District cooling – The sustainable solution for cooling cities

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The demand for cooling is expected to grow significantly in the coming decades, driven by rising living standards and increasing global temperatures. To minimize the impact of cooling demand, it is vital to both adapt building standards and designs to reduce cooling requirements and ensure that any remaining cooling demand is met in the most efficient and sustainable manner possible.

In dense urban areas, one of the most promising cooling solutions is district cooling (DC). However, the design and area coverage of a district cooling system (DCS) is highly dependent on local conditions, leading to a wide range of potential opportunities and benefits for local communities.

Although the technical solutions for establishing DC are mature and have been proven over multiple decades, a shift in mindset is needed regarding cooling supply solutions, particularly in dense urban areas. To facilitate the growth of the DC sector and enable it to reach its full potential, focused regulation and long-term energy planning are essential. Clear regulations and policies will help reduce the perceived risks associated with DCS, making it easier for utilities to attract the necessary capital for establishing such systems.

The purpose of this document is to highlight the benefits of DC and present selected case studies that operate in vastly different climate conditions. The case studies are chosen to showcase how different local opportunities can create a strong business case for the technology, even in locations which at a first glance might not be considered particularly suitable for DC. These case studies may inspire decision makers to look for local opportunities – synergies with other sectors – that can strengthen the case for development of DCSs as sound business investment opportunities.

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Nomenclature

DC	District cooling
DCS	District cooling system
DH	District heating
DHS	District heating system
ETS	Energy transfer station
LNG	Liquefied natural gas
TES	Thermal energy storage

Cooling demands

In general, cooling demands can be split into two main groups, comfort cooling and process cooling.

Comfort cooling is probably the first thing that comes to mind when considering cooling demands. By definition, comfort cooling refers to controlling the indoor climate, temperature as well as humidity, for the comfort of the occupants. The drivers for this cooling demand can be both climate and non-climate related. Climate related factors include outdoor temperatures, solar radiation and humidity. Non-climate related factors include heat generated by electric appliances, ventilation requirements, as well as heat generated by people. While climate related factors tend to be dominant in smaller buildings, particularly residential buildings, the non-climate related factors become increasingly influential in larger buildings. In general, the larger the building, and the higher the occupancy rate, the more dominant non-climate related cooling demands become. For example, in large shopping malls and office buildings, cooling demands are primarily influenced by occupancy rates. Higher occupancy levels contribute to increased internal heat loads, elevated humidity, greater ventilation requirements to maintain indoor air quality, and higher energy consumption from lighting and equipment usage[1].

As comfort cooling's purpose is to enhance the quality of the indoor environment for humans to live and work, the cooling demand inevitably varies greatly between seasons, as well as during the day.

While cooling is often associated with indoor comfort in hot climates the fact is that comfort cooling demands exist in cold climates as well, as is evident from Northern European cities like Stockholm, Sweden and Helsinki, Finland. Both Stockholm and Helsinki host large DCSs, which supply cost-efficient and reliable cooling to commercial and industry customers, while leveraging synergies with the district heating sector through the cogeneration of heating and cooling. Additionally, DCSs in Northern Europe benefit from regional familiarity with district heating (DH) business model, which lowers adoption barriers to the concept.

In the cold, dry climates of Stockholm and Helsinki, residential cooling remains a minor component of district cooling supply. However, as climates become hotter and more humid, residential cooling becomes increasingly important, as seen in desert and semi-arid regions such as Dubai, United Arab Emirates, and Honolulu, Hawaii.

Process cooling on the other hand is related to industrial applications, where there is a need to remove heat from a room or equipment to ensure stable operating conditions, both in terms of temperature and humidity. Examples can range from cooling of data centers, manufacturing equipment and processes, controlled cooling of newly manufactured products, food and drink production, laboratories, indoor agriculture, indoor fish farms, hospitals, and airports. Unlike comfort cooling demands, process cooling is, to a large extent, climate-independent and is therefore rather constant over the year.

[1] Ding, Y., Wang, Z., Feng, W., Marnay, C. and Zhou, N. *Influence of occupancy-oriented interior cooling load on building cooling load design.* Applied Thermal Engineering, Vol. 96, 2016, Pages 411-420. https://doi.org/10.1016/j.applthermaleng.2015.11.096

The basics of district cooling

A DCS is a closed-loop pipe network that circulates water between a central cooling plant and building energy transfer stations (ETS). The building systems use the cold water to absorb heat and cool the interior. The ETS transfers this heat back to the DC plant, where the water is re-cooled and recirculated. To enhance efficiency and reduce costs, these systems often use cold water storage to generate cooling at night, benefiting from lower power prices and higher efficiency due to cooler ambient temperatures. In essence, DC is an infrastructure, just like the power, DH, fresh water supply and wastewater infrastructures. As with other infrastructures, the success of the DCS originates from aggregating loads from multiple users, which enables the DCS operator to take advantage of opportunities that cannot be cost-effectively accessed at a building level. These opportunities can range from simple measures, such as reducing cooling generation capacities (and consequently investment costs) due to the varying cooling schedules of buildings, to more complex solutions such as using free cooling sources, e.g. deep-water sources.

The DC infrastructure, Figure 1, can be roughly divided into three parts:

- Cooling plant
- Distribution network
- Energy transfer stations

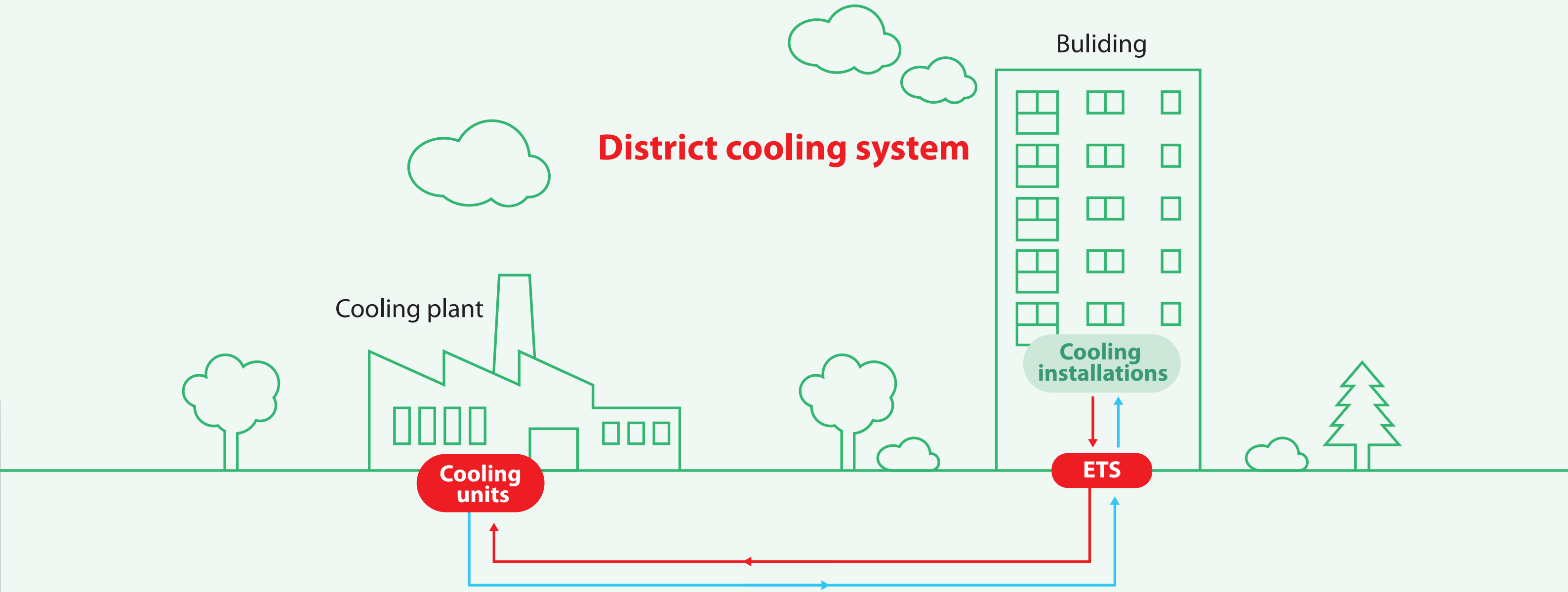

Figure 1. Key elements of a DCS.

The cooling plant can consist of a wide range of cooling technologies, such as compressor chillers, absorption chillers, heat pumps or free cooling. To minimize the cooling generation capacity and optimize cooling generation costs, thermal energy storages (TES) are commonly installed in the cooling plant. In a cogeneration setting, the TES can also be used as a hot water storage, which would not only be capable of reducing peak power demands and maximizing use of low carbon power, but can also offer effective decoupling of the cooling demands and generation, ensuring maximum synergy benefits.

The distribution pipeline is normally insulated to minimize heat gains from the ambient. To minimize the distribution cost, variable speed pumps are applied and controlled to deliver the minimal differential pressure necessary to operate the building's ETS. The variable speed pumps further enable variable flow operation, which minimizes the distribution pumps' power consumption.

The ETS is the interface between the DCS and the building. The main purpose of the ETS is to adapt the operating parameters, temperature and pressure, to the building's requirements. The key components of the ETS are heat exchangers, control equipment and a cooling meter.

The building's cooling installation distributes cooling around the building, using control valves and cool emitters, such as fan coils, cooling beams and floor cooling.

Symbiotic relationship

The DCS and building installations share a symbiotic relationship, mutually benefiting one another:

- The **DCS** provides efficient, centralized cooling to multiple buildings, eliminating the need for individual cooling generation equipment. For buildings, this results in energy savings, lower operational costs and reduced environmental impacts, including decreased noise pollution from air coils and visual intrusion on building architecture caused by cooling systems.
- In return, **building installations** generate demand and serve as distribution points for the DCS, enabling it to operate efficiently and at scale. The more buildings that are connected, the greater the energy and cost efficiency, driven by opportunities arising from the aggregated loads, economies of scale, diversification of cooling sources and optimized energy use.

Due to their symbiotic relationship, the success of the DCS is dependent on the correct design and operation of each building's cooling installation. As cooling installation inefficiency will inevitably lead to DSC inefficiency, just as it would lead to inefficiency in building-level chillers. While inefficient operation leads to higher cooling costs in both cases, the visibility of these cost increases can differ, as outlined below.

→ For building-level chillers, the added cost of inefficient operation is partly concealed because:

a) Most of the fixed costs, such as the investment in building-level chillers, which are generally over dimensioned, are already sunk costs for the building owners.

b) The variable costs, including electricity and make-up water for wet cooling towers, are often obscured within the building's general utility bills.

→ In the case of the DCS, the impact of inefficient building cooling operation will, on the other hand, become painfully visible on the bill from the DC utility, as the inefficient operation will be reflected in the DC bill through:

a) Increased cost of contracted cooling capacity (fixed cost),

b) Higher cooling consumption costs (variable cost), and

c) Potential penalties due to insufficient heating of the supplied water.

→ The reasons behind these impacts are as follows:

a) Inefficient building operation may require the building owner to renegotiate their contract for a larger cooling capacity, resulting in higher fixed costs.

b) Inefficiency leads to higher cooling consumption, increasing variable costs.

c) Inefficient operation reduces DCS efficiency in both cooling distribution and generation. This occurs when customers fail to operate their building according to contracted parameters, such as maintaining the required temperature difference between DC supply and return flows.

Benefits of district cooling systems

Depending on the local conditions, a DCS can deliver a wide range of benefits over individual and building-level cooling solutions. Depending on the climate at a particular location, a subset of the below-mentioned benefits may apply to a DCS.

General benefits

Economy of scale

- Aggregating the demands from multiple customers offers economic benefits in terms of equipment and energy costs
  - Different buildings and usage profiles require cooling at different times of the day. By aggregating the demand cooling generation capacity savings of 30% to 50% can be achieved[2].
- The large load, compared to in-building chiller operations, enables investing in more efficient equipment, optimized chiller applications, alternative cooling sources and large-scale TES.

Professional operation

- While cooling is the core function and professional foundation of the DC utility, it is often a secondary responsibility for building owners, leading to less specialized expertise and operational focus.

Considerably longer lifetime of equipment

- The economy of scale enables investment in industrial grade equipment.
  - Industrial chillers are estimated to have a technical lifetime of more than 30 years[3].
  - DC pipelines have an estimated technical lifetime beyond 75-100 years and TES of 50+ years[4].
- Continuous focus on maintaining high water quality maximizes the operational lifetime of DC components.
  - The DC utility can offer water quality services to customer installations, and by doing so increase the technical lifetime of each customer's cooling equipment.
- Professional operation ensures consistent maintenance which prolongs the technical lifetime.

Multi-source and diverse origin of the cooling supply

- DCS cooling plants can be based on multiple cooling technologies, compressor chillers, absorption chillers, waste cool sources and free cooling sources.
- By distributing the cooling plants around the supply area, DCS can provide exceptionally reliable and resilient cooling services.

Exceptionally high cooling generation efficiency

- DC utilities maximize the operational efficiency by taking advantage of the most efficient cooling source and generation technologies at their disposal at any given time.
- By leveraging various sector coupling opportunities and free cooling sources, a DCS often achieves 30%-70% electricity savings compared to individual building cooling solutions[5]. In situations with a large share of free cooling, savings can reach up to 80%, as seen in systems in Denmark[6], Sweden[7] and Canada[8].

Significantly lower level of fugitive refrigerant emissions

- With focus on reducing refrigerant leakage, the annual leakage rate in DC chiller plants can be brought below 1%[9], compared to medium and large building-level chillers where it could be as high as 6%[10].
- Refrigeration leakage should also be seen in the context of a DCS having vastly lower refrigerant volumes than the total refrigerant volume of all building-level chillers that it replaces.

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[2] Calderoni M., Babu Sreekumar B., Dourlens-Quaranta S., Lennard Z., Rämä M., Klobut K., Wang Z., Duan X., Zhang Y., Nilsson J., and Hargo L. *Sustainable District Cooling Guidelines*. IEA DHC/CHP Report, 2019.
[3] Tabreed. *District Cooling overview*. Webpage, accessed: 31.10.2024. https://www.tabreed.ae/district-cooling/
[4] Kraftringen Energi AB. *Environmental Product Declaration*. March 2023. https://api.environdec.com/api/v1/EPDLibrary/Files/49cbbd4b-0afd-40a2-2477-08db259f9365/Data
[5] District Energy in Cities Initiative. *National District Cooling Potential Study for India*. March 2021. https://eeslindia.org/wp-content/uploads/2021/03/Final-Report_National-District-Cooling-Potential-Study-for-India.pdf
[6] Danfoss A/S. *A cost-effective solution: district cooling in central Copenhagen*. Accessed: 31.10.2024. https://www.danfoss.com/en-in/service-and-support/case-stories/dds/a-cost-effective-solution-district-cooling-in-central-copenhagen/
[7] Calderoni M., Babu Sreekumar B., Dourlens-Quaranta S., Lennard Z., Rämä M., Klobut K., Wang Z., Duan X., Zhang Y., Nilsson J., and Hargo L. *Sustainable District Cooling Guidelines*. IEA DHC/CHP Report, 2019.
[8] Lenore Newman and Yuill Herbert. *The use of deep water cooling systems: Two Canadian examples*. Renewable Energy, vol. 34, issue 3, 2009. https://doi.org/10.1016/j.renene.2008.04.022
[9] Climespace and City of Paris. *Climespace - City of Paris: A District Cooling System to control impact of air-conditioning in Paris*. 2nd Global district energy climate awards 2011. https://www.districtenergyaward.org/wp-content/uploads/2012/10/District_Cooling_France_Paris_2011.pdf
[10] BREEAM. *BREEAM International New construction*. BRE Global Ltd, ver. 6, 2021. https://files.bregroup.com/breeam/technicalmanuals/sd/international-new-construction-version-6/content/resources/output/pdf/sd250-breeam-international-new-construction-version-6.pdf

Increased feasibility of using natural refrigerants, such as ammonia, CO_2, butane and propane

- Transitioning towards environmentally friendly refrigerants is simpler in a central cooling plant serving multiple buildings compared to the alternative of changing the chillers in every building.

Significantly lower power capacity demand

- Systems based on compression chillers commonly achieve a peak power capacity reduction ranging from 30%-35%[11].
- System based on deep lake or seawater cooling can achieve up to 70% peak power capacity savings[12], as the electricity consumption is only required for cool extraction from the free cool source and for operating the pumps of the distribution system.
- DCS with TES systems can avoid peak power consumption for cooling generation by evenly distributing the load over 24 hours. TES can also be used to shift the cooling generation to periods of the day that best serve the power grid, meaning that the only power consumption of the DCS is for operating the distribution pumps.
- In new city development areas, DCS reduces investment requirements in new power generation and power grid infrastructure.
- In retrofit cases, DCS frees up existing power generation capacity and limits the need for peak load power generation.

Ability to connect to high voltage power grids

- By connecting to higher voltage power grids, DC reduces both investment and losses in the power distribution system.

Enabling sector coupling opportunities

- Centralized cooling plants make it possible to operate chillers in a heat pump mode, e.g. using both the cold and hot side of the chiller and utilize the waste heat to meet local heating demands, whether for on-site/close by industry heat demands or general heating demands via district heating systems (DHS).

Large scale decoupling of cooling demand and cooling generation via TES, offer multiple advantages, such as:

- Maximizing cogeneration of cooling and heating.
- Ability to avoid power consumption during peak hours and consequently increase power consumption from cost-effective, energy efficient and low carbon base load power generators.
- Ability to prioritize cooling generation to low carbon, or low cost, power generation periods.
- Ability to offer short term (minutes to an hour) to long term (beyond an hour) balancing services to the power sector, using the same concept as is applied in the DH sector[13].

Advanced balancing services to the power sector

- With advanced compressor technology, e.g. Turbocor, DC utilities may even be able to play on the "ultra short/frequency" power balancing market.

Reduced strain on scarce freshwater supply

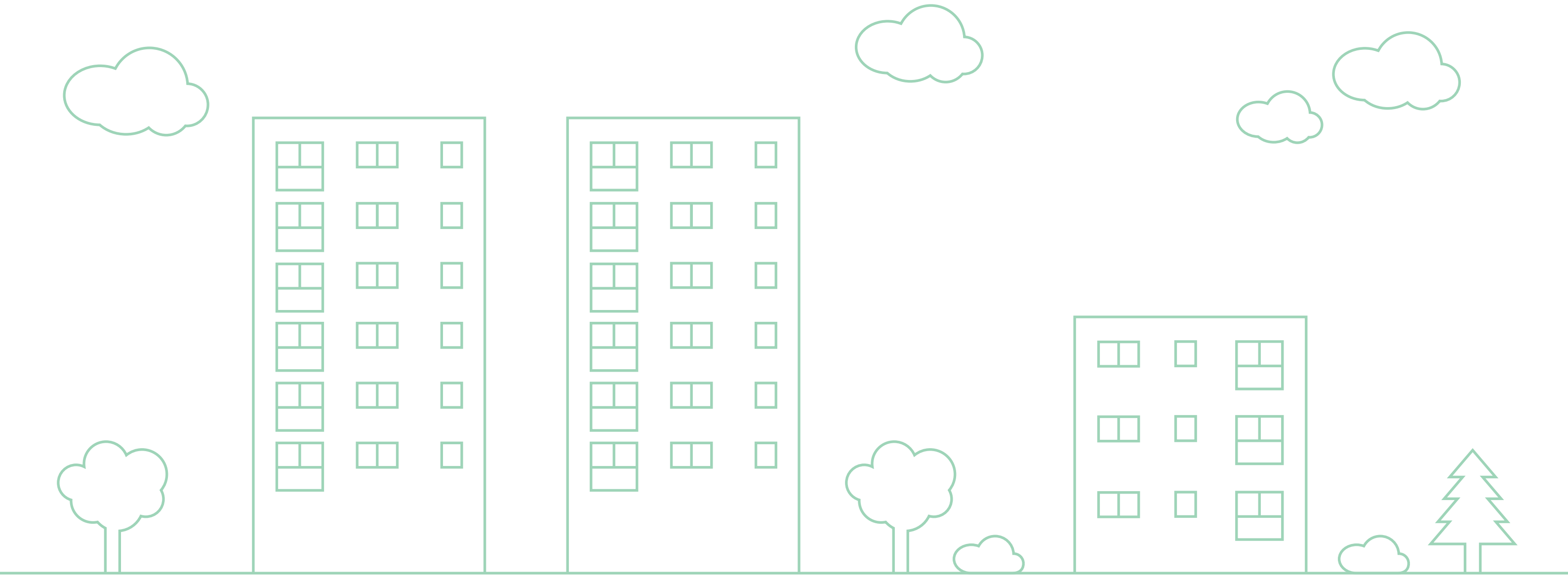
- DC plants can be designed for using treated sewage effluent[14], seawater or other local water sources instead of fresh potable water.

[11] District Energy in Cities Initiative. *National District Cooling Potential Study for India*. March 2021. https://www.districtenergyinitiative.org/sites/default/files/publications/final-reportnational-district-cooling-potential-study-india15032021clean-version-230320211216.pdf

[12] R.V. Anderson Associates Limited. *Enwave Energy Corporation Deep Lake Water Cooling Supply Expansion*. Report, September, 2020. https://www.toronto.ca/wp-content/uploads/2020/09/86d2-2020Sept-DLWC-EAPhase12_Report-Exec-Summary-AODA.pdf

[13] A. Boldrini, J.P. Jiménez Navarro, W.H.J. Crijns-Graus, and M.A. van den Broek. *The role of district heating systems to provide balancing services in the European Union*. Renewable and Sustainable Energy Reviews, vol. 154, 2022. https://doi.org/10.1016/j.rser.2021.111853

[14] Sewage water is generally classified by the source of the sewage water treatment, that is normal sewage water and effluent sewage water. Normal sewage water is wastewater from households. Effluent sewage water is on the other hand wastewater from industry, which can contain large amounts chemicals and toxic waste.



Customer/building benefits

Exceptionally reliable cooling supply

- DC utilities commonly guarantee 99.5%-99.9% availability[15]
- The average DC availability is above 99.99%[16].

Freeing up technical room and roof/ground space for cooling towers at individual buildings

- Enables more value adding usage of the building, e.g. more leasing or sellable space.
- Reduces construction costs due to lower load-bearing demands resulting from the avoidance of cooling generation equipment.
- Increased architectural freedom and aesthetic appeal of buildings.

Avoided upfront investments and maintenance cost of chillers

- Investments in chiller equipment is outsourced to the DC utility.
- Chillers are maintained by the DC utility.

Simple and no hassle cooling for building owners

- The DC utility takes care of all technical aspects of the cool supply to the building.

Increased resilience to energy price variations due to:

- Diverse cooling generation units.
- Simple to introduce new cooling production technologies, as it would be a central operation with no impact on the cooling users.
- Higher cooling generation efficiencies compared to building-level cooling units.

Reduced local noise pollution and emissions

- Cooling generation is performed off-site and therefore there is no noise generation at the building premises.
- Refrigerant leakage within the building complexes is avoided.

[15] Danny. *What are the benefits of District Cooling?* Accessed: 31.10.2024. https://districtcooling.pro/what-are-the-benefits-of-district-cooling/

[16] European Commission: Joint Research Centre, Aumaitre, V., Roger-Lacan, C., Gährs, U. and Galindo Fernández, M. *Efficient district heating and cooling systems in the EU – Case studies analysis, replicable key success factors and potential policy implications*, Publications Office, 2016. https://data.europa.eu/doi/10.2760/371045

Community benefits

→ **Reduced urban noise pollution**

- Cooling generation can be moved out of urban centers and DC plants can be cost-effectively designed to minimize noise pollution.

→ **Local job creation and alternative revenue potential for municipalities**

- Installing and operating the DCS creates local, value adding jobs.
- Local authorities will earn taxes from the DC utilities.
- Areas with better infrastructure attract more businesses, which creates more jobs and consequently increases the municipal revenue stream.

→ **Minimizes heat island effects in urban centers**

- DC mitigates heat island effects by enabling reusing the waste heat for heating processes; dissipating the waste heat into natural heat sinks, ground or water bodies; or dissipating it into the atmosphere outside of the city centers[17]. In comparison traditional air conditioning have been documented to increase the urban air temperature in Berlin, Germany, by up to 2°C during hot summers[18].

→ **Increases energy security due to reduced energy demands, more balanced energy demands and more diverse energy generation**

- By shifting demands from peak to off-peak hours using DC TES, the power generation is to a greater extent provided by base load power generators, leading to significant fuel savings (20%-30%) from power generation[19]
- In the United Arab Emirates, which has subtropical desert climates, power demands from space cooling activities can account for up to 80% of building electricity demands[20]
- In Hong Kong, which has a subtropical humid climate, up to 60% of the electricity consumption during the summer months is used for space cooling purposes[21]

→ **Increased architectural freedom, as cooling generating equipment is outsourced from the building**

[17] Lily Riahi. District Energy in cities- Paris case study. UNEP, 2017. https://www.districtenergy.org/viewdocument/district-energy-in-cities-paris
Angela Symons. *Paris' eco-friendly underground cooling system to become the largest in the world*. EuroNews.com, website, 2022. Accessed: 31.10.2024. https://www.euronews.com/green/2022/07/28/paris-eco-friendly-underground-cooling-system-to-become-the-largest-in-the-world

[18] Jin, L., Schubert, S., Hefny Salim, M., and Schneider, C. *Impact of Air Conditioning Systems on the Outdoor Thermal Environment during Summer in Berlin, Germany*. Int. J. Environ. Res. Public Health, vol. 17, 2020. https://doi.org/10.3390/ijerph17134645

[19] ASHRAE District Cooling Guide, Page 6.11.

[20] Shanks, K. and Nezamifar, E. *Impacts of climate change on building cooling demands in the UAE.* Paper presented at SB13 Dubai: Advancing the Green Agenda Technology, Practices and Policies, Dubai, United Arab Emirates, 2013.

[21] Giridharan, R., Ganesan, S. and Lau, S. *Daytime urban heat island effect in high-rise and high-density residential developments in Hong Kong*. Energy and Buildings, vol. 36, pp. 525–534, 2004. https://doi.org/10.1016/j.enbuild.2003.12.016

Cooling generation **capacity optimization**

When it comes to the installed cooling capacity, a DCS can take advantage of various benefits when aggregating the cooling demands, such as:

- Cooling load coincidental factors between different consumer types
- Adopting more rigorous capacity safety margins, as reserve capacity is shared between connected users
- Decoupling of cool generation and demands using TES

The diversity factor is a term to account for varying cooling demands over the course of the day when supplying multiple buildings using the same source. The hourly cooling profile depends on factors such as building typologies and occupancy habits; the climate and weather impact on each building; and the building's indoor comfort requirements and economic conditions. Figure 2 gives an example of how different buildings have varying demands over the day, leading to the collective hourly capacity demand being much lower than the sum of the peak capacity of each building.

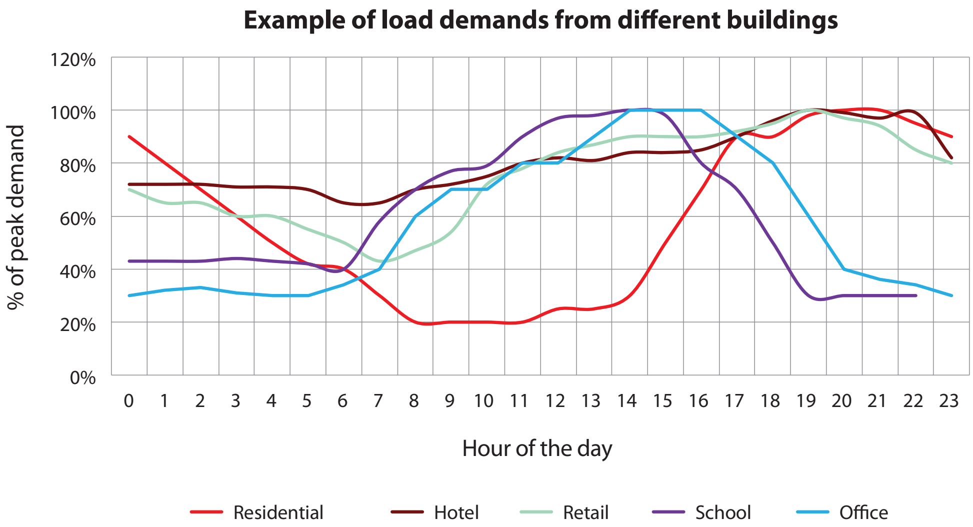


Figure 2. Example of cooling profiles of different cooling consumers.

The lower capacity safety margins originate from the fact that the DCS typically operates multiple cooling generation units, which results in a high cooling generation reliability. Compared to building-level chillers, DCS utilities operate industrial grade equipment and have 24/7 professional focus on the operation, which leads to significant operational reliability. For added supply security, the cooling generation units can be installed in in two or more locations of the network, which minimizes the impact of external disruptions and plant failures. Another often overlooked parameter is that utilities can have investment plans in place for incrementally increasing the cooling capacity as cooling demands grow. All in all, those factors enable utilities to design the system with safety margins as low as 5%. In contrast, building developers often oversize single-building cooling systems by 25%-50%[22] during the design phase to ensure flexibility in building usage. A side effect of oversizing cooling equipment is that it leads to low operating efficiencies, often 20% to 40% below optimum[23].

[22] D. A. Jones and C. M. Eckert. *Design margins: Impacts on building energy performance.* International design conference – Design 2016, Dubrovnik - Croatia, May 16 - 19, 2016. https://www.designsociety.org/download-publication/38940/DESIGN+MARGINS%3A+IMPACTS+ON+BUILDING+ENERGY+PERFORMANCE
Strategy&. Unlocking the potential of district cooling - The need for GCC governments to take action. 2019. https://www.strategyand.pwc.com/m1/en/reports/unlocking-the-potential-of-district-cooling.pdf

[23] D. A. Jones and C. M. Eckert. *Design margins: Impacts on building energy performance.* International design conference – Design 2016, Dubrovnik - Croatia, May 16 - 19, 2016. https://www.designsociety.org/download-publication/38940/DESIGN+MARGINS%3A+IMPACTS+ON+BUILDING+ENERGY+PERFORMANCE

Figure 3 shows an example of the benefits of a DCS in respect to avoiding peak loads and cooling generation capacity savings. The case assumes the load profiles shown in Figure 2, where the peak capacity demand of the end-user types is as follows: Residential buildings with 100 MW, hotels with 200 MW, retail with 150 MW, offices with 300 MW and schools with 25 MW. Applied safety margins for single-building cooling systems and the DCS are 25% and 5% respectively. Additionally, it is assumed that the DCS takes advantage of TES to balance out the load.

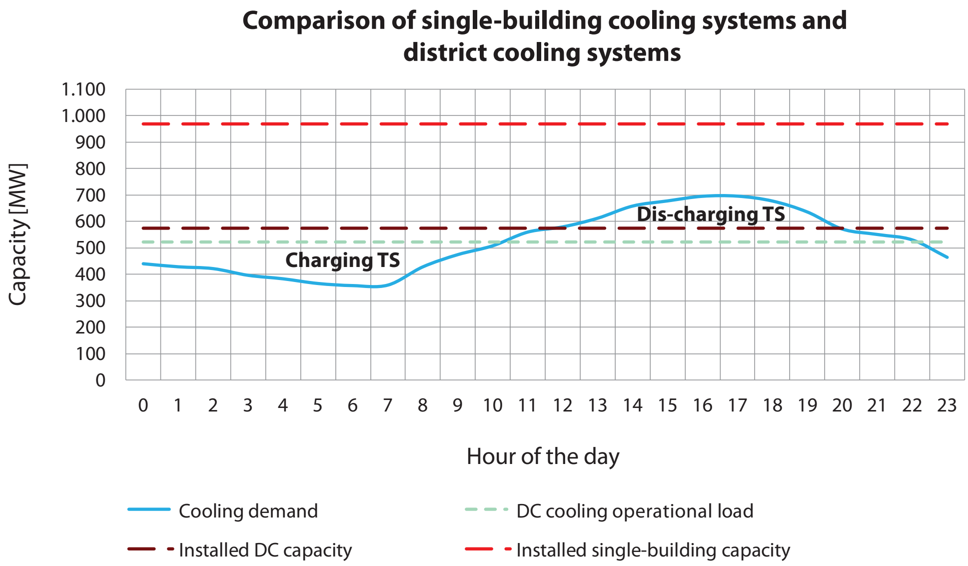


Figure 3. Example of single-building cooling operating loads and DC operating loads and sum of installed capacity of single-building cooling systems and a DCS.

In addition to the benefits presented in Figure 3, the DCS generally has more efficient cooling generation, usually in excess of 25% compared to single-building chillers, and can partly, or even fully in case of part load demands, defer the cooling generation to off-peak power periods with lower electricity prices.

District cooling system **area coverage**

Unlike a DHS, which often covers an entire city, a DCS tends to have a smaller geographical coverage, leading to multiple systems being implemented to cover the cooling demands of cities. This difference between DHS and DCS is to an extent due to the lower temperature differences used in a DCS compared to a DHS, which leads to larger pipe diameters for equivalent thermal capacities, as shown in Table 1.

Table 1. Pipe transportation capacities for DCS and DHS. DCS based on 6°C and 3.5 m/s flow velocity. DHS based on 30°C and 3.5 m/s flow velocity.

DN	DCS [MW]	DHS [MW]
100	1.1	5.2
200	4.1	20.0
400	14.3	70.4
600	32.8	161.1
800	58.4	287.2
1000	91.2	448.5
1200	131.6	647.1

The large pipe dimensions required for a DCS lead to a high investment cost in the distribution network, which limits the economically viable length of the DCS network. A simple method to identify grid length viability is shown in Figure 4, where customer demands are used to predict an economically viable pipe connection length using circles. A potential DCS coverage is then projected based on the overlap of the circles.

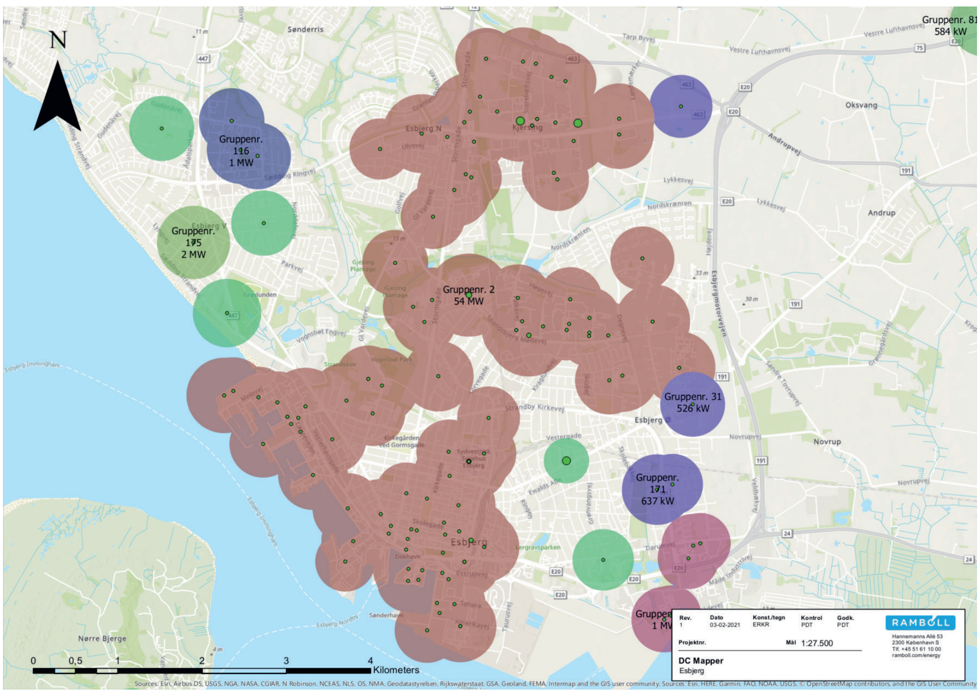


Figure 4. A graphical indication of an economically viable DCS grid coverage.

Due to the high upfront investments in the distribution network, it is common that a DCS forms clusters around the areas with the highest cooling demand densities. To maximize the economic viable distribution range, reliability and efficiency, the clusters commonly have two or more cooling plants distributed around the supply area. As the systems grow, the clusters may eventually be interconnected, which enables shared use of the cooling plants and increases the ability to optimize cooling generation.

District cooling system ready **building installations**

For buildings to be connected to a DCS, their cooling installations must be based on a centralized cooling supply and apply either a hydronic-based distribution system to distribute the cooling supply within the building or use centrally located air handling units.

The main components of the building cooling installation are:

Energy Transfer Station

The ETS, consisting of one or more heat exchangers, motorized pressure independent control valves, and water pumps, is responsible for adapting the operating conditions of the DCS—such as pressure and temperature—to the operating requirements of the building cooling installation. A well designed ETS will ensure energy efficient operation of the DCS at all load levels and enable building owners to adapt the contracted DC capacity over the building's lifetime and potentially varying usage.

Building Cooling Distribution System:

The distribution system, made up of supply and return pipes, distributes cooling from the ETS throughout the building.

Building Dynamic Balancing Valves:

These valves ensure optimal flow distribution to different parts of the building by adjusting the differential pressure. This supports the efficient operation of cooling emitters and minimizes the impact of incorrect or faulty operation.

Cooling Emitters:

Cooling emitters absorb heat within the building by warming the cold supply from the DCS. They can take the form of fan coils, which use fans to circulate air over a cooling coil, or radiant-based alternatives such as chilled beams or floors. For efficient operation, it is crucial that each cooling emitter is equipped with control equipment that adjusts the cooling supply to meet the specific demand of the room being cooled.

The future trend for building cooling installations is towards higher temperature cooling. The benefits of higher temperature cooling include both higher cooling generation efficiency and increased transportation capacity of the distribution network.

Local solutions depend on local conditions

As is typical for infrastructures, the design and operation of the DCS is highly dependent on local conditions. The most common factors that need to be considered when assessing the economic feasibility of DCS projects are:

→ **Climate**
- Hot, cold, diurnal variations, humidity, droughts and other climate-related factors.

→ **Local resources**
- Such as access to sea, lakes, rivers, available land area and high temperature waste heat.

→ **Sector coupling opportunities**
- The ability to leverage synergies with other sectors, such as the heating, power or water sectors.

→ **Local regulations**
- Whether existing regulations incentivize or penalize DCS.

→ **Building density**
- The higher the building density the higher the economic feasibility.

→ **Area zoning / combination of customers topologies**
- Commercial, industry, residential, public or mixed sectors.

→ **Energy markets**
- Power price spreads, power tariff structure and share of renewable power generation.

→ **Business models and market structure**
- Free market, monopoly, concession contracts, public owned, private public partnership, community owned.

Like other infrastructure systems, DC requires substantial upfront investment to establish the distribution network and cooling generation equipment. Attracting financing sources hinges on effective risk management and de-risking efforts, particularly during the early development phase. This involves ensuring regulatory clarity and securing long-term revenue certainty through customer agreements and strategic partnerships. Leveraging synergies with adjacent sectors can also play a critical role, either by providing stable, long-term income streams or by subsidizing initial investments. For example, co-utilizing heat pumps with district heating systems can enhance efficiency and cost-sharing. Additionally, the organizational structure and business model must be designed to support competitive pricing, reliable service delivery and transparent financial management, ensuring the DC business operates on solid commercial terms.

Due to the potentially wide range of local conditions, the way utilities choose to implement their DSC can vary significantly. Understanding the reason and benefits of the existing systems gives a good understanding and baseline for developing new systems.

The importance of sector integration for district cooling success

By analyzing existing DCSs, it becomes clear that their success is generally based on leveraging synergies from sector integration. Historically DC has been particularly successful in leveraging synergies with the power sector, by effectively using large cold storages to shift demands from peak to part load power periods. These opportunities will become even more important as the world transits from fossil based dispatchable power generation towards intermittent and fluctuating renewable energy sources. Figure 5 gives an example of potential synergy opportunities between PV based power generation (yellow) and cooling demands (blue), which are both positively correlated with solar radiation. This correlation is particularly strong on an hourly basis due to the influence of solar radiation on both temperature and human activity, as daylight hours often dictate when buildings are occupied and cooling systems are in use.

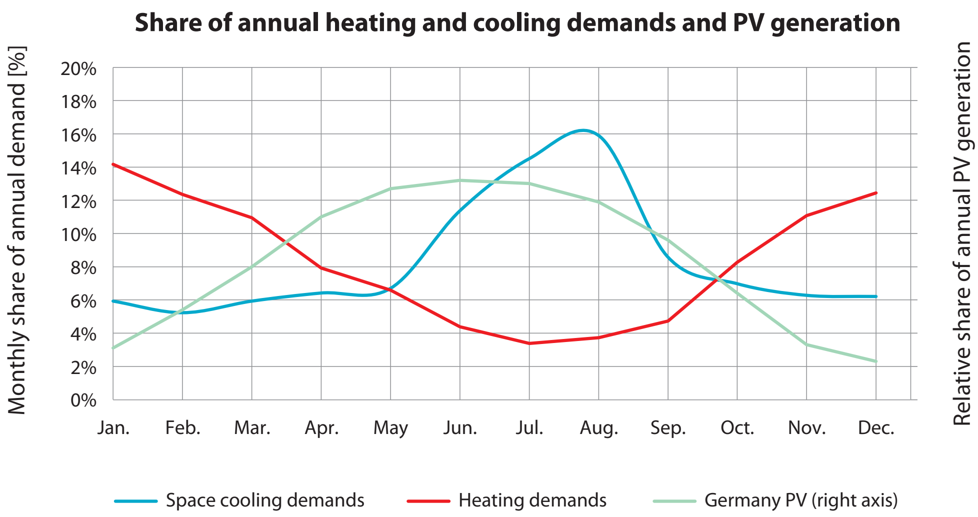


Figure 5. Relative distribution of heating[24] (red) and cooling[25] (blue) demands of a mixed area in Frankfurt and monthly share of annual solar PV based power generation (green) in Germany[26]

[24] Rohde, D., Andresen, T. and Nord, N. Interaction *Between a Building Complex with an Integrated Thermal Energy System and a District Heating System*. CLIMA 2016 - 12th REHVA World Congress, Aalborg, 2016. https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2581410/CLIMA_2016_submission_535.pdf?sequence=1

[25] Rohde, D., Andresen, T. and Nord, N. *Interaction Between a Building Complex with an Integrated Thermal Energy System and a District Heating System*. CLIMA 2016 - 12th REHVA World Congress, Aalborg, 2016. https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2581410/CLIMA_2016_submission_535.pdf?sequence=1

[26] Based on:
1) Pfenninger, S. and I. Staffell. *Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data*. Energy, vol. 114, pp. 1251-1265, 2016.
https://doi.org/10.1016/j.energy.2016.08.060
2) International Energy Agency – Photovoltaic power systems programme. *IEA PVPS Task 1 Strategic PV Analysis and Outreach Report*. IEA-PVPS T1-39:2021, April 2021. https://iea-pvps.org/wp-content/uploads/2021/04/IEA_PVPS_Snapshot_2021-V3.pdf

Another important sector integration opportunity is with the heating sector. The synergy with the heating sector is two-fold. First, it enables cogeneration of heating and cooling, which significantly boosts the power efficiency. And second, it enables increased heat pump utilization, as they can in principle be operated all year, which increases the return from capital investments. Integrating the cooling and heating sector also further extends the synergies between the thermal sectors and the power sector. For example, integration extends the synergies with solar generated power to the heating sector, and the heating sector's access to heat pumps enables leveraging the positive correlation between wind power generation and heating demands, as wind power generation is generally stronger during the heating season, as is shown in Figure 6.

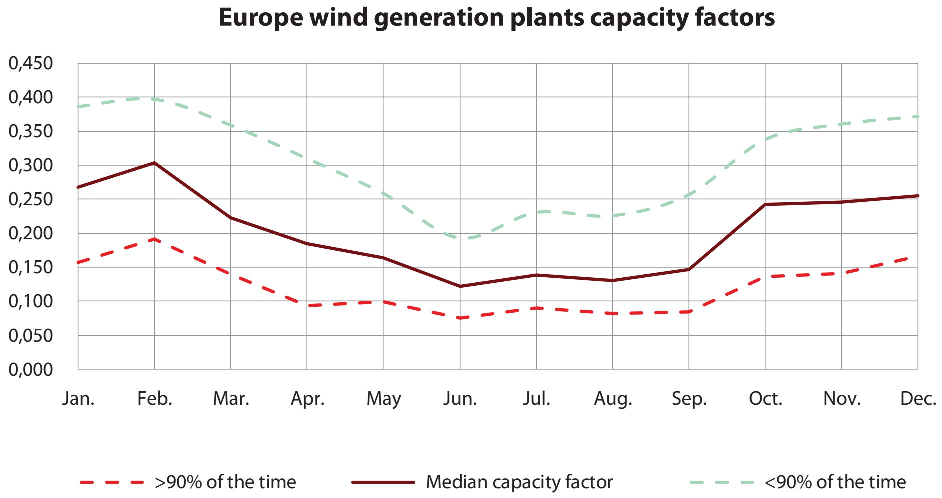


Figure 6. European wind power generation capacity factors over the year.

With the addition of large-scale TES, DCS can provide cost-efficient load shifting capabilities, enabling shifting large power demands from carbon intensive, or high cost, power periods to periods with less carbon intensity or lower costs. The TES can also decouple cooling and heating demands, which maximizes the synergetic benefits between the sectors.

Given the energy efficiency and cost benefits of integrating DC with the heating sector, this option should always be considered before opting for standalone systems producing cooling from lake- or seawater or using cooling towers.

In areas with scarce freshwater supply, and no cogeneration of heating and cooling opportunities, DCS can leverage synergies with the water sector, as the cooling plants can be located close to sewage mains. This enables them to operate cooling towers using effluent water instead of fresh water, and by that reduce the strain on the freshwater system.

Examples of innovative and replicable district cooling systems

Since modern DCS was introduced in the 1960s and 1970s, the technology has spread around the globe and proven itself as being both an energy efficient and cost-effective solution for fulfilling cooling demands. The most successful DCSs are based on a holistic approach, which includes long-term planning, leveraging synergies with other energy sectors, and alleviating strain on scarce local resources.

Below are examples of innovative, successful, and replicable DCS.

Stockholm, Sweden

Although Stockholm is located in Northern Europe, not commonly associated with comfort cooling demands, the city has established one of the most successful DCS in the world. The success is largely based on leveraging sector coupling opportunities with the DH sector and the power sector.

A central component of the system for enabling synergies is chilled water TES, which enables the utility to decouple cooling demand and generation. The TES is actively used for maximizing synergies between the cooling sector and heating and power sectors.

In 2022, heat pumps operated in a cogeneration mode, producing both useful heat and cold, accounting for 50% of the cooling supply, or 233 GWh of the 464 GWh cooling generation. The remaining supply came from chillers, 129 GWh, and free cooling from the sea, 102 GWh[27].

With respect to the power sector, the TES are used to shift the cooling generation from expensive power periods, typically peak load periods, to cheaper part load periods. The power sector benefits from the DCS through lower peak demands from cooling generation, which leads to more efficient power generation, increased possibilities of integrating renewable power sources and greater utilization of cheap baseload generators.

[27] Stockholm Exergy. *Års- och hållbarhetsredovisning Stockholm Exergi 2022*. Stockholm, March, 2023. https://www.stockholmexergi.se/content/uploads/2023/03/Ars-och-hallbarhetsredovisning-Stockholm-Exergi-2022.pdf

Copenhagen, Denmark

Since the greater Copenhagen utility HOFOR started its DCS operation in 2009, it has become HOFOR's fastest growing business segment, proving to be up to 40% more cost efficient than local cooling solutions. The HOFOR DCS is also effectively supporting Copenhagen in achieving its goal of becoming carbon neutral in 2030[28]. The principal design of the Copenhagen DCS is to enable synergies with the power and heating sectors, by combining free cooling using seawater, absorption cooling using excess waste heat from cogeneration plants and compression chillers for cogenerating cooling for DCS and heating for DHS[29]. When cogeneration is not beneficial, and the seawater is too warm for direct cooling, the plants change the operating mode to a combi mode, where the seawater is used to boost the efficiency of absorption and compression chillers.

Once fully implemented, the Copenhagen DCS is expected save 30,000 t of CO_2 emissions per year, which is estimated to be up to 70% CO_2 emission reduction compared to individual cooling solutions[30].

Paris, France

The Paris DCS started operation in 1991, and in 2019 it supplied cooling to 738 buildings, responsible for 38% of Paris' cooling demands[31], from 7 cooling plants, with a total capacity of 249 MW. During the next development phase, running until 2042, the ambition is to significantly grow the system and have 3,058 buildings connected.

A key success factor of the operation is the utilization of the Seine River, which runs through the city, as a heat sink for 147 MW of compression chillers capacity. Compared to cooling towers, using the Seine River offers several benefits. It increases the cooling generation efficiency, avoids freshwater consumption from cooling towers' operations, and it serves as a waste heat transportation mechanism, reducing the heat island effect in the city center by 1-2°C[32]. Cooling generation using the Seine River as a heat sink accounted for around 70%[33] of the cooling supply in 2019.

[28] *Climate City Contract – 2030 Climate Neutrality Commitments. City of Copenhagen*. Report, 2024. https://www.kk.dk/sites/default/files/2024-10/02.10.24%20-%20 Orienteringsnotat%20om%20indg%C3%A5else%20af%20en%20klimakontrakt%20-%20K%C3%B8benhavns%20Kommune%20deltagelse%20i%20EUs%20Cities%20Mission.pdf

[29] HOFOR. *District cooling*. Website. Accessed: 03.02.2025. https://www.hofor.dk/english/hofor-utilities/district-cooling/

[30] State of Green. *District cooling reduces CO2 emissions in central Copenhagen*, (n.d.). Website. Accessed: 03.02.2025. https://stateofgreen.com/en/partners/hofor-utility-company/solutions/district-cooling-reduces-co2-emissions-in-central-copenhagen/

[31] Aleksandra Kaźmierczak, et. al. *Urban adaptation in Europe: how cities and towns respond to climate change*. European Environment Agency, ISBN: 978-92-9480-270-5, 2020. https://www.eea.europa.eu/publications/urban-adaptation-in-europe

[32] Lily Riahi. District Energy in cities- Paris case study. UNEP, 2017. https://www.districtenergy.org/viewdocument/district-energy-in-cities-paris
Angela Symons. *Paris' eco-friendly underground cooling system to become the largest in the world*. EuroNews.com, website, 2022. Accessed: 31.10.2024. https://www.euronews.com/green/2022/07/28/paris-eco-friendly-underground-cooling-system-to-become-the-largest-in-the-world

[33] Aleksandra Kaźmierczak, et. al. *Urban adaptation in Europe: how cities and towns respond to climate change*. European Environment Agency, 2020. https://www.eea.europa.eu/publications/urban-adaptation-in-europe

Water cooled chiller condenser **explained**

In general, shallow natural water bodies will be much cooler than the ambient air, particularly during the hot season of the year. By using natural water bodies for cooling the condensers instead of cooling towers, see Figure 7, the chiller efficiency can be increased by 25% or more and made seasonably stable, compared to the seasonally varying efficiency when applying air-cooled condensers.

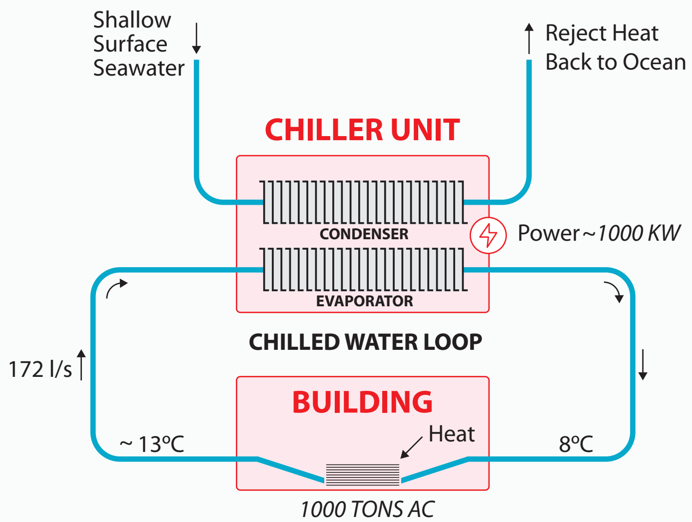


Figure 7. The principal schematics of a chiller with water cooled condenser.

Water bodies can also replace wet cooling towers and typically increases energy efficiency, eliminates noise and avoids cooling tower water consumption. The potential efficiency increase is dependent on the depth that can be accessed. See Figure 8 for an indication of temperature changes in relation to ocean depths.

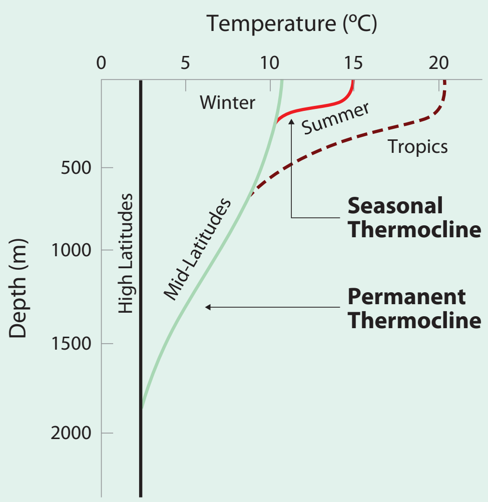


Figure 8. Ocean thermocline. Source: Welcome-1To1The1Jungle at English Wikipedia, CC BY 3.0.

If the return temperature to the water body exceeds environmental regulation limits, particularly relevant in case of rivers, wet cooling towers can be applied to reduce the return water temperature to the proper limit. Combining the use of natural water bodies and wet cooling towers for heat rejection is generally more efficient, has lower noise, lower fresh/treated water demands and minimizes sewage fees compared to a full reliance on wet cooling towers.

Barcelona, Spain

Barcelona hosts the first DCS that recovers waste cold from liquefied natural gas (LNG) regassification, with annual cold recovery potential of up to 131 GWh[34]. As LNG has a temperature of -161.5°C, it is an interesting cold source that has traditionally been wasted into the sea next to the regassification plant. From 2024 18 MW of waste cold, with a potential for an additional 12 MW, has been captured and used for cooling purposes at the local food hub, Mercabaran, and the local DCS, Ecoenergies. Due to the low temperatures, the captured waste cold is used for charging ice storages and replacing cooling supply from existing compression chillers in the DCS[35].

Regasification **explained**

The process of liquefying natural gas produced in natural gas-rich regions has become crucial for transporting it from producers to consumers, particularly when circumstances do not allow for pipelines, such as over vast distances or natural barriers like seas.

As liquefied gas occupies much less volume than gas in a gaseous form, it becomes more economical to transport it in vessels, such as trucks, trains or tank ships. Once it arrives at its destination, the process is reversed via the regasification process, which converts liquefied gas, such as natural gas, back into its gaseous state.

In essence, the liquefaction and regasification of natural gas has significant similarities to the well-known heat pump refrigeration cycle. During the liquification process (compression) it is possible to recover heat stored in the gaseous phase of the natural gas. During regasification (expansion) the LNG absorbs heat from its ambient, effectively cooling the ambient environment. By capturing the cooling effect in a DCS, the regasification process replaces alternative cooling generation.

With over 150 LNG regassification terminals worldwide[36], of which 37 are in Europe[37], and more terminals under construction, this solution has a substantial replication potential.

Dubai, United Arab Emirates

Due to the high temperatures and humidity, air conditioning is widely applied across the United Arab Emirates (UAE). Air conditioning accounts for up to 60% of the peak power demands during the summer[38], causing a large strain on the power system and high power prices. Another challenge in the UAE is water scarcity, due to its desert climate. To address both the strain on the power system from cooling and water scarcity, the UEA has identified DCS as an important solution for cooling demands.

Since the implementation of the first DCS in Dubai in 2002, DC has grown rapidly, reaching over 18% cooling market share in 2020, with a projected growth to 40% by 2030[39]. This success is largely due to the DCS's ability to operate cooling plants using compression chillers and wet cooling towers with treated sewage effluent water (a solution not economically feasible at the building level), thus alleviating strain on the fresh potable water system. The ability to use wet cooling towers further leads to significant efficiency improvements, 35% to 45%, compared to the alternative dry cooling towers used with building-level chillers.

To minimize the peak power consumption, the DCS uses TES to maximize cooling generation during the night, which not only effectively minimizes peak power demands, but also increases cooling generation efficiency due to the cooler nighttime temperatures.

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[34] Veolia. *Veolia implements a pioneering cold energy recovery solution in the port of Barcelona to produce local, carbon-free energy*. Press release, 15th of December 2023. https://www.veolia.com/sites/g/files/dvc4206/files/document/2023/12/pr-LNG-cold-recovery-Barcelona-12152023.pdf

[35] Alex Ivancic. *Waste cold recovery from the regasification process of Liquefied Natural Gas*. 38th Euroheat & Power Congress, Glasgow, United Kingdom, 14-16 May 2017. https://lsta.lt/files/events/170514_Glasgow/36_Aleksandar_IVANCIC.pdf

[36] Veolia. *Veolia implements a pioneering cold energy recovery solution in the port of Barcelona to produce local, carbon-free energy*. Press release, 15th of December 2023. https://www.veolia.com/sites/g/files/dvc4206/files/document/2023/12/pr-LNG-cold-recovery-Barcelona-12152023.pdf

[37] Alex Ivancic. *Waste cold recovery from the regasification process of Liquefied Natural Gas*. 38th Euroheat & Power Congress, Glasgow, United Kingdom, 14-16 May 2017. https://lsta.lt/files/events/170514_Glasgow/36_Aleksandar_IVANCIC.pdf

[38] Kankana Dubey. *Buildings sector: Energy Productivity in the GCC*. 7th International Forum on energy for Sustainable Development in Baku, 18 October 2016. https://unece.org/fileadmin/DAM/energy/se/pp/eneff/7th_IFESD_Baku_Oct.2016/3GEEE_ee_build/KankanaDubey.pdf

[39] Sustainable Energy for All (SEforALL). *Cooling Solutions for Urban Environments*. Sustainable Energy for All (SEforALL), march, 2018. https://www.seforall.org/system/files/2019-05/CoolingSolutionsforUrbanEnvironments.pdf

Wet cooling towers **explained**

Wet cooling towers, see Figure 9, operate on the principle of evaporative cooling to reduce the temperature of water from industrial processes or HVAC systems. Hot water is pumped to the top of the tower and distributed over a large surface area through spray nozzles or trays. Air is drawn through the tower, either naturally or mechanically. As the water flows downward, a portion evaporates, absorbing heat and cooling the remaining water. The cooled water is then collected at the bottom and recirculated back to the chiller. Drift eliminators are used to capture water droplets in the air flow, thus minimizing water loss. Make-up water is added to compensate for evaporation and blowdown. This process leverages the latent heat of vaporization and convective heat transfer to effectively cool the water, which is then circulated back to the chiller condenser for extracting heat from the process that needs cooling.

In comparison to building-level wet cooling towers, the DCS can take advantage of alternative water sources, such as treated sewage effluent, seawater or other local water sources, thereby reducing the strain on scarce potable water.

Figure 9. District cooling plant using wet cooling towers.

Willemstad, Curacao

The deep seawater DCS is expected to reduce power consumption for cooling purposes by 90% compared to building-level chillers, which would lead to a significant reduction in imported fuels. As a bonus, the cost of cooling would become very stable, as majority of the cost would be investment based, e.g. the investments in the deep seawater pipeline, cooling plant and distribution system. With an estimated USD 50M investment generating USD 86M in savings over 20 years, it would represent a highly sustainable investment.

The cooling capacity of the proposed system, see Figure 10, would be 11 MW (3,500 TR), displacing about 4 MW of electric capacity from chiller-based cooling. Deep seawater, at 6°C, would be collected at a depth of 850 meters, with a 6 km long pipeline and returned to 50 meters depth at 12°C. To avoid issues with salted seawater, the cooling plant would use a titanium heat exchanger to separate the seawater from the DC distribution water.

Willemstad, the capital of the island Curacao in the Caribbean Sea, has a tropical climate, leading to a rather constant cooling demand over the year. As a small island, it is reliant on imported fuels, leaving it vulnerable to disruptions in energy markets. To increase the energy supply security, the capital city has explored the possibility of using its local resources, in this case cold deep seawater, to minimize the energy used to meet comfort cooling demands.

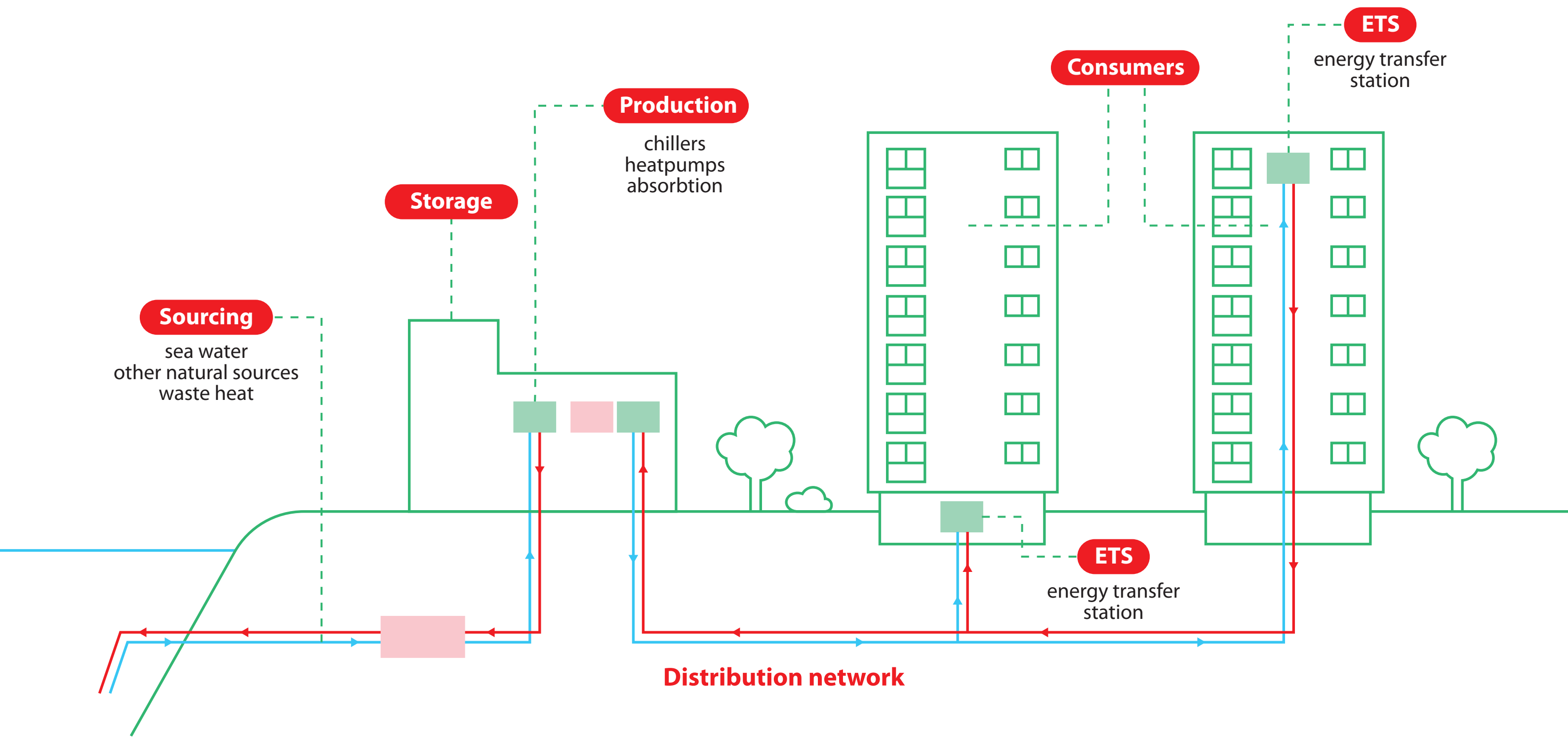

Figure 10. A principal design of a deep seawater DCS.
Image source: https://www.youtube.com/watch?v=roYfUXg4bLU

The bright future of district cooling

In IEA World Energy Outlook 2024[40], it is projected that space cooling demands will increase on average by 3.7% annually to 2035, continuing the trend of 4% annual growth since 2020. Over 90% of the growth will come from emerging and developing countries, driven by generally rising incomes, growing populations and warming climates. Additionally, the warming climates lead to less efficient air conditioner operation. In emerging markets and developing economies, space cooling demands are projected to increase peak demands and put additional strain on already burdened power systems, particularly during intense heat waves. These heat waves, which are becoming increasingly common, are already causing challenges for the power sector, such as lower power plant and distribution network efficiencies. Projections towards 2050 expect cooling demands in emerging markets and developing economies to rise between 200% and 280% compared to 2023, driven by the same growth factors mentioned above.

In advanced economies, cooling is generally expected to remain stable or with insignificant growth until 2035, as space cooling demands are mostly already met today. However, the ongoing electrification of heating demands is expected to lead to significantly increased electricity demands, which can be a source for significant cogeneration opportunities, that can be a driving force for DCS developments.

A common feature of established DCSs is that once they are put in operation, they quickly expand their customer base, based on their customer friendly and economic competitive advantage over building-based alternatives, as discussed in depth above. This experience, in addition to the generally increasing comfort cooling demands driven by increased living standards across the globe, and the need to decarbonize the energy system, paints a bright future for DC.

While the growth rate of established DCSs has been impressive, the overall DC market is predicted to experience annual growth, from 27.3 billion USD in 2024[41], ranging from 3.6% to 8.9% per year over the next decades[42] (see Figure 11).

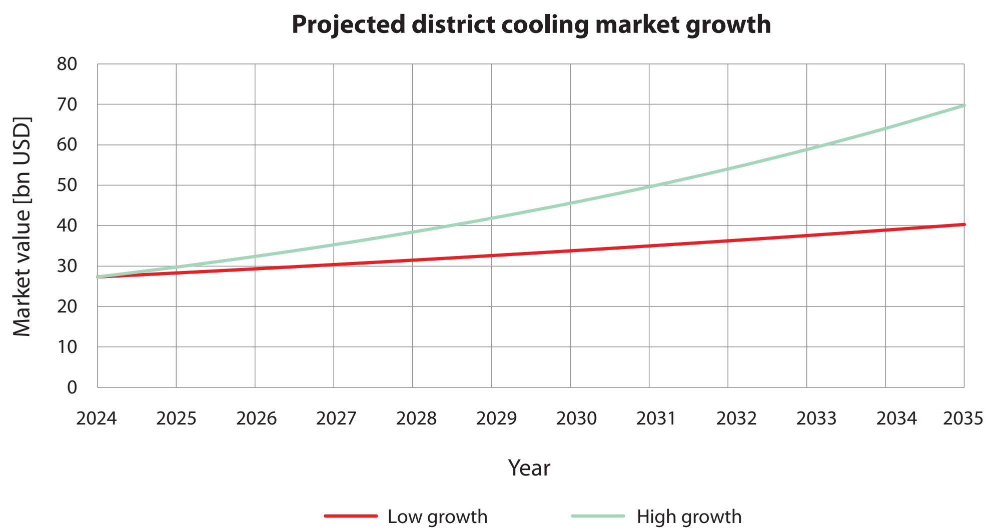

Figure 11. Expected growth of the DC sector from 2024 to 2035.

[40] International Energy Agency. World Energy Outlook 2024. IEA Publications, 2024.
https://iea.blob.core.windows.net/assets/fb481b31-df88-4f2c-a435-c8b075e992be/WorldEnergyOutlook2024.pdf

[41] District Cooling Market Size, Share & Trends Analysis Report By Production Technique (Free cooling, Absorption cooling, Electric chillers, Others), By Applications (Commercial, Residential and institutional, Industrial) and By Region(North America, Europe, APAC, Middle East and Africa, LATAM) Forecasts, 2025-2033.
https://straitsresearch.com/report/district-cooling-market

[42] Araner. *District cooling market: present and future*. Website. Accessed: 31.10.2024.
https://www.araner.com/blog/district-cooling-market-present-and-future#:~:text=All%20forecasts%20concur%20in%20anticipating,8.9%25%20in%20the%20same%20period.
District Cooling Market By End-Users (Residential, Industrial, And Commercial), By Production Technique (Absorption Cooling, Free Cooling, And Electric Chillers), And By Region - Global And Regional Industry Overview, Market Intelligence, Comprehensive Analysis, Historical Data, And Forecasts 2023 – 2030.
https://www.zionmarketresearch.com/news/global-district-cooling-market

Conclusions

DC has proven its reliability and adaptability across the globe, from the cold climate in Northern Europe to the tropical climate around the equator. A key to the technology's success is its ability to take advantage of local resources, which cannot be accessed economically on a building-by-building level.

As DC is an infrastructure, it unavoidably carries large upfront investments. These upfront investments depend on several factors, including:

- The cooling density of the area, where the cooling density represents the annual cooling demand within the considered supply area. The higher the cooling density, the more cost effective the distribution network.
- The mix of customers and their demand profiles. The more varying the demand profiles are the less cooling generation capacity is needed on an aggregated level, which leads to lower investment costs for the cooling plant.
- The condition of the development area can have large cost impacts.
  - For new development areas, the installation of distribution network can be coordinated with the installation of other infrastructures, leading to large cost savings.
  - For redevelopment areas, e.g. brown field, existing and reusable utility infrastructure can add complications compared to green field development areas.
  - For existing urban areas, there are several complications that can increase the cost of the system development. For example, the underground can be crowded with other infrastructure; getting permits and closing off roads can be expensive; and noise and other disruptions occurring during the system installation can cause public frustration, which may limit the allowable working hours for installing the distribution system.
- Availability, location and cost of land area for cooling plants can have substantial cost impacts, particularly in dense urban areas.

While the upfront DCS investments are often large, it is important to remember that the technical lifetime of the investments is generally longer than can be expected from cooling generation investments made on a building-by-building level. This is because utilities generally have long investment horizons, enabling them to invest in industrial grade equipment, whereas buildings typically use commercial-grade equipment. The utilities' business model is efficiency, which leads to a dedicated focus on maintenance to ensure continuous high operating efficiency and long equipment lifetime. Cooling plants generally have a technical lifetime of 30+ years, and the distribution pipeline is typically considered to have 75-100-year technical lifetime.

While one of the primary drivers for DCS is the cooling density of the supply area, local sector coupling opportunities can often decrease the minimal cooling density required through more cost-efficient cooling generation. Common sector coupling opportunities include:

- Cogeneration of heating and cooling with DHS.
- Utilization of treated effluent wastewater for wet cooling towers and avoiding usage of scarce fresh water.
- Minimization of peak power demands and offering general balancing services to the power sector.
- Utilization of waste cold from industry sectors, such as gasification of LNG.

DC further enables taking advantage of renewable energy sources for maximizing energy efficiency, such as:

- Direct utilization of cold water bodies, such as deep seawater or deep lakes.
- Utilization of shallow water bodies, such as shallow seawater, lakes and rivers, for cooling of condensers.
- Diurnal variations in ambient temperatures, taking advantage of cold storages for cooling generation during cooler night temperatures.
- Using large cold storages to tailor cooling generation according to the availability of renewable power generation, such as wind and solar, or take advantage of low-cost power generation from baseload power plants.
- Taking advantage of the coincidence of power generation from solar photovoltaics plants and cooling demands.

When it comes to energy efficiency, or system performance, compared to building-level solutions, it depends on local conditions, availability of renewable sources, sector integration opportunities and resource limitations.

- In cold regions, cogeneration of heating and cooling, as well as using the heat pump in a heat only mode during the heating season, provides both energy efficient operations and cost-efficient utilization of investments. During cogeneration of cooling and heating, the heat pump efficiency is more than doubled compared to cooling only.
- In areas with access to local heat sinks, such as rivers, lakes and seawater, the waste heat from the condenser can be removed/dissipated significantly more efficiently than in the case of dry or wet cooling towers applied by building-level cooling systems, leading to a more than 50% increase in energy efficiency.
- In regions with scarce fresh water supply, a DCS using treated effluent wastewater in wet cooling towers can achieve more than 35% higher system efficiency than building-level cooling systems using dry cooling towers.
- A DCS with access to free cooling, such as deep seawater, deep lake water, or waste cooling from processes (e.g., gasification of LNG), can be up to 10 times more energy-efficient than building-level cooling systems.

With the above in mind, it becomes clear that the cost-effectiveness of a DCS comes down to multiple factors, ranging from effective utilization of investments, high system efficiencies, ability to utilize low-cost energy sources, and leverage sector coupling opportunities. To fully realize its potential and mitigate investor risks, it is crucial to establish a well-defined business model tailored to the specific business case.

All in all, it is clear that DC is a sustainable and future proof solution for fulfilling cooling demands in urban areas.

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