consisting of an aluminium pipe, coated inside with PEX and outside with PE. The aluminium core protects 100% against cell gas diffusion into the media and water vapor diffusion into the insulation. It further makes the pipe dimensionally stable during installation in the trench and during installation of the force transmitting press-couplings.

4DHC allowed already a general reduction of the classical single steel pipe dimension used in 2DHC, however they resulted still in high heat losses resulting in the need of high investments for insulation.

The usage of a twin pipe design is a possible solution in order to lower such costs while maintaining a very high global performance (Averfalk & Werner, Novel low temperature heat distribution technology, 2018).

(Dalla Rosa, Li, & Svendsen, Method for optimal design of pipes for low-energy district heating, with focus on, 2011) performed a comparison of flexible twin Aluflex pipes versus rigid twin steel pipes have been carried out for the same output performance of a service pipe (T_{supply} = 55 °C, T_{return}= 25°C, T_{ground} = 8°C). Logstor A/S market solutions have been selected (Logstor, Design with TwinPipes, Version 2016.08): the Aluflex ø14-32 mm has been chosen for plastic pipes while steel twin pipes in straight length of 12-16 meters are used for DN ≥ DN32. They both have been chosen with low-lambda rigid polyurethane foam (PUR) insulation and an aluminium diffusion barrier between the insulation and the polyethylene (PE) casing. Because the insulation is encased between the outer diffusion barrier and the diffusion-tight media pipes, there will be no loss or contamination of the cell gas. The very low heat conductivity will therefore remain unchanged over time. In table 2 the results of the study are shown. At low operational temperatures, the heat loss from the return pipe is zero or negative, which is due to a small amount of heat transferred from the supply pipe to the return. In general, the heat losses listed in the table are very low demonstrating the higher performance of the plastic pipes applied to low energy network.

Table 20: Steel twin pipe Vs AluFlex twin pipe heat losses. Adapted from: (Dalla Rosa, Li, & Svendsen, 2011)

Steel twin pipe - Class 2		
Pressure class PN25		
Dimension (carrier pipe)	Casing pipe diameter	Heat loss
d_{supply}-d_{return}	D	Total
mm	mm	W/m
42-42 (DN 32)	182.7	4.96
48-48 (DN 40)	182.7	5.81
60-60 (DN 50)	227.9	5.62
76-76 (DN 65)	256.1	6.57
88-88 (DN 80)	283.8	7.34

AluFlex twin pipe - Class 2		
Pressure class PN10		
Dimension (carrier pipe)	Casing pipe diameter	Heat loss
d_{supply}-d_{return}	D	Total
mm	mm	W/m
14-14	110	2.84
16-16	110	3.09
20-20	110	3.66
26-26	125	4.05
32-32	125	5.07

Less insulation for the same performance

The fundamental idea of low-temperature DH networks is that such systems can meet the energy and comfort requirements in low-energy buildings without increasing the amount of insulation around the pipes and therefore in a cost-effective way.

(Dalla Rosa, Li, & Svendsen, Method for optimal design of pipes for low-energy district heating, with focus on, 2011) carried out an experiment taking two pipe types: the first, a distribution steel twin pipe (DN65, insulation series 2, Logstor), and the second, a plastic branch pipe (Aluflex 16-16, insulation series 2, Logstor). Comparing the heat losses in the case of normal operational temperature (supply: 85 °C, return: 50 °C) and in the case of low-temperature operation (supply: 55 °C, return: 25 °C). The result proved that, to achieve the same heat loss, steel pipe required 3 time less insulation while Aluflex needed 11 times less insulation for low operating temperature.

Possible solution for temperature contamination in service pipes

When the network heating demand becomes low, the required mass flow rate is reduced accordingly. Smaller mass flow rate causes larger water temperature drop along the pipeline due to heat loss to the ground. In non-heating season, the DHW load is low and its demand is intermittent with the total draw-off duration less than 1 hour/day. To keep high thermal comfort, bypass valves are installed at the DHW substation. When there is no draw-off, the DH supply water is bypassed and flows back to the network return line without any cooling, it increases the network return temperature significantly and subsequently increases the network heat loss and decreases the thermal plant performance. This network performance degradation is particularly relevant for LTDH and DH supply to sparse areas. To keep low network return temperature, it should be avoided to have the DH supply water directly mixed with the return water, thus by-pass application should not be allowed. To solve such problem different solution have been studied. Two example of novelty in the design of service pipe are now of particular interest for future studies: the use of an evolved twin pipe design (fig. 26), called double pipe (Dalla

Rosa, Li, & Svendsen, Method for optimal design of pipes for low-energy district heating, with focus on, 2011) and the use of a thee pipe design (Averfalk & Werner, Novel low temperature heat distribution technology, 2018).

- Double pipe: this concept is based on the fact that the supply line also acts as the recirculation line during low heating load periods, automatically by-pass is not needed anymore. Furthermore, the water flow in the return line has the same direction as in the supply line (clockwise in the example), so that the smallest size for the return pipes is expected to correspond to the biggest size for the supply size, and vice versa. This results in lower local pressure differences between supply and return lines and savings in operational costs due to lower heat losses. Double pipe have been demonstrated of having also better performance than twin pipes as showed in table 3.

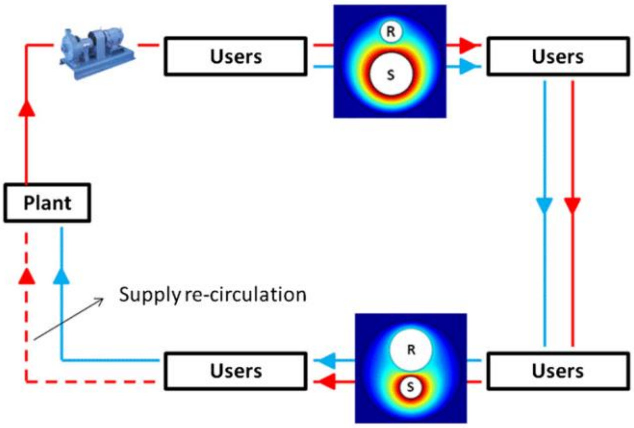


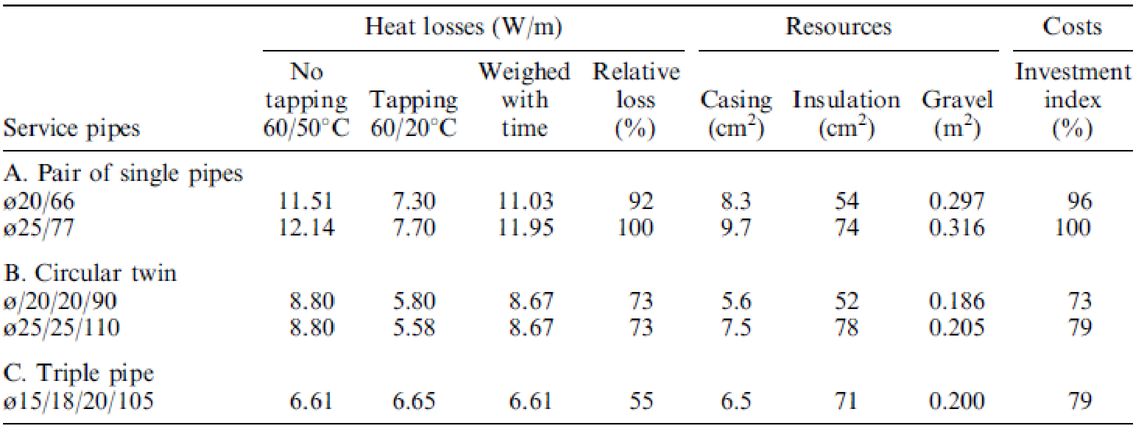
Figure 64: simplified double pipe concept. Adapted from (Dalla Rosa, Li, & Svendsen, Method for optimal design of pipes for low-energy district heating, with focus on, 2011)

Table 21: Twin pipes Vs double pipes heat loss for a service network. Tsupply/return/gound: 55/25/8 °C. Adapted from (Dalla Rosa, Li, & Svendsen, Method for optimal design of pipes for low-energy district heating, with focus on, 2011)

Size (DN)	Heat loss [W/m]			Total	[%]
	Supply	Return	Total		
40–40	−6.24	0.04	−6.20	Twin	6.1
80–80	−7.66	0.07	−7.59	−13.79	
40–80	−5.55	0.05	−5.58	Double	
80–40	−7.41	0.05	−7.36	−12.94	
100–100	−7.83	−0.55	−8.39	Twin	11.8
200–200	−8.92	0.24	−8.68	−17.06	
100–200	−6.4	0.08	−6.36	Double	
200–100	−8.07	−0.03	−8.69	−15.05	

Triple pipe design: resuming the configuration of such a design already explained in paragraph 2.4.2, the recirculating pipe allow the dismission of a by-pass bringing a positive impact in the system ensuring return temperature of 17 °C of fundamental importance for low temperature network to maintain a ΔT of 10°C. (Bohm & Kristjansson, Single, twin and triple buried heating pipes: on potential savings in heat losses and costs, 2005) have performed a comparison of such a system with a reference Ø25/77 pipe, taken as the most common service pipe used in Denmark (leading Country for district heating). The result shown in table 4 demonstrate a reduction of losses of 55% compared with this pipe the triple pipe has a heat loss of only 55%.

Table 22: Heat losses, ressources and cost of service pipes. Adapted from (Bohm & Kristjansson, Single, twin and triple buried heating pipes: on potential savings in heat losses and costs, 2005)



	Heat losses (W/m)				Resources			Costs
Service pipes	No tapping 60/50°C	Tapping 60/20°C	Weighed with time	Relative loss (%)	Casing (cm^2)	Insulation (cm^2)	Gravel (m^2)	Investment index (%)
A. Pair of single pipes								
ø20/66	11.51	7.30	11.03	92	8.3	54	0.297	96
ø25/77	12.14	7.70	11.95	100	9.7	74	0.316	100
B. Circular twin								
ø/20/20/90	8.80	5.80	8.67	73	5.6	52	0.186	73
ø25/25/110	8.80	5.58	8.67	73	7.5	78	0.205	79
C. Triple pipe								
ø15/18/20/105	6.61	6.65	6.61	55	6.5	71	0.200	79

Lowering the network investment

As seen in the previous table, it is also possible to lower the investment costs by using different kind of pipes. The investments in a new pipe network consist of the production costs of the pipe itself, the component costs (branch tees, etc.) which depend on the network structure, and the cost of pipe works and civil works. In this context we want to compare the costs of traditional single pre-insulated pipe systems with the costs of using twin or triple pipes (Bohm & Kristjansson, Single, twin and triple buried heating pipes: on potential savings in heat losses and costs, 2005). The civil costs among other things depend on the pipeline space demand in the trench. For calculating the investments, the following model developed in Kristjansson et al. (2004) was applied:

$$I_j = \left(\sum C_{ij}\right) F_j(G) + E_j \tag{1}$$

where j is a pipe dimension index and

$$C_{ij} = P_i\left(M_{ij}\right)^{0.8} \tag{2}$$

where i is a material index (steel, casing, insulation, etc.)

$$E_j = P_a\left(A_{aj}\right)^{0.8} + P_g\left(V_{gj}\right)^{0.8} + constant \tag{3}$$

where I is the investment in pipe network, C the cost of straight pipeline, F the cost factor of components, depending on the network structure index G, E the excavation costs, P the material price factor (incl. work) of the material, M the volume of pipe material and A the area of asphalt in the trench and V is the volume of gravel in the trench. All parameters including the power factors of 0.8 were found with a good correlation from multivariable regression of data from actual projects. Investments in new pipe geometries not installed yet was predicted by the above model. Applying the cost model explained above for the different types of pipes permits us to compare the results. At the end, savings of 15–19% were found by using twin pipes compared with horizontally placed single pipes. For the service pipes, the triple pipe reduced the heat loss by 45% compared with a common pair of single pipes and by 24% compared with circular twin pipes. The reduction in investment index is 21% (referring to table 4). The model gives consistent results with the findings in Schmitt and Hoffmann (1999) (Korsman, de Boer, & Smits, 2008). In figure 25 an example from (Logstor, Reduced operating costs and CO2 emissions by as much as 50 %) of the differences in investments and CO2 emission between a single pipe and twin pipes of Longstor catalogue.

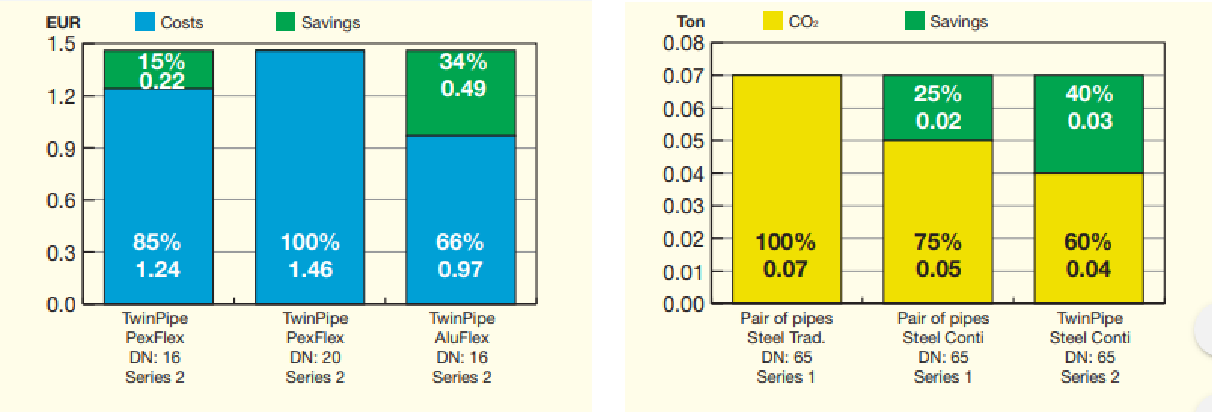


Figure 65: left: Investment comparison; right: emission comparison.
Adapted from (Logstor, Reduced operating costs and CO2 emissions by as much as 50 %)

Summary

Table 23: Summary of benefits and drawbacks of different pipes compared with classical single pipe

Benefit/ drawback	**Single pipe**	**Twin pipe**	**Triple pipe**
Heat losses	Very high	30% less	20% respect to twin
By-pass in service pipe	Yes	Yes	No
Recirculation	No	Yes (if double pipe)	Yes
Return T in summer	High	>20 °C	<18 °C
Insulation	High	Low	Even lower
Investment	High	20% less	Same of twin pipes
CO2 emissions	0.07 tons	Saved 40%	Same of twin pipes

A.2 Smart Thermal City Map

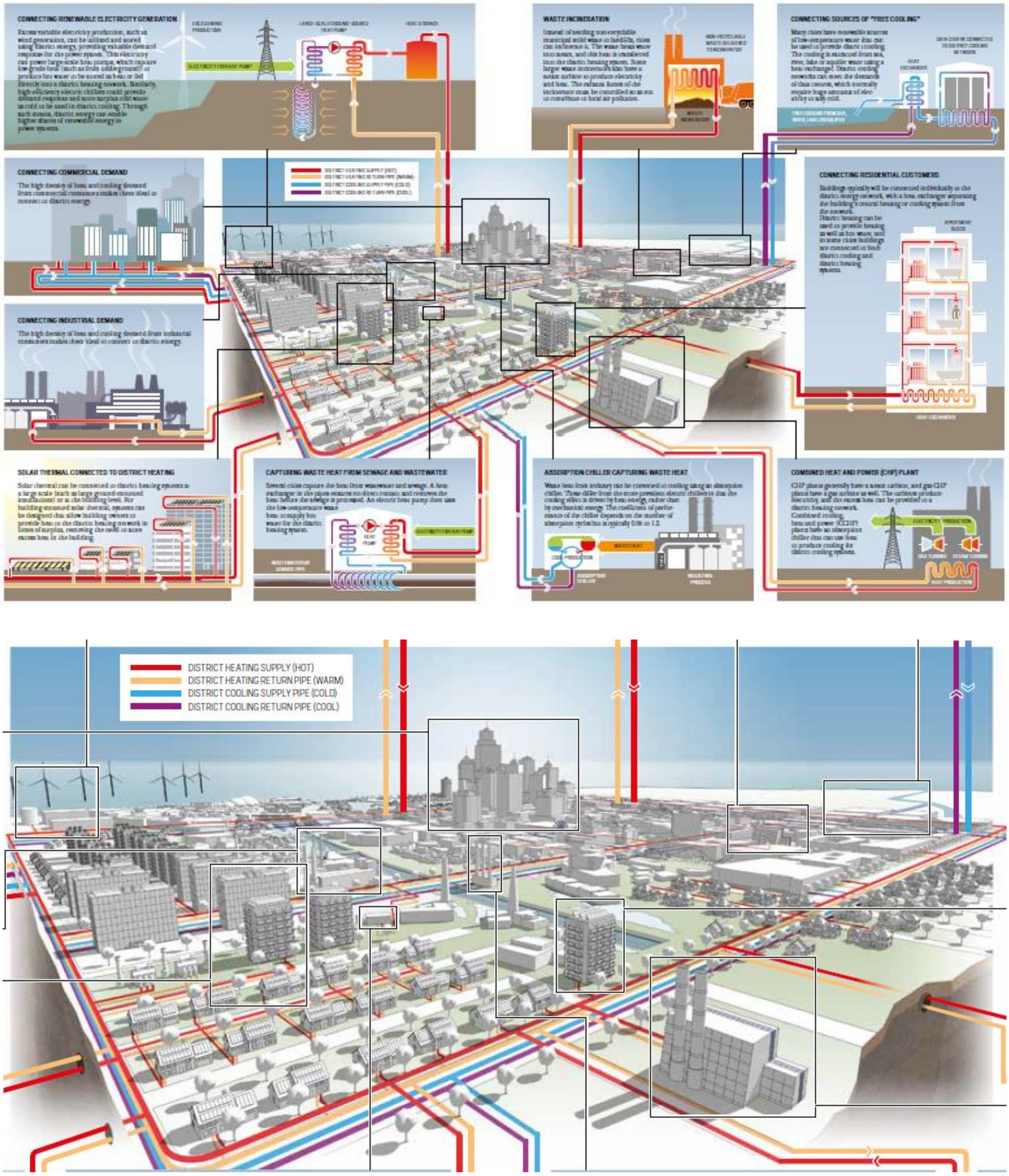
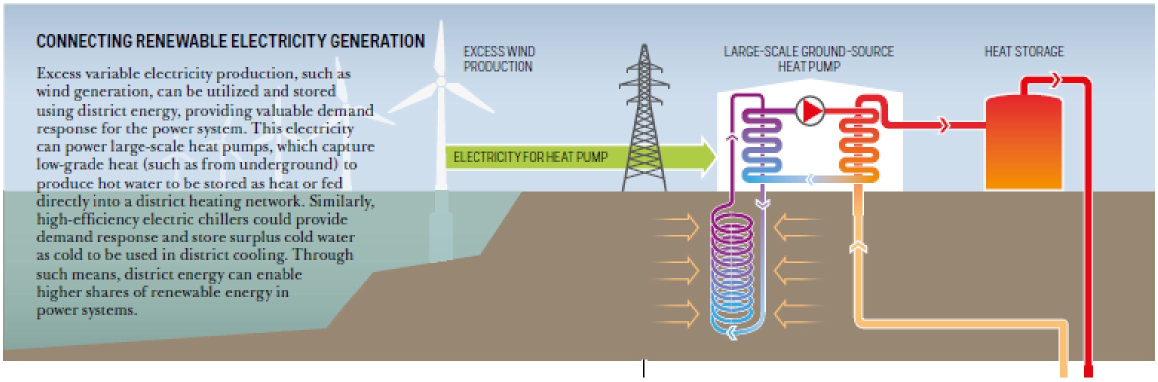


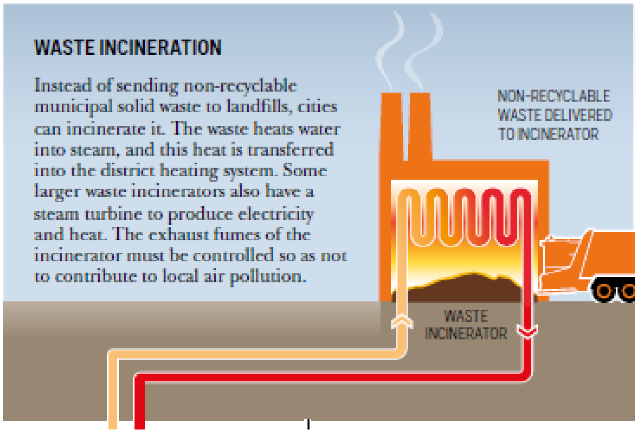
Figure 66 Smart thermal network. Reproduced according to.. (UNEP, 2015)



CONNECTING RENEWABLE ELECTRICITY GENERATION

Excess variable electricity production, such as wind generation, can be utilized and stored using district energy, providing valuable demand response for the power system. This electricity can power large-scale heat pumps, which capture low-grade heat (such as from underground) to produce hot water to be stored as heat or fed directly into a district heating network. Similarly, high-efficiency electric chillers could provide demand response and store surplus cold water as cold to be used in district cooling. Through such means, district energy can enable higher shares of renewable energy in power systems.

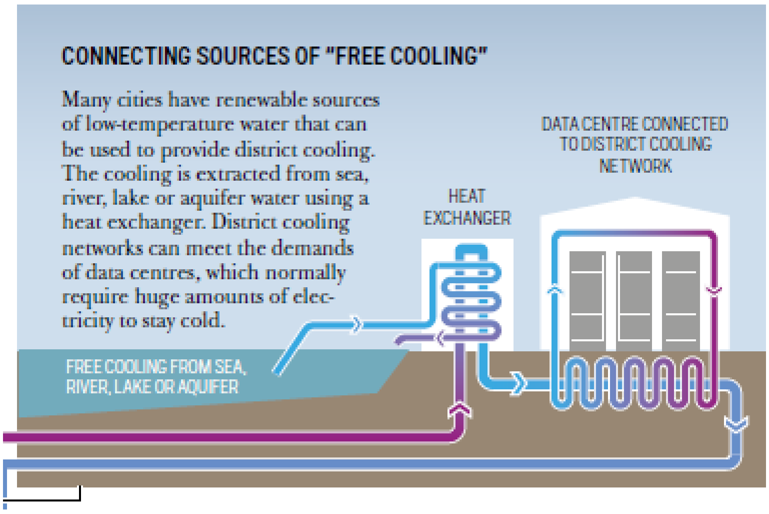
Figure 67 Smart thermal network. Reproduced according to.. (UNEP, 2015) - detail 1



WASTE INCINERATION

Instead of sending non-recyclable municipal solid waste to landfills, cities can incinerate it. The waste heats water into steam, and this heat is transferred into the district heating system. Some larger waste incinerators also have a steam turbine to produce electricity and heat. The exhaust fumes of the incinerator must be controlled so as not to contribute to local air pollution.

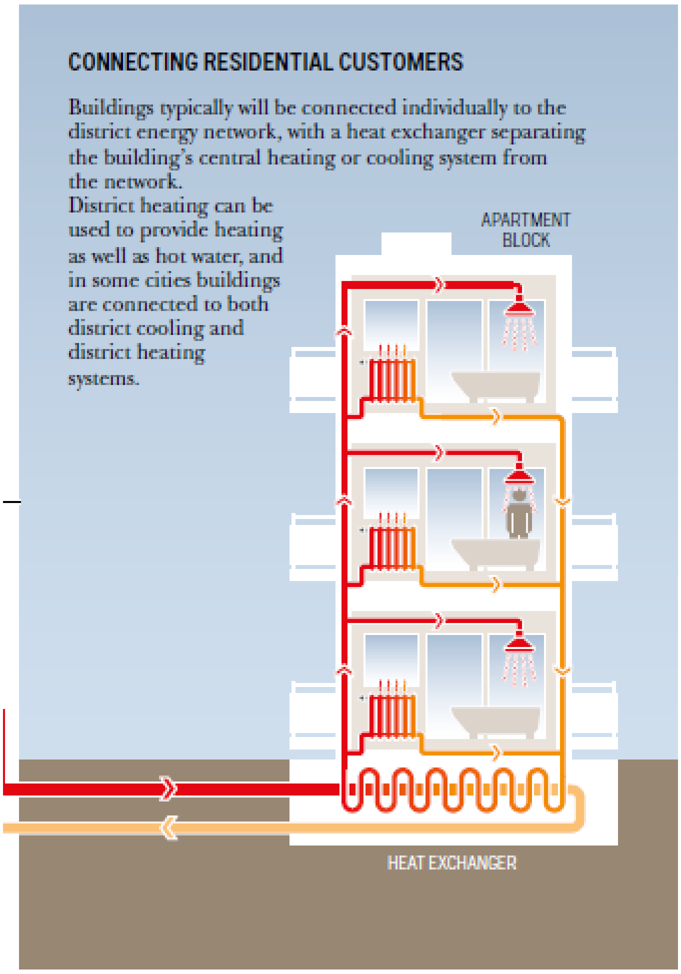
Figure 68 Smart thermal network. Reproduced according to.. (UNEP, 2015) - detail 2



CONNECTING SOURCES OF "FREE COOLING"

Many cities have renewable sources of low-temperature water that can be used to provide district cooling. The cooling is extracted from sea, river, lake or aquifer water using a heat exchanger. District cooling networks can meet the demands of data centres, which normally require huge amounts of electricity to stay cold.

Figure 69 Smart thermal network. Reproduced according to.. (UNEP, 2015) - detail 3

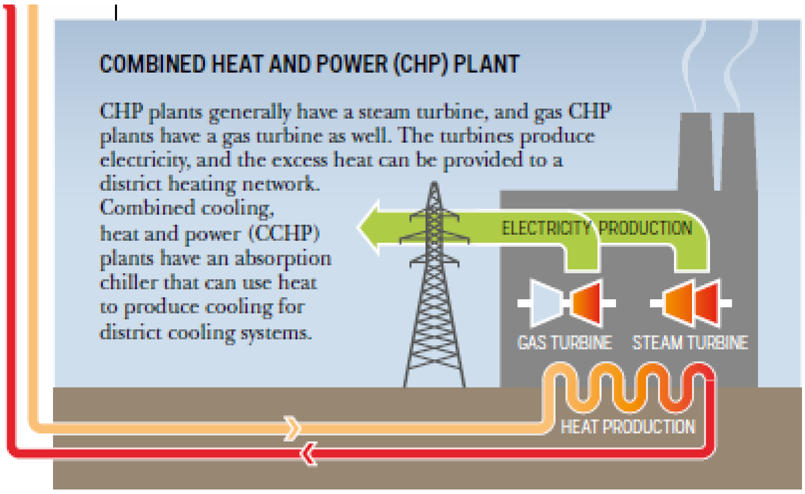


CONNECTING RESIDENTIAL CUSTOMERS

Buildings typically will be connected individually to the district energy network, with a heat exchanger separating the building's central heating or cooling system from the network.

District heating can be used to provide heating as well as hot water, and in some cities buildings are connected to both district cooling and district heating systems.

Figure 70 Smart thermal network. Reproduced according to.. (UNEP, 2015) - detail 4

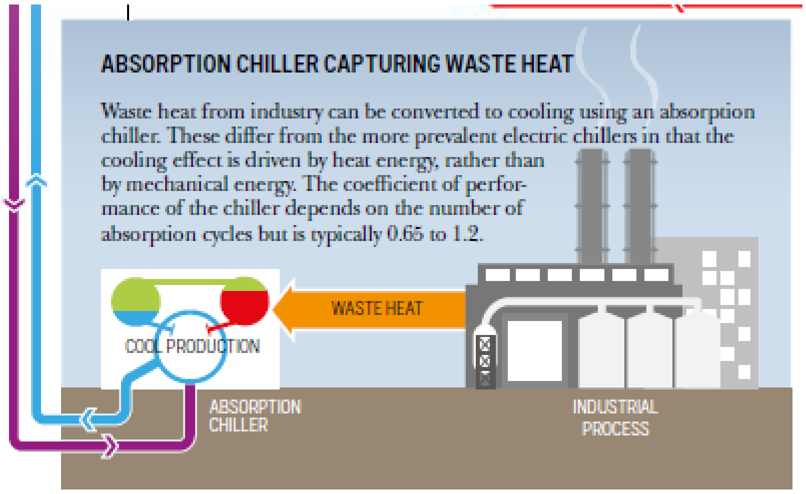


COMBINED HEAT AND POWER (CHP) PLANT

CHP plants generally have a steam turbine, and gas CHP plants have a gas turbine as well. The turbines produce electricity, and the excess heat can be provided to a district heating network.

Combined cooling, heat and power (CCHP) plants have an absorption chiller that can use heat to produce cooling for district cooling systems.

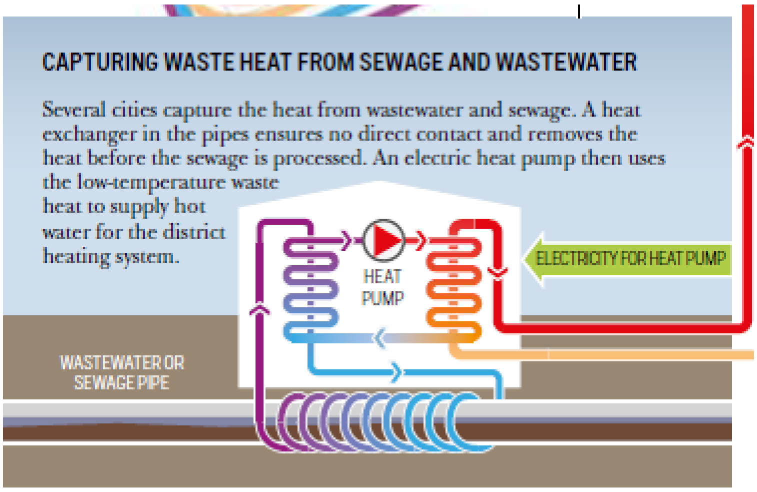
Figure 71 Smart thermal network. Reproduced according to.. (UNEP, 2015) - detail 5



ABSORPTION CHILLER CAPTURING WASTE HEAT

Waste heat from industry can be converted to cooling using an absorption chiller. These differ from the more prevalent electric chillers in that the cooling effect is driven by heat energy, rather than by mechanical energy. The coefficient of performance of the chiller depends on the number of absorption cycles but is typically 0.65 to 1.2.

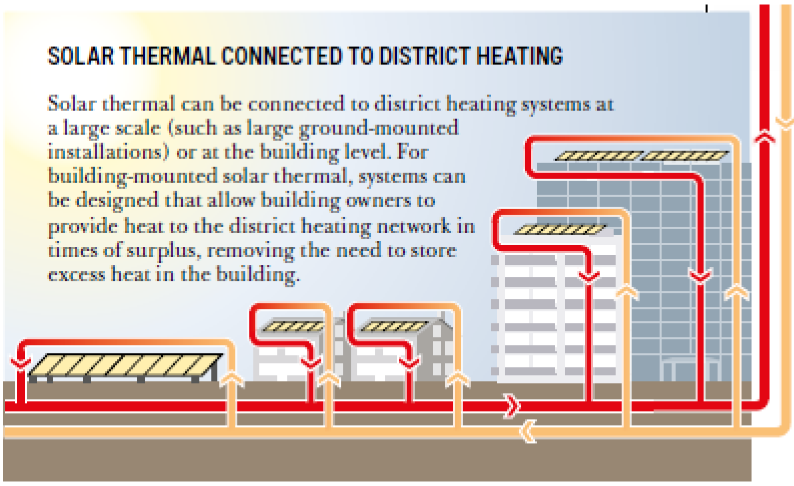
Figure 72 Smart thermal network. Reproduced according to.. (UNEP, 2015) - detail 6



CAPTURING WASTE HEAT FROM SEWAGE AND WASTEWATER

Several cities capture the heat from wastewater and sewage. A heat exchanger in the pipes ensures no direct contact and removes the heat before the sewage is processed. An electric heat pump then uses the low-temperature waste heat to supply hot water for the district heating system.

Figure 73 Capturing waste heat with absorption chillers



SOLAR THERMAL CONNECTED TO DISTRICT HEATING

Solar thermal can be connected to district heating systems at a large scale (such as large ground-mounted installations) or at the building level. For building-mounted solar thermal, systems can be designed that allow building owners to provide heat to the district heating network in times of surplus, removing the need to store excess heat in the building.

Figure 74 Smart thermal network. Reproduced according to.. (UNEP, 2015) - detail 7

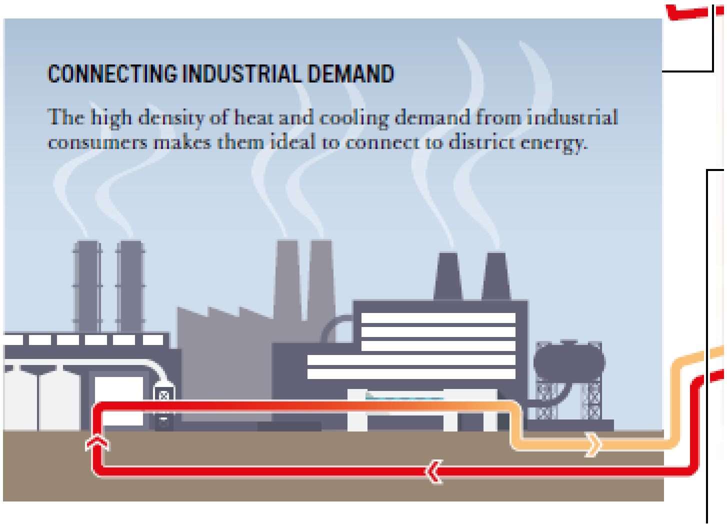


Figure 75 Smart thermal network. Reproduced according to.. (UNEP, 2015) - detail 8

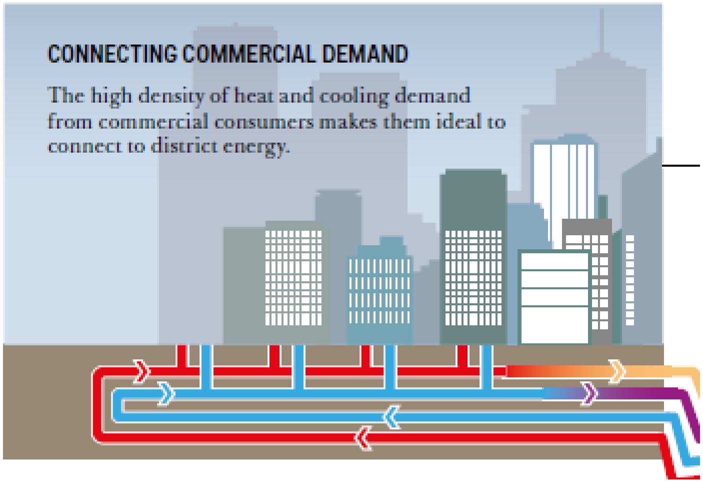


Figure 76 Smart thermal network. Reproduced according to.. (UNEP, 2015) - detail 9

Thermal Storage Integration in a Smart Thermal Grid

Ottawa Case Study with ENGIE

Erika Dal Monte