Module 4
District Cooling

Part of the SHaKE Educational Package on District Heating and Cooling Systems

Guidebook

Reusable teaching resource for higher education and professional training

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Project

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Guide to using Module 4

This module is part of the SHaKE educational package developed to support the teaching of district heating and cooling (DHC) systems in higher education and professional training contexts.

Module 4 focuses on district cooling systems, with particular attention to combined heat and cold production, cold production technologies, refrigerants, thermal energy storage, waste heat utilisation, renewable energy applications and the economic and environmental assessment of district cooling solutions. The module introduces the fundamental operating principles of district cooling networks and explains how cooling can be produced, distributed, stored and integrated into wider district heating and cooling infrastructures.

The primary objective of this written material is to provide a comprehensive understanding of district cooling systems, including combined heat and cold production, waste heat utilisation and renewable energy applications. In addition, the module aims to illustrate the practical implementation of district heating and cooling infrastructures through realised project examples.

The module examines the joint production of heat and cold, the technical evaluation of thermal efficiencies, the operation of chillers and absorption refrigeration machines, the role of heat pumps, the environmental relevance of refrigerants and the feasibility of district cooling in different urban and climatic contexts. It also introduces optimisation strategies for improving system performance while reducing economic and environmental costs.

The guidebook is primarily intended as a reusable teaching resource for educators, lecturers and trainers. It can be used to support lectures, blended learning activities, classroom discussions, practical assignments, technical calculations, performance simulations, case-study work and continuing professional development training. The accompanying presentation slides, extended case-study slides, question bank, self-check quiz and practical activities are designed to help educators adapt the content to their own teaching context.

Students and professionals may also use the module for independent study, especially if they already have basic knowledge of thermodynamics, heat transfer, HVAC systems, refrigeration cycles, heat pumps, chillers, district heating and building energy systems.

Main topics covered in the module

- District cooling systems and their role in modern district energy networks
- Heating and cooling principles
- Combined heat and cold production and simultaneous heating and cooling applications
- Heat pump and chiller technologies
- Integration of heat pumps, chillers and renewable energy sources into district cooling networks
- Waste heat utilisation and renewable heat integration
- Cold production technologies, including air-cooled and water-cooled chillers
- Absorption refrigeration machines
- Thermal energy storage for district cooling
- Combination of mechanically driven and thermally driven cooling systems
- Refrigerants, their classification, designation, safety and environmental impact
- Low-GWP and natural refrigerants
- Cooling demand density and feasibility assessment
- Economic and environmental aspects of district cooling
- Viability of district cooling compared to conventional cooling technologies
- Optimisation of district cooling technologies
- Realised district cooling and district heating and cooling case studies
- Practical implementation of district cooling systems in different climatic and urban contexts

Learning outcomes of Module 4

The module is designed to support the development of the following skills and competences. Upon completion of this module, learners should be able to:

- understand the thermodynamic principles and technologies underpinning district cooling systems;
- explain the fundamental operating principles of district cooling networks;
- analyse the processes of combined heat and cold production and calculate their operational efficiencies;
- distinguish between different cold production technologies, including air-cooled chillers, water-cooled chillers and absorption refrigeration machines;
- evaluate and justify the optimal integration of heat pumps, chillers, thermal energy storage and renewable energy sources in district cooling networks;
- assess the environmental impact derived from the use of various refrigerants and cooling technologies;
- compare refrigerants from the perspective of safety, performance, GWP and environmental impact;
- evaluate the economic feasibility of district cooling systems in relation to cooling demand density, investment costs, operational costs and long-term system performance;
- compare district cooling solutions with conventional cooling technologies from technical, economic and environmental perspectives;
- interpret realised district cooling and district heating and cooling case studies and identify the main factors influencing their feasibility and transferability;
- apply optimisation strategies to improve system performance while simultaneously reducing economic and environmental costs.

Estimated workload

This module represents approximately 7.9 learning hours, including lectures, practical application, case-study work, independent study and assessment.

Educators may adapt the workload depending on the level of the course, the selected materials and the teaching format. The module can be used as:

- a complete teaching unit,
- a set of selected lecture materials,
- a blended learning component,
- a practical calculation and simulation package,
- a case-study and discussion package,
- or a supplementary resource for existing courses.

Activities and Learning Hours

Activity Type	**Time Allocation**	**Description**
Lectures / Theoretical Assimilation	3 h	In-depth coverage of the principles, technologies and applications of district cooling through theoretical lectures and guided learning materials
Practical Application	1 h	Exercises including system design tasks, technical calculations, performance simulations and comparison of cooling or heat pump configurations
Case Analysis	0.5 h	Critical review of real-life district cooling projects, considering their technical design and their adaptation to different climatic, urban and operational conditions

Independent Research / Self-Study	3 h	Independent reading, review of specialised literature, revision of the learning materials and preparation for assessment tasks
Assessment / Evaluation	0.4 h	Module-level self-check quiz, selected questions from the question bank, technical report, project presentation or final assessment activity
Total Learning Hours	approx. 7.9 h	

Target groups

This guidebook is primarily intended for educators, lecturers and trainers who wish to use or adapt the SHaKE materials in their own teaching or training activities.

The primary target groups are:

- higher education lecturers in engineering, building services, energy systems, district heating and cooling, HVAC and refrigeration;
- trainers involved in professional or continuing education on district heating and cooling systems;
- educators developing blended, modular or practice-oriented learning activities;
- academic staff seeking reusable teaching resources on sustainable district energy systems;
- trainers and lecturers working with topics related to district cooling, heat pumps, chillers, refrigerants, thermal energy storage, urban energy infrastructure and energy efficiency.

The materials may also be used by students, professionals and independent learners who wish to study selected topics individually. For independent use, basic prior knowledge in the relevant engineering fields is recommended.

Recommended use by educators and trainers

Module 4 can be used flexibly as a complete teaching unit or as a set of selected teaching resources. Educators may combine the materials according to the level of the course, the available teaching time and the intended learning outcomes.

Teaching need	Suggested Module 4 resource
Introducing the topic	Use the module overview and introductory slides to present the relevance of district cooling, combined heat and cold production, and the role of cooling in modern district energy systems.
Preparing learners before class	Assign selected guidebook sections as pre-reading for flipped classroom or blended learning activities.
Supporting lectures or seminars	Use the main presentation slides to explain district cooling principles, simultaneous heating and cooling, chillers, absorption refrigeration, refrigerants, thermal energy storage, economic and environmental aspects, and selected case studies.
Extending case-study discussion	Use the extended case-study slides to present additional realised district cooling and district heating and cooling projects from different contexts.
Checking understanding	Use selected questions from the question bank for discussion, short in-class checks, formative assessment or LMS-based quizzes.
Developing applied engineering skills	Use the practical exercise for calculation-based or simulation-based work on cooling and heat pump

	performance, refrigerant comparison, COP/EER analysis and environmental impact.
Supporting environmental assessment	Use the refrigerant-related sections and exercises to discuss GWP, low-GWP refrigerants, natural refrigerants and the environmental implications of refrigerant choice.
Supporting economic and feasibility analysis	Use the economic and environmental assessment sections to discuss cooling demand density, investment costs, operational costs, tariff considerations and long-term viability.
Supporting case-study work	Use the realised project examples to compare how district cooling solutions are adapted to different climatic, urban, technical and economic contexts.
Supporting independent review	Direct learners to the module-level self-check quiz after they have studied the relevant materials.
Adapting to local teaching contexts	Select, combine or modify the guidebook sections, slides, questions, practical exercise and case-study materials according to the curriculum, participant level and professional context.

Recommended pathway for independent learners

Students and professionals using the module independently may follow the sequence below.

Step	**Suggested activity**
Review the introductory presentation	Familiarise yourself with the main concepts, terminology and structure of the module.
Study the guidebook materials	Read the detailed explanations, engineering principles and district cooling concepts presented in the guidebook.
Review the sections on combined heat and cold production	Understand how simultaneous heating and cooling can improve energy efficiency and support district energy integration.
Study the cold production technologies	Compare chillers, absorption refrigeration machines and thermal energy storage solutions.
Review the refrigerant sections	Study refrigerant classification, historical development, safety designation, environmental impact and future refrigerant trends.
Examine the economic and environmental aspects	Analyse the role of cooling demand density, feasibility, investment costs, environmental performance and optimisation.
Watch the module video	Use the module video and its attached assessment questions to explore one selected topic, concept or practical aspect of the module.
Complete the self-check quiz	Test your understanding of the key concepts and technical principles covered in the module.
Attempt the practical exercise	Apply the acquired knowledge by analysing cooling and heat pump performance, refrigerant comparison and environmental impact.
Review the case studies	Compare realised district cooling and district heating and cooling projects and reflect on their transferability to other contexts.
Review the question bank	Use the questions for revision, discussion or preparation for assessment.

Available supporting materials

The available learning resources and assessment materials include:

- presentation slides for the module topics;
- extended case-study slides presenting additional realised district cooling and district heating and cooling projects;
- a reusable question bank and answer key;
- a module-level self-check quiz;
- a module video with attached assessment questions;
- a practical exercise based on cooling and heat pump simulation, refrigerant comparison, COP/EER analysis and environmental impact assessment, including suggested solutions;
- a case-study activity based on realised district cooling and district heating and cooling projects.

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District cooling

1.1. Heating and cooling principles

Introduction

Heating and cooling are vital for comfort in winter and summer. Heating is also needed in buildings for hot water services, usually at different temperatures. However, the biggest heating and cooling consumers are found in industry, and the latter also for food processing, storage, and transport. Temperature requirements for heating and cooling vary across applications; cooling can be found to be from -150 °C and heating up to 1000 °C. Cooling processes are mostly based on vapor compression systems, also known as chillers, when they are cooling water around 10 °C. Heating production is based on heat pumps, a similar concept to chillers. However, at higher temperatures or depending on the application, it is still based on fossil-fuel boilers, which will eventually and progressively be replaced by renewable processes [1].

Technical aspects such as durability, easier maintenance, simplicity, volume, and safety are essential in heating and cooling. However, every day is more critical to the system's efficiency, as this will impact cost and environmental impact. Traditional heating and cooling technologies can be combined with district heating and district cooling networks (Fig. 1) to improve in several ways efficiency and economic profit. District heating networks can be used as heat carriers for heating produced in central or distributed heating production plants. The same is valid for district cooling networks and chillers. Furthermore, district heating and cooling networks can set favourable operational conditions for heat pumps and chillers to produce more efficient heating and cooling. They can also be used to preheat or precool the heat sink or source.

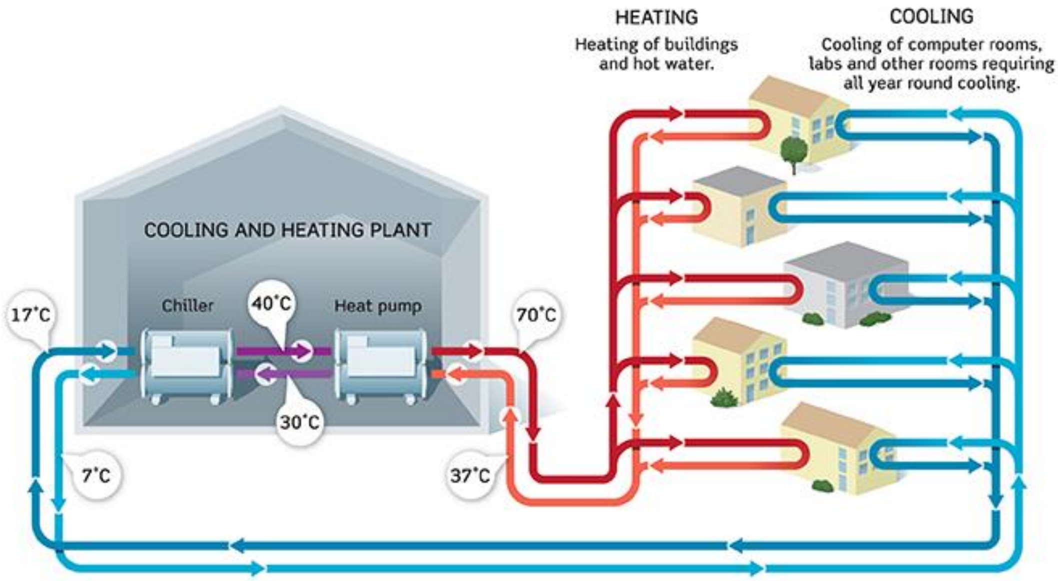

Fig. 1. Connections of DCN and DHN [2].

1.1.1. Cooling

Cooling is removing heat from a substance or space to lower its temperature. It is essential for thermal comfort, preservation of materials, and industrial applications. Cooling processes include:

1. Heat Extraction.

Heat is removed from a system via conduction, convection, or radiation. Commonly achieved by transferring heat to a cooler fluid (Eg, air or water).

2. Evaporation.

Utilizes the latent heat of vaporization, where heat energy is absorbed to convert a liquid into vapor. Widely applied in evaporative cooling systems and refrigeration cycles.

3. Refrigeration Cycles

Based on vapor compression systems, it mostly requires an electricity input. High performance. Maximum limited by reverse Carnot cycle.

Heating

Heating provides heat from a substance or space to increase its temperature. It is essential for thermal comfort, industrial processes, and water heating. Heating processes include:

1. **Heat Extraction**

Heat is provided to a system via conduction, convection, or radiation. Commonly achieved by transferring heat to a cooler fluid (e.g., air or water). Can incorporate renewable heat, thermal solar panels, boilers, waste heat recovery…

2. **Condensation**

Utilizes the latent heat of vaporization, where heat energy is absorbed to convert vapor into liquid.

3. **Heat pump**

Based on vapor compression systems, it mostly requires electricity input and presents high performance.

As can be seen, the processes are similar to cooling but in reverse direction. Therefore, the study of cooling can help to understand heating, and vice versa.

1.1.2. Heat pumps

Besides waste heat or renewable heat, which can be injected into district heating networks with a low operational cost, most heating is provided by boilers (which can be considered renewable if biomass, biogas, etc., are used) or heat pumps.

Heat pumps, mostly based on vapor compression systems, can operate for heating, cooling, or both (Fig. 2). It mostly depends on which target of the heat process is considered, but heat pumps always generate simultaneous heating and cooling. Once the installation is sized, the magnitude of cooling and heating depends on the frequency of the compressor, which is controlled by an inverter depending on the primary need. However, both vary proportionally.

If the heat pump (term used for heating purposes) is programmed to choose between heating and cooling, it is called a reversible heat pump. Depending on the purpose, only cooling, air conditioner, refrigeration system, freezer, chiller, etc.

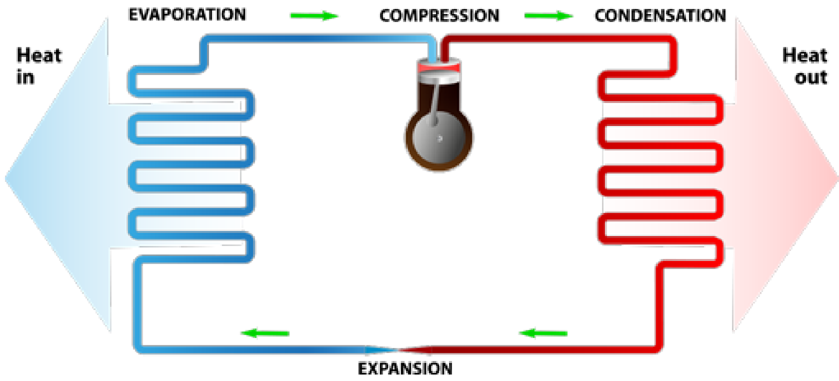

Fig. 2. Vapor compression system (heat pump) [3].

1.2. Simultaneous heating and cooling applications

1.2.1. Simultaneous heating and cooling (SHC) principle

Simultaneous heating and cooling is majorly produced in heat pumps (Fig. 3), the most common technology for cooling and heating below 100 °C. Simultaneous heating and cooling are not usually considered in small systems, as there are many challenges to making it profitable. District heating and cooling networks are beneficial for transporting the excess heating or cooling not used in the same plant where the primary heating or cooling is generated, bringing additional economic profit to the plant's owner and reducing the overall energy use. District heating and cooling networks avoid the necessity of thermal energy storage or can even be combined.

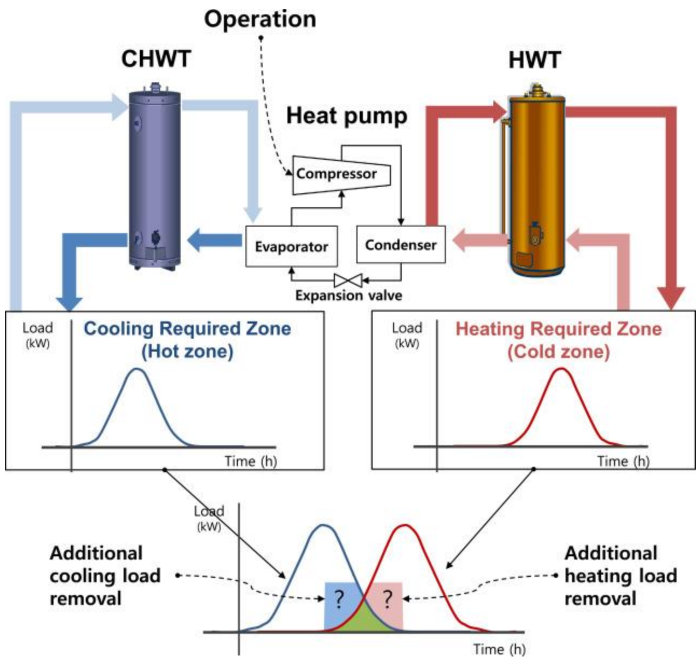

Fig. 3. Simultaneous heating and cooling heat pump [4].

For example, supermarket refrigeration systems (Fig. 4) can use heat in a gas cooler or condenser, which is usually dissipated into the air and injected into a district heating network.

The Figure shows an example in which the central vapor compression system (right) is used for refrigerators and freezers, and the heating at the compressor discharge is produced for space heating. The remaining heat is dissipated, but with a proper control system, it can also be injected into DHN or stored.

The auxiliary system (left) injects heat into the district heating network and uses cooling to mechanically subcool the central system (to increase energy performance).

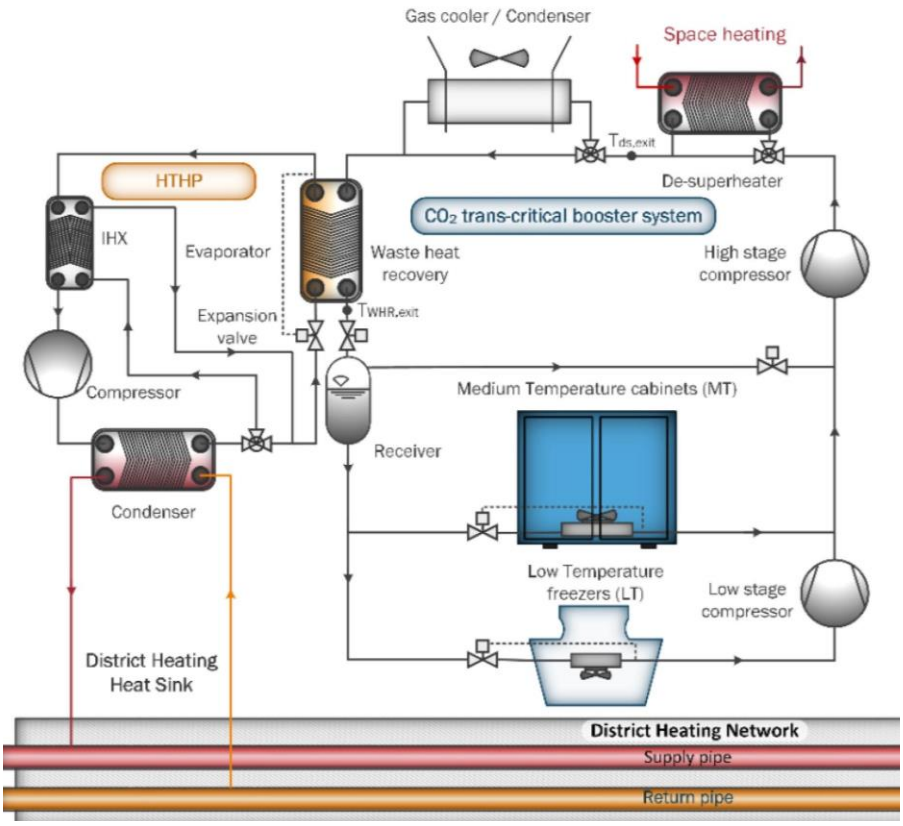

Fig. 4. Simultaneous heating and cooling supermarket refrigeration systems [5].

1.2.2. Key Components in Simultaneous heating and cooling (SHC)

In DHC systems, the energy is transported to buildings through a network of insulated pipes carrying hot water, steam, chilled water, or refrigerants. However, the following key components can be considered for diversifying options and extending energy utilization possibilities.

1. Heat Pumps/Chillers. Heat pumps are central to SHC systems, as they can simultaneously extract heat from a cooling process and transfer it to a heating system, acting as a bridge between the heating and cooling needs. They use vapor compression or absorption cycles to move energy between heat sinks and sources.
2. Thermal Energy Distribution Network. Insulated pipelines transport heating and cooling energy to and from buildings. Advanced controls ensure efficient distribution based on real-time demand.
3. Energy Recovery Systems. Heat exchangers capture and transfer waste heat (free heat) from one side of the system (cooling load) to another (heating load) to satisfy heating demands. For instance, the heat rejected by chillers or air-conditioning systems during cooling can be captured and repurposed for heating.
4. Combined Heat and Power (CHP). CHP units can be integrated into DHC systems to generate electricity and produce heat, enhancing system efficiency.
5. Thermal Energy Storage (TES). TES systems (e.g., hot water tanks or chilled water tanks) are often incorporated to store excess thermal energy during periods of low demand, ensuring efficient operation during peak times.

1.2.3. Advantages of SHC

1. Energy Efficiency: By recovering and reusing waste heat, SHC systems significantly reduce energy consumption compared to separate heating and cooling systems.
2. Reduced Carbon Footprint: Using waste heat minimizes reliance on fossil fuels, lowering greenhouse gas emissions.
3. Economic Savings: Sharing infrastructure for heating and cooling reduces capital and operational costs for the network.
4. Flexibility: SHC systems are adaptable to varying demands for heating and cooling, making them ideal for mixed-use developments (e.g., residential, commercial, and industrial areas).
5. Peak Load Management: SHC systems smooth energy demand peaks by simultaneously meeting both heating and cooling needs.

1.2.4. Challenges of SHC

1. Initial Investment: High upfront costs for infrastructure and heat pump systems.
2. Complex System Design: Requires precise engineering and sizing to balance simultaneous heating and cooling loads.
3. Energy Storage: Effective TES systems are crucial to handle mismatched heating and cooling demands over time.
4. Integration with Renewable Energy: Coupling SHC systems with renewable energy sources (e.g., solar thermal or geothermal) can enhance sustainability but requires careful planning.
5. Control: Heating and cooling must always be consumed, transported, stored, or dissipated to have proper control of temperatures.

1.2.5. Applications of SHC in DHC Networks

Perfectly conceived for 5DG DHC networks, but it can also fit with traditional DHN and DCN. Particularly:

1. Mixed-Use Urban Developments: Residential, commercial, and office buildings with varying thermal demands can be served efficiently.
2. Industrial Parks: Industries with high cooling requirements (e.g., data centers) can provide heat for nearby processes or communities.
3. Hospital Complexes: Hospitals require simultaneous heating for sterilization and cooling for patient comfort, making SHC highly applicable.
4. University Campuses: Large campuses with diverse thermal needs can optimize energy use through centralized SHC systems.

Future:

1. Hybrid System
2. stems: Integration of renewable sources and advanced heat pump technologies.
3. Digitalization: Using smart grids and IoT to optimize thermal energy distribution.
4. Circular Energy: Greater emphasis on waste heat recovery from diverse sources like data centres and industrial processes.

1.3. Heat pump and chillers technologies connection to DHCNs

1.3.1. Heat Pump Technologies Remarks

Once visualized those technologies in section 3.5.5, those technologies when connected to DHN or DCN, it will change that instead of dissipating or absorbing heat from the ambient, groundwater, seawater, water connected to a cooling tower, etc., it will be connected to the thermal network.

Most cases will be water-source heat pumps or water-cooled chillers, but the heat can also be transferred to air as heat transfer fluid or stored in the ground.

Vapor compression-based heat pumps are currently the most efficient systems, with coefficients of performance (COP) ranging from 3 to 6. In contrast, absorption systems have lower COPs, typically between 0.5 and 1.5, but they can operate economically when driven by waste heat or renewable thermal sources, requiring electricity only for auxiliary components. Hybrid systems remain largely in early development stages, mostly limited to research projects or case studies. Meanwhile, caloric technologies are still decades away from commercialization, but they hold long-term potential as they do not rely on refrigerants, which eliminates leakage and reduces maintenance needs.

1.3.2. Emerging Technologies and Future Trends

1. **Natural Refrigerants**:

   a) Increasing use of refrigerants like ammonia (NH_3), carbon dioxide (CO_2), and hydrocarbons (e.g., propane, isobutane) due to their low global warming potential and zero ozone depletion potential.

   b) Challenges associated with flammability (hydrocarbons) and high operating pressures (CO_2).

2. **High-Temperature Heat Pumps**:

   a) Capable of delivering heat at temperatures above 100 °C, suitable for industrial applications and integration into DHN.

   b) Use advanced working fluids like R-1234ze(E) or R-1336mzz(Z) for better thermal stability

3. **Digitalization and IoT:**

   a) Smart heat pumps and chillers equipped with sensors and IoT connectivity for real-time performance monitoring, fault detection, and predictive maintenance.

Advanced algorithms for demand-response and peak shaving.

4. **Thermoelectric and Magnetocaloric Cooling**:

   a) Thermoelectric Heat Pumps: Use the Peltier effect to achieve cooling or heating without moving parts.

   b) Magnetocaloric Cooling: Exploits magnetocaloric materials to provide cooling without refrigerants.

   c) Challenges associated with limited scalability and high costs.

5. **Hybrid Systems**:

   a) Integration of heat pumps and chillers with renewable energy sources (e.g., solar thermal, geothermal).

   b) Use of thermal energy storage to optimize load management.

6. **Integration with District Energy Systems:**

   a) District heating and cooling networks for simultaneous heating and cooling applications with heat pumps and chillers and energy recovery systems for enhanced efficiency.

1.4. Heat pump and chillers technologies connection to DHCNs

1.4.1. Compressors

Technology for chillers and heat pumps depends on the type of compressors, which are primarily selected depending on the application, the heating or cooling capacity (Fig. 5), and the temperature difference between the heat sink and the source (pressure ratio).

This will influence the refrigerant selection, the size of the installation, the cost, the control, and other safety or auxiliary components. According to sizing or optimization, compressors can also be connected in parallel. The chiller is named depending on the type of compressor and the heat dissipation or absorption with the ambient (air-cooled or water-cooled).

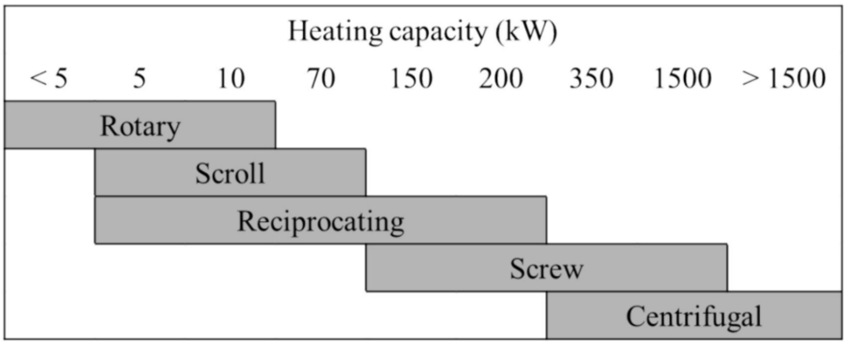

Fig. 5. Compressor type as function of heating capacity range [6].

- **Advanced compressors**

Depending on the type of compressor, advanced and high-capacity chillers can also be named:

1. Magnetic Bearing Chillers:

a) Use magnetic bearings for the compressor, reducing mechanical friction.

b) Advantages: High efficiency, low noise, and reduced maintenance.

c) Limitations: High initial cost.

2. Centrifugal Chillers:

a) Use a centrifugal compressor to circulate refrigerants.

b) Advantages: High capacity and efficiency for large-scale applications.

c) Limitations: Not ideal for smaller systems due to high costs.

1.4.2. Heat exchange

Most heat exchanges between heat pumps and chillers and DCN and DHN are based on heat exchangers. There are different types of technologies, according to different classifications as shown in section 3.5.3.1. The most common heat exchangers are shell-and-tube type, used in petrochemical processes, microchannel, used for mobile air conditioning, or air-cooled heat exchangers, for air dissipation in condensers. As it is more efficient, heat exchange is convective or plus phase change. However, it can be based on natural convection, like domestic freezers or refrigerators. The most compact and efficient technology for liquid-to-liquid heat exchange is plate heat exchangers.

Plate heat exchangers are the most common for water-to-water heat exchange, condensers, and evaporators.

1. **Heat transfer precision** – improved temperature approach, accurate counter-current flow, 80-90% less hold-up volume.
2. **Low cost** - low capital investment, installation, limited maintenance, and operating costs.
3. **Greatest reliability** - less fouling, stress, wear, and corrosion.
4. **Responsible** - least energy consumption for most process effects, reduced cleaning.
5. **Easy to expand capacity** – adjustable plates on existing frames.

Limitations associated with high temperature, pressure, sealing, and particle blockage. This is addressed with proper design and maintenance.

1.4.3. Thermal energy storage

Thermal energy storage (TES) (Fig. 6) is essential for shifting peak load in heating or cooling. They are also used in networks where night or day temperatures can be used for free cooling or heating and when renewable or waste heat is generated at a peak. The leading TES technologies are sensible, latent heat (water tanks), phase change materials or ice storage, and thermochemical TES. TES includes heating or cooling storage. The main drawback is the volume required per kWh. Materials for phase change and thermochemical TES are in an earlier stage of development but can contribute to solving this issue.

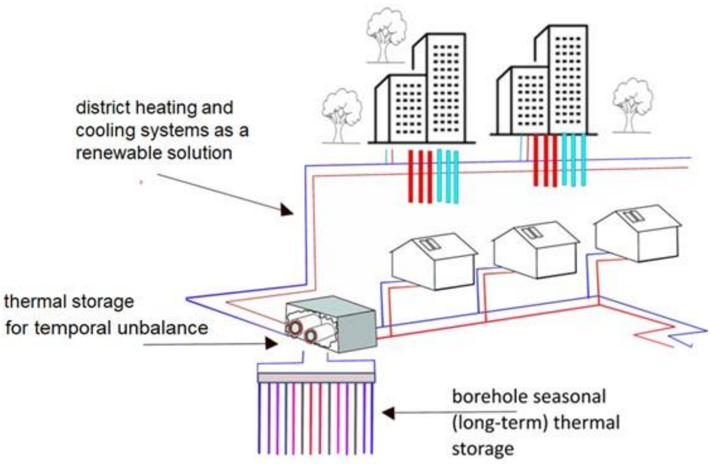

Fig. 6. TES connection to DHC [7].

1.5. Integration of heat pumps, configurations, and refrigerants

The input information for sizing, designing, or selecting the heat pump, including configuration and refrigerants, will be based on its dissipating or absorbing heat applications. The following questions are required.

1. Which type of heat pump will be used? For only thermal purposes (heating/cooling), a hybrid system with an absorption system, a hybrid system with electricity generation, or TES, available…
2. How will the heat pump be used? Heating, cooling, both simultaneously, both alternatively…
3. Is the thermal network used to support or to receive the heating/cooling?

a) Low-temperature DHN for evaporator connection and high-temperature heating production in the condenser

b) DCN connection in the evaporator, economic profit in the evaporator (cooling) and condenser (high-temperature heating)

4. What is the targeted process, temperature (fixed or variable), and heat transfer medium? DHN, DCN, chiller, commercial refrigeration (low or medium temperature), air conditioning, comfort heating, water heating, industrial heating, etc.

1.5.1. Possibilities of integration

A combination of urban and industrial heating and cooling consumptions by a heat pump with the possibility of simultaneous production (table 1 and Fig. 7).

	Application	Temperature Range	Traditional technology
Heat source	Ambient air	0-30 °C (15 °C)	Several technologies
	Data cooling centre	20-50 °C (35 °C)	R-410A based cooling technologies
	Low-temperature district heating	40-70 °C (55 °C)	Mix technologies (waste-to-heat, gas boiler, coal, etc.)
Heat sink	Low-temperature space heating	45-50 °C	Solar, electric or gas boiler
	Domestic hot water	45-65 °C	Electric or gas boiler
	Industrial processes/Heating radiators	75-90 °C	Centralized gas burned system

Table 1. Heat pump application for simultaneous heating and cooling [8].

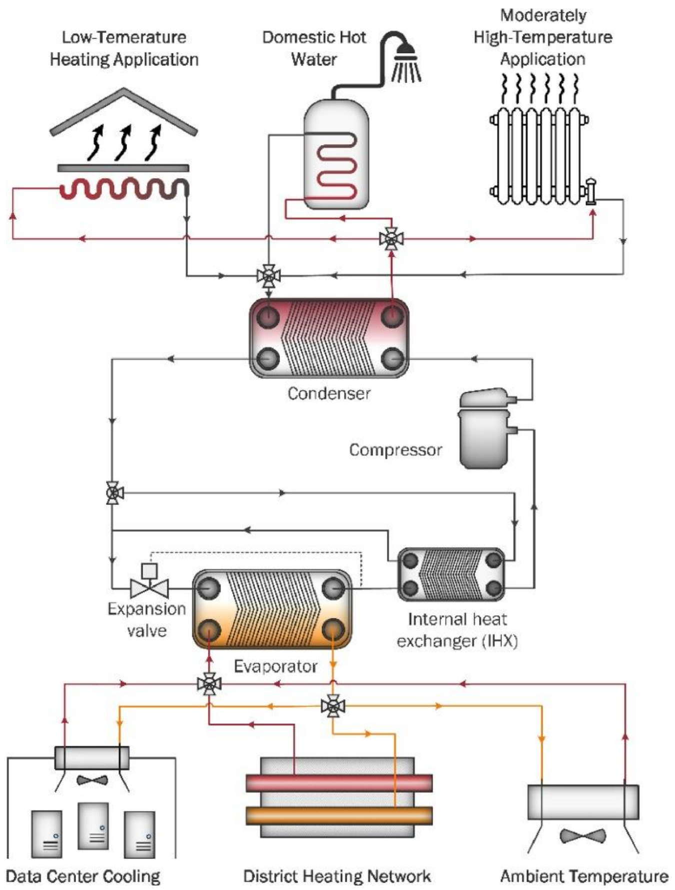

Fig. 7. Heat pump application for simultaneous heating and cooling [8].

1.5.2. Influence of the operational temperatures

Depending on the temperature of the heat sink and the heat source, the COP will vary significantly (Fig. 8). COP represents the kW of heating or cooling per kW of electricity absorbed. A higher COP represents lower energy consumption, lower operational costs, and lower CO_2 emissions. (a higher potential of decarbonization).

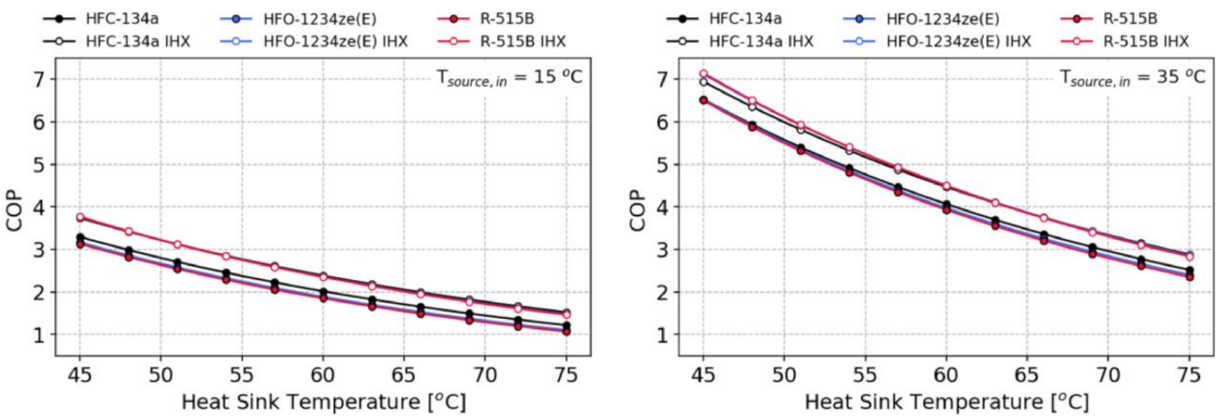

Fig. 8. COP evolution as function of heat sink and heat source [8].

Combination with DHN, DCN, and industrial processes

Depending on the temperature and connection between DHN and DCN, different possibilities can be considered for the heat pump (central/local heat pump).

Combination with DHN, DCN, and industrial processes: energy perspective

A higher difference between heat sink and heat source will require more than one stage in the vapor compression cycle of the heat pump. Moreover, the Internal Heat Exchanger can benefit energy performance, depending on the refrigerant and application.

Combination with DHN, DCN, and industrial processes: economic perspective

Operational and investment costs depend significantly on the applications considered, while a fossil fuel boiler is mainly affected by the heating requirement. Each situation must be studied in detail to see which combination can reduce costs and make investment more attractive.

Combination with DHN, DCN, and industrial processes: Environmental perspective

The COP obtained clearly influences the sustainability of the solution once environmentally friendly if refrigerants are chosen. Another critical factor is the electricity grid and the carbon emission factor (the origin of the electricity generated).

Combined COP

Combined or aggregated COP considers that the heat pump's heat transfer output is cooling and heating (quantified by the EER and COP, respectively). At the same time, electricity is the input as it is dissipated from the ambient.

Comparison with fossil fuel boilers

The economic benefit compared to fossil fuel boiler is significant, but it depends on the operational temperatures

1.6. Waste and renewable heat

Introduction

Waste and renewable heat can be integrated to complement the heat pump's lack of cooling or heating or to help during peak hours.

Certain heat pump elements can also be combined with waste and renewable heat sources to increase the overall COP. It will be implemented at different levels depending on the renewable or waste heat source's availability, variability, and temperature.

1. Solar thermal panels can be connected to evaporators to increase the temperature and COP. However, the temperature and thermal panel will be highly variable.
2. Low-temperature waste heat can also be connected to the evaporator. It can be more constant. Waste heat can appear at many different temperatures. Greywater can be another valuable heat source in smart cities.
3. Data centres require significant cooling at constant temperatures. Still, they can be used to fix evaporation temperature and produce cooling simultaneously, with significant energy and economic benefits.
4. Higher temperature heating can be connected to elements that combine with ejectors, increasing the final COP. However, ejectors are only available for CO_2 supermarket refrigeration, which is in an intermediate stage of development.
5. Ground-source heat pumps must be studied in detail to determine ground conditions, which can make the investment nonprofitable in technical terms.

Example 1. A Novel compound waste heat-solar driven ejector-solar assisted heat pump for simultaneous heating and cooling purposes. The system utilizes waste heat from three different sources, PV/T (photovoltaic thermal) with flat plate collector, milk pasteurization process, and condenser exchange heat.

Example 2. A novel compound PV/T (photovoltaic thermal) waste heat driven ejector-heat pump system for simultaneous data centre cooling and waste heat recovery for district heating networks. The system uses PV/T waste heat with an evaporative condenser as a driving force for an ejector while exploiting the generated electric power to operate the heat pump compressor and pumps.

Example 3. Combined organic Rankine and compound ejector-multi evaporator vapour compression system for two cooling levels and heating purposes with power generation, geothermal and condenser waste heat utilisation. The system is considered for two modes: power-cooling with condenser waste heat utilisation and power-heating.

Example 4. An ORC combined with a compound greenhouse waste heat-driven ejector-VCC for energy-efficient power-cooling and heating. The system operates in a wide range of ground sources. This system uses waste heat from two sources for multipurpose simultaneous cooling, heating, and power generation (three modes: power-cooling, power-heat pump heating, or power-ground source heating modes). It also has an associated ground source that supports the ORC.

1.7. Waste and renewable heat

1. Simultaneous heating and cooling is possible with heat pumps/chillers
2. It allows for maximizing the energy output of the heat pump. Otherwise, it would be wasted.
3. DHN and DCN are ideally suited for maximizing profit and reducing the need for expensive peak shifting strategies or larger thermal energy storage.
4. Heat pumps can use several compressor technologies, depending mainly on the unit's thermal capacity and the pressure ratio set by the application.
5. Simultaneous heating and cooling contribute to better operational conditions for the heat pump.
6. Energy efficiency is vital for making heat pumps competitive compared to boilers.
7. Heat pumps are particularly efficient when their components use renewable or waste heat. A wide variety of heat sources can be considered.

2. Cold production technologies

2.1. Chillers

Introduction

A chiller removes heat from a process, machinery, or building to maintain a controlled temperature. This is done by circulating a cooled fluid (often water or a water-glycol mixture) that absorbs heat from the target area and transfers it to the environment.

They are commonly used in industrial, commercial, and HVAC (heating, ventilation, and air conditioning) systems to cool equipment, processes, or buildings. Therefore, from hundreds to thousands of kW of cooling.

Chillers are widely used in industries such as manufacturing, medical facilities, data centres, and food processing to maintain optimal temperatures.

Operation

As observed in Fig. 9, the role of the evaporator is to produce chilled water. The device releases the water at about 6°C and pushes it throughout the facility with the help of a pump. The water returns to the evaporator where the refrigerant at about 12°C where absorbs the unwanted heat.

There is another loop connected to the condenser, which is between the cooling tower and the condenser. After entering the condenser at about 27 °C or ambient temperature, the water leaves at approx. 5 degrees higher. Note that at no time do the refrigerant can dissipate heat directly through an outdoor fan-coil [9].

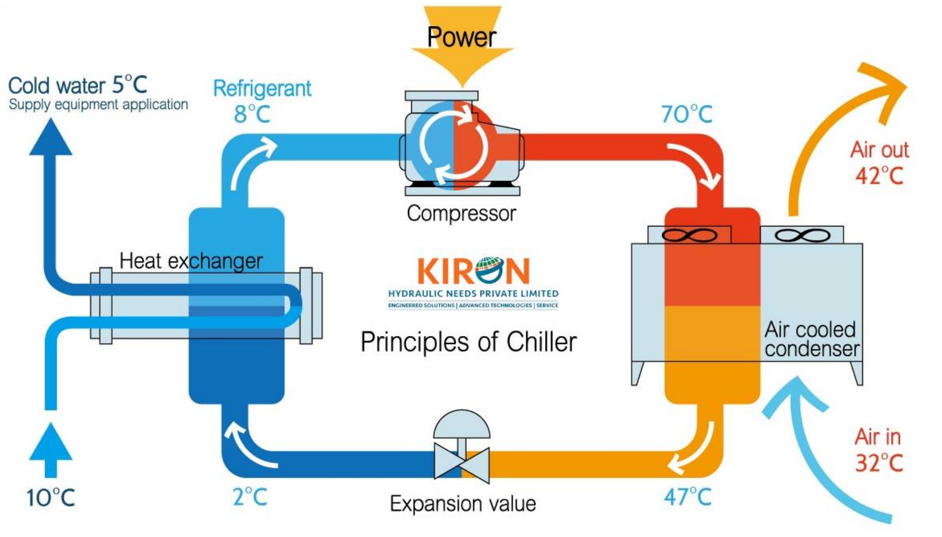

Fig. 9. Chiller operation scheme [10].

2.1.1. Types of Chillers

Chillers are classified based on how they dissipate heat:

1. **Air-Cooled Chillers**:

    a) Use fans to blow air over a condenser coil to release heat.

    b) Ideal for small to medium-sized systems or where water access is limited.

    c) Common in commercial HVAC systems.

2. **Water-Cooled Chillers (Centrifugal)**:

    a) Use water and cooling towers to dissipate heat more efficiently.

    b) Suitable for large-scale industrial applications where greater efficiency is required.

Cooling tower: This is where the dissipated heat from the condenser ends up in the form of water. Then the heat is dissipated to the ambient air. They use a humid air stream (ambient air stream + water spray). These open-topped devices come in many designs depending on many factors: cross flow, counter flow, natural draft and mechanical draft.

Water-cooled chiller: They have a cooling tower, so the efficiency is higher than air-cooled chillers because it condenses depending on the ambient wet bulb temperature, which is lower than the ambient dry bulb temperature (Fig. 10). The lower a chiller condenses, the more efficient it is. This system has several essential components:

1. Cooling towers
2. Water pumps

3. Thermal Energy Storage reservoirs

They have smaller size, last longer, and they can be placed indoors.

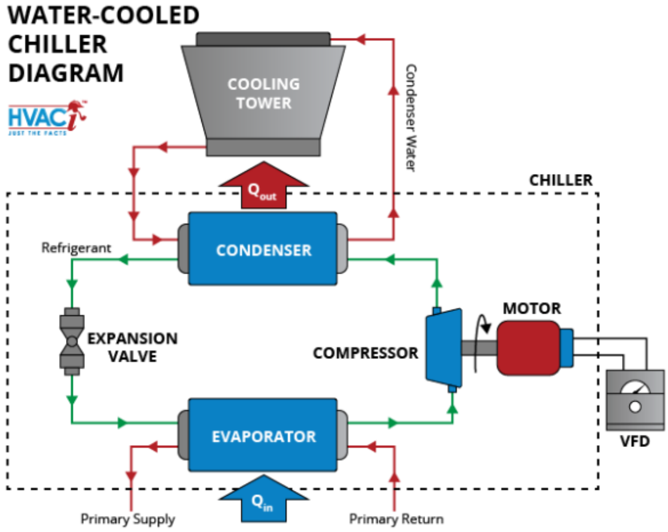

Fig. 10. Water-cooled chiller operation scheme [11].

Air-cooled chiller (Fig. 11)

Benefits compared to water chillers:

1. No water consumption.
2. When used in part-load applications, these chillers are very reliable.
3. No cooling towers.
4. Better environmental stability.
5. Low maintenance costs.
6. Easier to operate and control.
7. Chemical costs avoided.
8. Water costs avoided, especially in cities.
9. No water problems to deal with in case of disaster.

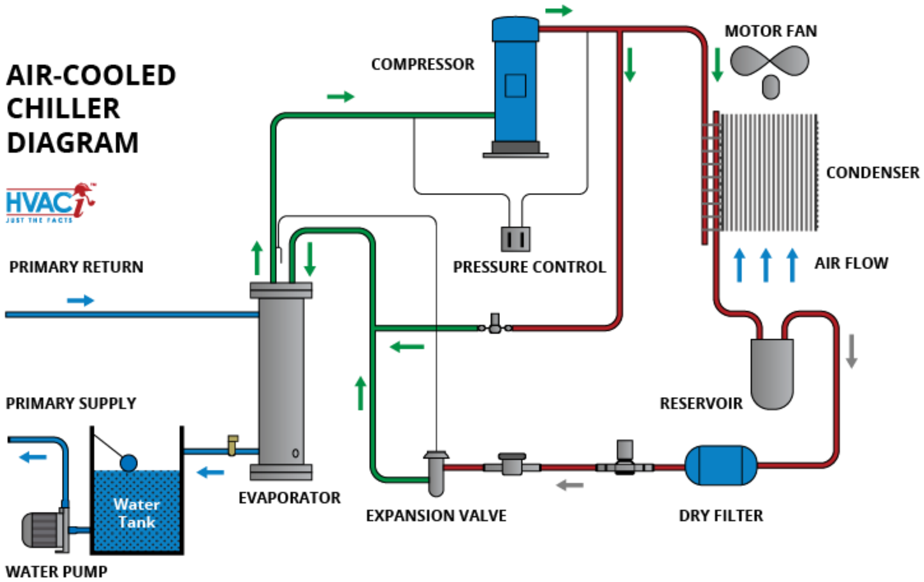

Fig. 11. Air-cooled chiller operation scheme [11].

2.1.2. Key Metrics and Efficiency

1. Cooling Capacity (Q_o): Measured in tons of refrigeration or kilowatts (kW), indicating the amount of heat removed.

2. Power Consumption (W_c): Compressors consume (kW) the most electricity in the system, making their design critical for efficiency. Water pumps and fans must be considered as they can represent 10% of the consumption.

3. Energy efficiency ratio (EER): A measure of efficiency calculated as the ratio of cooling provided to energy consumed (kW cooling / kW electricity) (Eq. (1)).

$$EER = \frac{\dot{Q}_o}{\dot{W}_c} \quad (1)$$

4. Seasonal energy efficiency ratio (SEER): Like the EER, but over an entire season, by calculating the cooling output divided by total electric energy input (kWh cooling / kWh electricity).

2.1.3. Seasonal energy efficiency ratio (SEER)

1. SEER uses a set indoor temperature, along with different outdoor temperatures and load capacities to simulate real life.

2. The EN 14825 standard [12] defines the test methodology (Table 2).

		Capacity			
		100%	**74%**	**47%**	**21%**
Outdoor temperature	**Air source**	35 °C	30 °C	25 °C	20 °C
	Water source	30 °C	26 °C	22 °C	18 °C

Table 2. Case example of temperature set and load capacities for SEER

3. Energy efficiency class depends on SEER and type of equipment. Between A+++ and G, being the first the most efficient classification.

System performance

It depends on:

1. Good design and professional installation of the entire system.
2. Regular maintenance.
3. The size of the building being conditioned and its energy efficiency.
4. The size of the system and its air handling capacity.
5. The amount of time the system is used daily.
6. The indoor temperature.
7. The outdoor air temperature.

Energy Efficiency Ratio (EER)

Air-Cooled Chillers:

1. Typical EER: Between 9 and 12.
2. These systems are generally less efficient than water-cooled chillers, but they are more suitable for smaller to medium-sized applications.

Water-Cooled Chillers:

1. Typical EER: Between 12 and 15, reaching values above 15 for high-efficiency models.
2. Water-cooled chillers are more efficient, especially in large-scale or industrial applications, due to the higher heat dissipation capacity of water compared to air.

Large Industrial Chillers:

1. High-performance industrial water-cooled chillers can have an EER exceeding 15 depending on their size and application.

Applications of Chillers

1. HVAC Systems
2. Industrial Processes (Food processing, plastic processing, metal finishing…)
3. Data Centres
4. Refrigeration
5. Healthcare
6. Power plants
7. Ice rinks
8. District Cooling

2.2. Absorption refrigeration machines

2.2.1. Type of Chillers

Vapor Compressor Chillers

A compressor is the driving force to pump refrigerant around the system. Electricity is required to activate the motor mechanically connected to the compressor.

2.2.2. Vapor Absorption Chillers

Vapor absorption chillers have no compressor in the unit. Instead, they use a heat source, e.g., solar energy or waste heat, to drive the coolant through the system. No electricity is required. Moreover, they are more silent and resistant to leakages as no vibrant elements exist. The gases used are based on natural refrigerants only.

This section will explain the operation of vapor absorption chillers.

2.2.3. Absorption refrigeration

They use a heat source to drive the refrigeration cycle (instead of mechanical energy like compressors). These systems typically use refrigerant and an absorbent fluid (Fig. 12).

1. The process starts with liquid coolant in an evaporator, making it gaseous.
2. Next, the gaseous coolant is absorbed by a concentrated absorbent, such as Lithium Bromide or Ammonia, provided by a generator.

3. Finally, the diluted solution absorbs the coolant while the cooling water absorbs heat.
4. The diluted solution of coolant and absorbent flows through a heat exchanger to the generator, where it is heated.
5. The coolant vaporizes out of the solution, condenses, and is sent out for cooling again. The now-concentrated absorbent is recycled as well.

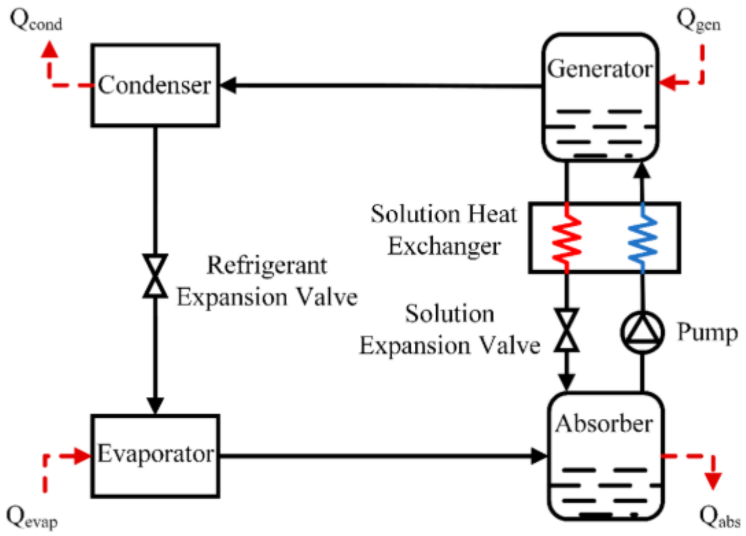

Fig. 12. Absorption machine [13].

Main Components:

1. Evaporator: Where the refrigerant absorbs heat and evaporates.
2. Absorber: Where the refrigerant vapor is absorbed by the absorbent fluid.
3. Generator: Where the refrigerant is separated from the absorbent using heat, regenerating the refrigerant.
4. Condenser: Where the refrigerant releases heat and condenses back into a liquid.

Absorption Refrigeration Steps:

Evaporation: The system's evaporator is where the refrigerant (typically ammonia or water) absorbs heat from the space or object to be cooled. The heat causes the refrigerant to evaporate, turning it from a low-pressure liquid into a vapor.

Absorption: The refrigerant vapor flows to the absorber, where it is absorbed by an absorbent liquid solution (usually water in ammonia-water systems or lithium bromide in water-lithium bromide systems). This process occurs at a lower pressure.

Generation: A generator uses a heat source (e.g., gas burner, hot water, waste heat, renewable heat) to separate the refrigerant from the absorbent. The heat applied to the absorber causes the refrigerant to vaporize and leaves the absorbent. This step regenerates the refrigerant, which now returns to the condenser.

Condensation: The refrigerant vapor then moves to the condenser, releasing heat (from the generator) to the surroundings. It condenses back into a high-pressure liquid refrigerant, which is then returned to the evaporator, and the cycle repeats.

The Absorbent Solution: After the refrigerant is separated from the absorbent in the generator, the concentrated absorbent (after losing the refrigerant) is returned to the absorber to begin the cycle.

Properties of substances used in n Absorption Refrigeration Systems

1. The refrigerant should be more volatile than the absorbent, this means the boiling point of refrigerant should be much lower than the absorbent, so the solution in the Generator needs only to be heated to the boiling temperature of the refrigerant.
2. The refrigerant should exhibit high solubility with solution in the absorber.
3. The absorbent should have a strong affinity for the refrigerant, which will minimize the amount of refrigerant circulated.
4. Operating pressure should be low, so the walls of the shells and connecting pipes need not be thick.
5. It should not undergo crystallization or solidification of the system. Because crystallization will block the free flow of solutions in the line.
6. The mixture should be safe, chemically stable, noncorrosive, inexpensive, and available easily. The refrigerant should have high heat of vaporization.

2.2.4. Types of Absorption Refrigeration Systems

Regarding the previous requirements, there are two mixtures (refrigerant/absorbent):

For applications below 50°C Ammonia-Water (NH_3-H_2O): One of the most common systems used in large-scale applications like industrial cooling, where ammonia is the refrigerant and water is the absorbent.

As a drawback, the water is volatile and cannot be separated easily from ammonia. A rectifier should improve efficiency; the cycle is more complex than the other mixture. Since ammonia is not compatible with materials such as copper or brass, the entire system is normally fabricated out of steel. Ammonia is flammable and highly toxic.

For applications above 50°C (primarily air-conditioning) Water-Lithium Bromide (LiBr): Commonly used for air conditioning and hot water in large buildings and commercial applications. In this case, water is the refrigerant, and lithium bromide is the absorbent. The main problem of this mixture is the possibility of solidification at 0 °C. LiBr crystallizes at moderate concentrations also. Additional drawbacks of the mixture are low pressure (vacuum) and high solution viscosity. Ambient air can leak into the machine. It has advantages such as high safety, volatility ratio, affinity, stability, and latent heat. They adapt to load by varying the absorbent’s reconcentration rate.

Relevant Parameters

1. Cooling Capacity ($\dot{Q}_o$): The amount of heat removed by the evaporator from the space or process being cooled, typically measured in kW.
2. Heat Input ($\dot{Q}_g$): The heat required to drive the absorption cycle, typically provided by a heat source like natural gas, waste heat, or solar energy. It is often measured in kW.
3. Coefficient of Performance (COP): The cooling capacity (Qo) ratio to the heat input (Q_g) (Eq. (2)).

$$\mathrm{COP} = \frac{\dot{Q}_o}{\dot{Q}_g} \tag{2}$$

COP is a key performance indicator of energy efficiency. A higher COP indicates a more efficient system. In absorption refrigeration, typical COP values range from 0.5 to 1.5, significantly lower compared to vapor compression systems.

Advantages of Absorption Refrigeration:

1. No Moving Parts: Since it doesn't rely on compressors, absorption refrigeration is mechanically simpler and often more reliable.
2. Energy Source Flexibility: This can be powered by different energy sources, such as natural gas, solar energy, or waste heat, making it suitable for off-grid or renewable energy applications.
3. Quiet Operation: Since no mechanical compressors exist, these systems operate quietly.

Disadvantages of Absorption Refrigeration:

1. Efficiency: Absorption refrigeration systems are generally less efficient than conventional compressor-based systems, requiring significant heat input.
2. Higher Initial Cost: The technology can be more expensive to install, especially for larger units.
3. Slow Response: These systems may take longer to adjust to cooling demand changes than compression-based systems.
4. Complex Maintenance: They require careful maintenance, particularly with the absorbent solution, which must be checked for proper concentration and contamination.

Compared to vapor compression systems (Fig. 13):

Compression systems	Absorption systems
Work operated	Heat operated
High COP	Low COP (currently maximum ≈ 1.4)
Performance (COP and capacity) very sensitive to evaporator temperatures	Performance not very sensitive to evaporator temperatures
System COP reduces considerably at part loads	COP does not reduce significantly with load
Liquid at the exit of evaporator may damage compressor	Presence of liquid at evaporator exit is not a serious problem
Performance is sensitive to evaporator superheat	Evaporator superheat is not very important
Many moving parts	Very few moving parts
Regular maintenance required	Very low maintenance required
Higher noise and vibration	Less noise and vibration
Small systems are compact and large systems are bulky	Small systems are bulky and large systems are compact
Economical when electricity is available	Economical where low-cost fuels or waste heat is available

Fig. 13. Absorption systems compared to compression systems [14].

Applications

1. Commercial Air Conditioning
2. Industrial Cooling
3. Data Centers
4. Refrigeration
5. Air Conditioning in Remote Locations
6. Waste Heat Recovery Systems
7. Healthcare and Hospitals
8. Solar Thermal Applications
9. Combined Heat and Power (CHP) Plants
10. District Heating and Cooling Networks

2.3. Thermal energy storage (TES)

Thermal energy storage (TES) stores heat or cooling for later use, separating generation from consumption. The concept is similar to electrical batteries, but instead of storing electricity, heating or "cooling" is stored, increasing a fluid's temperature, or using phase change (generally solid to liquid and vice versa). This means that heating or cooling can be generated when an extra surplus or renewable electricity, or waste heat, is available and then consumed when needed. This is especially interesting in DCNs, where central or waste cooling is independent of individual or industrial consumers.

Types of Energy Storage

1. Mechanical: Compressed Air, Hydro Pumped, Flywheel…
2. Electrochemical: Battery.
3. Electrical: Supercapacitors, Superconducting magnetic energy storage (SMES).
4. Chemical: Hydrogen.
5. Thermal: Sensible, Latent, Thermo-chemical.

2.3.1. Main benefit of TES

In DCNs, TES typically involves storing cool energy in an insulated water tank. The tank is cooled or frozen during off-peak periods (nights or weekends) and melted or warmed during on-peak periods (weekdays) (Fig. 14).

This reduces the need for large chillers during peak demand by discharging TES to meet some or all of the load. Extra chiller capacity charges TES during off-peak times while meeting off-peak cooling loads.

Lower-capacity chillers reduce investment and operational costs and reduce electrical stress from the grid.

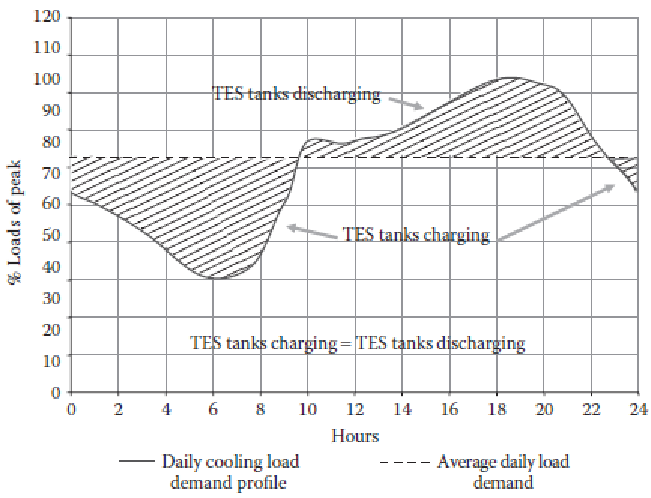

Fig. 14. TES tank charging and discharging periods [15].

2.3.2. Type of TES (Table 3)

Generally, TES technologies for cooling storage include three distinct types:

Latent heat storage systems, such as ice TES or phase change materials (PCM), store thermal energy as a change of phase of the storage medium, usually between solid and liquid states. Medium changes in temperature are not relevant for heat storage but rather depend on the changing state of a medium.

PCMs have been developed to store heat in their mass as latent heat at a specific temperature. These materials are commonly used in solar applications and building materials, where they absorb and store excess building heat.

Sensible heat storage systems, based on chilled water and low-temperature fluids, store thermal energy as a temperature change in the storage medium. They use water or rock to store and release heat energy. This type of thermal energy storage is most applicable to residential buildings.

Thermochemical heat storage systems, based on chemical reactions.

Borehole thermal energy storage and Aquifer thermal energy storage, for long term.

	Ice storage tank	**Chilled water storage tank**	**Low-temperature liquid storage tank**
Type of storage	Latent heat	Sensible heat	Latent heat
Discharge temperature	1°C to 7°C	4°C to 6°C	-1°C to 2°C
Recharge temperature	-8°C to -2°C	4°C to 6°C	-1°C to 2°C
Recharge chiller plant and power (kW electricity in/kW thermal out)	0.8 to 1.1 kW/ton (0.23 to 0.31)	0.6 to 0.7 kW/ton (0.23 to 0.31)	0.7 to 0.8 kW/ton (0.23 to 0.31)

Table 3. Types of TES tank [16].

Applications

1. Educational facilities: schools, colleges, and universities.
2. Healthcare facilities: hospitals, clinics, laboratories, and medical research.
3. Airports, museums: and sports and entertainment complexes.
4. Government facilities: institutional; military; research; administrative; and correctional facilities, at federal, state, and local levels.
5. Private industry: commercial and industrial facilities (including aeronautics and aerospace, automotive, computing, data processing, electronics, pharmaceuticals, telecommunications.
6. District cooling utilities: CHW utility systems selling cooling to multiple customers.
7. Energy services/Performance Contracting: third-party financed projects, funded by energy-efficiency-related cost savings.
8. Turbine inlet cooling: increasing hot-weather power output and efficiency of combustion turbine power plants.

Latent Heat TES

Advantages:

1. Higher Energy Density: Latent heat storage systems can store more energy in a smaller volume because they store energy during phase changes (e.g., from liquid to gas or solid to liquid), which occurs at constant temperature.
2. Stable Temperature: The temperature remains constant during the phase change, making it easier to manage thermal outputs.
3. Efficient for Large-Scale Systems: Due to the higher energy density, latent heat TES is often more efficient in larger, centralized cooling or heating systems.

Disadvantages:

1. Complexity: Latent heat TES systems tend to be more complex and expensive to design and operate due to the need for specialized materials (like phase change materials or PCM).
2. Material Limitations: The performance of latent heat storage depends heavily on the choice of phase change material, which may have limitations in terms of temperature range, cycle stability, and cost.

Sensible Heat TES

Advantages:

1. Simpler Design: Sensible heat storage involves heating or cooling a storage medium (e.g., water or rock), which is simpler and cheaper to implement compared to latent heat systems.
2. Wide Range of Materials: Sensible heat TES can use a variety of materials (like water, air, or stones), which are widely available and inexpensive.
3. Proven Technology: Sensible heat systems are widely used and understood, with established performance characteristics.

Disadvantages:

1. Lower Energy Density: Sensible heat systems store less energy in the same volume compared to latent heat systems because the energy is stored by changing the temperature of the medium, not by phase change.
2. Temperature Fluctuations: The temperature of the storage medium varies as it charges and discharges, which can make it harder to manage and less consistent than latent heat systems.

Integration of TES into DCN (Fig. 15)

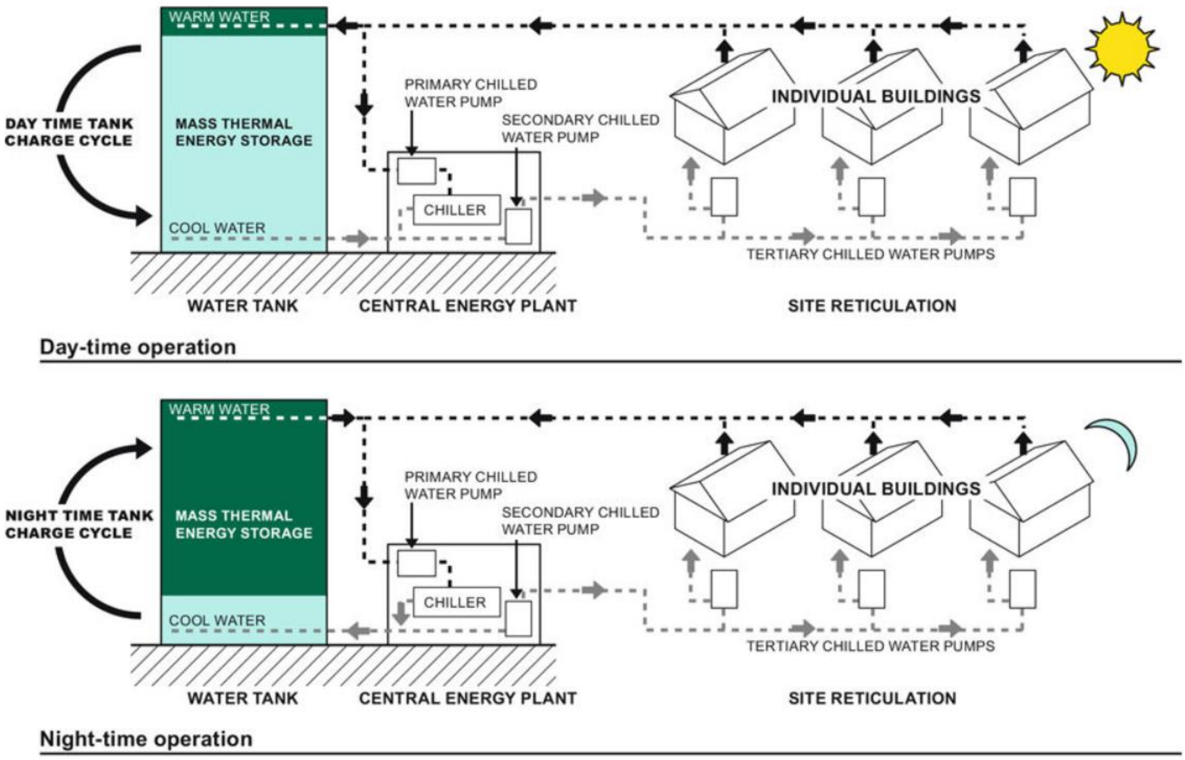

Fig. 15. TES tank integration into DCN [17].

General benefits of integration of TES into DCN:

1. The overall cost of the installation is lower due to the reduction of the refrigeration plant installed capacity. The refrigeration equipment size is smaller because it is designed for average loads rather than peaks.
2. Operational costs are reduced compared to an online cooling system because peak consumption can be avoided during high electrical tariff periods.
3. The environmental impact is reduced because of the reduction of CO_2. Storing the energy and improving operating efficiency with the thermal energy storage tank helps reduce the CO_2 emissions of a district cooling system even more.
4. The plant dimension of the refrigeration system could be reduced. This is given by the fact that the refrigeration capacity of energy produced by the plant will be lower due to the energy already accumulated in the tank. Therefore, a smaller refrigeration system can be used.

2.4. Combination of mechanically driven systems and thermal energy-driven absorption systems.

Introduction

A combination of mechanically driven systems (such as vapor compression refrigeration) and thermal energy-driven absorption systems (Fig. 16). It integrates two distinct cooling technologies to enhance overall system performance, energy efficiency, and sustainability. They can be combined through the condenser, in which the heat rejected by the vapor compression system is used as useful heat by another cycle, as the absorption system. Otherwise, this heat would be rejected to the ambient, and lost. It consequently maximizes the energy efficiency of the overall system.

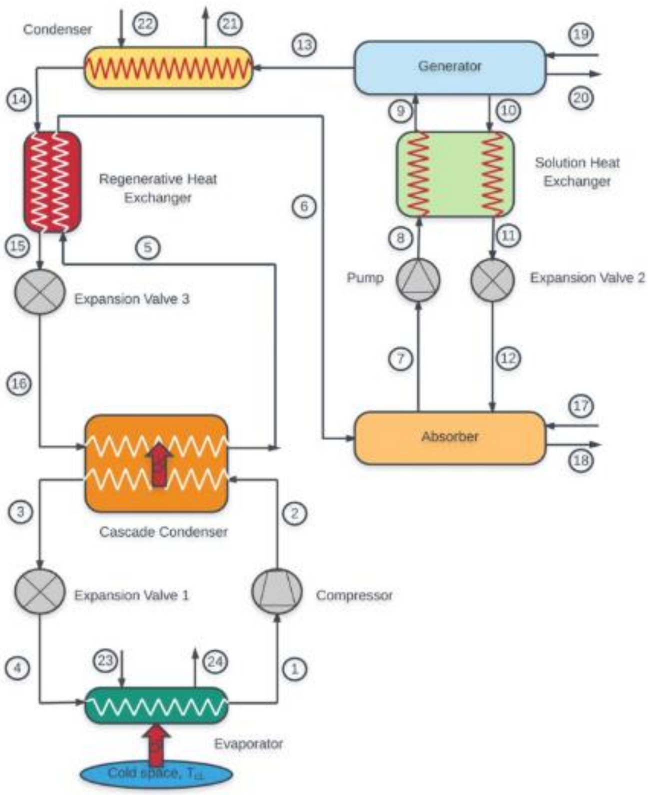

Fig. 16. Scheme of combination of mechanically driven systems and thermal energy-driven absorption systems [18].

Applications

Vapor compression systems and absorption refrigeration systems, when combined are particularly suitable for applications in areas where both cooling and heating are required, or where there is a need to use excess heat, such as in district heating and cooling systems, industrial plants, or large commercial buildings.

Combining these systems allows the hybrid setup to take advantage of each technology's strengths.

For example, during periods of low cooling demand or when waste heat is available, the absorption system can take over, reducing electricity consumption.

On the other hand, during high demand or when thermal energy is insufficient, the mechanical system can be activated to provide additional cooling capacity.

This integration helps optimize energy use, lower operating costs, and contribute to sustainability using renewable thermal sources like waste heat or solar energy. Additionally, the system can work across various temperature conditions, providing flexibility and adaptability.

Key parameters

In this case, the COP considers the whole system inputs and outputs (Eq. (3)):

COP_c: combined coefficient of performance (whole system)

$\dot{Q}_{cas,\,cond}$: cascade condenser load

$\dot{Q}_g$: heat load input

$\dot{W}_C$: compressor power consumption

$\dot{W}_P$: pump power consumption

$$COP_C = \frac{\dot{Q}_{cas,\,cond}}{(\dot{Q}_g + \dot{W}_C + \dot{W}_P)} \tag{3}$$

Advantages

1. Higher Energy Efficiency (Improved COP).
2. Reduced Carbon Footprint.
3. Adaptability to various heat sources.
4. Low Temperature Operation.
5. Low Power Consumption in the Absorption Part.

Drawbacks

1. Higher Complexity and Initial Cost
2. Higher Maintenance Costs
3. Variable Efficiency
4. Larger Size and Space Requirements
5. Cooling Capacity Limitations
6. Additional Heat Required

Applications of this system

1. Industrial Refrigeration
2. District Cooling Systems

3. Combined Heat and Power (CHP) Plants
4. Combined Heating and Cooling (CHC)
5. Chemical and Petrochemical Industries
6. Data Centers

District Heating and Cooling with Waste Heat Recovery

1. Refrigerated Transport
2. Ice Rinks and Sports Arenas
3. Pharmaceutical and Medical Applications
4. Solar Cooling System

However, they are not widely used because of the costs and complexity. Technological advancements or regulations promoting their use are required to enter into the market.

2.5. Conclusions

Air-cooled and water-cooled chillers differ significantly in their advantages and drawbacks, influencing system selection based on application and climate. The performance of heat pumps and chillers is commonly quantified by their COP (Coefficient of Performance) and EER (Energy Efficiency Ratio), which reflect nominal operation, while seasonal COP and EER provide a more realistic assessment by accounting for year-round performance. Absorption chillers, which operate using heat rather than electricity, can be powered by natural gas, but their sustainability is greatly enhanced when driven by renewable sources, waste heat, or district heating networks. These systems rely on two working fluids, whose suitability must be evaluated based on the specific application. While thermal energy storage is traditionally achieved through sensible heat in hot water tanks, phase change materials and thermochemical storage offer promising alternatives for medium- and long-term storage. Finally, combining vapor compression and absorption technologies can optimize cooling production, particularly in applications requiring simultaneous heating and cooling, allowing for diversified thermal energy generation and improved peak load management.

3. Refrigerants

3.1. Introduction

Definition:

According to the International Institute of Refrigeration (IIR): A refrigerant is a substance or mixture, typically fluid, used in a refrigeration cycle to

1. absorb heat at a low temperature and pressure and
2. release it at a higher temperature and pressure.

This heat transfer occurs as the refrigerant changes phase, typically from liquid to gas and vice versa, enabling cooling or heating in applications like refrigeration, air conditioning, and heat pumps.

Primary refrigerant vs. Secondary refrigerant (Fig. 17)

Primary refrigerant (blue pipes), also known as working fluid.

1. Rejects heat at higher pressure/temperature
2. Absorbs it at a lower pressure/temperature

Secondary refrigerant (red pipe), also known as:

1. Secondary fluid.
2. Secondary coolant.
3. Heat transfer fluid.

"Any fluid used for transferring heat from the products to be cooled to the primary refrigerant"

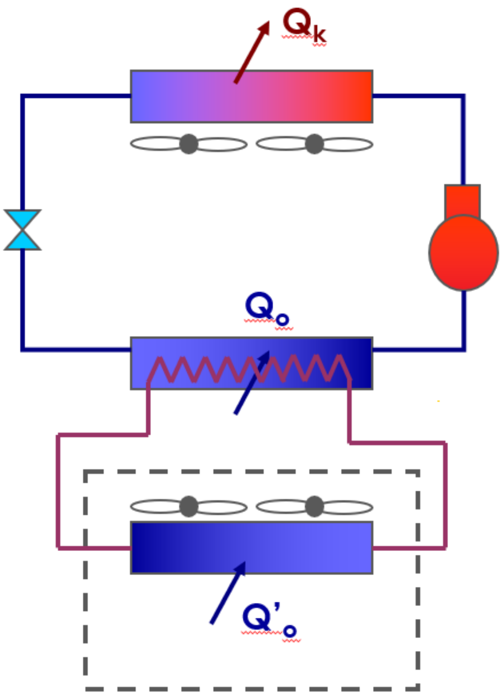

Fig. 17. Scheme of primary refrigerant and secondary refrigerant cycle [3].

Importance of refrigerants

The global market value of refrigerant products reached 20.05 billion U.S. dollars in 2022 and is projected to grow significantly, reaching approximately 36.77 billion U.S. dollars by 2030. The Asia-Pacific region is expected to dominate this growth, with a market contribution rising from 6.42 billion U.S. dollars in 2022 to an estimated 12.85 billion U.S. dollars by 2030 (Statista, 2025). This is an evolving market, with commonly used refrigerants including R134a primarily for automotive air conditioning, commercial refrigeration, and chillers R32 for residential air conditioning, and Isobutane for domestic refrigerators. Emerging alternatives like carbon dioxide for commercial refrigeration and propane for residential applications are also gaining traction. The use and development of refrigerants are tightly regulated under international agreements such as the Montreal Protocol and the Kyoto Protocol, which aim to minimize environmental impact and phase out substances with high global warming potential [19].

The International Institute of Refrigeration estimates:

The global refrigeration, air conditioning, and heat pump sector comprises approximately 3 billion systems, including around 1.5 billion domestic refrigerators. This industry employs nearly 12 million people worldwide and is responsible for about 17% of global electricity consumption. The environmental impact of these systems is significant: roughly 20% of their contribution to global warming stems from direct emissions due to fluorocarbon refrigerant leakages—typically ranging between 5% and 30%—while the remaining 80% is attributed to indirect emissions from the fossil-fuel-based electricity required to operate them. A globally coordinated phasedown of hydrofluorocarbon (HFC) refrigerants could potentially prevent up to 0.5 °C of global temperature rise by 2100, highlighting the crucial role of refrigerant management and energy efficiency in climate change mitigation [20].

Basic classification of refrigerants

Pure Fluid: It is a single substance with consistent chemical composition and properties. In refrigeration, pure fluids undergo phase changes (liquid to gas and vice versa) without separating into different components.

Mixture: A refrigerant may be either a pure compound or a mixture (blend) of two or more refrigerants (Fig. 18):

a) Zeotropic (Non-azeotropic) Mixture. When evaporating, the most volatile component will boil off first, and the least volatile component will last. The opposite happens in condensation. This results in a gliding evaporation and condensing temperature along the heat transfer surface.

b) Azeotropic Mixture. Vapor and liquid phases in equilibrium have identical (or close-to-identical) compositions under given conditions of composition and pressure.

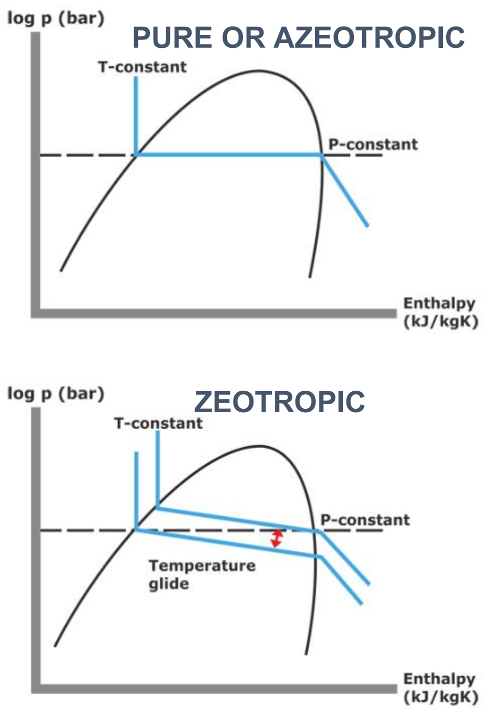

Fig. 18. Pure or azeotropic and zeotropic P-h diagram [21].

Pure Fluid: Pressure and temperature are constant under phase change, so one can define the other (Fig. 19).

During phase change:

P→T and T→P

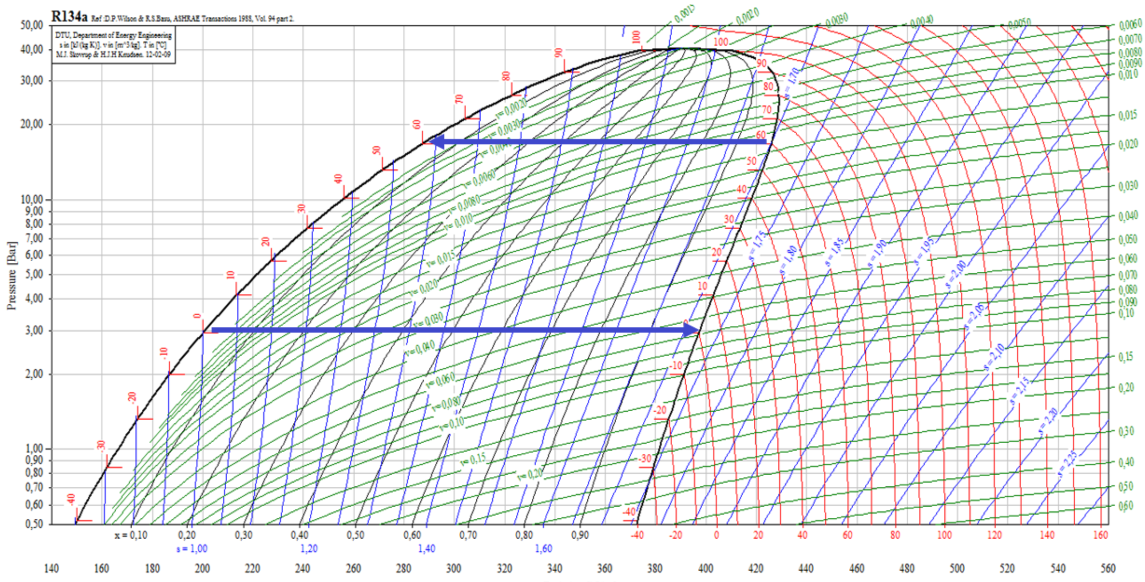

Fig. 19. Pure Fluid P-h diagram properties [22].

Azeotropic mixture: The composition and the zeotrope temperature do not appreciably change as the azeotrope evaporates or condenses under constant pressure (Fig. 20).

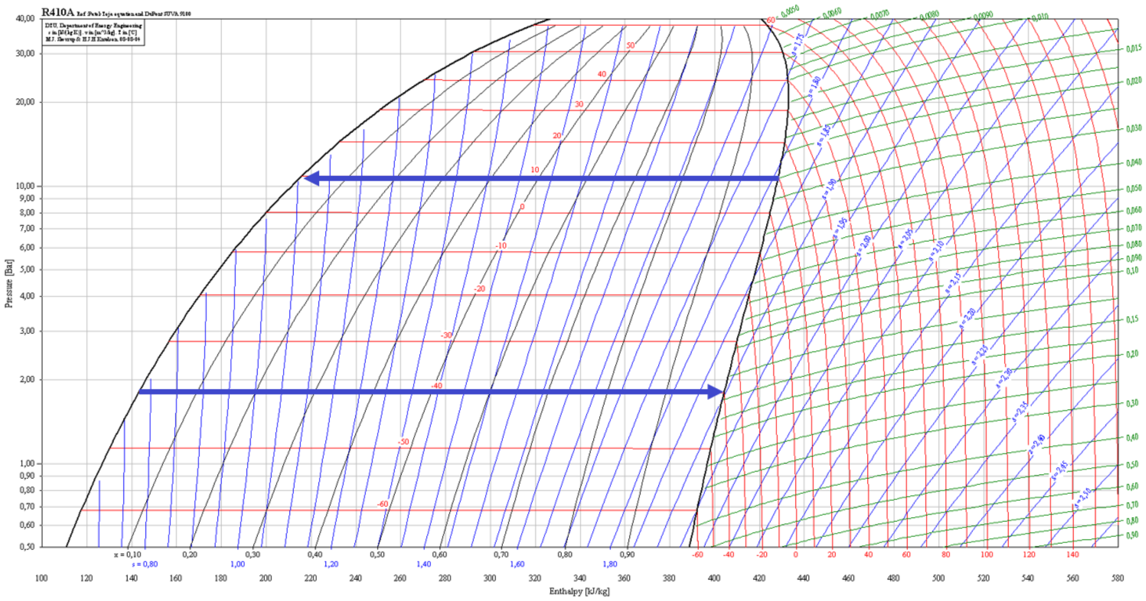

Fig. 20. Azeotropic mixture P-h diagram properties [22].

Zeotropic mixture: Under constant pressure, during the liquid-vapor phase change, the temperature and composition of a zoetrope vary. P-T needs another parameter to be defined (Fig. 21).

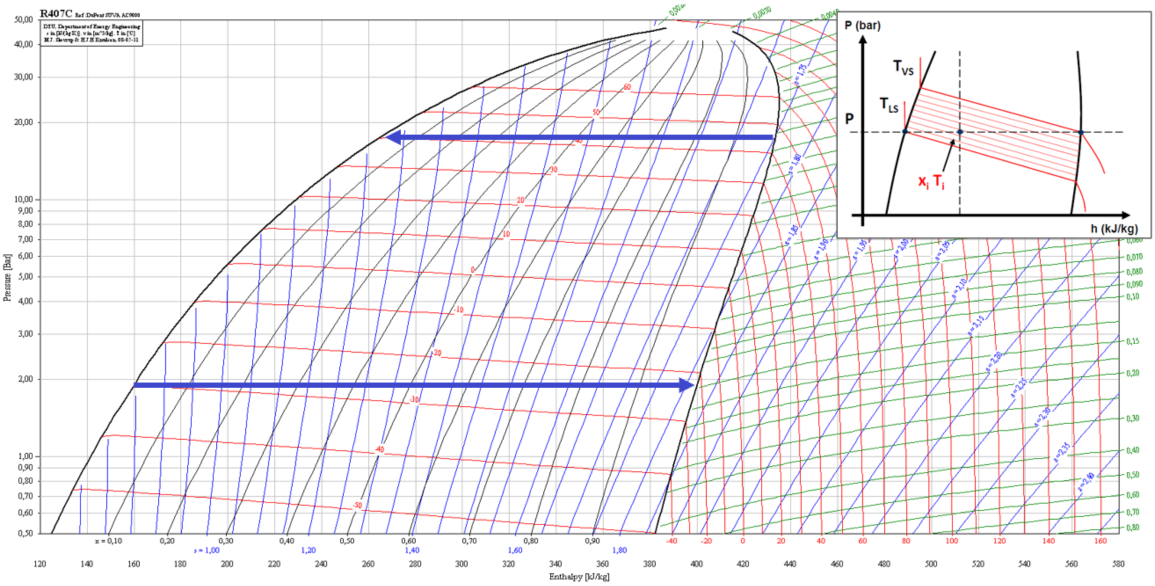

Fig. 21. Zeotropic mixture P-h diagram properties [22].

Zeotropic mixtures require special measures for properties determination, parameters calculation, manipulation, etc. A zeotropic mixture with a lower temperature glide (below 0,5 to 1 K, depending on the source) is called near-azeotropic and can be considered an azeotropic mixture in practical terms.

3.2. History and evolution

The first generation of refrigerants emerged in the 19th century, long before the advent of synthetic chemistry. During this period, natural substances were commonly used for refrigeration due to their availability and favourable thermodynamic properties. These included ammonia (NH_3), carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrocarbons such as propane and butane, as well as water (H_2O) and air. While effective in terms of performance, these refrigerants presented significant safety and technical challenges: toxicity in the case of SO_2 and NH_3, flammability for hydrocarbons like propane, and the requirement for high operating pressures with CO_2. Despite these limitations, this generation laid the foundation for modern refrigeration technologies [19].

Second Generation (1930s–1990s): The Rise of Synthetic Refrigerants

Driven by the need for safer and more efficient refrigeration systems, the second generation saw the introduction of synthetic refrigerants primarily chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Common examples included CFC-12 (dichlorodifluoromethane) and HCFC-22 (chlorodifluoromethane). These substances quickly gained popularity due to their advantageous properties: they were non-flammable, non-toxic, chemically stable, and provided efficient heat transfer. However, by the 1970s and 1980s, scientific research revealed that CFCs and HCFCs were major contributors to stratospheric ozone layer depletion. This discovery triggered widespread environmental concern and led to international regulatory action, most notably the Montreal Protocol signed in 1987, which aimed to phase out ozone-depleting substances and initiated the transition toward more environmentally friendly alternatives [19].

Third Generation (1990s–Present): Environmental Awareness and HFCs

In response to the phase-out of ozone-depleting substances, the third generation of refrigerants introduced hydrofluorocarbons (HFCs) as alternatives. Common examples include R-134a (tetrafluoroethane), R-404A, and R-410A. These refrigerants do not contain chlorine, making them harmless to the ozone layer. However, they possess high global warming potentials (GWPs), contributing significantly to climate change. For instance, R-134a has a GWP of 1,430, meaning it traps

1,430 times more heat than CO_2 over a 100-year period. As environmental awareness grew, regulatory efforts intensified—most notably through the Kigali Amendment to the Montreal Protocol (2016), which established a global roadmap for the phasedown of HFCs to mitigate their climate impact. This marked a pivotal shift toward sustainability in the refrigeration sector [19].

Fourth Generation (Present–Future): Low-GWP and Natural Alternatives

The fourth generation of refrigerants is defined by a strong commitment to environmental sustainability, with a focus on substances that have zero ozone depletion potential (ODP) and low or ultra-low global warming potential (GWP). A key development in this phase is the emergence of hydrofluoroolefins (HFOs), such as R-1234yf and R-1234ze, which offer GWPs below 1. While HFOs are less chemically stable than their predecessors, they are generally safe when managed correctly. In parallel, there has been a revival of natural refrigerants like ammonia (NH_3), carbon dioxide (CO_2), and hydrocarbons, which are environmentally benign but require careful handling and advanced system design due to their toxicity, flammability, or high operating pressures. Additionally, blended refrigerants—combinations of HFCs and HFOs—have been developed to strike a balance between performance, safety, and environmental impact. This generation reflects the refrigeration industry's shift toward long-term climate responsibility and compliance with evolving global regulations [19].

The Future of Refrigerants

The future of refrigerants is being shaped by three major trends. First, environmental regulations are accelerating the phaseout of high-GWP refrigerants, driven by frameworks such as the European F-Gas regulations and the U.S. AIM Act. Second, technological innovation is focused on improving system efficiency, reducing refrigerant charge and leakage, and advancing smart refrigeration systems that optimize performance and monitoring. Third, the principles of sustainability and the circular economy are gaining prominence, emphasizing the recovery, recycling, and reuse of refrigerants, along with life cycle assessments and eco-design of cooling equipment. In parallel, research efforts are exploring entirely new classes of refrigerants, such as ionic liquids and magnetic fluids, and investigating alternative refrigeration cycles including absorption, thermoelectric, and magnetic cooling. These advances aim to reduce environmental impact while meeting growing global cooling demands. Overall, the evolution of refrigerants reflects a dynamic balance between technological progress and environmental responsibility. From early natural substances to synthetic compounds and now back to low-impact, sustainable solutions, the field continues to evolve in response to climate challenges. Understanding these transitions is critical for the next generation of engineers and scientists working to develop resilient, climate-friendly cooling technologies.

3.3. Designation and properties

Designation

The nomenclature of refrigerants, particularly for halogenated refrigerants (CFCs, HCFCs, HFCs, and HFOs), follows a standardized system developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). This system uses the prefix "R-" followed by a number that encodes the molecular structure of the refrigerant.

General Format: R-xyz

Where:

x = Number of double bonds (for unsaturated compounds like HFOs)
y = Number of carbon atoms minus 1
z = Number of hydrogen atoms plus 1
w = Number of fluorine atoms

The number of chlorine atoms is determined by the remaining valence requirements. This system works for fully halogenated hydrocarbons and follows this logic for R-xyz:

R-(m−1)(n+1)p

Where:

m = number of carbon atoms
n = number of hydrogen atoms
p = number of fluorine atoms

The rest of the valence is assumed to be filled by chlorine or bromine atoms (or none).

Examples

R-22 (HCFC-22)

Chemical formula: $CHClF_2$
Number of carbon atoms: 1 → (1 − 1) = 0
Number of hydrogen atoms: 1 → (1 + 1) = 2
Number of fluorine atoms: 2

→ Therefore: R-022 → simplified as R-22

R-134a (HFC-134a)

Chemical formula: CH_2FCF_3
Number of carbon atoms: 2 → (2 − 1) = 1
Number of hydrogen atoms: 2 → (2 + 1) = 3
Number of fluorine atoms: 4

→ Therefore: R-134

The "a" suffix denotes an isomer (a different structural arrangement of the same atoms).

R-1234yf (HFO-1234yf)

Unsaturated compound (double bond present)
The first digit "1" signifies one double bond
The rest follows the same carbon-hydrogen-fluorine rule
The "yf" indicates a specific isomer

Special Prefixes

CFC: Chlorofluorocarbon (no hydrogen)
HCFC: Hydrochlorofluorocarbon (contains hydrogen)
HFC: Hydrofluorocarbon (no chlorine)
HFO: Hydrofluoroolefin (contains double bonds)
R-600 series: Hydrocarbons (e.g., R-600a = isobutane)

Blends and Mixtures

Zeotropic blends: Labeled as R-4xx (e.g., R-404A)
Azeotropic blends: Labeled as R-5xx (e.g., R-507)
The suffix A, B, C indicates variations in composition

Properties: Overview

Suitable thermodynamic and transport properties

1. Critical point and boiling point temperatures appropriate for the application
2. High latent heat of vaporization
3. Low viscosity
4. High thermal conductivity
5. Non-flammable and non-toxic
6. Stable chemically and thermally, inert
7. Compatibility with materials, miscibility with lubricants

Other

1. Satisfactory oil solubility/miscibility
2. High dielectric strength of vapor
3. Low freezing point
4. Easy leak detection
5. Low cost

Properties: Thermodynamic and operational

Boiling point: The lowest temperature in phase change (evaporator inlet) should be above it to not operate below 1 atm (in case of leakage moisture enters into the installation)

Critical point: The higher the critical point, the lower the efficiency drop at higher ambient (condensation) conditions

Compression ratio: This parameter (Pdisc/Psuc) defines the operation of the compressor and, hence, the efficiencies. The lower, the better

Discharge pressure: Lower discharge pressure allows for lighter and cheaper components

Discharge temperature: Typically, refrigeration systems' discharge temperature should be below 105°C in regular operation and 120 °C peak.

To be a replacement should have a similar P-T relationship (Fig. 22)

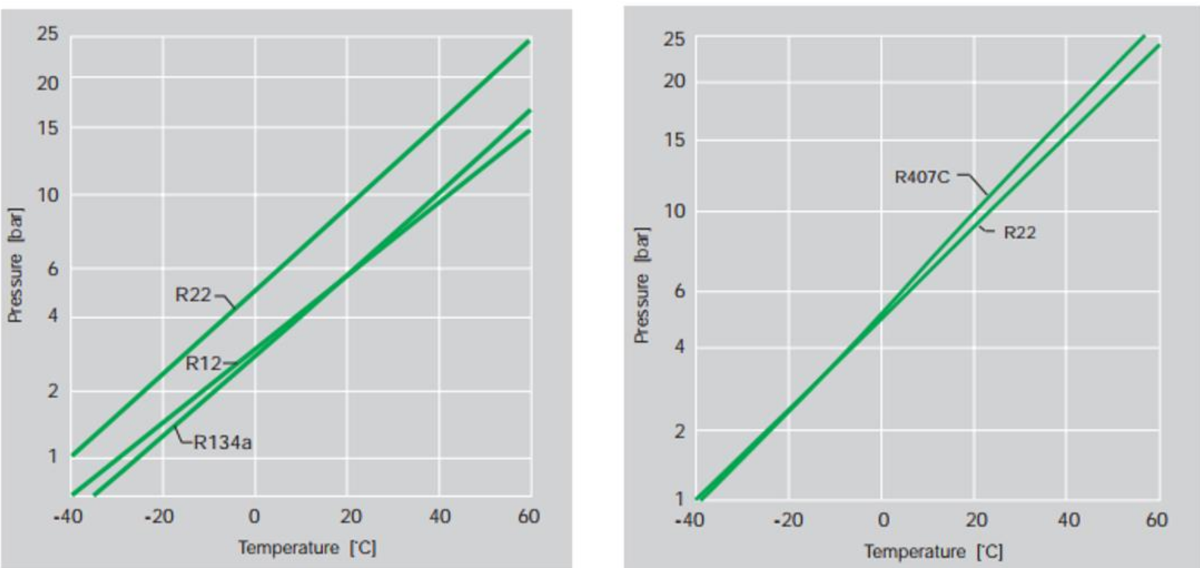

Fig. 22. Pressure and temperature comparison between refrigerants [23].

Properties: Performance

Latent heat of vaporization: Allows lower swept volume of the compressor to reach the same cooling capacity.

Isentropic index of compression: As small as possible so that the temperature rise during compression will be small

Liquid-specific heat: Small so that the degree of subcooling will be large, leading to a smaller amount of flash gas at the evaporator inlet

Vapor-specific heat: Large so that the degree of superheating will be small

Thermal conductivity: In both liquid as well as vapor phases, it should be high for higher heat transfer coefficients

Viscosity: Small in both liquid and vapor phases for smaller frictional pressure drops

Rule of thumb: the optimum value of molar vapor-specific heat lies in the range of 40 to 100 kJ/mol.K.

Proprerties: Technical

Chemical stability: basic property, so all common refrigerants must present this characteristic.

Cost/availability: This characteristic dramatically influences the decision of the refrigerants, now more than ever.

Compatibility:

1. With metals, for the components and the pipes (ammonia and carbon dioxide have problems)
2. With lubricant oil, there are relevant differences between generations and types of refrigerants
3. With elastomers and plastics, one of the requirements that must be checked before the decision in case of a new refrigerant

Properties: Safety

Nomenclature is defined by ASHRAE 34 (International), then EN378 (Europe), then depends on the country (Table 4).

The classification influences the maximum refrigerant amount of charge for each refrigeration application.

	Lower Toxicity	**Higher Toxicity**
Higher Flammability	A3	**B3**
Lower Flammability	A2	**B2**
	A2L	**B2L**
No Flame propagation	A1	**B1**

Table 4. Safety nomenclature [24].

A: Toxicity has not been identified at concentrations ≤ 400 ppm by vol.

3.4. Environmental metrics summary (Fig. 23)

1. ODP: Measures the stratospheric ozone decomposition compared to R-11.
2. GWP: Measures the relative heat-trapping impact of a refrigerant compared to CO_2 over a specific time.
3. TEWI: Evaluates the combined warming effect of refrigerant leaks and energy consumption but does not include manufacturing.
4. LCCP: Accounts for the total climate impact over a refrigerant's full life cycle, including production, use, and disposal.
5. LCA: Broadly assesses environmental impacts across multiple categories throughout a product's life.

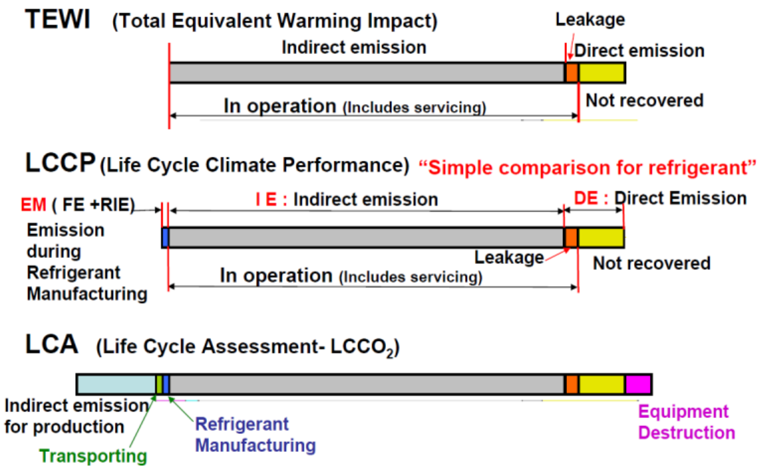

Fig. 23. Graphical representation for CO_2 equivalent emissions [25].

GWP

Global Warming Potential (GWP) measures the relative impact of a greenhouse gas in terms of its heat-trapping ability over a specific time period, typically 20, 100, or 500 years (example Fig. 24), compared to carbon dioxide (CO_2), which has a GWP of 1 by definition. GWP considers the amount of energy a gas absorbs, its atmospheric lifetime, and its concentration over time. The GWP of a substance over a time period t is given by the Eq. (4) [19]:

$$\mathrm{GWP_{gas,t}} = \frac{\int_0^t a_{gas} \cdot C_{gas}(t)dt}{\int_0^t a_{CO_2} \cdot C_{CO_2}(t)dt} \quad (4)$$

where:

a_{gas}: Radiative efficiency of the gas (how much heat it traps per unit mass).

$C_{\text{gas}(t)}$: Concentration of the gas in the atmosphere over time.tt: Time horizon (typically 20, 100, or 500 years).

a_{CO_2}: Radiative efficiency of CO_2.

$C_{CO_2}(t)$: Concentration of CO_2 over time.

GWP informs us how much a given mass of a refrigerant (or other greenhouse gases) contributes to global warming compared to the same mass of CO_2.

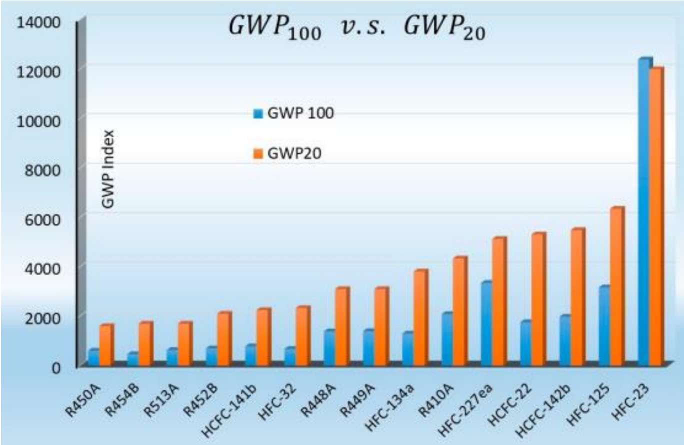

Fig. 24. GWP_{100} compared to GWP_{20} [26].

Total Equivalent Warming Impact (TEWI) (example Fig. 25) estimates the overall global warming impact of a refrigeration or air conditioning system during its use and disposal stages. TEWI considers both direct and indirect emissions. The TEWI formula is given by: TEWI = Direct Emissions + Indirect Emissions.

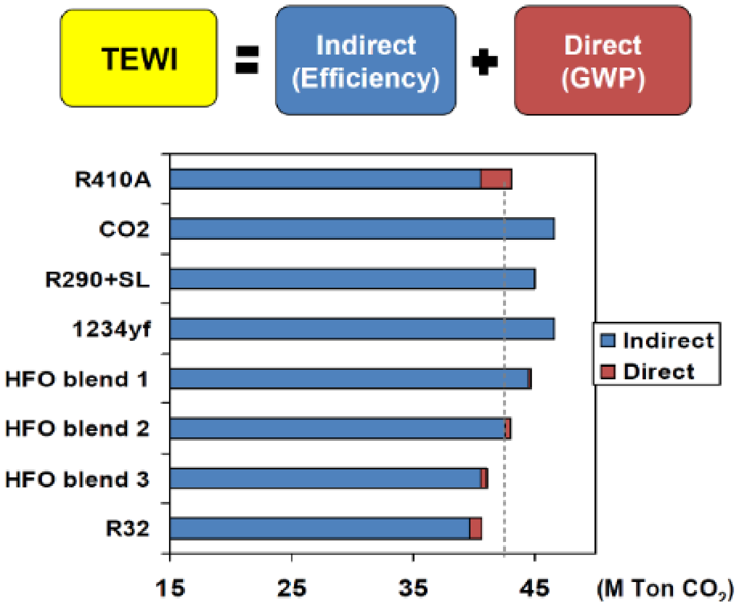

Fig. 25. TEWI comparative between refrigerants typically used in heat pumps [27].

TEWI [19]

1) Direct Emissions: Refrigerant accidental leakage and losses during the operation, maintenance, and end-of-life disposal phases. It's calculated as:

Direct Emissions = Leakage Rate × Charge ×GWP + End-of-Life Emissions × Charge × GWP

Leakage Rate: Annual leak percentage of the refrigerant.

Charge: Total refrigerant charge (mass of refrigerant in the system).

End-of-Life Emissions: Percentage of refrigerant lost or not recovered at disposal.

2) Indirect Emissions: CO_2 equivalent emissions resulting from the energy consumption of the system over its lifespan. It's calculated as:

Indirect Emissions = Annual Energy Use × Lifespan × Emission Factor

Annual Energy Use: The energy consumed by the system in one year.

Lifespan: Expected operating lifetime of the system.

Emission Factor: CO_2 emissions per unit of energy consumed, depending on the electricity generation mix.

LCCP

Life Cycle Climate Performance (LCCP) assesses the total climate impact of a refrigerant throughout its lifecycle, accounting for both direct and indirect emissions. Direct emissions occur when the refrigerant is released (through leaks or disposal), while indirect emissions come from the energy required to operate refrigerant equipment [19]. The general formula for LCCP is:

$LCCP = E_{direct} + E_{indirect} + E_{manufacturing} + E_{end\text{-}of\text{-}life}$

E_{direct}: Direct emissions from refrigerant leaks or releases during operation and servicing:

$E_{direct} = GWP \times \text{leaked amount}$

$E_{indirect}$: Indirect emissions from energy used by the system:

$E_{indirect} = \text{Total Energy Use} \times \text{Emission Factor of Energy Source}$

$E_{manufacturing}$: Emissions from refrigerant production and transport.

$E_{end\text{-}of\text{-}life}$: Emissions from disposal or recovery at the end of the system's life.

LCA

Life Cycle Assessment (LCA) is a systematic evaluation of the environmental impacts associated with all stages of a product's lifecycle, from raw material extraction, production, use, and disposal. Unlike LCCP, LCA covers various impact categories beyond climate change, such as resource depletion, acidification, and eutrophication [19].

The Life Cycle Impact of a refrigerant or system can be calculated with Eq. (5):

$$\mathrm{LCA_{total}} = \sum_{i=1}^{n} \mathrm{Inventory_i} \times \mathrm{Impact\ Factor_i} \qquad (5)$$

$Inventory_i$: Quantity of each environmental factor (e.g., CO_2 emissions, water usage, energy consumption) at each stage of the life cycle.

Impact Factor: Coefficient representing the environmental impact per unit of each factor.

LCA results are typically presented across multiple categories (Fig. 26), such as:

Global warming potential (GWP) (kg CO_2-equivalent).

Ozone depletion potential (ODP) (kg CFC-11-equivalent).

Acidification potential (AP), which measures the potential for acid rain (kg SO_2-equivalent).

Eutrophication potential (EP), which assesses nutrient enrichment leading to water pollution (kg PO_4^{3-}-equivalent).

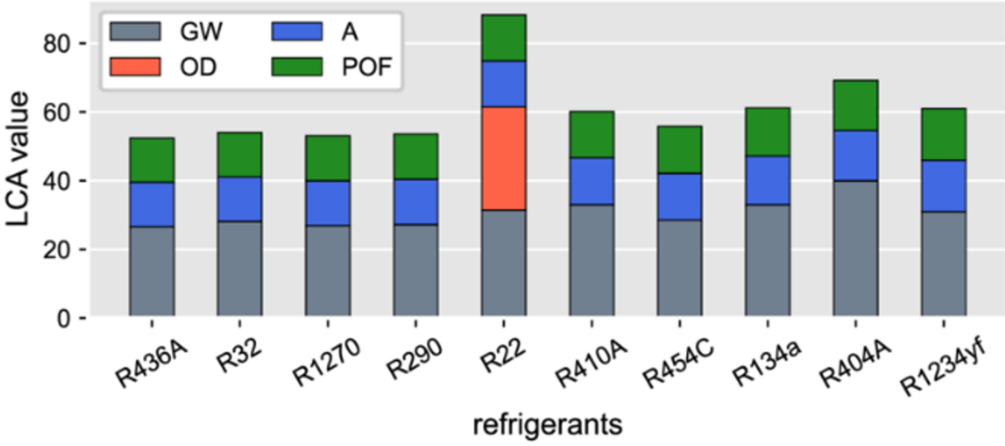

Fig. 26. LCA values for the investigated refrigerants: GW: global warming, A: acidification, OD: ozone depletion, POF: photochemical ozone formation [28].

HFCs regulations - Worldwide

2016 - Kigali's amendment to the Montreal Protocol: phasing down HFCs could reduce global warming by 0.5 °C by 2100 (Fig. 27) [29].

The Montreal Protocol commits countries, including EU members, to reduce HFC consumption. The EU implements this commitment through internal regulations, such as Regulation 517/2014. Developed countries will financially and technically help the developing countries [30].

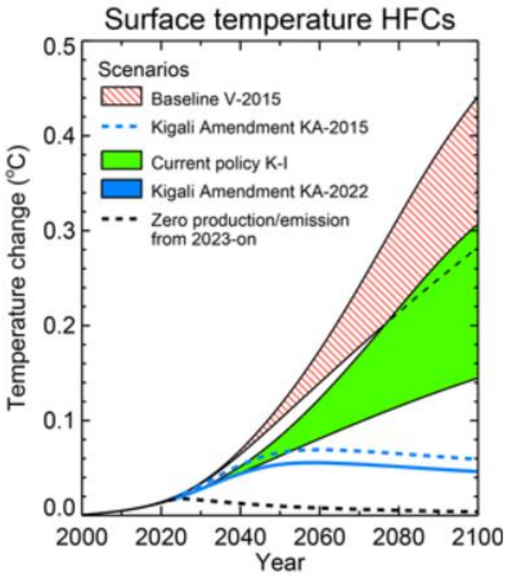

Fig. 27. Temperature change reducing HFCs use [31].

HFCs regulations - Europe

Regulation (EU) No. 517/2014 (F-Gas Regulation) [32]

This regulation is the main framework regulating the use and reduction of fluorinated gases in the EU, replacing Regulation (EC) No. 842/2006. Its main objectives include:

1. Phase-down: It establishes a progressive reduction in HFCs available on the European market. By 2030, a 79% reduction in HFCs compared to 2015 levels is expected.

2. Usage restrictions: It limits the use of HFCs in new equipment, including refrigeration and air conditioning systems, and prohibits their use in certain applications where alternatives are available.
3. Leak maintenance and control: It requires operators to perform regular leak checks, especially in systems with high levels of fluorinated gases.
4. Recovery requirements: It mandates the recovery of gases at the end of the equipment's life.

Regulation (EU) No. 2024/573 (F-Gas Regulation) [33]

Improved, increased and extended previous measures, including:

1. Quota system for HFCs, beyond 2030 and to be phased out by 2050.
2. Restrictions on the use and disposal of F-gas.
3. Sets stricter rules to prevent emissions.
4. Facilitates more automation of control to monitor F-gas trade.
5. Equipment labelling.

Current refrigerants

Currently, two options are considered:

1. Synthetic refrigerants, including HFO and mixtures of HFC with HFCs
2. Natural refrigerants

They are significantly different, so the selected refrigerant must consider several requirements.

HFOs

Advantages of HFOs

1. Low GWP: HFOs, like R-1234yf and R-1234ze, have a much lower GWP (less than 1), making them a more climate-friendly option compared to HFCs.
2. Thermal and chemical stability: HFOs are stable at typical refrigeration system operating temperatures and pressures but break down more quickly in the atmosphere, reducing their long-term persistence.
3. Low toxicity: Many HFOs have low toxicity and do not contain chlorine, making them safer for the ozone layer in case of leakage.
4. Lower flammability: Compared to hydrocarbons, their flammability is slight.
5. Lower pressures: Compared to CO_2, the operating pressure is reduced.
6. Easier combination with HFCs: Resulting in drop-in (direct) replacements of HFCs for servicing.
7. HFCs/HFOs Mixtures.

Required characteristics: HFCs often provide better efficiency, heat transfer, and lower flammability, which are critical in many refrigeration applications. HFOs, on the other hand, offer lower GWP but may have slightly higher flammability or lower efficiency compared to HFCs.

Environmental: The primary reason for developing HFC/HFO mixtures is to reduce the GWP while maintaining the thermodynamic efficiency and operational characteristics of traditional refrigerants. The GWP of the mixture is often calculated to ensure it meets regulatory standards.

Flammability: This can be mitigated by adjusting the mixture ratio or by using flame-retardant components.

Efficiency and Performance: Achieving a blend that has similar or better efficiency and cooling performance than the HFC it replaces is challenging.

Thermodynamic properties: The refrigerant must have similar or better thermal performance (exm., heat capacity, pressure, enthalpy changes) than the refrigerants it is replacing.

Lubricant compatibility: The mixture should be compatible with the lubricants used in existing systems to ensure long-term performance and system reliability.

Concerns About HFOs

1. TFA
2. PFAS
3. European Regulation that prohibits F-gases
4. Green washing
5. Pressure from governments
6. Evolution of cost and quota allowance
7. Natural vs. Synthetic

TFA

Trifluoroacetic acid (TFA), an organofluorine compound with the formula CF_3CO_2H, is a notable degradation product formed in the atmosphere from the breakdown of certain refrigerants. According to a report by the German Federal Environment Agency, approximately 5% of TFA detected in the environment originates from human activities, including manufacturing, agriculture, wastewater treatment, and refrigerant emissions. Among refrigerants, R-1234yf completely degrades into TFA (100%), while R-134a contributes between 7% and 20%. Other refrigerants show lower TFA production: R-1234ze(E) generates less than 10%, R-1336mzz(Z) less than 20%, and R-1233zd(E) only about 2%. Understanding TFA formation is important due to its environmental persistence and potential ecological impacts associated with the increasing use of fluorinated refrigerants [34].

PFAS

Perfluorinated and polyfluorinated alkyl substances (PFAS): PFAS are a large group of over 4,700 synthetic "forever chemicals" known for their persistence in the environment and potential harm to human health. This family includes various fluorinated gases used in HVAC&R applications, such as certain HFCs (e.g., R-134a, R-125, R-143a, and R-152a) and HFOs (e.g., R-1234yf, R-1234ze(E), and R-1233zd(E)). Notably, trifluoroacetic acid (TFA), a degradation product of some refrigerants, is also classified as a PFAS due to its CF_3- and CF_2- chemical groups. Reflecting growing concerns, the state of Maine in the USA will become the first government to ban the sale of products containing PFAS starting January 1, 2030. For more detailed information, refer to the report by the Norwegian Environment Agency [35].

Natural refrigerants

Natural refrigerants are increasingly regarded as safer and more sustainable alternatives to HFOs. Unlike many synthetic refrigerants, natural refrigerants do not produce harmful by-products such as trifluoroacetic acid (TFA) or hydrogen fluoride (HF) during atmospheric breakdown. They also have zero ozone depletion potential (ODP) and significantly lower global warming potentials (GWP). The most commonly used natural refrigerants include carbon dioxide (CO_2), ammonia (NH_3), and hydrocarbons.

Carbon Dioxide (CO_2):

Carbon dioxide (CO_2) has a global warming potential (GWP) of 1, making it an excellent environmentally friendly refrigerant with minimal climate impact. It is non-toxic and non-flammable, ensuring safety under normal operating conditions. CO_2 systems perform efficiently, especially in low-temperature applications, but they require higher operating pressures, which can increase equipment costs and complexity. One key challenge is that CO_2's efficiency declines at higher ambient temperatures, limiting its suitability for such conditions unless significant system modifications are implemented.

Ammonia (NH_3):

Ammonia is a natural refrigerant with a global warming potential (GWP) of zero, meaning it does not contribute to global warming. It offers high thermodynamic efficiency, making it especially suitable for large-scale industrial refrigeration systems. However, ammonia's main drawback is its toxicity, which poses significant safety concerns in case of leaks, despite it being non-flammable. This necessitates careful handling, robust safety protocols, and advanced leak detection systems. Despite these challenges, ammonia is widely recognized as a sustainable refrigerant and remains extensively used in industrial applications.

Hydrocarbons (HCs) (ex, propane (R-290), butane (R-600a)):

Hydrocarbons have a very low global warming potential (GWP) of around 3, making them a cost-effective and environmentally friendly alternative to HFCs and HFOs. Their main drawback is flammability, which requires careful system design, stringent safety measures, and effective leak detection to mitigate risks. Hydrocarbons are well-suited for low to medium-temperature applications, such as household refrigeration and small commercial systems. They also offer high thermodynamic efficiency, making them a strong alternative for many residential and small-scale cooling applications.

Natural Refrigerants as Alternatives

Advantages

1. No Harmful By-products: Natural refrigerants do not decompose into harmful compounds like TFAs or HF.
2. Sustainability: They have very low to zero GWP and zero ODP.
3. Efficiency: Especially ammonia and CO_2, offer high thermodynamic performance and efficiency.
4. Availability and Cost-effectiveness: They are abundant and relatively inexpensive, making them cost-effective alternatives to synthetic refrigerants.

Challenges

1. System Modifications: Switching to natural refrigerants may require modifications to existing systems (new vapor compression system)

2. Safety Considerations: The flammability of hydrocarbons and the toxicity of ammonia require careful handling and safety measures. This can increase system costs and complexity.

3. Infrastructure and Training: To handle natural refrigerants safely, which may pose challenges for widespread adoption.

3.5. Future of the refrigerants

Summary

As explained in the previous section, the future trend in refrigerants is expected to focus on sustainability and reducing environmental impact.

1. Low Global Warming Potential (GWP) Refrigerants: The transition to refrigerants with low or near-zero GWP and without generating harmful By-products, such as natural refrigerants (CO_2, ammonia, hydrocarbons), will be a major trend due to stricter regulations.

2. A2L and A3 Refrigerants: There will be an increased use of mildly flammable (A2L) and more flammable (A3) refrigerants like R-32, R-290, and R-1234ze(E), due to their lower GWP and efficiency, although handling safety will be a challenge.
3. Energy Efficiency: Refrigerants that improve energy efficiency in cooling systems will be prioritized, as energy consumption regulations become stricter to reduce overall carbon footprints.
4. Synthetic and Blended Refrigerants: Continued development of new blends that balance GWP reduction, energy efficiency, and safety, while meeting industry needs in various applications.
5. Regulations and Global Agreements: Global agreements, such as the Kigali Amendment to the Montreal Protocol, will drive the phase-out of high-GWP substances like HFCs, prompting a shift to alternative refrigerants.

Final considerations for machines connected to DHC

What refrigerant should be charged in my cooling/heating machine? You must consider

1. Temperature for producing heating or cooling (DHN, DCN, industrial process, hot water, etc.)
2. Temperature of dissipation/absorption of heating (ambient, geothermal, DHN, DCN, waste heat, etc.)
3. Size of the machine (cooling/heating capacity)
4. Location of the machine
5. Current local regulations
6. Be aware of future regulations or quota
7. Cost of machine and refrigerant
8. Safety regulations
9. Always consult experts or local distributors

3.6. Conclusions

The history of refrigerants provides essential insights into current standards and requirements. Since the commercialization of refrigeration and heat pump technologies, significant efforts have focused on identifying the most sustainable refrigerants. While an optimum refrigerant exists for each application, no perfect refrigerant meets all criteria simultaneously. Thus, a trade-off is always necessary, balancing thermodynamic performance, technical feasibility, safety, economic factors, and environmental impact. Alternative refrigerants for existing systems (drop-in or retrofit) differ from those intended for new installations, which may have distinct safety or operational demands. Looking ahead, the trend favors natural refrigerants to address environmental concerns comprehensively. Additionally, technologies like District Heating Networks (DHN) and District Cooling Networks (DCN) can facilitate heat transfer and enable the use of refrigerants with stricter safety requirements by allowing the design of large, isolated vapor compression systems.

4. Economic and environmental aspects

4.1. Introduction

District Cooling Networks (DCNs) offer an alternative to (multi-)split air conditioners, reversible heat pumps, chillers, and variable refrigerant flow (VRF) systems. Unlike this decentralized system where each apartment, floor, or comfort zone in a building has its own unit DCNs centralize cooling production for an entire district or group of buildings.

This centralized approach enhances energy efficiency, reduces equipment costs, and improves sustainability, all while maintaining the same level of indoor comfort.

However, implementing a DCN requires substantial investment in distribution infrastructure, particularly in the construction of cooling pipelines. The economic viability of such systems depends on several key factors, including demand density, regulatory conditions, and political support.

DCNs share many of the advantages and limitations of district heating networks. Nevertheless, cooling systems generally operate with more uniform temperature requirements. On the other hand, sources of waste cooling are scarce, except when using heat pumps capable of simultaneous heating and cooling.

This chapter explores the main factors influencing the economic feasibility and sustainability of DCNs, including legal, regulatory, and political considerations.

4.2. Density demand

Cooling demand density in DCN

Cooling demand density refers to the thermal energy required for cooling per unit area in a specific zone. It is a critical parameter for assessing the technical and economic feasibility of a district cooling network (DCN) system. The higher the cooling demand density, the most financially feasible the DCN will be compared to other individual or distributed cooling systems.

The cooling demand density will be higher in highly populated areas (cities versus single family house suburb district) and in warmer climates, or areas with high cooling consumers such as data centers.

Several factors must be assessed in the study of cooling demand density:

1. Feasibility Assessment: Areas with high cooling demand density are more suitable for DCN systems due to lower distribution costs per unit of delivered energy.
2. Network Optimization: It contributes in properly sizing system components such as pipelines, heat exchange stations, and cooling plants.
3. Sustainability: High-density areas enable efficient energy distribution, reducing environmental impact and promoting sustainability.

Cooling users

Cooling demand typically comes from

1. Urban areas: For thermal comfort, used in AC systems, for fan-coils, radiating ceiling, or large systems as a substitution of chillers. Includes domestic applications but also offices, shops, public buildings, etc. Similar temperature range.
2. Industrial processes: In this case, the temperature range is wide as it includes every process that needs to cool down the process manufactured or manipulated.
3. Data centers: They are present in cities and industrial areas. Every time more representative.

Cooling demand factors

Factors Influencing Cooling Demand Density:

1. Urban Characteristics: High-rise buildings and densely populated urban areas often exhibit higher cooling demand density.
2. Climate: Hotter climates increase cooling demand, making DCN systems more attractive.
3. Building Usage: Commercial and industrial zones typically require more cooling than residential areas.

Analysis of density demand

A detailed analysis of cooling demand is fundamental for designing an efficient and cost-effective district cooling network (DCN) system. The following steps must be considered:

1. Data Collection and Preprocessing

Building Data: Collect detailed data on building types, usage (residential, commercial, industrial), sizes, and occupancy rates and include historical cooling demand data (if available).
Climate Data: Use weather datasets to account for local temperature, humidity, and solar radiation, which impact cooling requirements.
Energy Consumption Patterns: Analyze energy profiles to understand peak and off-peak cooling demand.

2. Cooling Load Estimation

Dynamic Simulation: Use energy simulation tools (e.g., TRNSYS, EnergyPlus) to calculate hourly cooling loads for each building based on envelope properties, HVAC systems, and internal loads.
Peak Load Identification: Identify peak cooling loads, as they influence the sizing of plants and distribution networks.

3. Spatial Demand Mapping

Geographical Information Systems (GIS): Map cooling demand spatially to visualize high-demand zones and assess the feasibility of network layouts. Overlay data on infrastructure availability (roads, utilities, etc.).
Zoning: Divide the service area into zones based on demand density and prioritize zones with high potential.

4. Demand Profiles and Load Diversity

Temporal Analysis: Develop hourly, daily, and seasonal cooling demand profiles to account for fluctuations. Use diversity factors to account for the non-coincidence of peak demands across buildings.
Simultaneous Load Factors: Evaluate the simultaneous operation of buildings to reduce plant capacity requirements.

5. Demand Growth Projections

Urban Development Trends: Incorporate future growth plans for residential, commercial, and industrial areas.
Energy Efficiency Improvements: Account for evolving building codes and retrofitting efforts that might reduce cooling loads.

6. Feasibility Analysis

Threshold Density: Ensure the cooling demand density exceeds thresholds (e.g., 30-50 MWh/ha/year) for economic viability.
Cost-Benefit Analysis: Assess the trade-offs between infrastructure investments and operational costs against centralized and individual cooling systems.

7. System Integration and Optimization

Source-Side Analysis: Evaluate the potential for integrating renewable sources, waste heat-driven absorption chillers, or combined heat and power (CHP) systems for cooling.
Network Losses: Analyze and minimize thermal and hydraulic losses in the distribution system.

Flexibility: Design systems with scalability and modularity to adapt to varying future demands.

4.3. Viability of district cooling compared to other technologies

General characteristics

District cooling features two significant differences when compared to distributed systems.

1. First, the network of pipes that circulate chilled water from the central plant to buildings is an additional cost.
2. Second, district cooling consumes water. The amount of water consumed is relatively small because of closed- loop operation.

By offsetting network costs, district cooling offers three main benefits:

1. Low energy requirement.
2. Efficient capacity use because of load diversity and flexibility in capacity design and installation.
3. Peak-period saving potential. DCN can store up to 30 % of potential output by holding chilled water in tanks.

District cooling network (DCN) systems present distinct economic advantages and challenges compared to conventional cooling solutions (table 5).

1. Capital Investment	
DCN	**CONVENTIONAL**
High Initial Costs: DCN systems require significant upfront investment for centralized plants, pipeline networks, and connection infrastructure. Economies of scale can justify these costs in areas with high cooling demand density, as the fixed costs are distributed over a larger user base.	Standalone air conditioning or rooftop chillers have lower initial costs since each unit is independently installed and operated. However, these systems duplicate equipment across buildings, leading to inefficiencies in capital deployment.
2. Operational costs	
Centralized operations lead to lower energy costs due to the use of high-efficiency chillers, optimized load sharing, and the ability to use off-peak electricity for thermal storage. Maintenance costs are also lower per unit of cooling because a single system serves multiple users.	Decentralized systems often have higher energy consumption due to smaller, less efficient chillers and lack of load diversity. Maintenance is costlier as each unit requires individual servicing.
3. Cost-Effectiveness Over Time	
DCN	**CONVENTIONAL**
Long-term cost savings can outweigh the initial investment through reduced energy bills, lower maintenance expenses, and economies of scale. These systems are especially cost-effective in	While cheaper upfront, the total cost of ownership increases over time due to higher operational and maintenance expenses.

regions with high cooling demand and stable energy prices.	
4. Revenue Potential	
DCN providers can generate stable revenue streams through long-term contracts with customers, ensuring predictable cash flows. Selling excess cooling capacity or integrating with renewable energy systems can create additional revenue opportunities.	No centralized revenue model exists, as individual systems do not generate income beyond their operation.
5. Risk and Financial Flexibility	
DCN	**CONVENTIONAL**
The financial risk is higher during the initial phase due to large investments and dependence on demand density. Once operational, DC systems benefit from predictable cash flows and lower market volatility.	Lower initial financial risk but more exposure to fluctuating energy prices and maintenance costs over time.
6. External Economic Benefits	
Reduces urban electricity peak loads, potentially lowering energy tariffs and infrastructure upgrade costs for utilities. Creates opportunities for job creation during construction and operation phases.	Limited impact on broader economic factors, with benefits confined to equipment manufacturers and service providers.

Table 5. DCN economic advantages and challenges compared to conventional cooling technologies.

Summary

1. Capital Costs: DCN systems have high upfront costs, but economies of scale make them cost-effective in dense areas, unlike cheaper standalone systems with duplicated equipment.
2. Operational Costs: DCN systems are more energy-efficient and cheaper to maintain due to centralized operations, while conventional systems have higher long-term costs.
3. Long-Term Savings: DCN offers significant cost savings over time, whereas standalone systems incur higher total ownership costs.
4. Revenue: DCN creates stable revenue streams via contracts, unlike conventional systems.
5. Risk: DCN has higher initial financial risk but stable long-term benefits; conventional systems have lower startup risks but volatile operating costs.
6. External Benefits: DCN reduces urban peak loads and supports local economies, whereas standalone systems have limited broader impact.

Tariff regulation by the government

Like most utilities, district cooling requires a proper regulatory framework that protects developers, providers, consumers, and the broader economy.

Singapore has designated specific service areas for the award of district cooling concessions and subjects tariffs to a defined return on assets.

Governments in Denmark, the Netherlands, Norway, and Poland have encouraged the adoption of district heating and employ methods such as price regulation, mandated zones of application, financial support, and state ownership of heat circulation networks.

Governments should establish a consistent tariff framework for district cooling. That means defining the allocation model of up-front, recurrent, and consumption charges to property developers, individual property owners, and tenants. Governments must enforce the consistent use of such charging models across projects. These models must protect individual owners and tenants from arbitrage on real estate prices.

The charging models should seek to align the charges paid by users with actual cooling consumption. In some cases, price regulation will be required to provide equitable tariffs to users, while granting returns to district cooling utilities commensurate with industry risks.

Study of Alajmi and Zedan (2020) in Kuwait (Fig. 28).

This study demonstrates significant cost and operational advantages of district cooling (DC) systems compared to traditional cooling methods. The total cost decreases substantially, from $22,669 million for rooftop units (RTU) and $20,829 million for variable refrigerant flow (VRF) systems down to $17,395 million for the DC system. Moreover, the RTU system requires 660,200 cooling units, the VRF system 220,800 units, whereas the DC system only needs 624 units. This drastic reduction affects several factors: it lowers the labor hours needed for service, maintenance, and operation; reduces the roof space required for cooling equipment in residential buildings; decreases the number of spare parts necessary; and significantly lowers the risk of refrigerant leakages due to fewer individual units in operation [36].

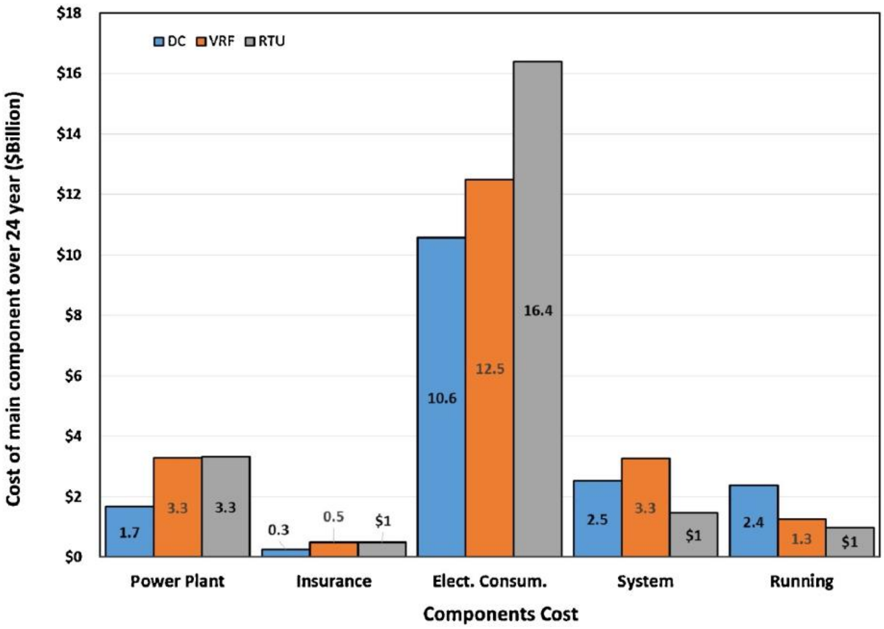

Fig. 28. Economic cost of different technologies in Alajmi and Zedan (2020) in Kuwait [36]

How can businesses, governments, and individuals contribute to DHC?

Governments play a pivotal role in setting the stage for progress by establishing ambitious climate targets and implementing supportive policies. By incentivizing the adoption of energy-efficient technologies like district cooling, they not only reduce greenhouse gas emissions but also stimulate economic growth in green industries.

These policies can encourage businesses to diversify their portfolios, investing in clean energy projects and innovative solutions. As businesses adapt and evolve, they contribute to a thriving green economy that not only creates jobs but also ensures long-term sustainability.

Individuals can make conscientious choices about energy consumption, from using energy-efficient appliances to reducing water waste. Moreover, individuals can engage in community initiatives and raise awareness about the importance of sustainability.

Ultimately, it is through collaborative effort, where governments, businesses, and individuals work in tandem, can achieve the transformative change necessary to address the pressing challenges of climate change and build a more sustainable world for generations to come.

The case of Gulf countries

In many cases, power prices are overly low, making district systems appear viable only at very high levels of cooling density. Governments should designate appropriate zones of sufficient density for district cooling and include the technology in urban planning.

Cooling accounts for 50 % of annual electricity consumption, a yearly fuel opportunity cost of roughly $20 billion. Properly employed, district cooling could provide around 30 percent of the forecast cooling needs by 2030. This would prevent the region from having to build 20 GW in new electricity-generating capacity, and save 200,000 barrels of oil equivalent per day in fuel [37].

4.4. Environmental impact of district cooling

Carbon Emissions

Reduced Greenhouse Gas (GHG) Emissions: High efficiency and integration with renewable energy sources (e.g., solar cooling, geothermal) or waste heat recovery can significantly reduce CO_2 emissions compared to conventional systems. Using low-emission electricity sources (e.g., hydropower or wind) amplifies these benefits.

Refrigerant Management: Centralized systems allow for the use of environmentally friendly refrigerants with low global warming potential (GWP) and better containment to reduce leakage.

Resource Optimization

1. Water Use: Centralized systems can optimize water consumption for cooling processes, especially in evaporative cooling systems. However, water-intensive systems may strain local water resources in arid regions unless alternative water sources (e.g., treated wastewater) are used.
2. Land Use: DCN systems reduce the need for mechanical equipment in individual buildings, freeing up rooftop and indoor space for other uses, such as solar panels or green roofs.

Study of Alajmi and Zedan (2020) in Kuwait.

High CO_2 emission factor makes even more important high energy efficiency (Figs. 29, 30).

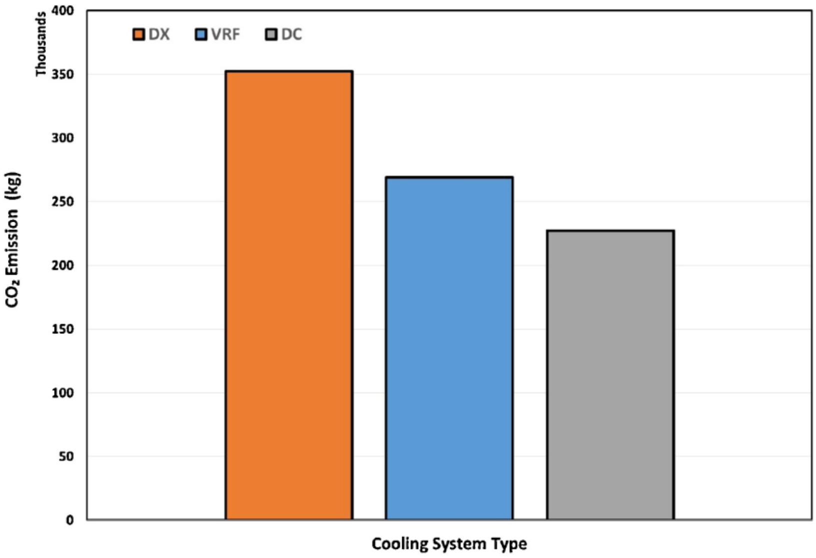

Fig. 29. CO_2 Emissions as function of cooling system type [37].

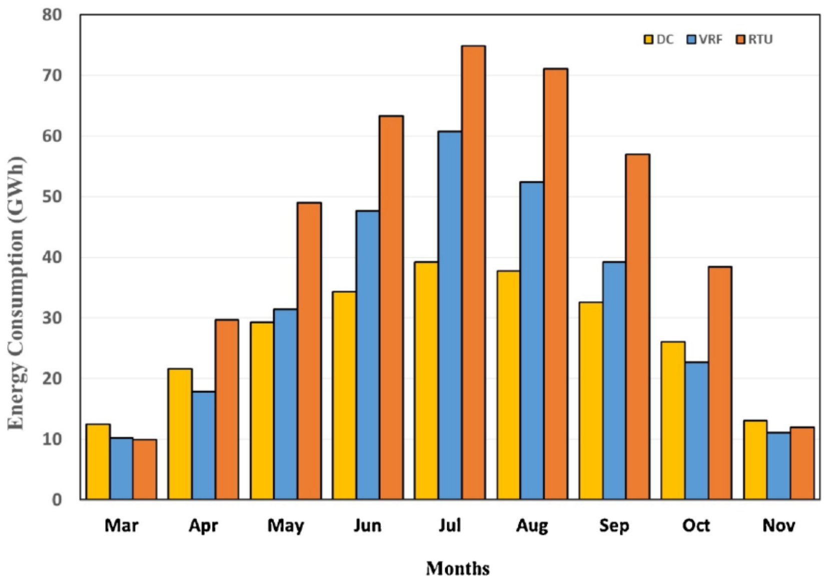

Fig. 30. Energy consumption for different cooling systems [37].

Urban Heat Island (UHI) Effect

1. Centralized Heat Rejection: By relocating heat rejection from multiple buildings to a centralized location, DCN systems reduce the localized heat generation that contributes to the UHI effect.
2. System Design: DCN systems can utilize water bodies or underground systems for heat dissipation, minimizing the environmental impact on urban temperatures.

Integration with Sustainable Technologies

1. Waste Heat Utilization: DCN systems can integrate with waste heat recovery from industrial processes or power plants, turning excess heat into a cooling resource, enhancing overall energy utilization.

2. Renewables and Low-Carbon Sources: DCN systems can incorporate renewable energy sources like solar thermal, geothermal, or low-temperature waste heat, reducing dependency on fossil fuels.

Waste Management and Lifecycle Impacts

1. Reduced Equipment Disposal: Centralized systems reduce the need for numerous small cooling units, cutting down on the production and disposal of equipment over time.
2. Infrastructure Longevity: DCN systems typically have longer lifespans compared to conventional cooling systems, leading to lower lifecycle environmental impacts.

Potential Drawbacks

1. Energy Source Dependence: If powered by fossil fuels, DCN systems may have higher emissions, especially in regions with carbon-intensive electricity grids.
2. Construction Impacts: Building a DCN network requires significant excavation and infrastructure development, which can temporarily disrupt ecosystems and urban environments.
3. Thermal Losses: Inefficient pipeline insulation or long-distance heat transfer can lead to energy losses, reducing overall system efficiency.

4.5. Optimization of district cooling technologies

Economic optimization for operational cost reduction

Economies of Scale:

In large-scale district cooling systems, the initial capital costs (e.g., plant construction, pipeline infrastructure) can be spread over multiple consumers. This reduces the per-unit capital cost compared to decentralized systems.

Careful design and standardization of equipment (e.g., chillers, pumps, and pipes) can lead to lower construction costs and faster implementation.

Modular Design:

Modular systems allow for phased implementation, reducing the initial investment burden. This flexibility enables operators to scale the system as demand grows, ensuring efficient use of capital.

Centralized Maintenance:

Centralized operations simplify maintenance and reduce costs, as the entire system can be serviced at once, avoiding the need for separate maintenance of individual units in decentralized systems.

Predictive maintenance using data analytics can further reduce downtime and unexpected repair costs, improving operational efficiency.

Energy Efficiency:

Optimizing energy use through the integration of high-efficiency chillers, variable-speed drives, and advanced control systems can lower the overall energy consumption of DCN systems.

Implementing central thermal energy storage systems allows for off-peak cooling, reducing costs associated with peak electricity demand, which is often more expensive.

Integration with Waste Heat:

Utilizing waste heat from industrial processes or power plants, creating an opportunity to recycle excess thermal energy with sorption systems for cooling to the DCN. Cooling from evaporator not used in heat pumps can be also injected in the DCN.

Renewable Energy Integration:

Incorporating renewable energy sources such as solar thermal, geothermal, or low-carbon electricity combined with sorption systems that provides cooling to the DCN further reduces operational costs by reducing dependency on fossil fuels and stabilizing energy prices.

Solar cooling, for example, can be directly integrated into the DCN network to reduce operational costs, especially in sunny regions. The technology stills needs to be more developed.

Use of Low-GWP Refrigerants:

Optimizing the choice of refrigerants to use low Global Warming Potential (GWP) fluids, such as natural refrigerants or low-GWP synthetic alternatives, reduces the environmental impact of the cooling system.

Advances in refrigerant management (e.g., leak detection systems and proper maintenance) ensure minimal refrigerant losses, reducing the system's overall carbon footprint.

Decarbonizing Energy Supply:

Connecting DCN systems to a decarbonized grid, powered by renewable sources like wind, solar, or hydroelectric power, significantly reduces the emissions associated with cooling.

When DCN systems are paired with renewable energy generation (e.g., solar PV for auxiliary power), the system's overall environmental performance improves.

Efficient Water Management:

DC systems that utilize water in cooling processes can optimize water consumption by implementing closed-loop systems or using non-potable water sources, such as treated wastewater.

Smart Grids and IoT:

Integration of smart grid technology and Internet of Things (IoT) sensors into the DC system enables real-time monitoring, dynamic load balancing, and predictive analytics, optimizing energy use and operational efficiency.

Intelligent algorithms can adjust system parameters based on demand, weather forecasts, and energy prices, reducing energy waste and optimizing performance.

Demand Response:

Incorporating demand response strategies, where cooling demand is shifted to off-peak hours, reduces the overall energy cost and alleviates grid stress. It also supports the integration of variable renewable energy sources.

Backup Systems:

Including redundancy in the system design (e.g., backup chillers or thermal storage) ensures that cooling demands are met even during peak demand or equipment failure, avoiding operational disruptions and reducing emergency repair costs.

Resilient systems minimize system downtime, which can otherwise result in high costs and environmental consequences due to the need for temporary solutions like emergency cooling.

4.6. Conclusions

To determine the suitability of a district cooling network (DCN), a thorough study of demand density is essential, taking into account buildings, industrial consumers, and data centers. This analysis goes beyond conventional HVAC and refrigeration projects by incorporating additional disciplines like Geographic Information Systems (GIS). When demand density is properly justified and risks minimized, a well-designed DCN can outperform traditional cooling systems, offering attractive payback periods. Unlike conventional cooling solutions, government involvement is crucial in developing and regulating DCNs, promoting them from economic, environmental, and urban planning perspectives. Beyond energy efficiency, DCNs contribute to reducing urban heat island effects, minimizing waste, and enabling integration with sustainable technologies. However, DCNs require more sophisticated control and optimization strategies to ensure profitability and energy efficiency, where advances in IoT and communication technologies play a vital role.

5. Realised projects case studies

This subject presents ten representative case studies, each with its conditions and particularities. The aim is to understand the following topics:

1. Successful district heating and cooling projects using chillers with different climates
2. Performance and energy savings using chillers in DCN
3. Desing, installing, and operating heat pumps in district heating and cooling projects
4. Best practices for integrating heat pumps into district cooling infrastructure, including considerations for system sizing, thermal storage, and control strategies

Case studies will include only district heating networks, and combined district heating and cooling networks.

More case studies can be found in literature.

5.1. DCN James cook university (Townsville, Australia) [38]

Overview (Fig. 31)

James Cook University in Townsville occupies a distributed campus of about 255 hectares with 28 academic buildings. The total air-conditioned floor area is 69,000 m². The campus expanded in stages, with each new building equipped with its own separate, stand-alone air conditioning plant. Many of the refrigeration chillers are aging some up to 35 years old and most are expected to require replacement within the next five years, at an estimated cost of $9 million. Currently, the total plant capacity across 29 locations on site is approximately 11.5 MW of cooling. The campus plans to expand further, adding 25,200 m² of air-conditioned floor area by 2010 and another 25,000 m² by 2015.

Design (Fig. 32)

Thermal Energy Storage (TES) takes advantage of times during the day or night when cooling demand exceeds the average by operating the central chilled water plant to re-chill return water (from 15°C) back to chilled water at 6°C. The Central Energy Plant (CEP) building contains three high-efficiency centrifugal chillers, each rated at 4.2 MW, with space planned for two additional chillers in the future. The plant also includes primary and secondary chilled water pumps equipped with variable speed drives, condenser water pumps also with variable speed drives, and four cooling towers rated at 5.1 MW each, with provisions for a fifth tower. Fans on the cooling towers are fitted with variable speed drives for improved efficiency.

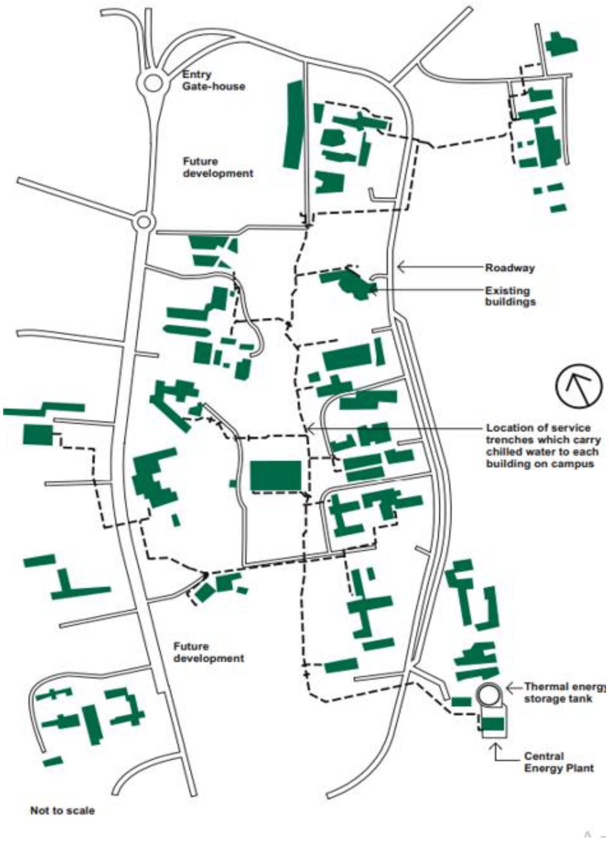

Fig. 31. Site plan James Cook University Townsville Campus [38].

The 12 mega liter TES tank contains specially engineered top and bottom water diffusers, which allow water to leave or enter the tank without turbulence.

The chiller and water storage facility is located in the southeast part of the campus at a sufficient elevation to ensure that the water level in the thermal storage tank represents the highest point in the chilled water network, thus ensuring the static head.

The central energy plant **has a design Coefficient Of Performance (COP is a measure of efficiency) of 6 at summer conditions of 33°C dry bulb and 27°C wet bulb.**

The water is distributed to 7.8 km of underground uninsulated piping, fed to each building.

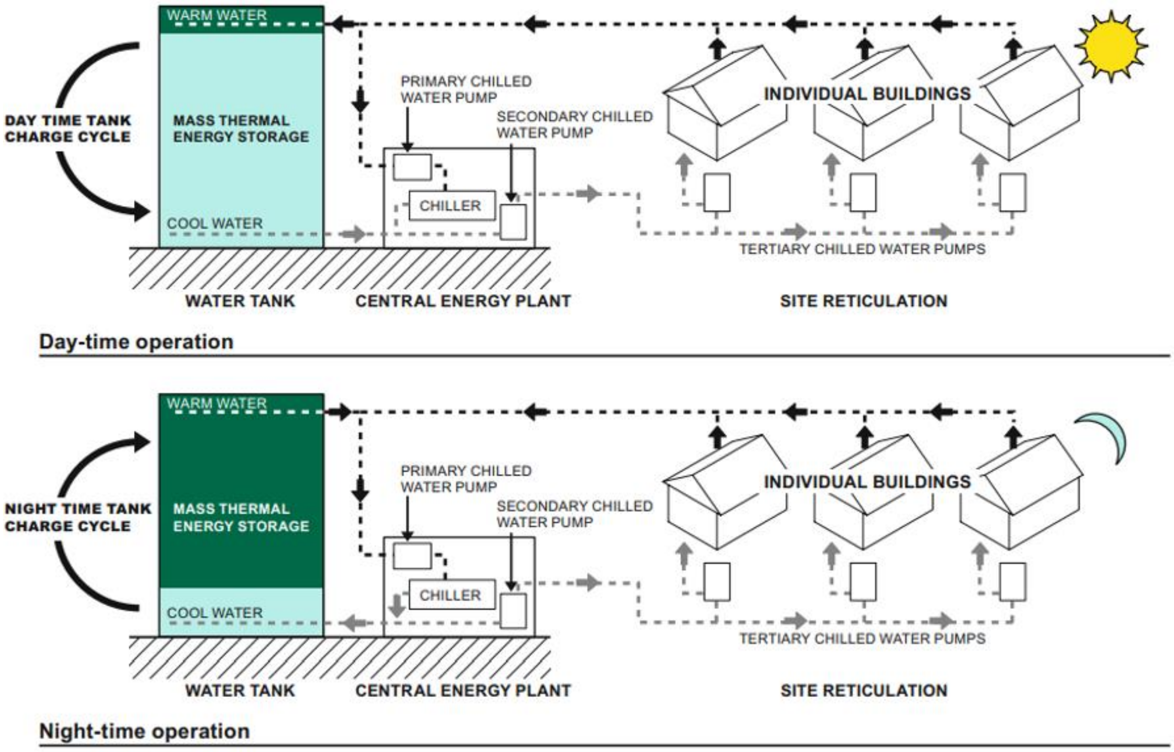

Fig. 32. Process Flow Chart [38].

Main conclusions

1. System efficiency improvements: Key features that enhance efficiency include the central plant's control strategy, high-voltage chiller motors, optimized CEP piping arrangement, and the use of underground chilled water piping, all of which contribute to cost savings and system flexibility.
2. Capital cost savings: Using high-voltage motors and avoiding low-voltage transformers eliminates transformer losses and additional infrastructure, saving $800,000 in capital costs.
3. Chilled water reticulation: Using MDPE pipes instead of insulated ones reduces costs, minimizes joints, and offers flexibility for future expansions.
4. Energy and efficiency gains: A higher temperature differential (9°C) reduces pumping energy and pipe size, resulting in lower energy consumption and long-term savings.
5. Environmental and economic impact: The project will reduce energy costs by $990,000, lower the site's Maximum Demand by 4.5 MW, and cut greenhouse gas emissions by 12,000 tons of CO_2e.

5.2. Barrio la Pinada [39]

Overview

Barrio La Pinada is a private urban development located in Paterna, close to the city of Valencia, which is expected to cover 320,000 m^2.

Barrio La Pinada is a new urban development that has yet to start construction. This provides the opportunity to create the network from scratch, matching the characteristics of a new network case study.

The total demand to be satisfied is 9.4 GWh (7.52 residential and 1.88 commercial).

The supply is also a new construction using RES (renewable energy system) as its source. Specifically, 60% of the demand will be covered using DCL (design cooling load) geothermal energy and the remaining 40% using aerothermal heat pumps. Even though this division is acknowledged, to perform a conservative case study, the costs considered will be those of a geothermal power plant, which are higher and thus more restrictive.

The main characteristics of the supply are presented in table 6.

	Supply
Technology	Geothermal/Aerothermal
Fuel used	Electricity
Maximum capacity	5 MW
Fixed costs	200,000 €
Capacity costs	500 €/Kw
Annual O&M costs	30 €/kW
Supply costs	1.4 c€/kWh

Table 6. Network characteristics [39].

Network topology

Barrio La Pinada plans to connect all the neighborhood's demands to the district heating and **cooling** network, so almost all buildings were set as required.

The only ones left out of the case study were two at the southernmost end of the development, which correspond to a school. This choice is because those buildings have already been constructed and thus will not be part of the upcoming development. 73 buildings were connected, covering 100% of the proposed demand and only leaving out the school.

The optimization determines that only 3.3 MW of the available capacity (5 MW) would be needed to cover the project’s demand. The associated capital investment of 2.14M € aligns with other geothermal energy developments.

Network solution (Table 7)

Pipework solution		**Production solution**		**Demand solution**	
Length	**6.76 km**	**Total Capacity Required**	**3.88 MWp**	**Total Peak Demand**	**6.16 MW**
Total Cost	1.35 M€	Output	11.05 GWh/year	Demand	9.2 GWh/year
Linear Cost	200 €/m	Capital cost	2.14 M€	Revenues	0.405 M€/year
Losses	1.85 GWh/year	Operating cost: O&M	0.12 M€/year	-	-

Capacity	3.88 MW	Operating cost: heat production	0.15 M€/year	-	-

Table 7. Network solution Barrio la Pinada [39].

Analysis (Table 8)

The most important fact to consider when analyzing the project's financials is the decision not to consider economic profitability as the development's main driver. Instead, Barrio La Pinada aims to provide its inhabitants with clean and innovative technology while maintaining a price that is not prohibitive for modest dwellings.

To achieve this, the case study's methodology has been modified. Instead of setting the tariff and allowing the tool to decide which demands to connect for the project to be profitable, an initial tariff was defined and then reduced until the minimum positive NPV (considering a time horizon of 50 years and a discount rate of 3%) was achieved. Thus, the minimum profitable tariff (15 €/kW + 3,4 c€/kWh) was obtained, which explains the project's low NPV.

	Capital cost	**Operating cost**	**Operating revenue**	**NPV**
Pipework	-1.35 M€	-	-	-1.35 M€
Heat supply	-2.14 M€	-0.27 M€/year	-	-9.35 M€
Demands	-	-	0.41 M€/year	-10.74 M€
Emissions	Not included at this stage			
Network	**-3.49 M€**	**-0.27 M€/year**	**0.41 M€/year**	**0.06 M€**

Table 8. Network analysis Barrio la Pinada [39].

5.3. DHC Bristol Redcliff network extension [40]

Overview

Bristol City Council (Fig. 33) has been actively planning heat networks for over 10 years to help deliver affordable, low-carbon heat across the city and contribute to its net-zero carbon target by 2030.

The Council has initially been developing a City Centre network that it hopes to expand in the future. It will use low or zero-carbon heat sources such as waste heat, local waterways, and old mine workings.

This case study considers expanding the development network comprising eight new buildings by adding one or more buildings. The broader network plan will ultimately connect around 60, mostly existing buildings.

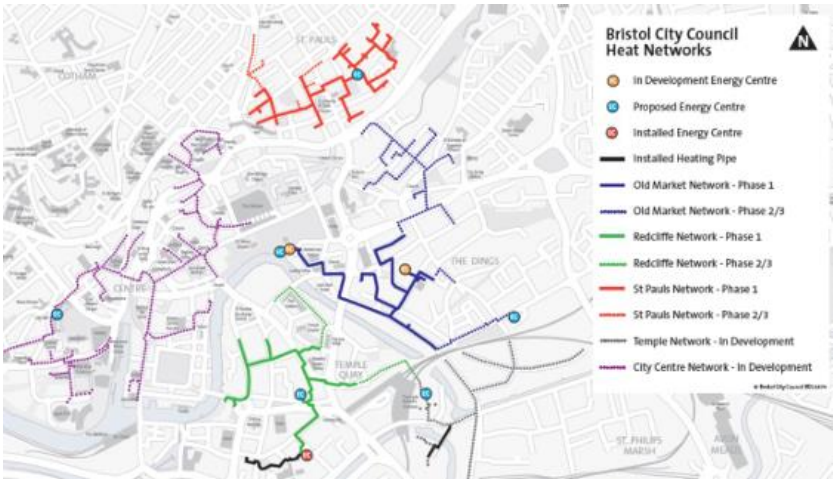

Fig. 33. DHC Bristol Redcliff network plan [40].

Key findings

1. Accuracy of THERMOS Modeling

The final heat network design modeled using THERMOS was validated against a detailed hydraulic model. The analysis covered 47 pipes, totaling 1,365 meters out of the entire 5,969-meter network. Results showed that 70% of the pipe segments matched exactly in size between the two models, and 97% were within one pipe size difference. These findings indicate that THERMOS provides a reliable approximation and can effectively serve as a proxy for more detailed hydraulic modeling

2. Load Expansion and Capacity Assessment

To evaluate available capacity in the network, additional loads were introduced on two branches. Since as-built heat capacity data was unavailable, pipe size served as the primary reference parameter. The method involved incrementally increasing building loads at the end of the network lines until the existing pipe size limit was surpassed. This approach enables a rapid estimation of spare capacity, facilitating quick assessments for accommodating new load requests.

3. Pipe Sizing and Load Impact Analysis

A specific section of the network with an installed 160mm pipe was analyzed. THERMOS calculations indicated that only a 100mm pipe was initially needed, confirming there was sufficient capacity for new connections. However, when two new loads of 1.75 MW and 2 MW were added, the required pipe size increased to 150mm. Given that the installed pipe size is 160mm, this suggests that the section is approaching full capacity.

4. Energy Center Capacity Review

The diversified peak load at the energy center was initially 5.05 MW. After adding the additional loads, the peak load increased to 7.37 MW.

5.4. DHC Parc de l'Alba [41]

Overview and Motivation for Network Expansion (Fig. 34)

Parc de l'Alba already operates a profitable district energy network and aims to expand it progressively in line with urban development.

The initial focus is on commercial and educational buildings, potentially extending to residential areas.

Expanding to individual residential customers presents management challenges due to the large number of end users. The expansion is structured into different phases

Fig. 34. DHC Parc de l’Alba network expansión [41].

Scenarios considered

a) Base scenario (buildings that are already included in the construction plans and the plots for public facilities placed in their way)

Heat demand: 63 GWh/year

Cold demand: 165 GWh/year

b) Scenario 1 (includes, in addition to what has been included in the base scenario, all the additional public facilities and the residential plots)

Heat demand: 77 GWh/year

Cold demand: 170 GWh/year

C) Scenario 2

This scenario includes the same buildings as Alternative Scenario 1. In this case, all the plots for public facilities will be included as required, thus forcing their connection to the network, and the residential buildings will remain as optional.

Considerations

The emissions considered in this case study were provided:

CO_2 emissions: 0.202 kg/kWh.

Emissions cost: 40 €/t CO_2.

Network construction costs and energy sale tariffs have been elaborated and validated through conversations with Parc de l'Alba. The following tariffs have been used for the study:

Unit charge: 3.3 €c/kWh.

Capacity charge: 28 €/kWp/year.

In the capacity charge, the one-off connection costs of 152 EUR/kW have also been merged and spread over the time horizon considered for the project.

Comparison between the base scenario and its two alternatives (Table 9)

	Total supply capacity (MW)	Connected buildings	Demand satisfied (GWH/yr)	Total network length (km)	Capital costs (M€)	NPV (M€)
Base scenario	60,5	82	140.88	8.9	27.42	14.95
Alternative 1	60,5	97	140.87	10.34	28.76	13.61
Alternative 2	60,5	102	141.43	12.89	31.01	11.50

Table 9. Scenario comparison of DHC Parc de l'Alba [41].

5.5. DHC Barcelona (Spain) [42]

Phased Modular Development

The district heating and cooling (DHC) system began operation in 2012 and follows a three-phase expansion plan.

Phase 1 (2011-2012) – Initial Infrastructure

The system includes a biomass plant, gas boilers, conventional and industrial chillers, along with a partial distribution network. It serves the areas of "La Marina" and "Zona Franca," which were originally industrial zones but are transitioning to mixed-use developments with new residential projects.

Phase 2 (2017-2019) – Integration of Surplus Cold Recovery

The system utilizes surplus cold generated from the LNG regasification process. It features ice storage facilities and a transport network designed to distribute the recovered cold, primarily serving the port area.

Phase 3 (2017-2024) – Network Expansion

Aims to connect 15 million m² of heated floor area.

Key facts and location (table 10)

DH market share	N.a.
Heating & Cooling capacity	DH: 23 MW (target: 40 MW)

	DC: 14 MW (target: 70 MW + 36 MW ice storage)
Heat & Cold production	DH: 12 GWh/y (target: 59 GWh/y) DC: 7.6 GWh/y (target: 54 GWh)
Km network (double-pipe)	12 km (target: 36 km)
CO_2 emissions	DH: 94.9 kg/MWh DC: 0 kg/MWh (net emissions, compensated with CHP electricity production)

Table 10. DHC Barcelona characteristics [42].

1. Gradual Expansion & Adaptive Energy Mix

The system is designed for phased growth, integrating various energy sources and operational strategies over time.

2. Main Energy Production & Storage Facilities

The system features a biomass plant with a capacity of 10 MWth and 2 MWe, fueled by garden and regional forest biomass to provide base load energy. Gas boilers are used to cover peak demand periods. Surplus cold recovery captures thermal energy from LNG regasification at Barcelona's Enagas LNG terminal, making use of previously wasted cold. Cold storage tanks are located in Zona Franca to store this energy. A SCADA-based smart control system, connected via optic fiber, enables real-time monitoring and optimization, implementing a smart grid approach.

3. LNG Terminal Integration

The Enagas terminal features a 760,000 m³ LNG storage capacity and an emission capacity of 1.95 million m³(n)/h. Ecoenergies' approach focuses on recovering cold from LNG at -160 °C, effectively reducing energy waste. While contractual terms are still under negotiation, it is anticipated that Enagas will provide the surplus cold at no cost.

Demand and Supply in Barcelona's Energy Market

1. Climate & Energy Demand

    a) Barcelona has a subtropical-Mediterranean climate, with mild winters (~1150 HDD) and high cooling demand.

    c) Heating demand is relatively low, while cooling demand continues to grow.

2. Current Energy Sources & Consumption

    a) Heating: Mainly natural gas-based individual solutions.

    b) Cooling: Primarily electricity-based systems.

    c) Solar Thermal Integration: Due to the Solar Thermal Ordinance (1999), new and refurbished buildings must incorporate solar thermal for domestic hot water (DHW).

    d) Energy Use:

        Existing buildings: ~80 kWh/m²/year.

        New buildings: ~45 kWh/m²/year.

3. Market Structure

a) Consumers can freely select their gas and electricity suppliers.

b) The market is moderately concentrated, with 5-6 suppliers covering 90% of total energy supply.

District Heating and Cooling (DHC) Market & Pricing

1. Regulation & Tariff Management

District Heating and Cooling (DHC) is regulated by the Barcelona City Council through the public company Tersa, which oversees concession contracts. Operators are required to offer competitive pricing relative to conventional energy sources.

2. Price Competitiveness of DHC

District Heating (DH):

a) EUR 42/MWh (excluding VAT & connection costs).
b) ~10% cheaper than natural gas (including fuel, O&M, and equipment costs).
c) District Cooling (DC): EUR 38/MWh, 5-12% cheaper than electricity.
d) Industrial Consumers (B2B Model): Pricing negotiated case by case.

3. Demonstrating Competitiveness: Mercabarna Case Study

a) Large-scale electricity measurement campaign conducted by Ecoenergies.
b) Identified potential replacement of 32 GWh/year of electricity demand with DC.
c) Estimated savings:
d) 20% reduction in electricity costs.
e) 8,730 tCO_2 reduction in emissions.

5.6. DHC Greater Stockholm [43]

DHN Overview

District Heating (DH) as a Key Decarbonization Strategy: Sweden aims to achieve carbon neutrality by 2045 and views DH as a crucial enabler in this goal. The country has shifted from relying entirely on fossil fuels—mainly oil—in the 1970s to only 6% today, primarily natural gas. This fuel transition was initially driven by the 1970s oil crisis, which prompted the move away from fossil fuels, and has recently accelerated with increased adoption of sustainable energy sources.

Current Energy Sources in DH

1. Biomass (mainly through CHP plants).
2. Waste-to-energy.
3. Surplus heat recovery.
4. Renewable electricity (via heat pumps and electric boilers).

Impact on CO_2 Emissions (Fig. 35)

1. Fuel mix evolution between 2003-2013 shows a significant decline in CO_2 emissions.
2. DH has been instrumental in decarbonizing Sweden's heat supply.

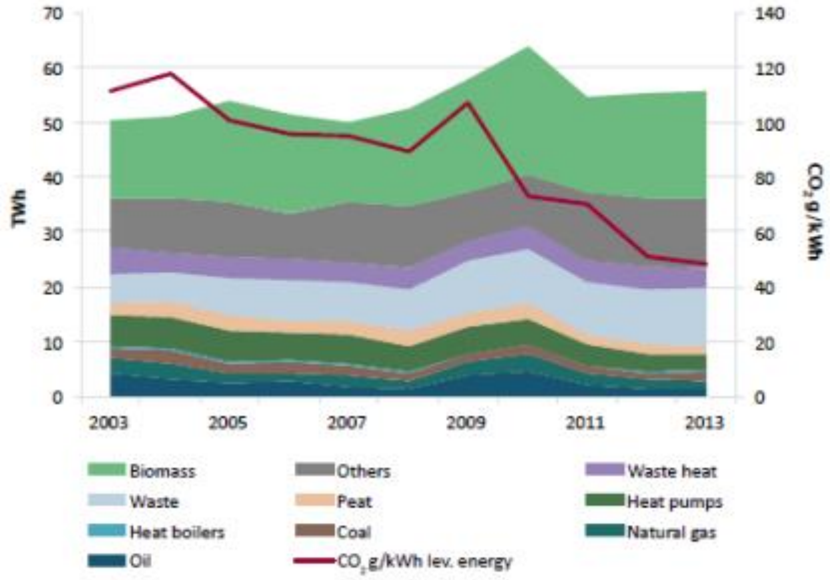

Fig. 35. Fuel mix evolution between 2003-2013 in DHC Stockholm [43].

District Cooling (DC) in Sweden has experienced rapid expansion (Fig. 36), growing at an approximate annual rate of 20% since the establishment of the first DC network in Västerås in 1992, with a significant increase in supply thereafter. Key drivers of this growth include rising cooling demand driven by higher comfort standards and the cost-saving potential that attracts large consumers such as office buildings, data centers, and supermarkets. Many DC networks take advantage of free cooling by utilizing natural cold sources like seawater and lakes, which reduces energy consumption and enhances system efficiency. The main clients are primarily offices, data centers, and supermarkets. This upward trend is expected to continue as both demand and sustainability goals increase.

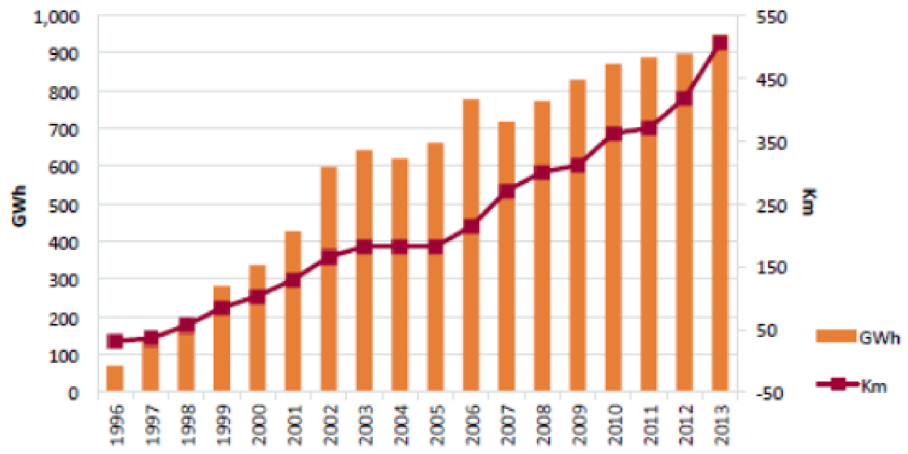

Fig. 36. Energy and network growth through the years in DHC Stockholm [43].

Key facts

1. Large system: Average 8 TWh/y, ~10 000 clients, direct supply to 6 municipalities
2. Public-private partnership: The DHC system is owned and operated by Fortum Värme AB (50 % City of Stockholm, 50 % Fortum Heat & Power)
3. Flexible and optimised DH production:
   a) 7 CHP plants (fuelled by biofuels, waste or fossil fuels)

b) Heat pumps
c) Electric boilers
d) Several HOBs (fuelled by bio-oils or fossil oils)

4. District Cooling: One major system in the city centre, and several smaller ones around.
5. Above 50 % of sales produced through free cooling from the sea and other water bodies

Table 11 shows the networks characteristics

DH market share	80% (area covered by DH)
Heating & Cooling capacity	DH: 3600 MW DC: 220 MW
Heat & Cold production	DH: 7.4-10.8 TWh/y DC: 380-440 GWh/y
Km network (double-pipe)	DH: 1330 km DC: 200 km
CO_2 emissions	DH: 0.136 kg/MWh DC: 0 kg/MWh (certified renewable electricity)

Table 11. DHC Stockholm characteristics [43].

5.7. DCN cold energy recovery from liquefied natural gas vaporization [44]

Background

Buildings account for approximately 40% of global energy consumption, with cooling demand steadily increasing. Global residential cooling demand is projected to rise sharply from 300 TWh in 2000 to 4,000 TWh by 2050, reaching 10,000 TWh by 2100. Unlike heating demand, cooling demand is more difficult to predict due to its sensitivity to factors such as solar radiation, internal heat gains, and urban heat island effects.

District Cooling Systems (DCSs)

District Cooling Systems (DCSs) provide a centralized cooling solution serving multiple buildings (Fig. 37). They consist of key components including the generation unit, distribution network, customers, and heat rejection system. DCSs are recognized as Best Available Technology (BAT) within the European Union.

Waste Cold Energy from LNG

LNG regasification releases a significant amount of cold energy approximately 1,245 MWh per year in Italy from L-CNG stations offering potential for free cooling that can reduce electricity demand in air conditioning systems. However, there have been no prior studies exploring the coupling of District Cooling Systems (DCSs) with cold energy recovery from L–CNG.

Case study

Cold Energy Potential (Fig. 38)

1. Annual LNG consumption in L–CNG stations: 5400 t/year
2. Cold energy wasted during regasification: 830 kJ/kg LNG
3. Recoverable cold energy:

~380 kWht/day (if operating 365 days/year)

~550 kWht/day (if excluding weekends, 253 days/year)

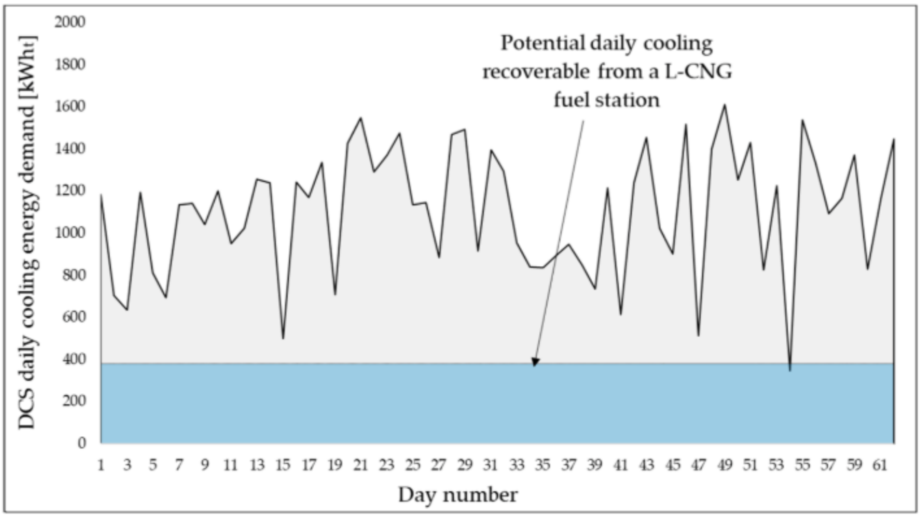

Fig. 37. Potential daily cooling recoverable from L-CNG fuel station for DCS [44].

Cooling Power Profiles

P1: Constant supply (10 h/day, 365 days/year).

P2: Constant supply (excluding weekends & lunch breaks).

P3: Variable profile with peak at 6–7 p.m.

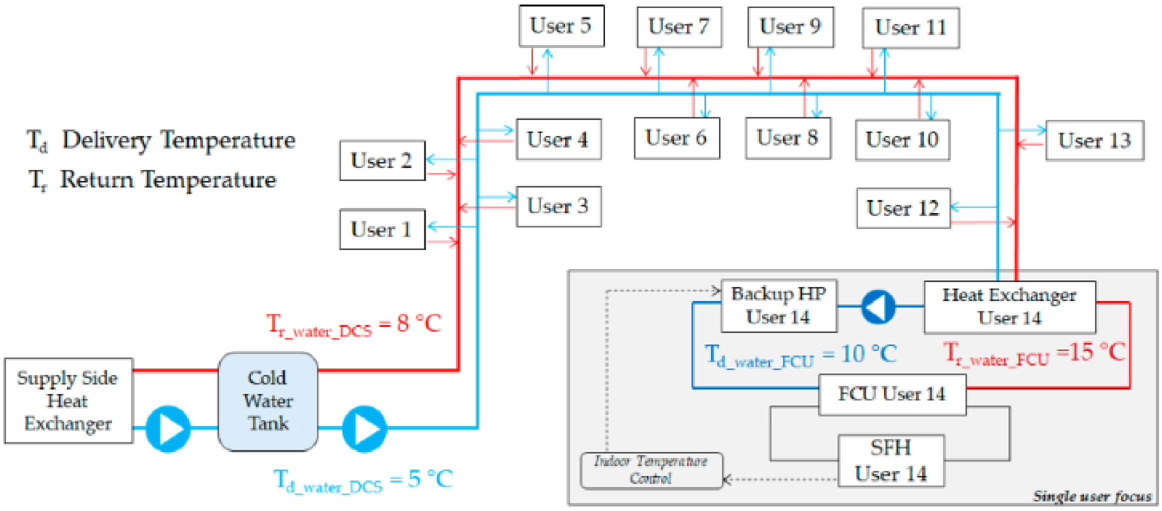

Fig. 38. DCS scheme for LNG [44].

Simulation Results

District cooling system demand (Fig. 39)

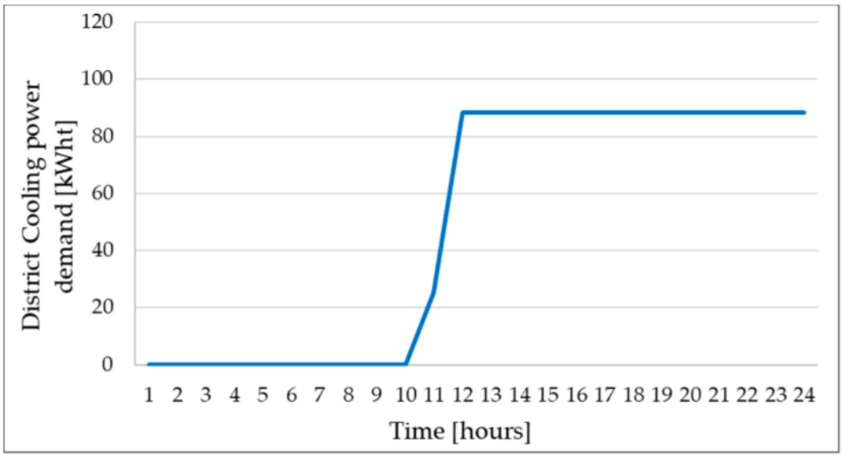

Fig. 39. District cooling system demand from LNG [44].

Energy consumption (Fig. 40)

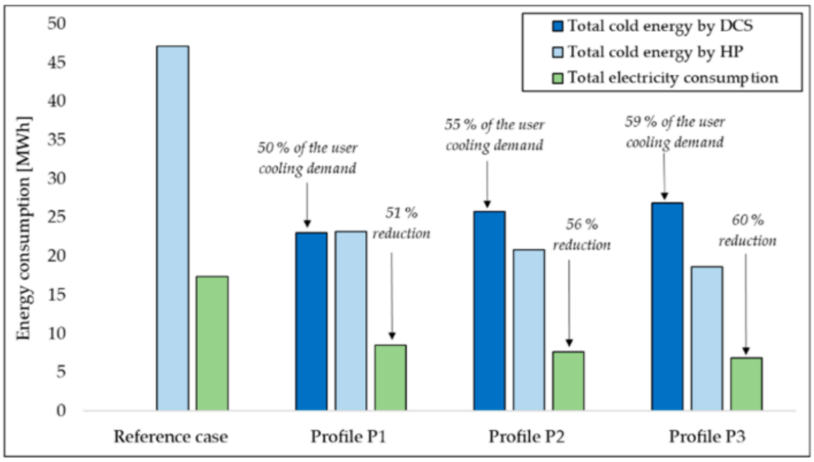

Fig. 40. Energy consumption [44].

Reference Case

1. Separate cooling systems: Fan coil units powered by a heat pump
2. Cooling demand (July–August): 47 MWht
3. Electricity consumption: 17 MWhe

Free Cooling Power Analysis

DCS directly connected to the heat exchanger (no TES):

P1 (constant supply): 50% cooling demand covered, 52% electricity savings

P2 (weekday adjustment): 58% electricity savings

P3 (variable supply): Less efficient due to demand-supply mismatch

Thermal Energy Storage (TES) Impact

60 m³ tank introduction:

P3 case: 59% cooling demand covered, 60% electricity savings

P1 & P2 cases: Minimal impact due to regular supply

Enables better demand-supply balance

TES Sizing Considerations

1. Optimal range: 30–90 m^3
2. Smaller tanks: Insufficient thermal inertia
3. Larger tanks: Increased heat losses & slower system response

Conclusions

District Cooling Systems (DCS) offer significant benefits, including low-cost cold energy supply with reduced CO_2 emissions, integration with renewable energy, trigeneration, and thermal storage, as well as efficient recovery of waste cold energy, such as from L–CNG refueling stations. A case study demonstrated that an L–CNG station supplying cooling to a residential neighborhood achieved up to 60% electricity savings using a P3 load profile combined with a 60 m^3 thermal energy storage, with general savings exceeding 50% across all scenarios. However, results depend on assumptions about the availability of LNG vaporizer energy, indicating the need for further studies on optimal DCS sizing and user connection strategies. Overall, LNG vaporization shows strong potential to effectively supply residential district cooling, and integrating transport and residential cooling systems can enhance urban sustainability.

5.8. DCN Stockholm city [45]

Overview (Table 12)

A preliminary study pointed to the possibility of using an existing heating pump plant with seawater as the resource for simultaneous heat and refrigeration production for district cooling in Stockholm City.

Stockholm City consists of various properties serving different purposes, such as offices and commercial centers. The city's cooling demand is high and growing with increased trade, more stringent comfort requirements, and computerization. Stockholm City was the first area to provide environmentally friendly district cooling, produced using heating pumps and free cooling from cold seawater. The key facts are represented in Table 13.

	kW/contract	MWh/contract	Number of contracts
Public building	300	300	35
Hospitals	1000	1500	5
Universities and schools	2000	3000	5
Business centers	1500	1500	15
Industry and pharmaceuticals	500	500	10
Offices	500	500	330

Table 12. Characteristics of DCN Stockholm city [45].

Key facts

Installed power	170 MW
Energy	240 GWh/annum
Mains	8.6 km
Distribution network	12 km
Operating pressure	10 bar
Feed temperature	+6 °C
Return temperature	+16 °C
Number of customers	300

Table 13. DCN Stockholm city key facts [45].

Distribution

District cooling is transferred to the City area in a mains that is 8.6 km long and has a diameter of 800 mm. The mains are installed in existing pipe tunnels and in the ground. In the City area, a distribution network has been established with a total length of 12 km. The distribution network is also installed in tunnels and in the ground.

Main conclusions

Stockholm's district cooling system was launched in 1995 with a 60 MW cooling plant located next to an existing heat pump in Värtan. The system combines free cooling and heat recovery, delivering strong environmental and economic performance. In 1998, an aquifer energy storage system was introduced, primarily charged with cold seawater, providing 25 MW during peak demand periods. By 2000, a new 50 MW excess-power plant with heat recovery was added, supporting both district heating and peak summer cooling needs. The distribution network was carefully designed and constructed using specialized methods to minimize disruption to road traffic.

5.9. DCN combined with hydrogen electrolyzes [46]

Overview

In this case study, a district with a district heating and cooling network is partially supplied by hydrogen technologies. An energy supply for an exemplary district with 6 buildings is planned (the energy center is in building A) (Fig. 41). The district's location is assumed to be Berlin (Germany) with a demand profile represented in table 14.

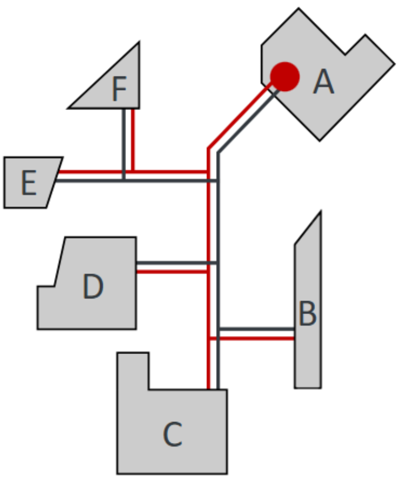

Fig. 41. DCN with hydrogen electrolysers Germany [46].

Demand profile

Building	Usage	Floor area (m^2)	Space heating (MWh)	Domestic hot water (MWh)	Space cooling (MWh)	Electricity (MWh)
A	Hotel	20,000	1700	640	980	3000
B	Office	18,000	1170	144	1062	936
C	Retail	24,500	1593	74	784	2352
D	Museum	16,500	1073	83	578	859
E	Theater	6,700	503	40	101	563
F	Restaurant	2,500	188	125	50	358

Table 14. Characteristics of DCN for each building (hydrogen electrolyzers case) [46].

Fig. 42 shows the heat demand and Fig. 43 the electricity demand

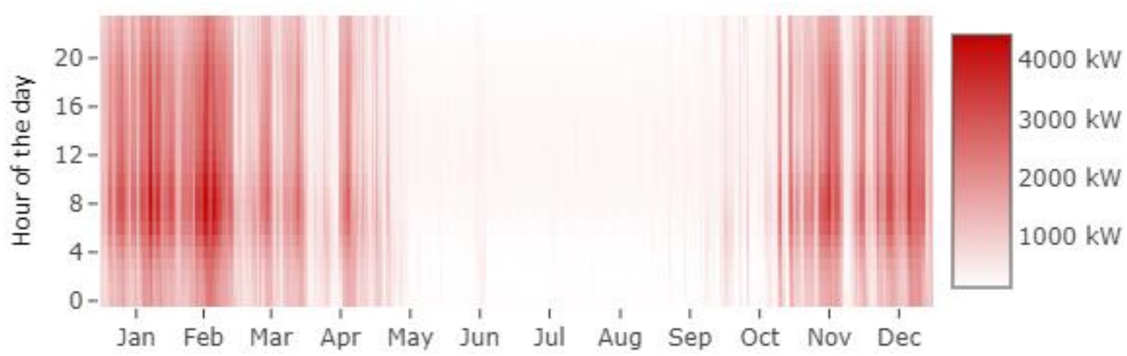

Fig. 42. Heat demand (hydrogen electrolyzers case) [46].

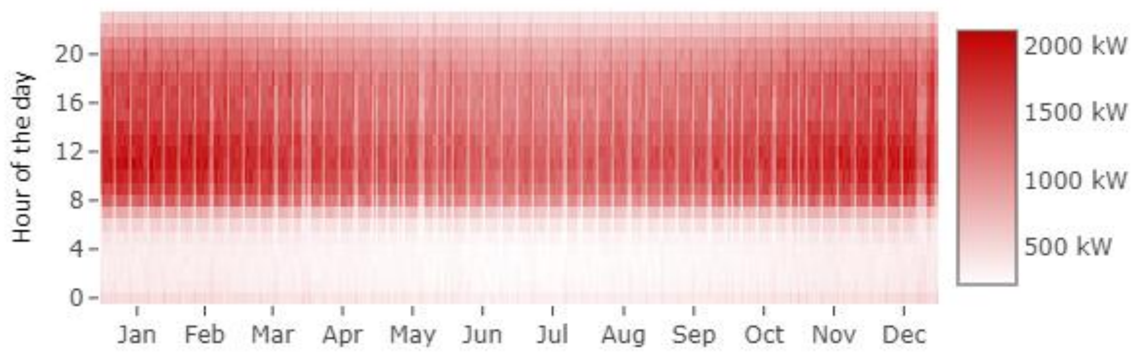

Fig. 43. Electricity demand (hydrogen electrolyzers case) [46].

Design of the energy center

1. Hydrogen technologies support heating and cooling in the district, with a 3 MW connection to an existing district heating network.
2. An electrolyzer uses surplus PV electricity to produce hydrogen, which is fed into the natural gas grid, with waste heat recovered for district heating (Fig. 44).

3. Compression chillers provide cooling, and the optimal PV system capacity is 58,800 m², covering 62% of the district's electricity needs (Fig. 45).
4. 92.1% of the heat supply comes from the district heating network, while 7.9% is covered by waste heat from electrolysis.
5. The district's CO_2 emissions total 4,370 metric tons per year.

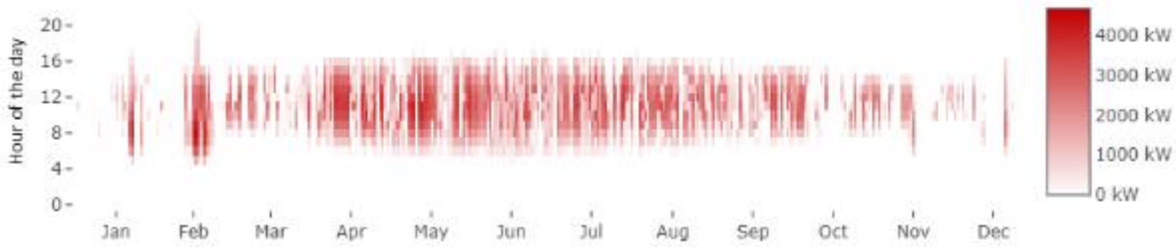

Fig. 44. Hydrogen feed-in (hydrogen electrolyzers case) [46].

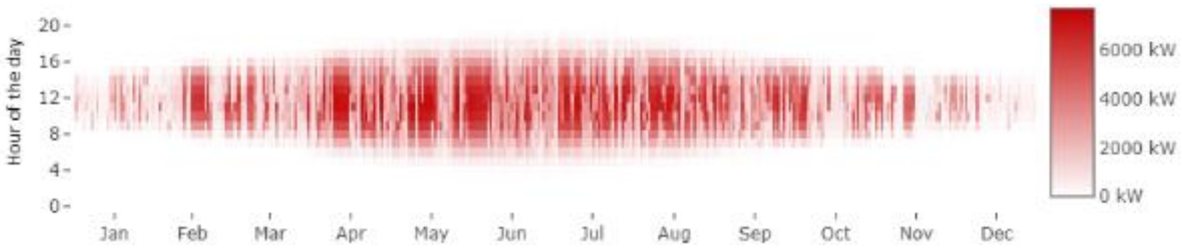

Fig. 45. Generation of PV electricity (hydrogen electrolyzers case) [46].

5.10. DCN for hotel resorts [47]

Background

This district energy project in Punta Cana, Dominican Republic, is widely recognized, particularly in the eastern tourist area. BROAD supplied eight single-stage hot water chillers that utilize waste heat from Wartsila generators in a heavy oil power plant. The system delivers 19 MW of cooling by transferring pressurized hot water at 120°C over a distance of 4 km to air conditioning units serving five hotels. Continuous cooling is essential due to the tropical climate, which also demands strict performance and stability standards. The project’s success has earned recognition from CEPM and attracted interest from energy companies in the U.S. and Latin America, opening up new opportunities for collaboration.

System design concept (Fig. 46)

1. The system provides 17.58 MW of chilled water and domestic hot water (DHW) to nearby hotels.
2. Waste heat from diesel engine exhaust and cooling water (6 MWe each) is used for heating and cooling.
3. 248°F (120°C) HTHW is produced at the power plant and sent to hotels to drive single-stage absorption chillers.
4. After cooling, the HTHW at 158°F (70°C) is further used to generate DHW before returning to the power plant.
5. A 50°C temperature drop optimizes heat utilization, allowing a single loop to serve both cooling and DHW needs.

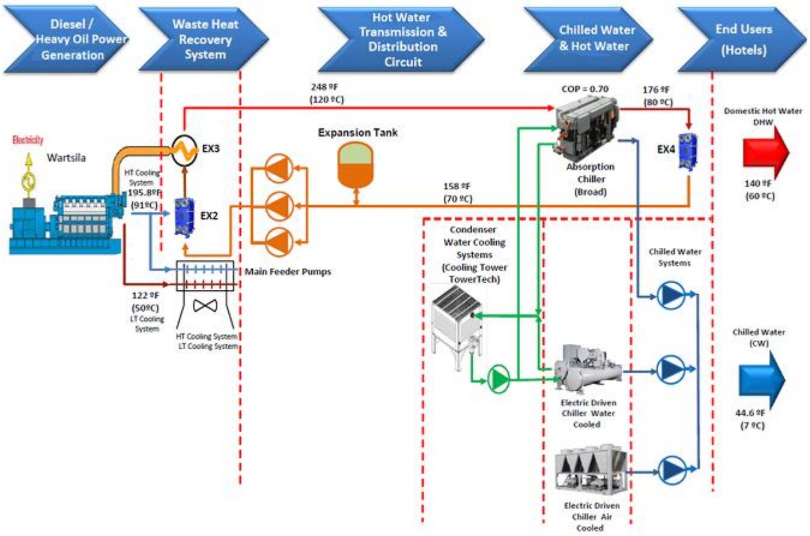

Fig. 46. System design concept for DCN Hotel resorts [47].

Economic and environmental aspects

1. 25% reduction in electrical energy consumption at resorts compared to traditional cooling methods.
2. Previously, 34% of the resorts' electricity bill was for cooling, but cogeneration reduced reliance on the grid.
3. The project eliminated the need for domestic hot water boilers, cutting fuel consumption to zero.
4. Waste energy was efficiently reused, covering both cooling and DHW needs, benefiting both resorts and utilities.
5. 25% of thermal energy was recovered, reducing fuel use by 35,740 barrels of HFO and 32,881 barrels of LPG annually.
6. CO_2 emissions were reduced by over 28,872 metric tons annually, showcasing significant environmental benefits.

This project represents the most innovative energy arrangement in the Caribbean, effectively utilizing residual thermal energy and cascade energy use. Hotels benefit from reduced operating costs, enhanced competitiveness, and more sustainable energy consumption. By optimizing thermal energy utilization, the system frees up electrical capacity to support future developments and new facilities. Overall, the project contributes to regional economic growth while promoting long-term sustainability.

5.11. Conclusions

Table 15 display the external key success factors of DCN based on the case studies, and table 16 the same for internal.

Key success factors (external)	Description
Adequate national policy and regulatory environment	The national energy policy and regulatory environment provide adequate ground and incentives for the development of DHC systems

Direct/indirect financial support	DHC projects benefit from existing direct/indirect subsidies
Focused local policy and coherence with urban planning	Local authorities promote DHC as part of their energy supply and climate strategy and integrate heat planning in their urban development projects
Alignment of interests / Cooperation maturity	Public authorities at national and local level, regulating bodies, end users, the DHC company and other local actors cooperate in an efficient manner to achieve a good quality service and a sustainable and cost-efficient heat and cold supply

Table 15. External key success factors of DCN.

Key success factors (internal)	**Description**
Availability and relevance of local resources	The DHC system relies to a large extent on available local resources such as renewable energy sources
Comprehensive project development	The DHC system was conceived, developed and implemented following a comprehensive, seamless approach aimed at achieving a high quality, cost-efficient and sustainable heat/cold supply.
Price competitiveness against alternative energy solutions	DHC prices are competitive against alternative energy solutions available in the market. This price competitiveness can be enhanced through an optimized system design, through competitive procedures for the market or by allowing competition between different heat/cold supply solutions.
Flexible heat and cold production	A flexible production allows better cost-efficiencies, mainly through a dynamic optimization of the supply. This can be achieved through a diversified and complementary energy mix, the use of CHP and enhanced ramp-up/cycling practices, connecting the electricity and heating markets, etc.
Combining technical and non-technical innovation	The DHC system embraces and cross-fertilizes innovation at all levels: from the use of state-of-the-art technologies to new governance modes, keeping a long-term approach when making strategic decisions.

Table 16. Internal key success factors of DCN.

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