Module 4: District Cooling

Combined heat and cold production, cooling technologies, refrigerants and district cooling case studies

SHaKE – Sharing Heat and Knowledge on Energy Communities
Erasmus+ KA220-HED Cooperation Partnerships in Higher Education
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SHaKE
Sharing Knowledge on Energy Communities

INDEX

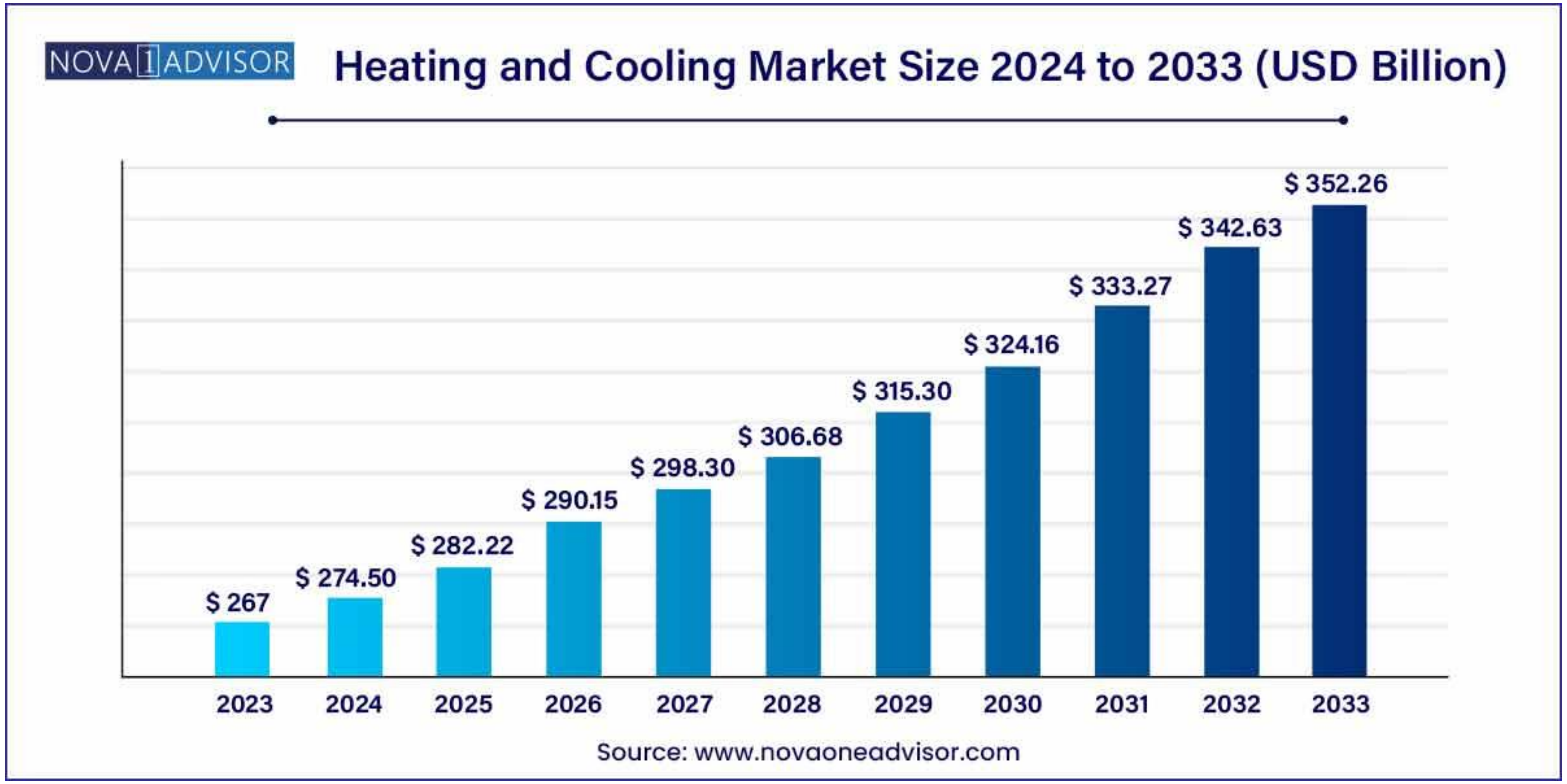
INDEX

INDEX

1. COMBINED HEAT AND COLD PRODUCTION

1.1. HEATING AND COOLING PRINCIPLES

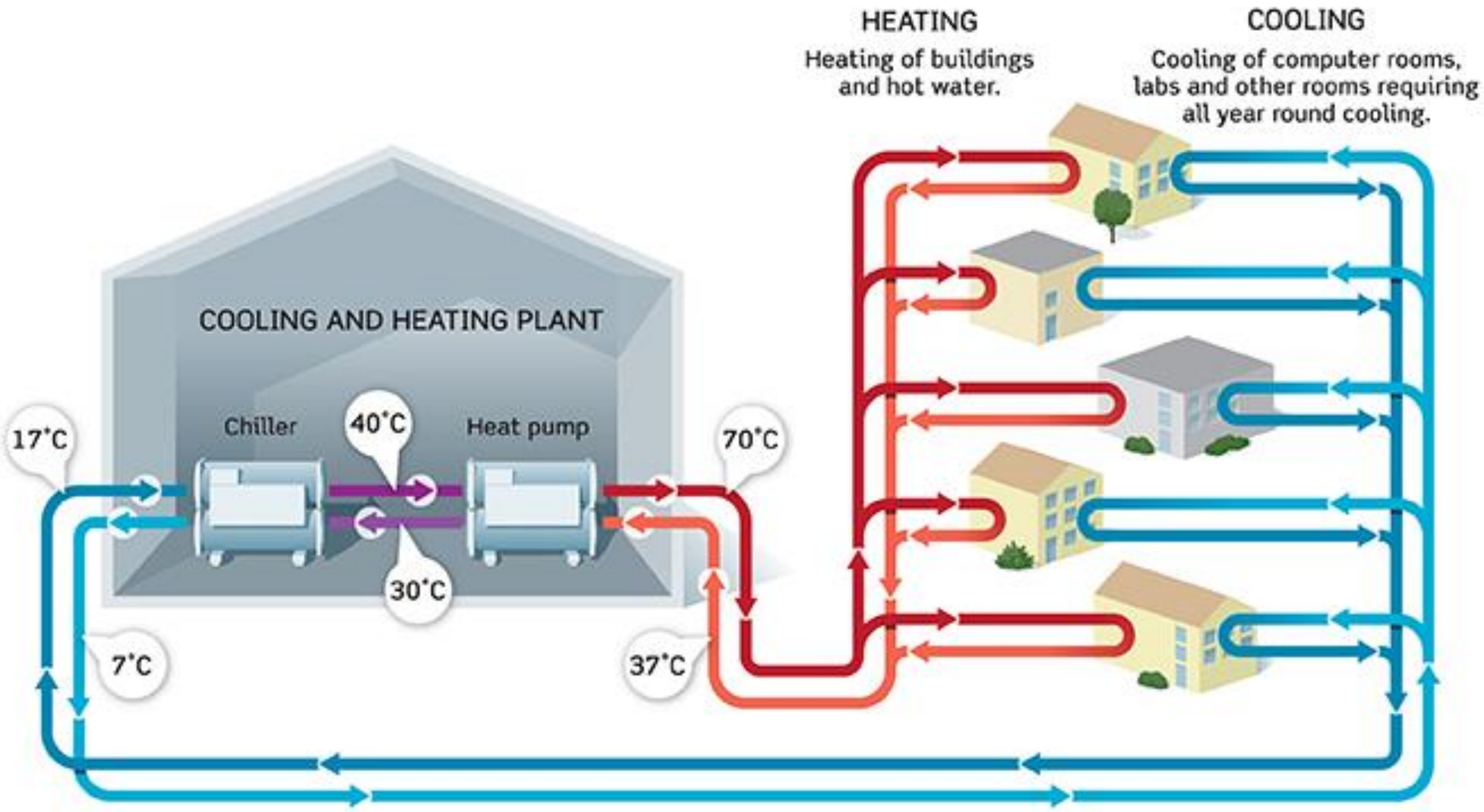
Introduction



Source: www.novaoneadvisor.com

1.1. HEATING AND COOLING PRINCIPLES

Introduction

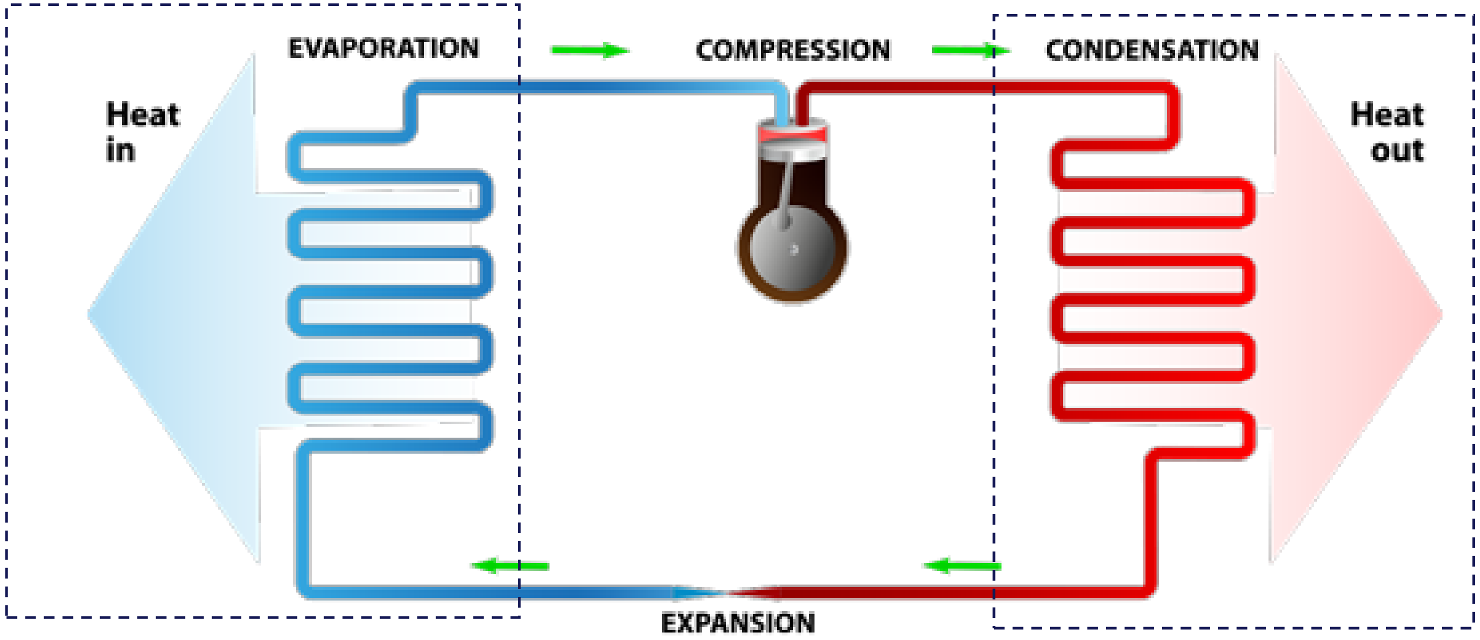


Connections of DCN and DHN

Source: KTH

1.1. HEATING AND COOLING PRINCIPLES

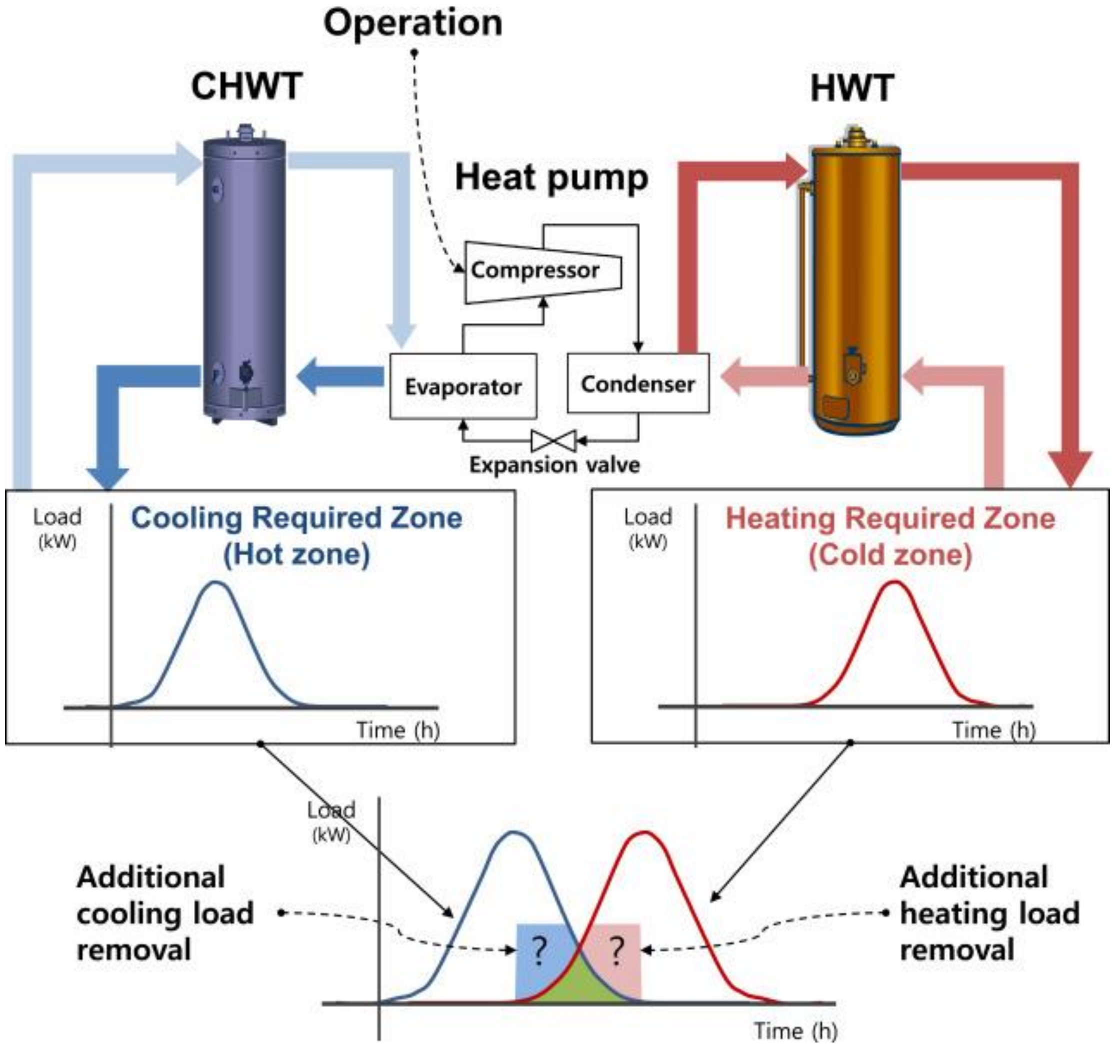
Heat pump operation type



Source: Goodman

1.2. SIMULTANEOUS HEATING AND COOLING APPLICATIONS

Simultaneous heating and cooling (SHC) principle



Source: Shin et al. (2019)

1.2. SIMULTANEOUS HEATING AND COOLING APPLICATIONS

Advantages of SHC

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

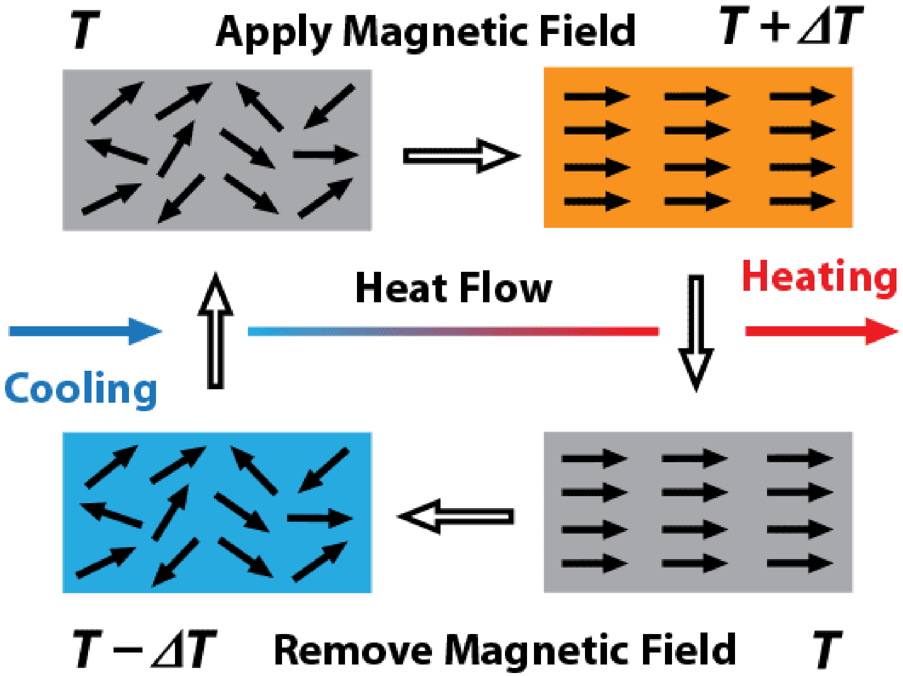
Challenges of SHC

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

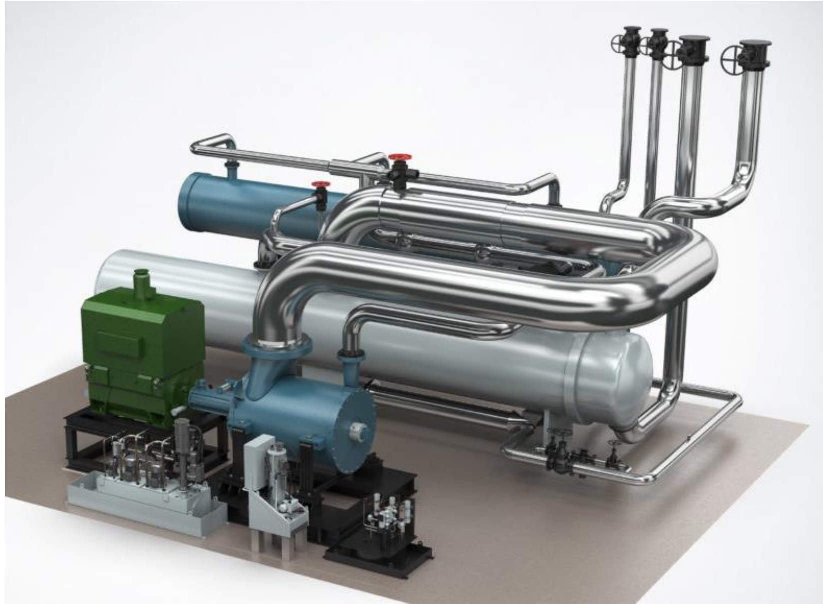
1.3. TECHNOLOGY FOR HEAT PUMP AND CHILLERS

Emerging Technologies and Future Trends

1. Natural Refrigerants
2. High-Temperature Heat Pumps
3. Digitalization and IoT
4. Thermoelectric and Magnetocaloric Cooling
5. Hybrid Systems
6. Integration with District Energy Systems



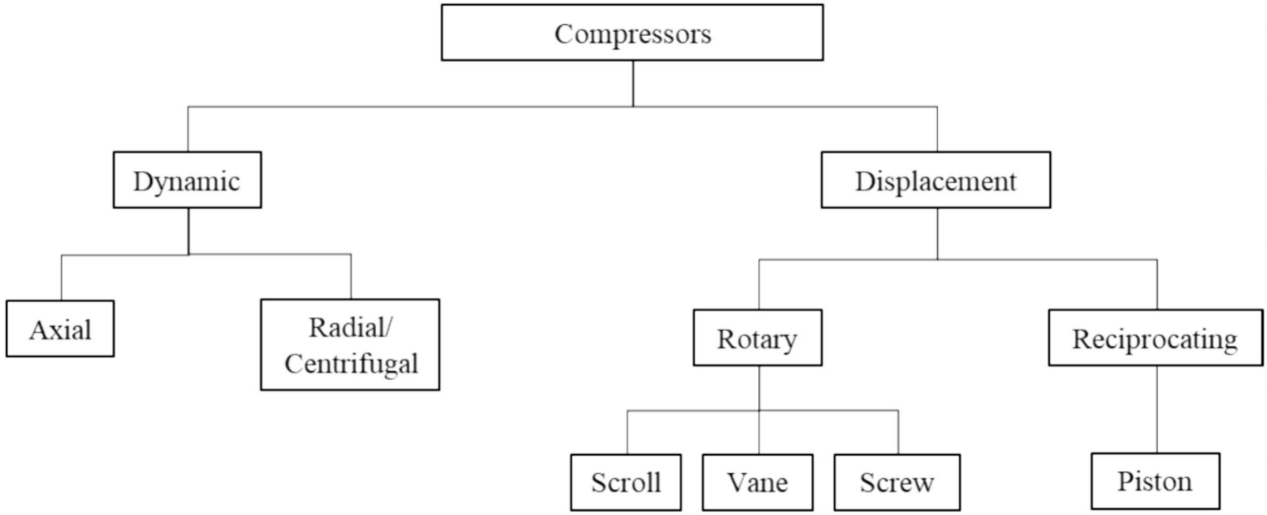
Magnetocaloric heat pump/chiller
Source: Access Inc.

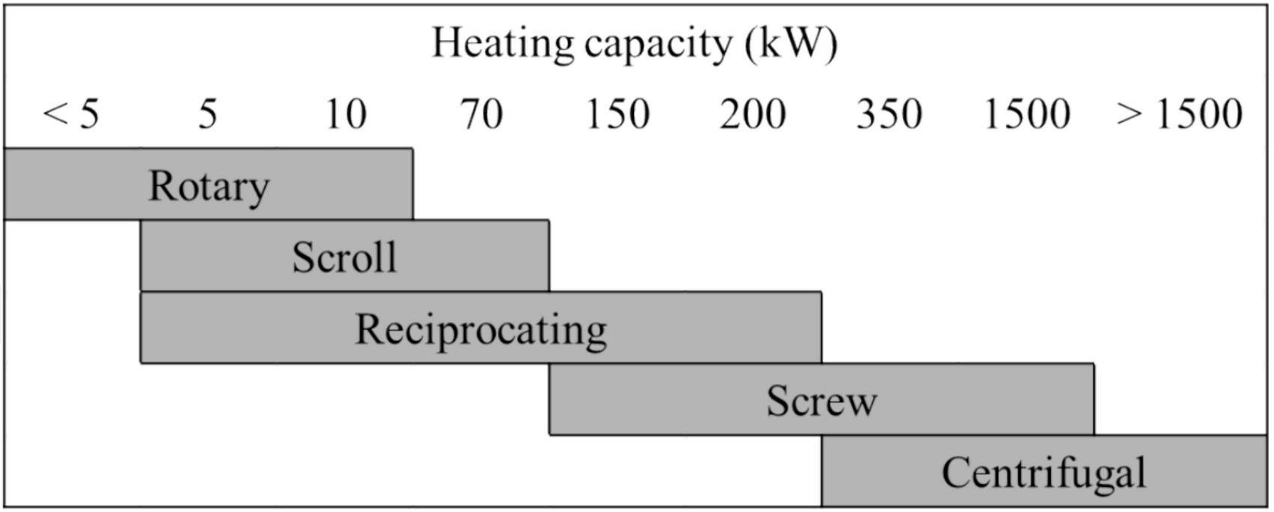


High temperature heat pump
Source: PV Magazine

1.4. CURRENT TECHNOLOGY

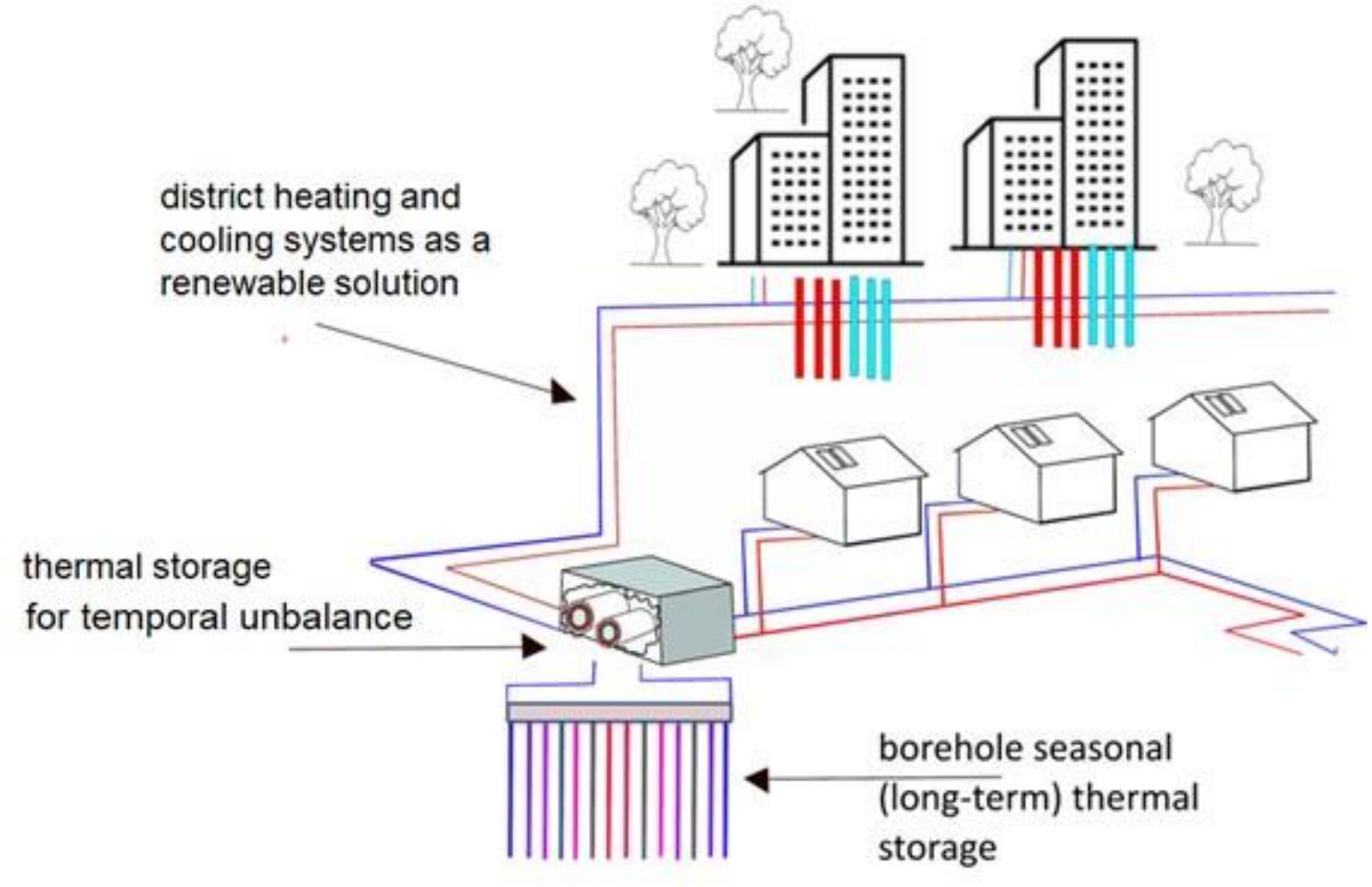
Compressors





1.4. CURRENT TECHNOLOGY

Thermal energy storage

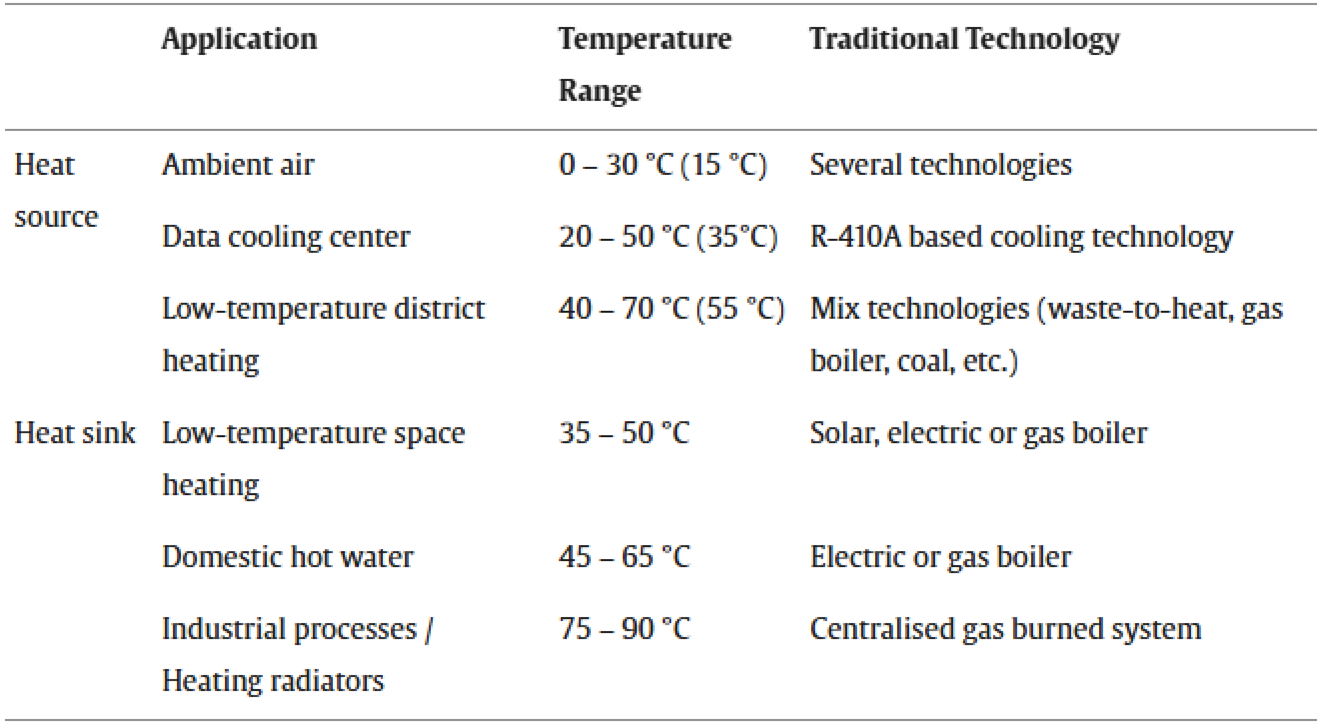


Source: EEA Grants Portugal

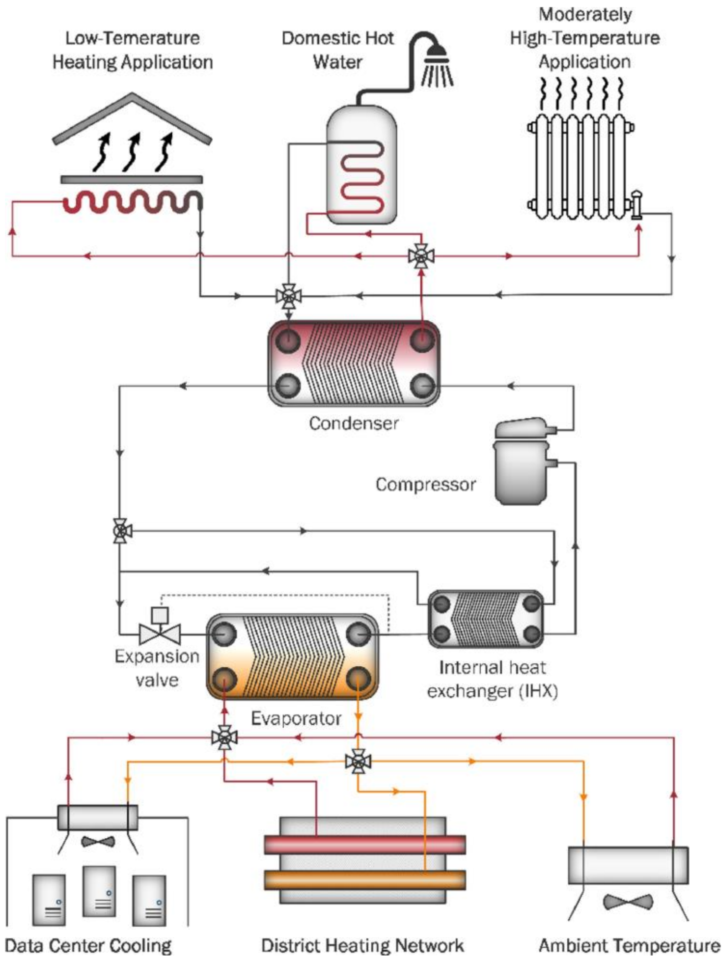
1.5. INTEGRATION

Possibilities of integration

A combination of urban and industrial heating and cooling consumptions by a heat pump with the possibility of simultaneous production.



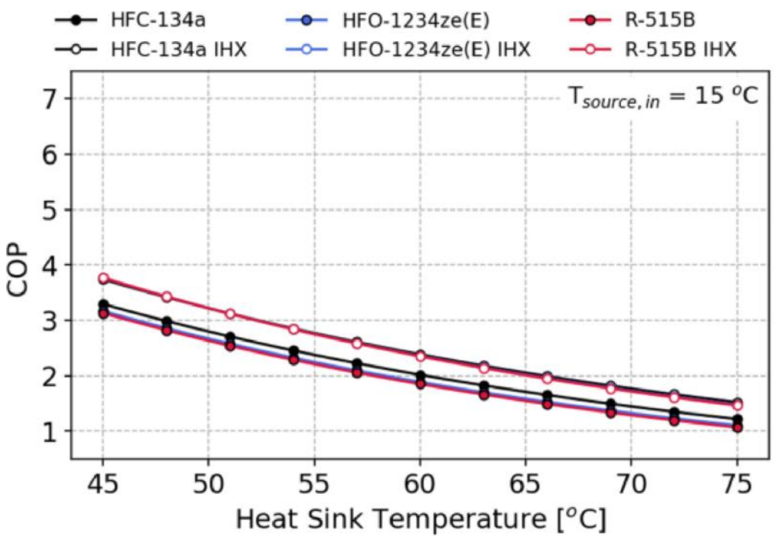
	Application	Temperature Range	Traditional Technology
Heat source	Ambient air	0 – 30 °C (15 °C)	Several technologies
	Data cooling center	20 – 50 °C (35°C)	R-410A based cooling technology
	Low-temperature district heating	40 – 70 °C (55 °C)	Mix technologies (waste-to-heat, gas boiler, coal, etc.)
Heat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

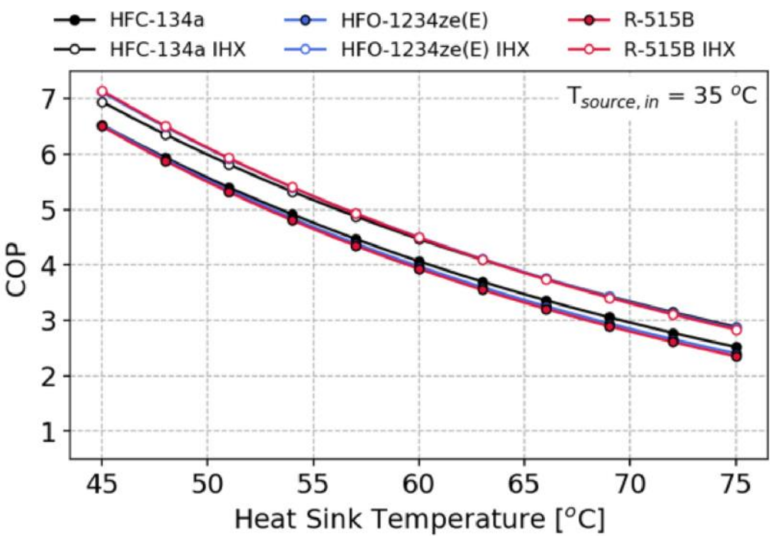


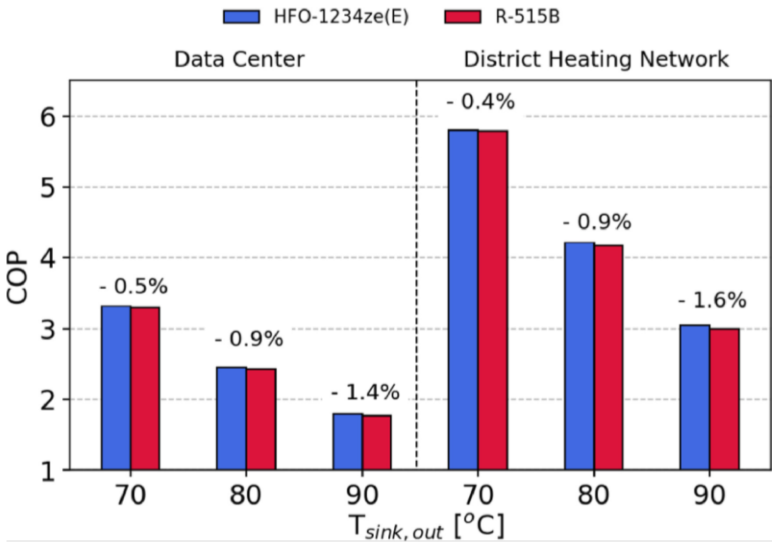
Source: Mateu-Royo et al. (2021)

1.5. INTEGRATION

Influence of the operational temperatures





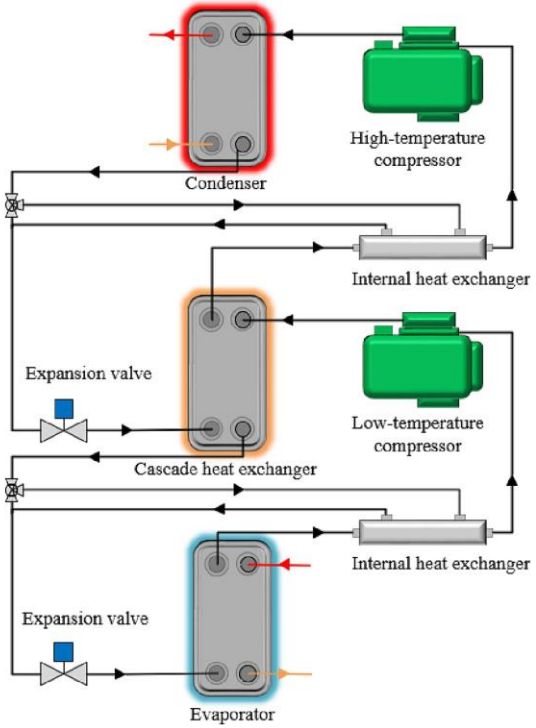


Source: Mateu-Royo et al. (2021)

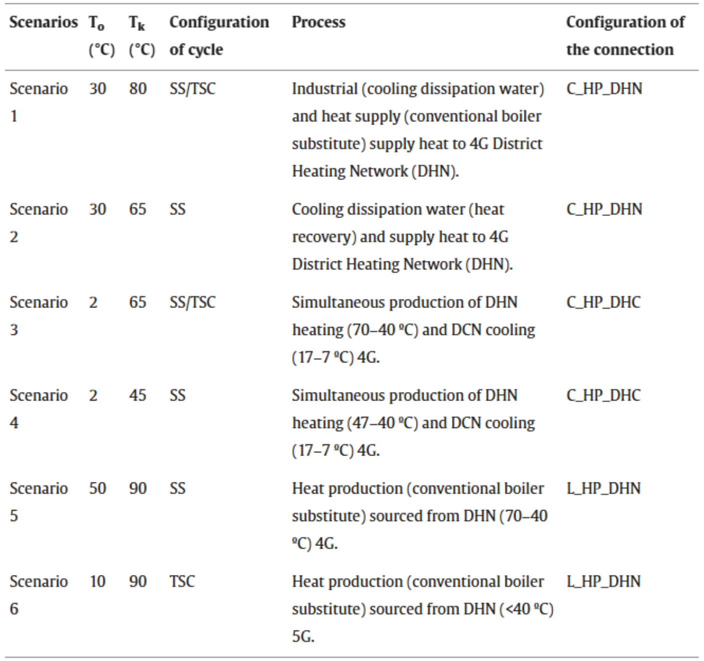
1.5. INTEGRATION

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

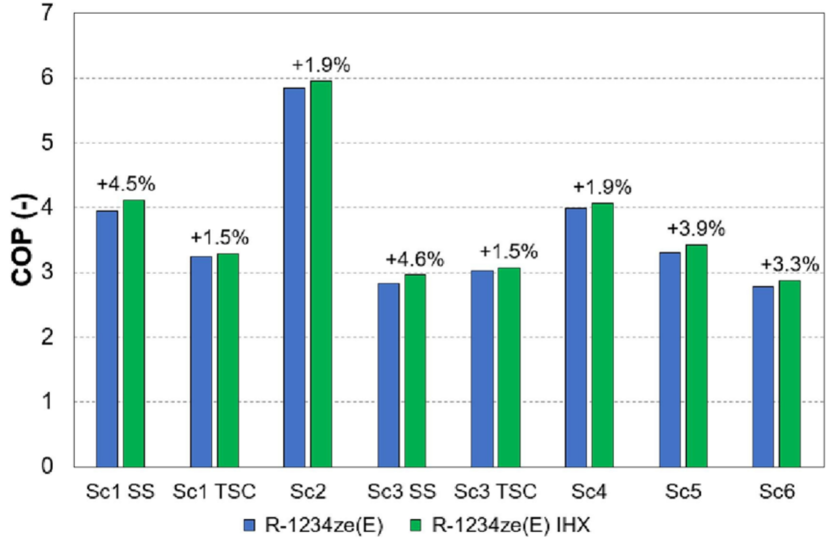
A higher difference between heat sink and heat source will require more than one stage in the vapor compression cycle of the heat pump. Moreover, the Internal Heat Exchanger can benefit energy performance, depending on the refrigerant and application.



Two-Stage Cascade



Scenarios	T_o (°C)	T_k (°C)	Configuration of cycle	Process	Configuration of the connection
Scenario 1	30	80	SS/TSC	Industrial (cooling dissipation water) and heat supply (conventional boiler substitute) supply heat to 4G District Heating Network (DHN).	C_HP_DHN
Scenario 2	30	65	SS	Cooling dissipation water (heat recovery) and supply heat to 4G District Heating Network (DHN).	C_HP_DHN
Scenario 3	2	65	SS/TSC	Simultaneous production of DHN heating (70–40 ºC) and DCN cooling (17–7 ºC) 4G.	C_HP_DHC
Scenario 4	2	45	SS	Simultaneous production of DHN heating (47–40 ºC) and DCN cooling (17–7 ºC) 4G.	C_HP_DHC
Scenario 5	50	90	SS	Heat production (conventional boiler substitute) sourced from DHN (70–40 ºC) 4G.	L_HP_DHN
Scenario 6	10	90	TSC	Heat production (conventional boiler substitute) sourced from DHN (<40 ºC) 5G.	L_HP_DHN

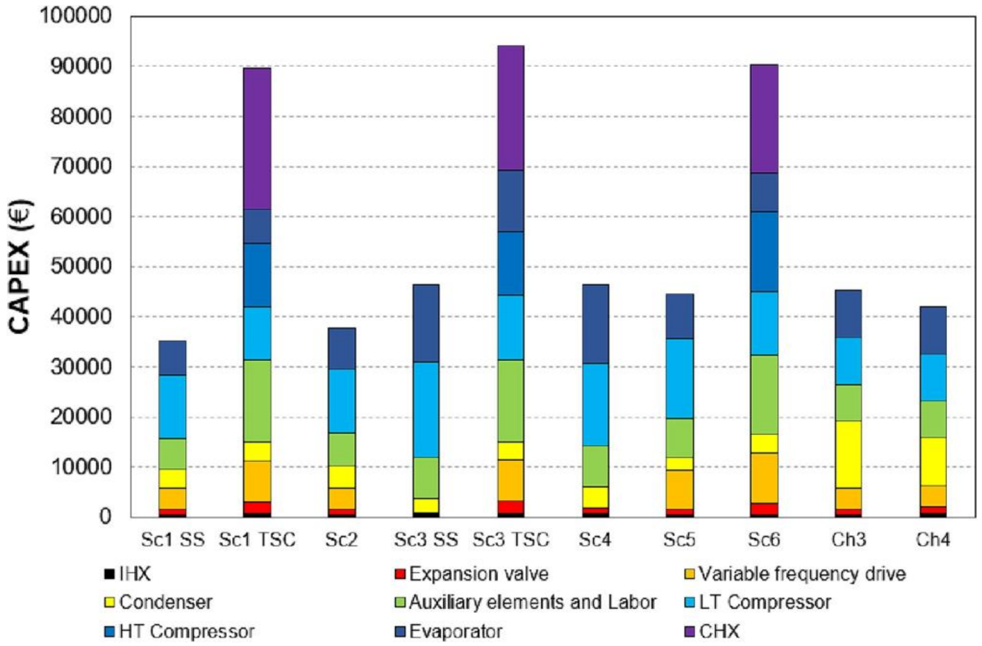


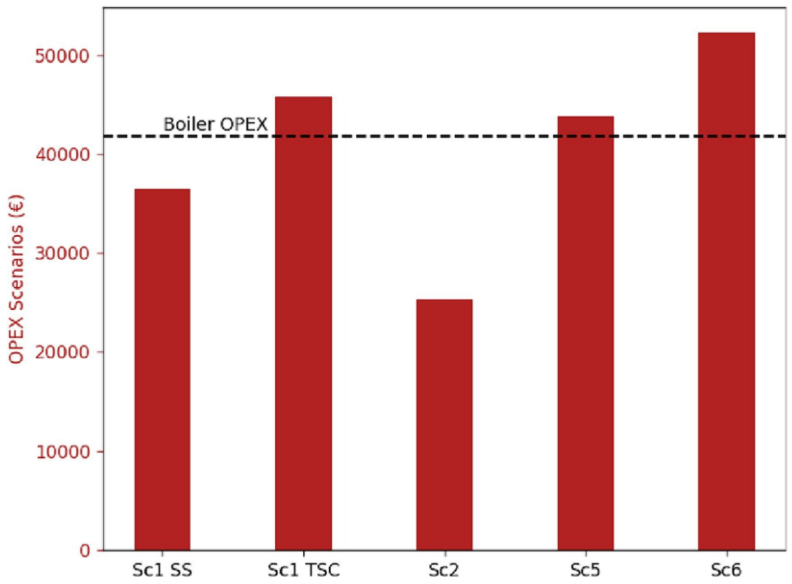
Source: Alarnaot et al. (2024)

1.5. INTEGRATION

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 the investment more attractive.



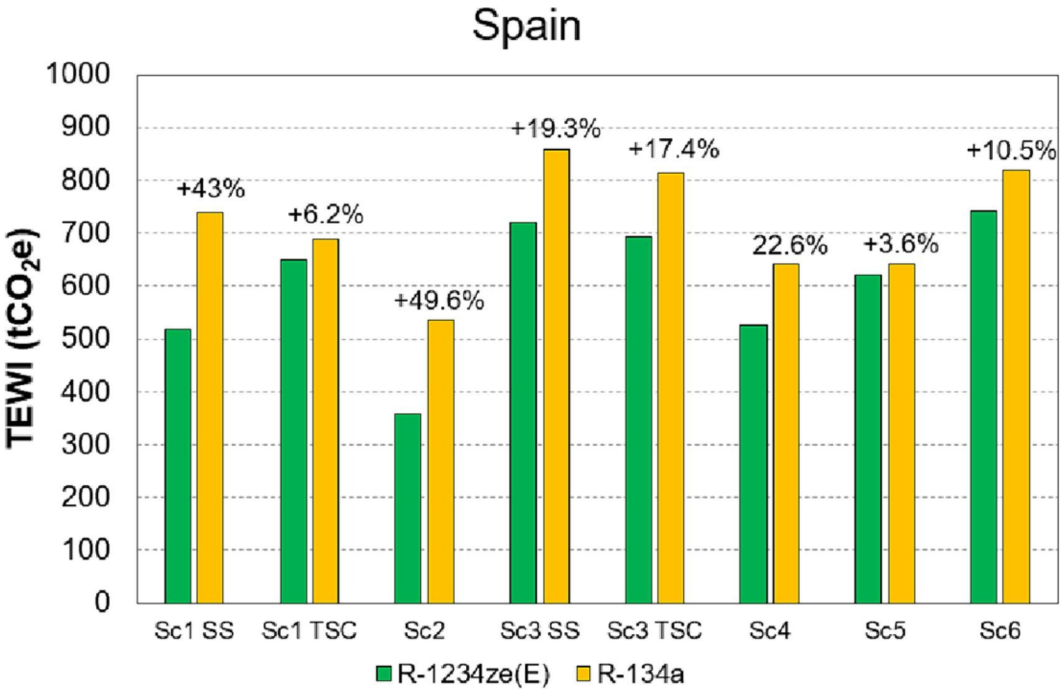


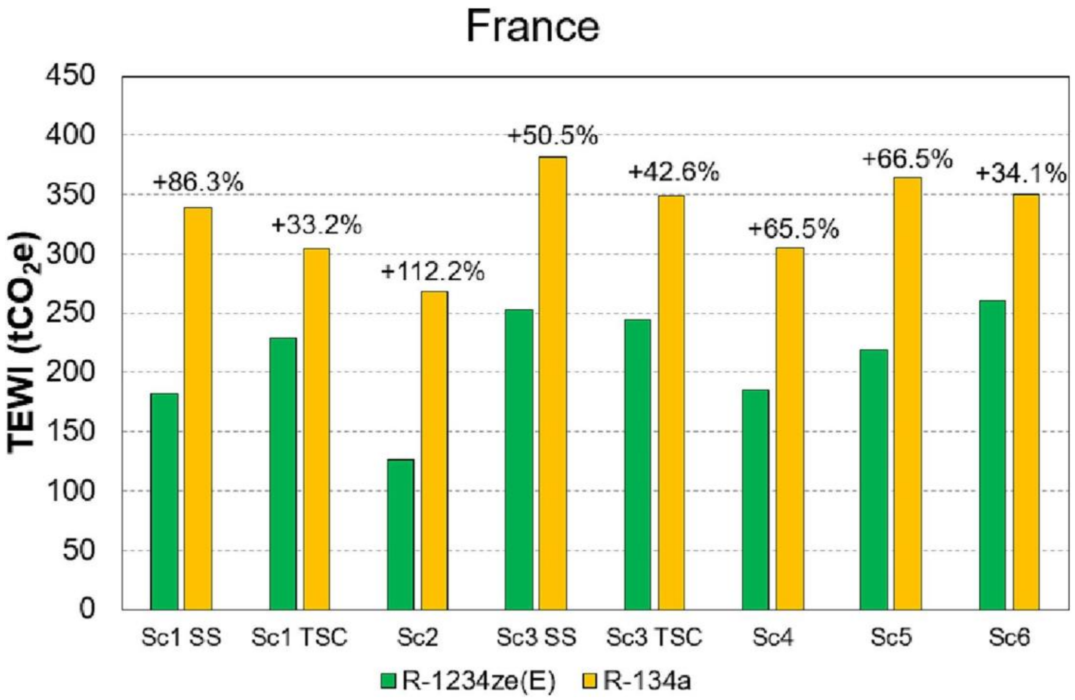
Source: Alarnaot et al. (2024)

1.5. INTEGRATION

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).



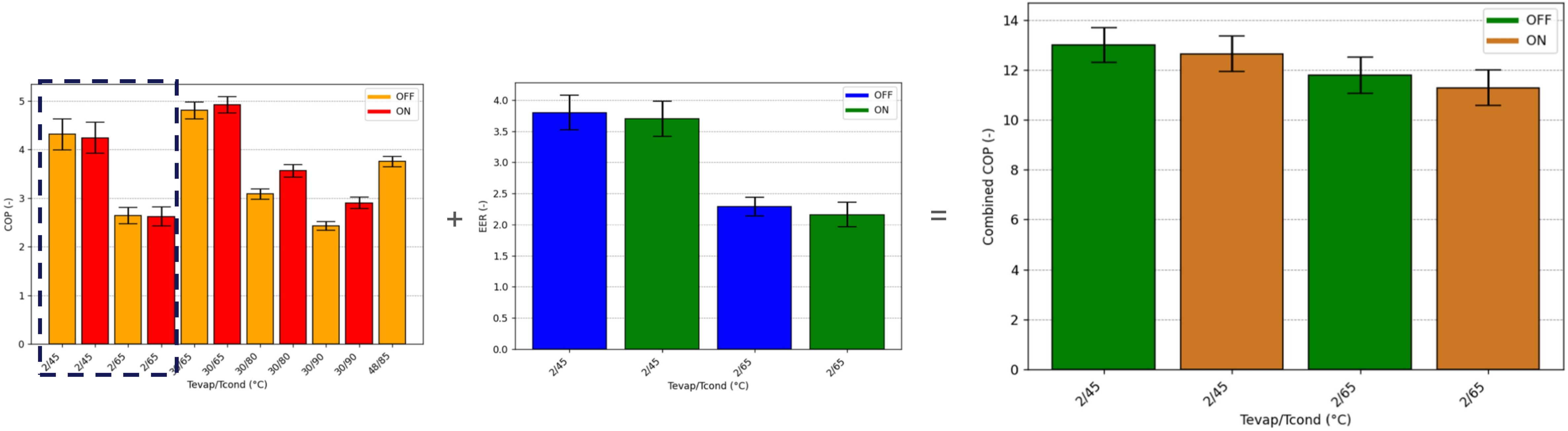


Source: Alarnaot et al. (2024)

1.5. INTEGRATION

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.

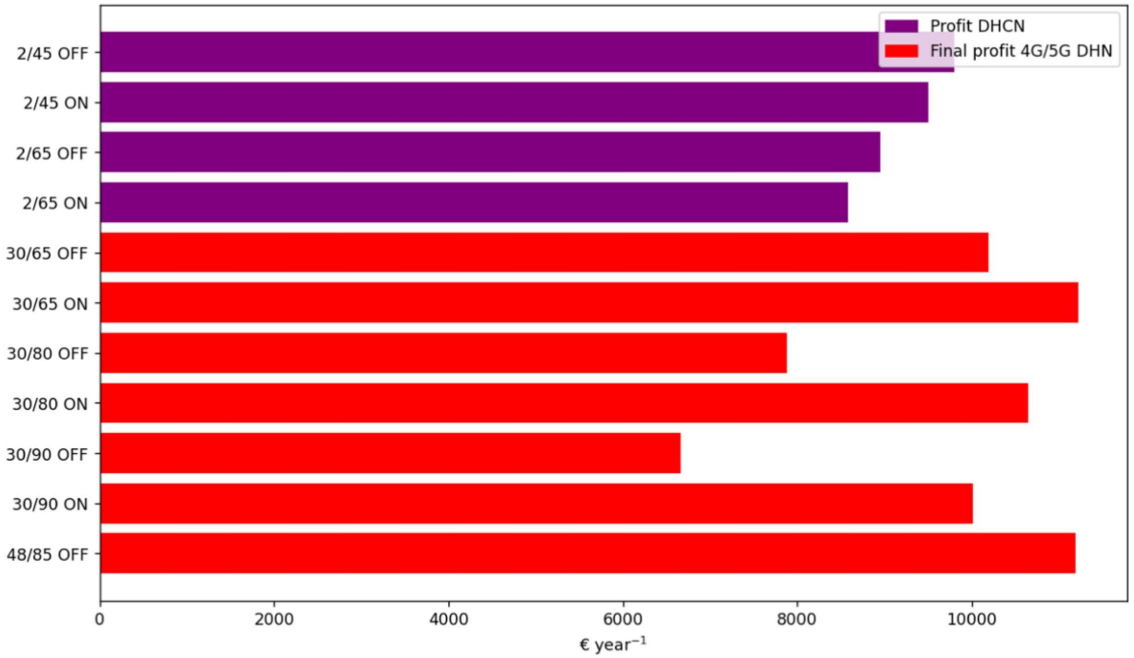


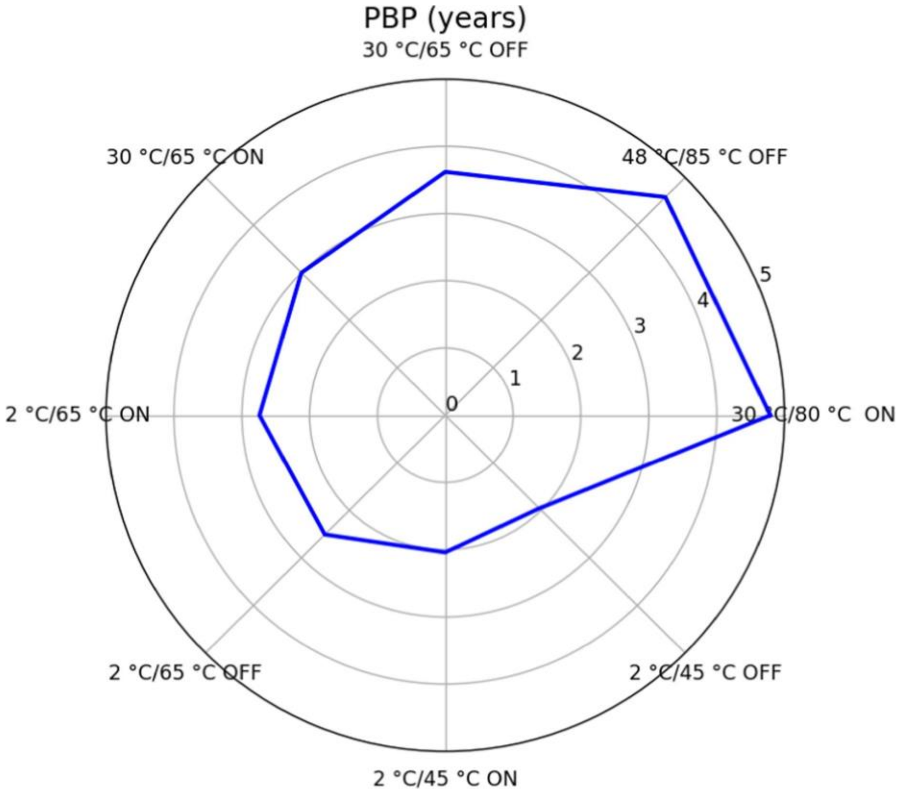
Source: Alarnaot et al. (2024)

1.5. INTEGRATION

Comparison with fossil fuel boiler

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

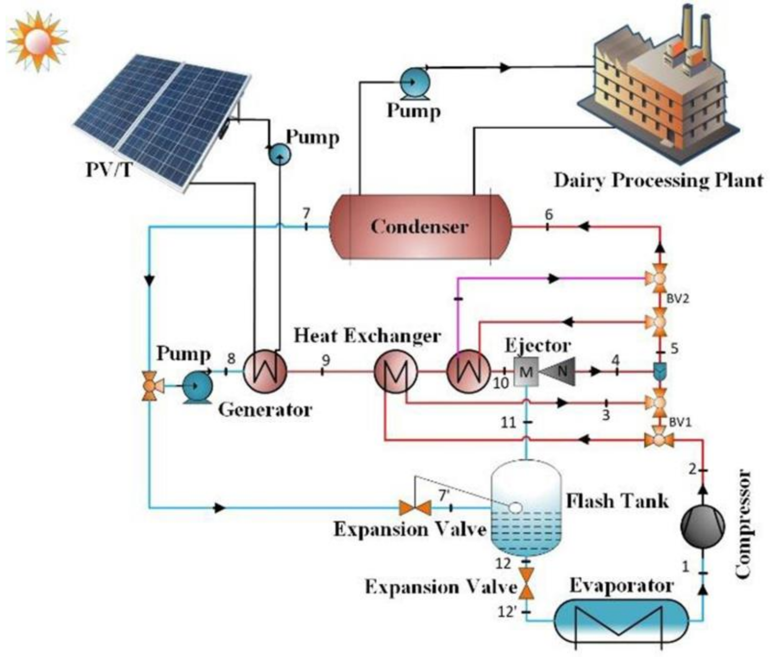




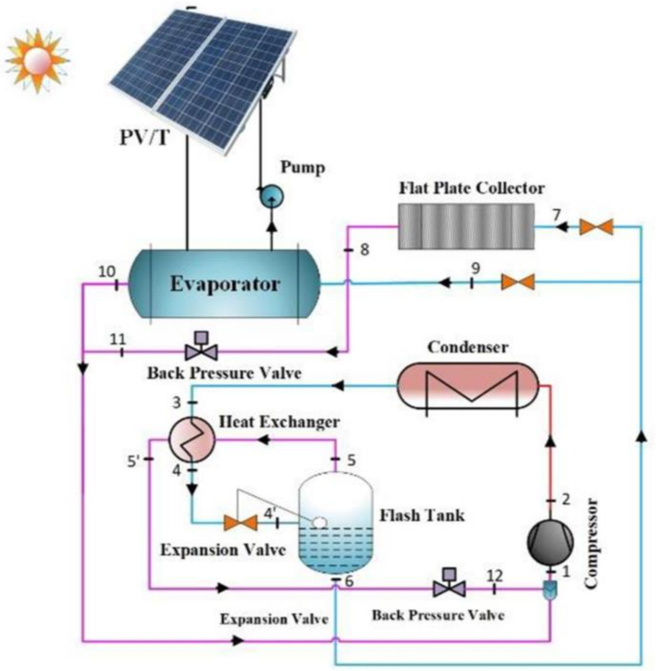
Source: Alarnaot et al. (2025)

1.6. WASTE AND RENEWABLE HEAT

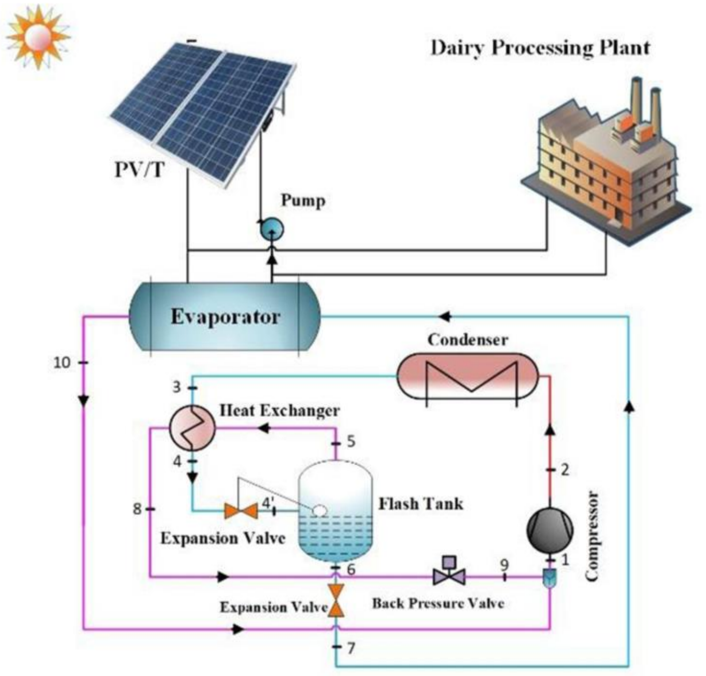
Example 1. A Novel compound waste heat-solar driven ejector-solar assisted heat pump for simultaneous heating and cooling purposes.



Cooling mode



Heating mode with PV/T waste heat



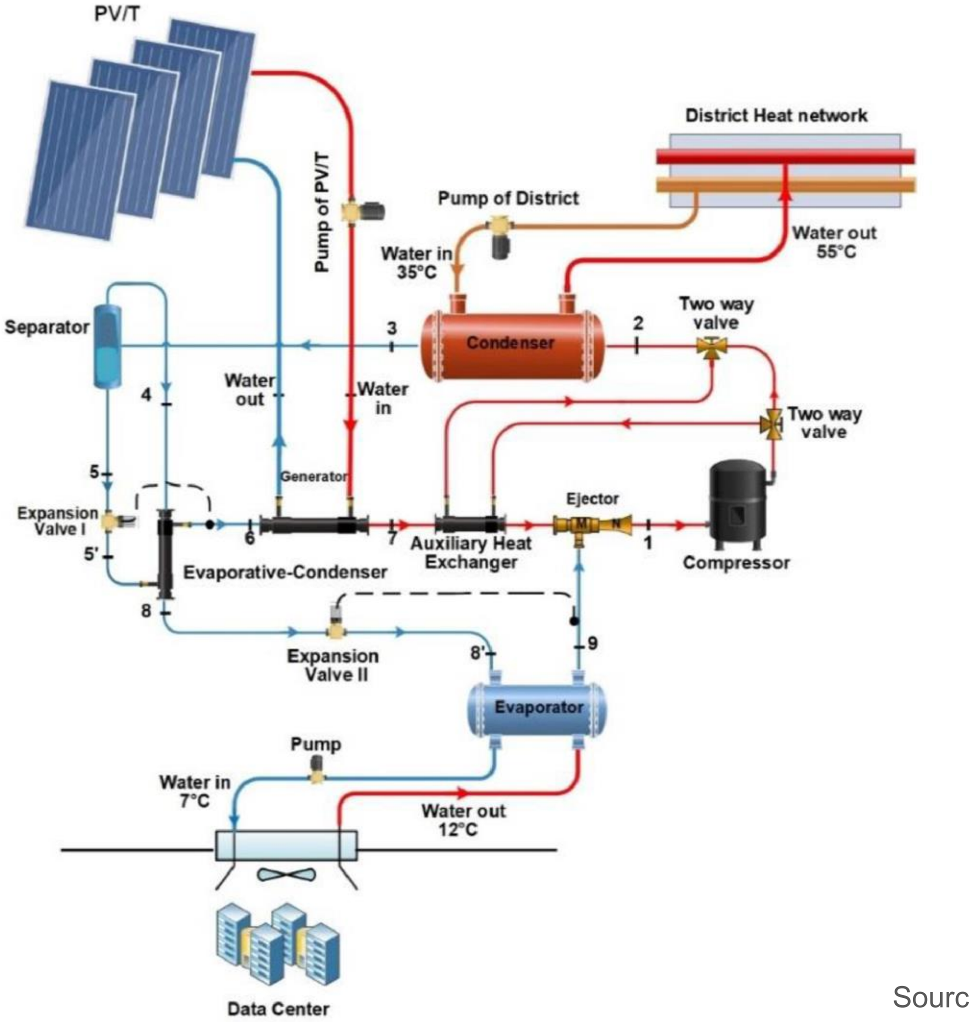
Heating mode with milk waste heat

Source: Al-Sayyab et al. (2021)

1.6. WASTE AND RENEWABLE HEAT

Example 2

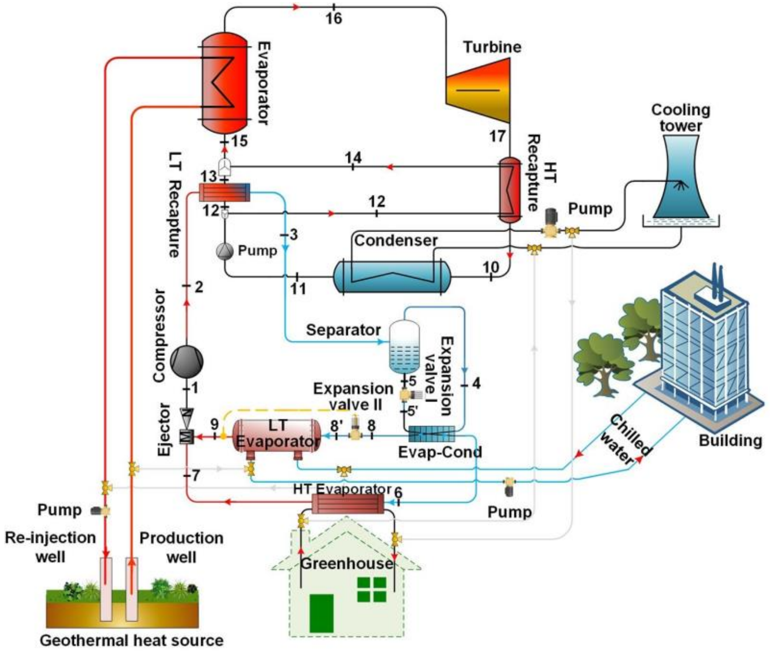
A novel compound PV/T (photovoltaic thermal) waste heat driven ejector-heat pump system for simultaneous data center cooling and waste heat recovery for district heating networks.



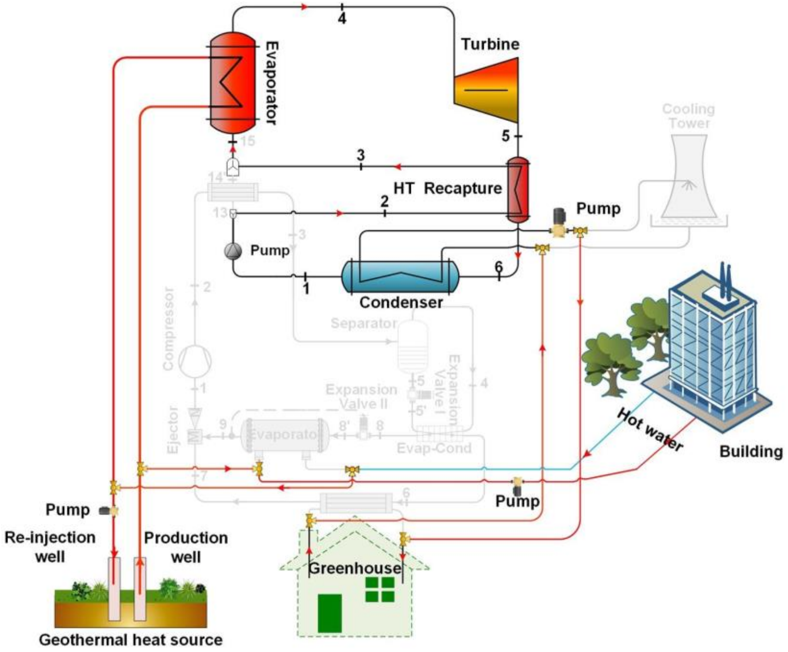
Source: Al-Sayyab et al. (2022)

1.6. WASTE AND RENEWABLE HEAT

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.



Combined power-cooling

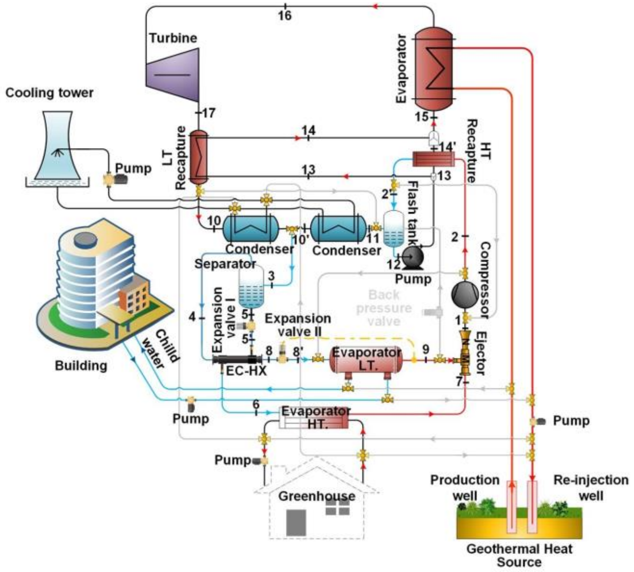


Combined power-heating

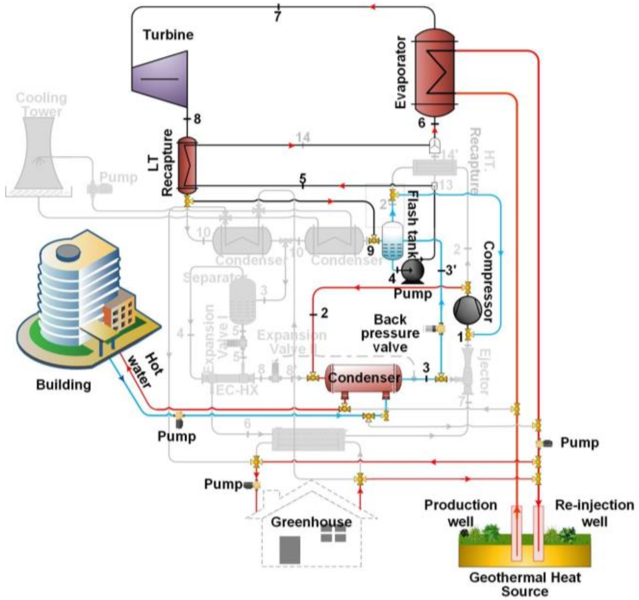
Source: Al-Sayyab et al. (2022)

1.6. WASTE AND RENEWABLE HEAT

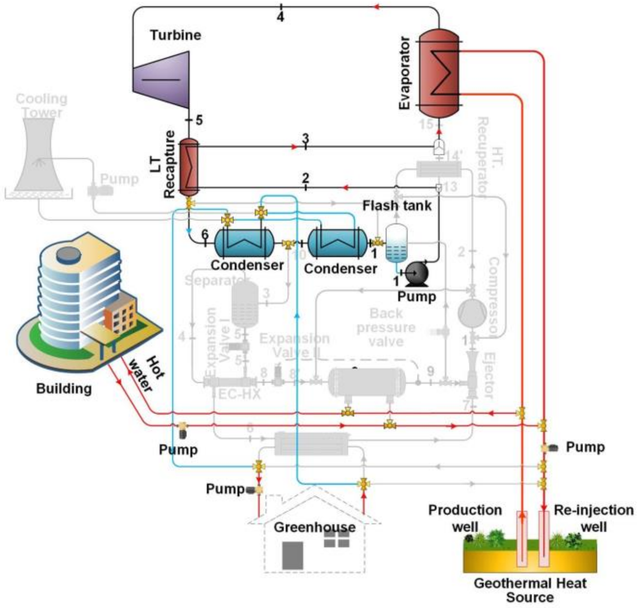
Example 4. An ORC combined with a compound greenhouse waste heat-driven ejector-VCC for energy-efficient power-cooling and heating.



Power-cooling



Power-heat pump heating



Power-ground source heating

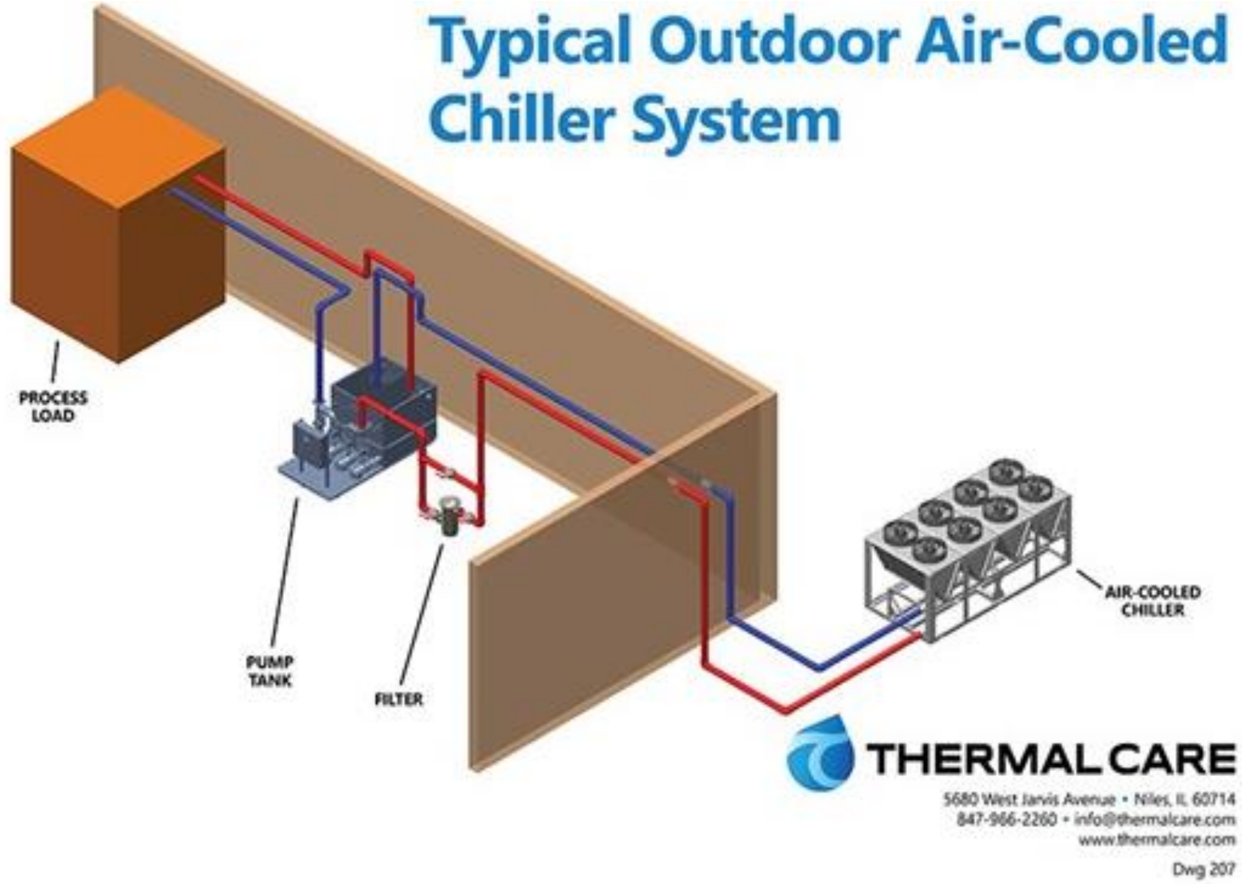
Source: Al-Sayyab et al. (2023)

1.7. CONCLUSIONS

- Simultaneous heating and cooling is possible with heat pumps/chillers
- It allows for maximizing the energy output of the heat pump. Otherwise, it would be wasted.
- DHN and DCN are ideally suited for maximizing profit and reducing the need for expensive peak shifting strategies or larger thermal energy storage.
- Heat pumps can use several compressor technologies, depending mainly on the unit's thermal capacity and the pressure ratio set by the application.
- Simultaneous heating and cooling contribute to better operational conditions for the heat pump.
- Energy efficiency is vital for making heat pumps competitive compared to boilers.
- 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

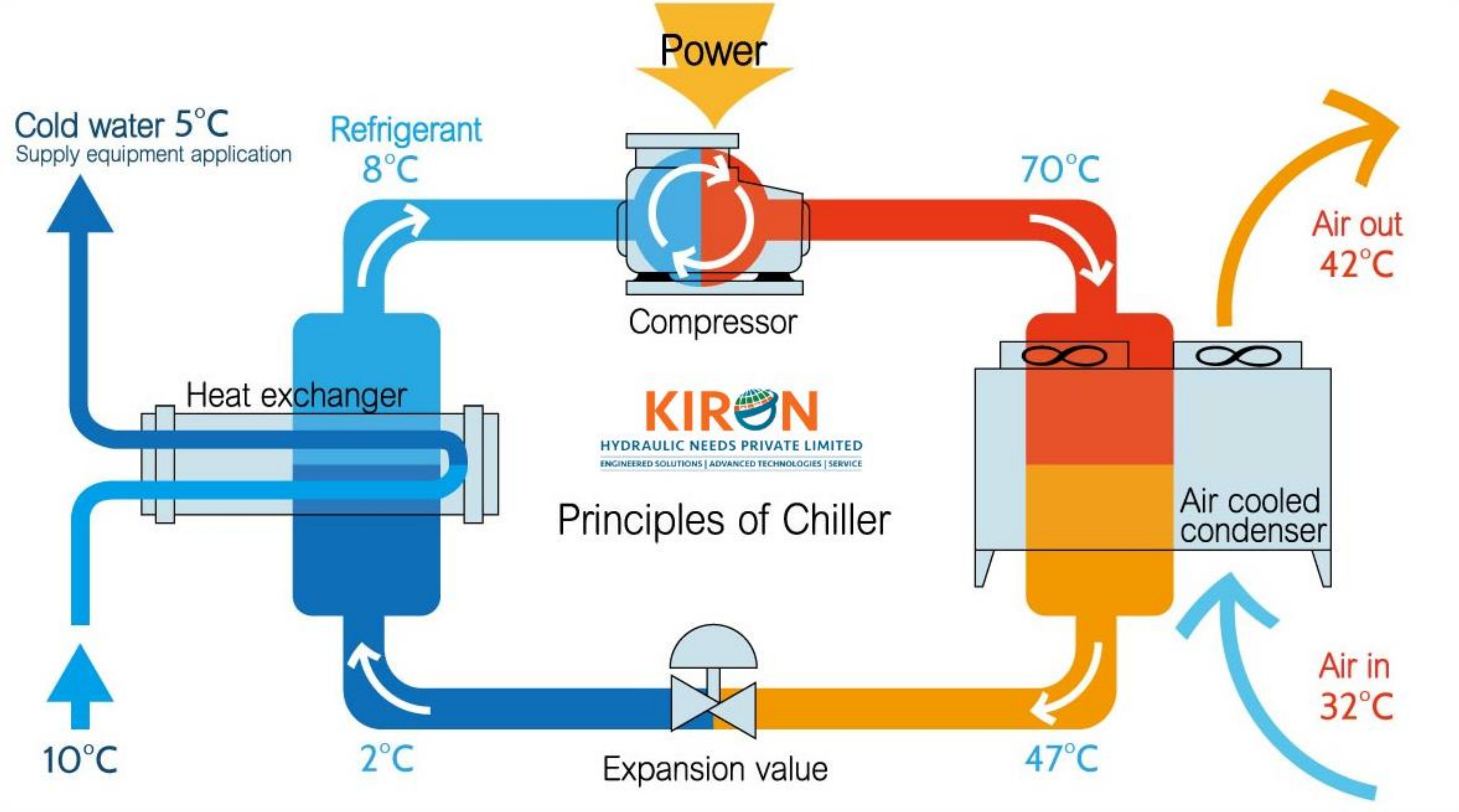
2.1. CHILLERS



Source: Thermal Care

2.1. CHILLERS

Operation



Source: Kiron Hydraulic Needs

2.1. CHILLERS

Types of Chillers

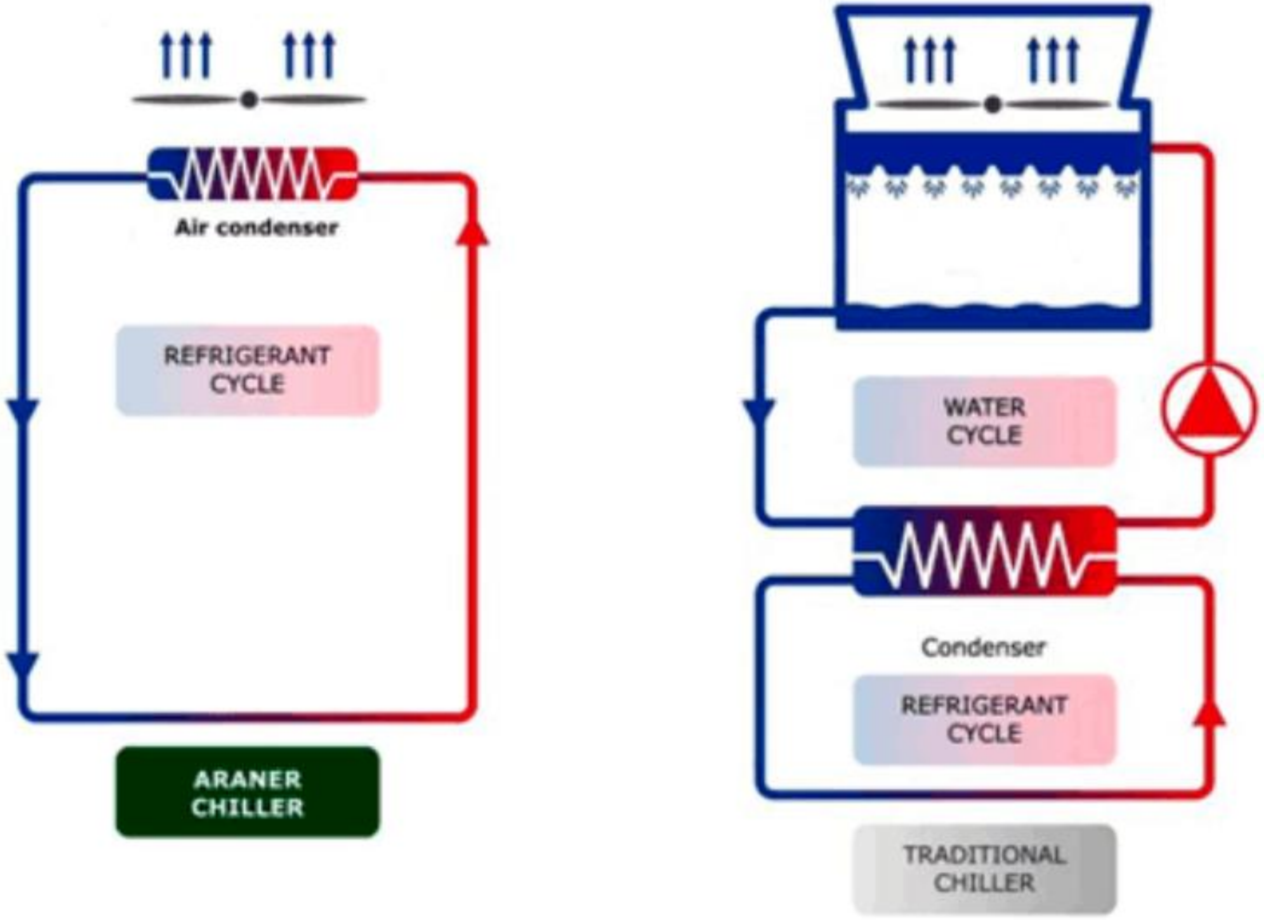
Chillers are classified based on how they dissipate heat:

1. Air-Cooled Chillers:

   1. Use fans to blow air over a condenser coil to release heat.
   2. Ideal for small to medium-sized systems or where water access is limited.
   3. Common in commercial HVAC systems.

2. Water-Cooled Chillers (Centrifugal):

   1. Use water and cooling towers to dissipate heat more efficiently.
   2. Suitable for large-scale industrial applications where greater efficiency is required.

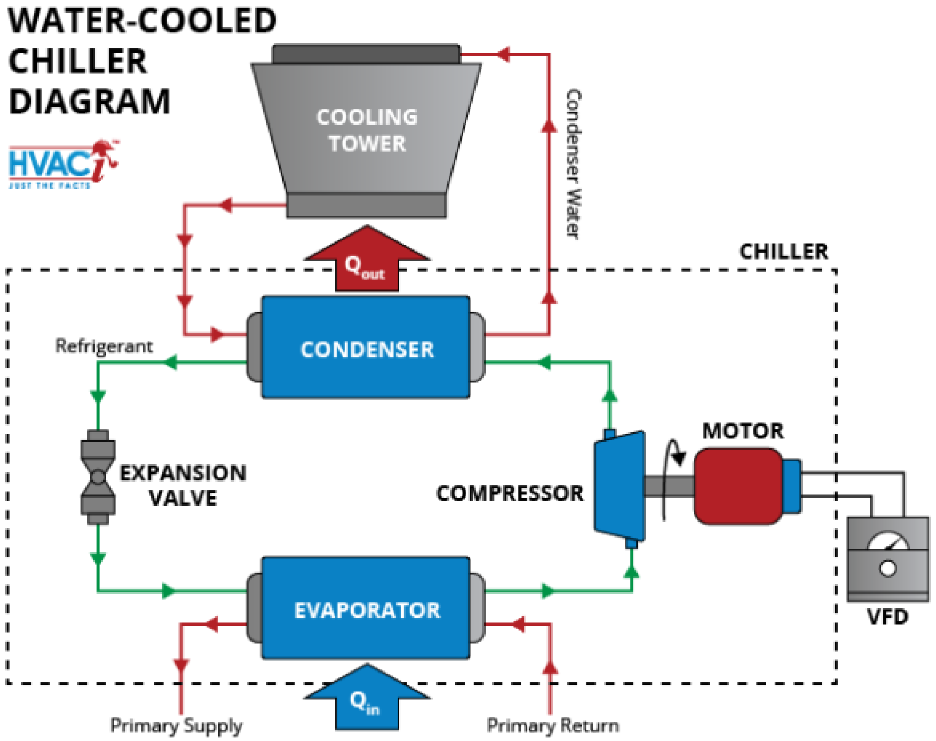


Source: Araner

2.1. CHILLERS

Water-cooled chiller

Range: 50 kW to 10000 kW



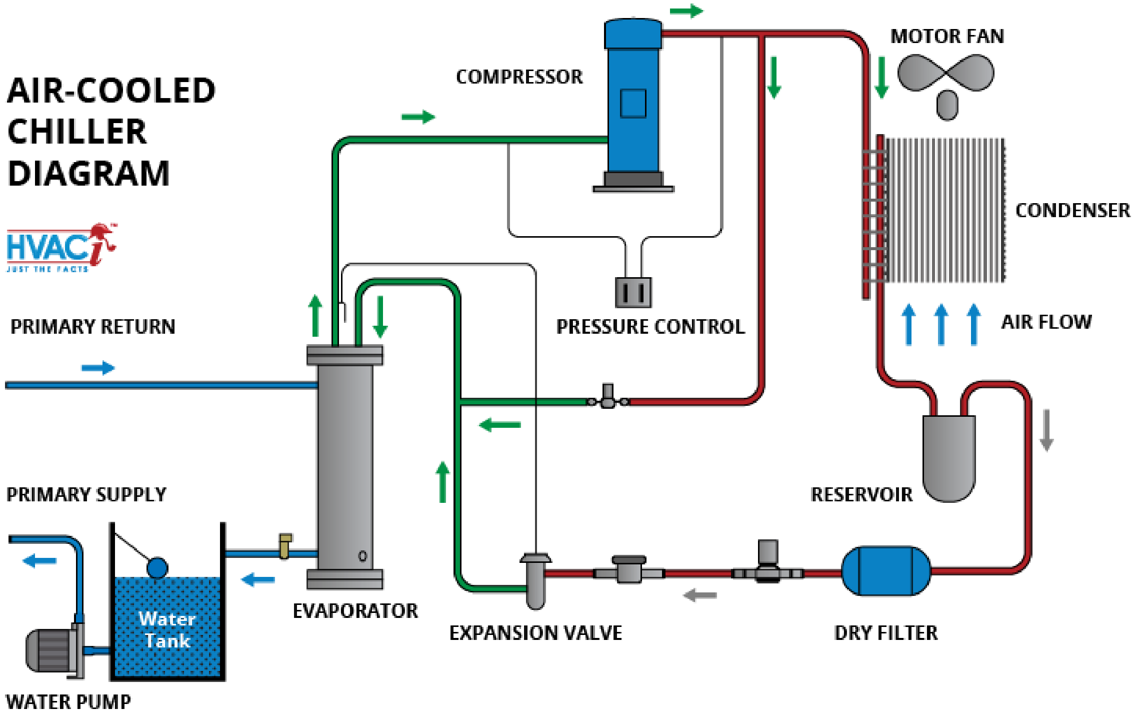
Source: Alpine Intel

Source: Carrier

2.1. CHILLERS

Air-cooled chiller

Range: 15 kW to 1500 kW



Source: Alpine Intel

Source: Aicool

2.1. CHILLERS

Key Metrics and Efficiency

- **Cooling Capacity (Q_o)**: Measured in tons of refrigeration or kilowatts (kW), indicating the amount of heat removed.
- **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.
- **Energy efficiency ratio (EER)**: A measure of efficiency calculated as the ratio of cooling provided to energy consumed (kW cooling / kW electricity).

$$EER = \frac{\dot{Q}_o}{\dot{W}_c}$$

- **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. CHILLERS

Seasonal energy efficiency ratio (SEER)

- SEER uses a set indoor temperature, along with different outdoor temperatures and load capacities to simulate real life.
- The EN 14825 standard defines the test methodology.

		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

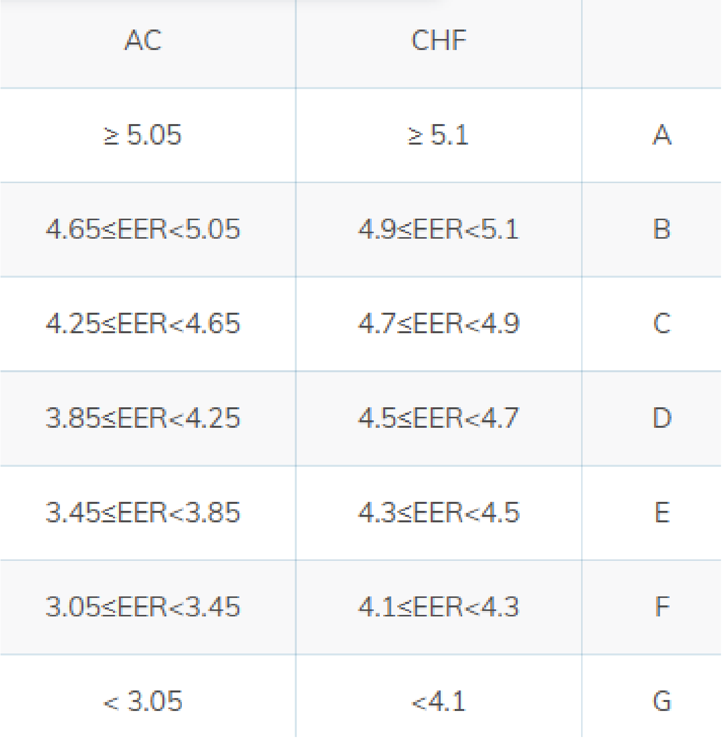
- Energy efficiency class depends on SEER and type of equipment. Between A+++ and G, being the first the most efficient classification.

2.1. CHILLERS

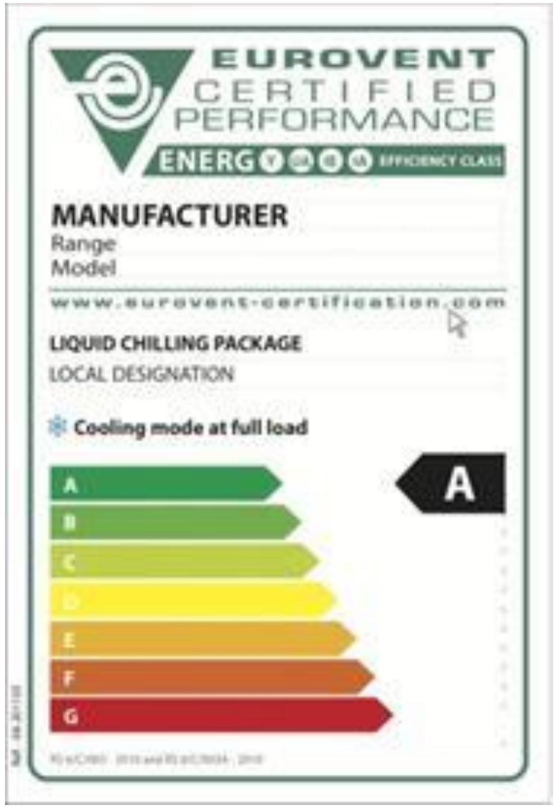
System performance

It depends on:

- Good design and professional installation of the entire system.
- Regular maintenance.
- The size of the building being conditioned and its energy efficiency.
- The size of the system and its air handling capacity.
- The amount of time the system is used daily.
- The indoor temperature.
- The outdoor air temperature.



AC	CHF	
≥ 5.05	≥ 5.1	A
4.65≤EER<5.05	4.9≤EER<5.1	B
4.25≤EER<4.65	4.7≤EER<4.9	C
3.85≤EER<4.25	4.5≤EER<4.7	D
3.45≤EER<3.85	4.3≤EER<4.5	E
3.05≤EER<3.45	4.1≤EER<4.3	F
< 3.05	<4.1	G



2.1. CHILLERS

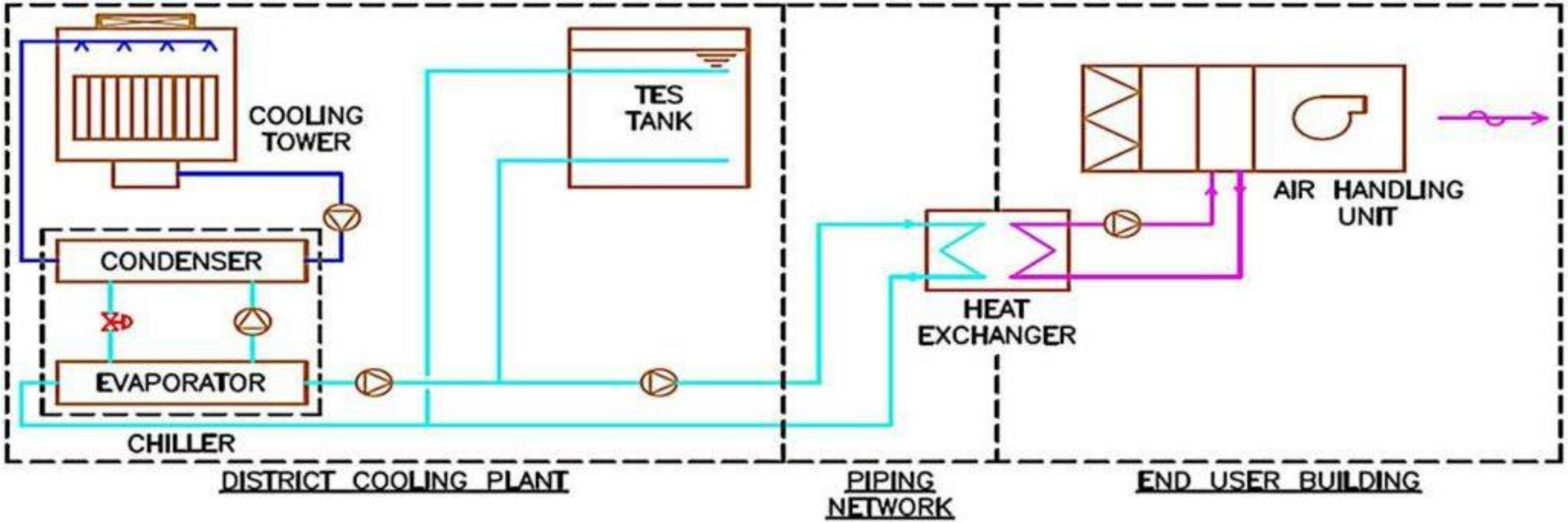
Applications of Chillers

- HVAC Systems
- Industrial Processes (Food processing, plastic processing, metal finishing…)
- Data Centers
- Refrigeration
- Healthcare
- Power plants
- Ice rinks
- **District Cooling**

Source: Cold Shot Chillers

2.1. CHILLERS

Integration of Chillers into DCN



Source: District Cooling

2.2. ABSORPTION REFRIGERATION MACHINES

Absorption refrigeration

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.

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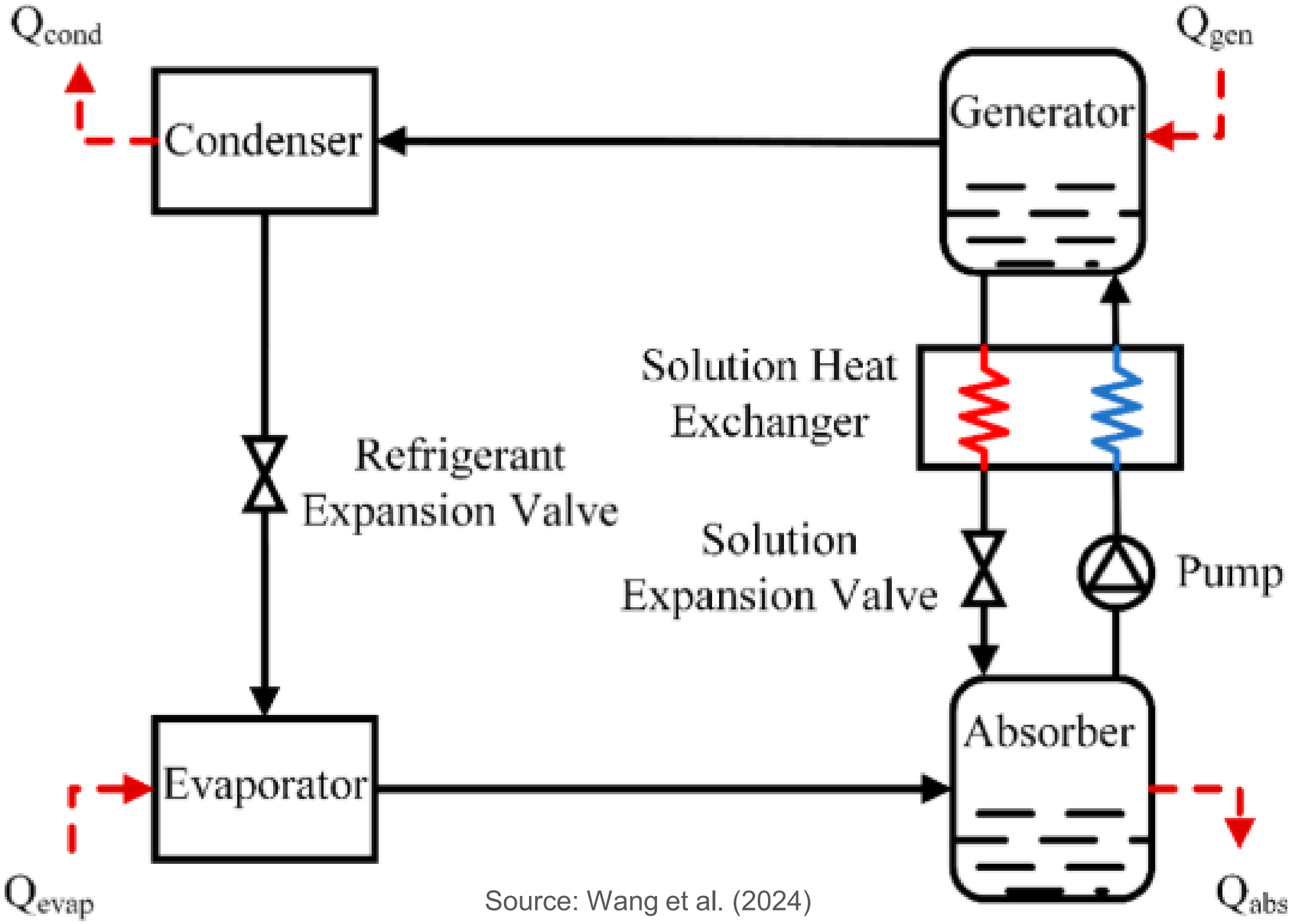


Source: Wang et al. (2024)

2.2. ABSORPTION REFRIGERATION MACHINES

Types of Absorption Refrigeration Systems

Two main refrigerant/absorbent pairs are used based on temperature range:

1. **Ammonia–Water (NH_3–H_2O)** – for applications below 50 °C
   Ammonia acts as the refrigerant, water as the absorbent. Common in industrial cooling.

   Pros: High performance in low-temperature applications

   Cons: Water is volatile, requiring a rectifier; system is complex. Ammonia is flammable, toxic, and incompatible with copper/brass, so systems are built from steel.

2. **Water–Lithium Bromide (H_2O–LiBr)** – for applications above 50 °C
   Water is the refrigerant, LiBr the absorbent. Widely used in air conditioning and hot water for large buildings.

   Pros: High safety, stability, strong affinity, and latent heat; adjustable load via absorbent reconcentration

   Cons: Risk of crystallization near 0 °C; operates under vacuum; high viscosity; air leakage risk.

2.2. ABSORPTION REFRIGERATION MACHINES

Relevant Parameters

Cooling Capacity (Q_o): The amount of heat removed by the evaporator from the space or process being cooled, typically measured in kW.

Heat Input (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.

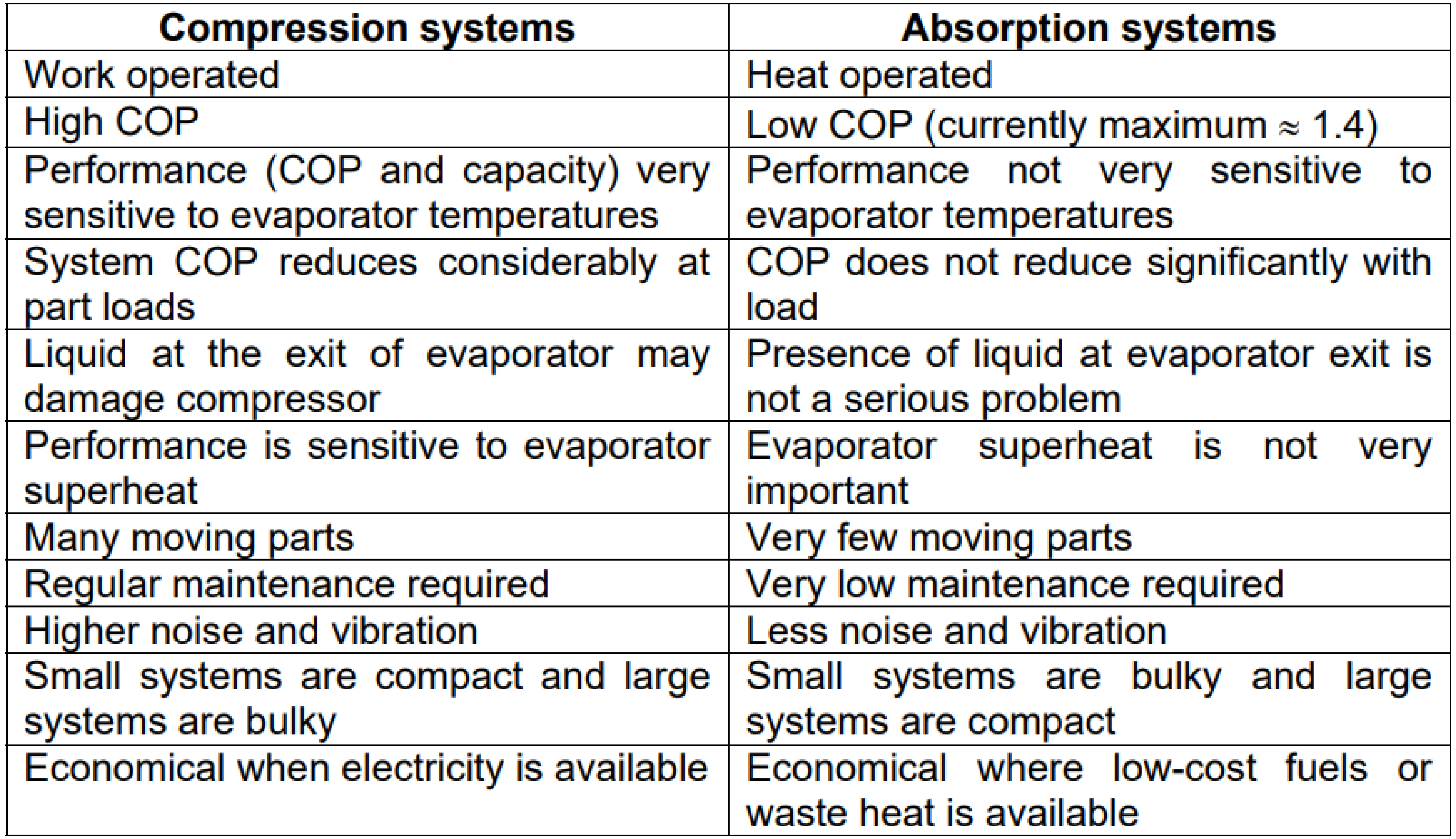
Coefficient of Performance (COP): The cooling capacity (Qo) ratio to the heat input (Q_g).

$$COP = \frac{Q_o}{Q_g}$$

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.

2.2. ABSORPTION REFRIGERATION MACHINES

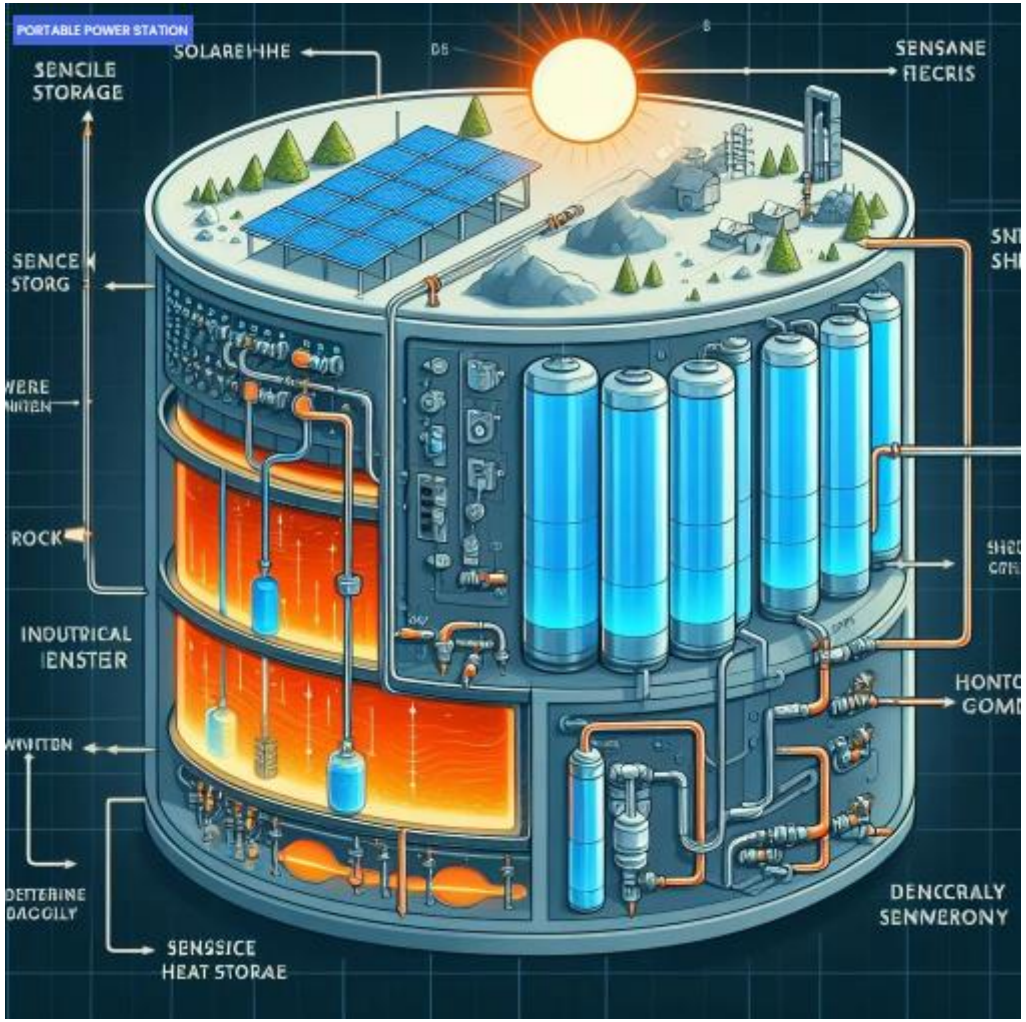
Compared to vapor compression systems:



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

2.3. THERMAL ENERGY STORAGE (TES)

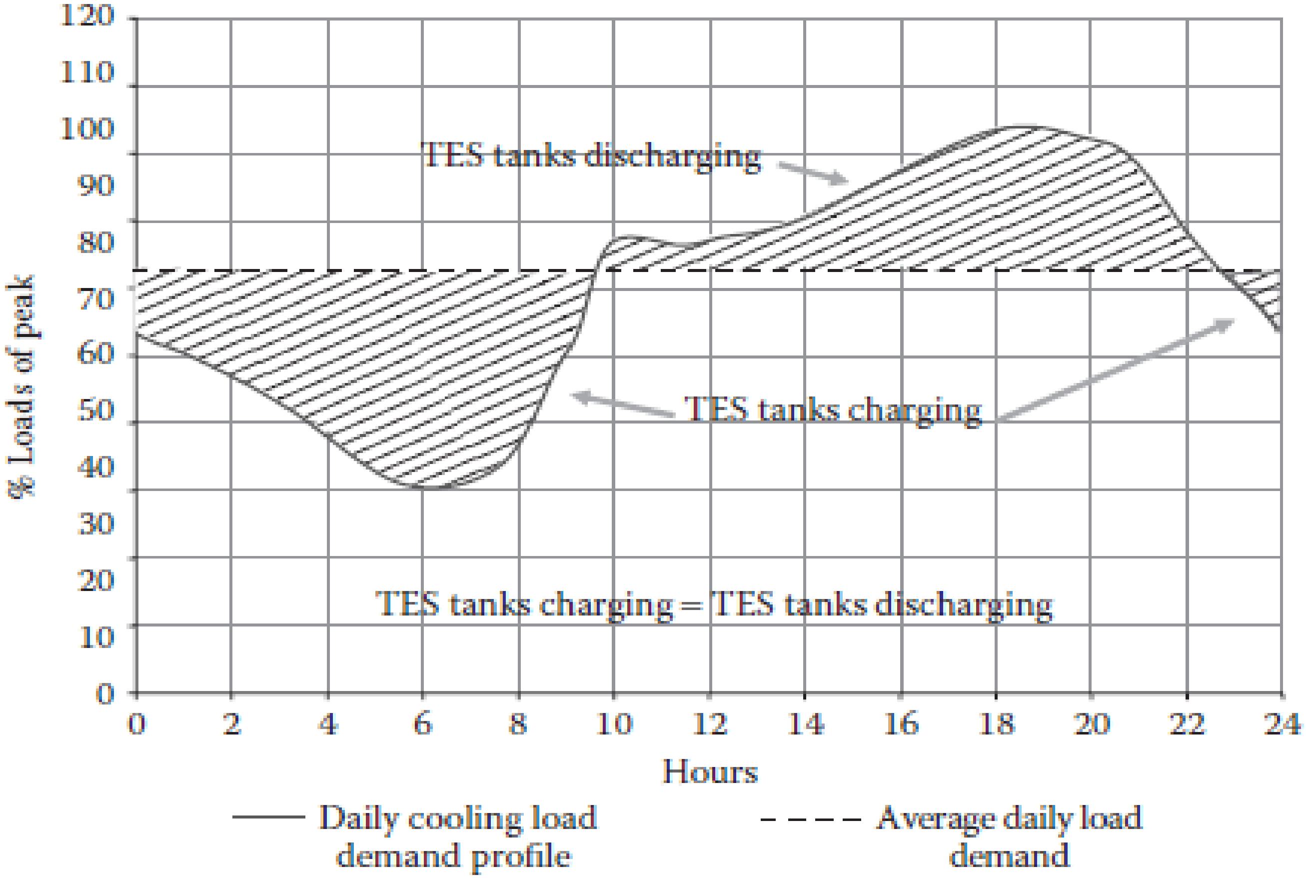
Introduction to TES



2.3. THERMAL ENERGY STORAGE (TES)

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).
- 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.



Source: Ghajar et al. (2018)

2.3. THERMAL ENERGY STORAGE (TES)

Type of TES

	Ice storage tank	**Chilled water storage tank**	**Low-temperature liquid storage tank**
Type of storage	Latent heat	Sensible heat	Latent heat
Discharge temperature	1ºC to 7ºC	4ºC to 6ºC	-1ºC to 2ºC
Recharge temperature	-8ºC to -2ºC	4ºC to 6ºC	-1ºC to 2ºC
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)

(ASHRAE, 2013)

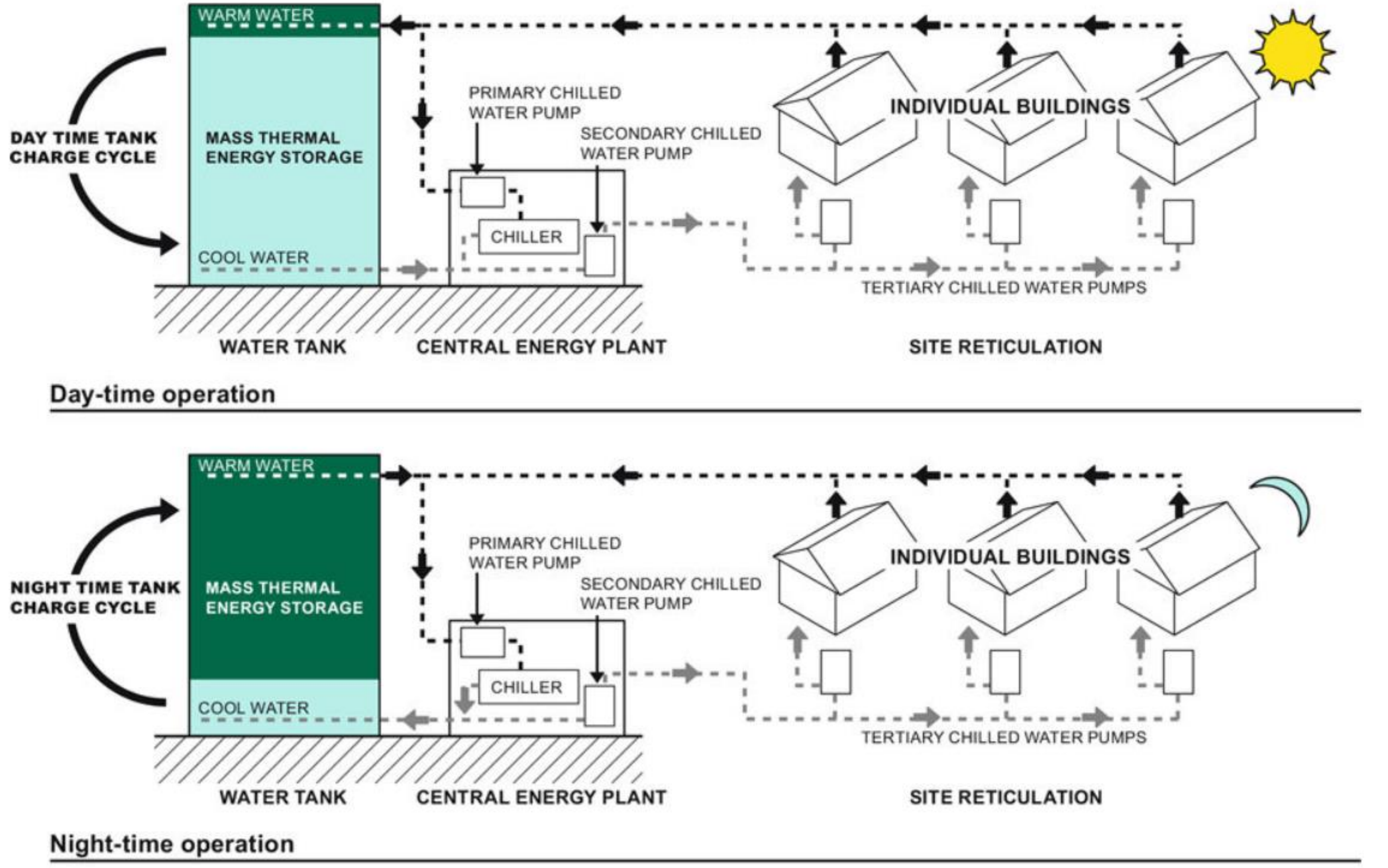
2.3. THERMAL ENERGY STORAGE (TES)

Applications

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

2.3. THERMAL ENERGY STORAGE (TES)

Integration of TES into DCN



Source: Thirkell

2.3. THERMAL ENERGY STORAGE (TES)

General benefits of integration of TES into DCN:

- 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.

- **Operational costs are reduced** compared to an online cooling system because peak consumption can be avoided during high electrical tariff periods.

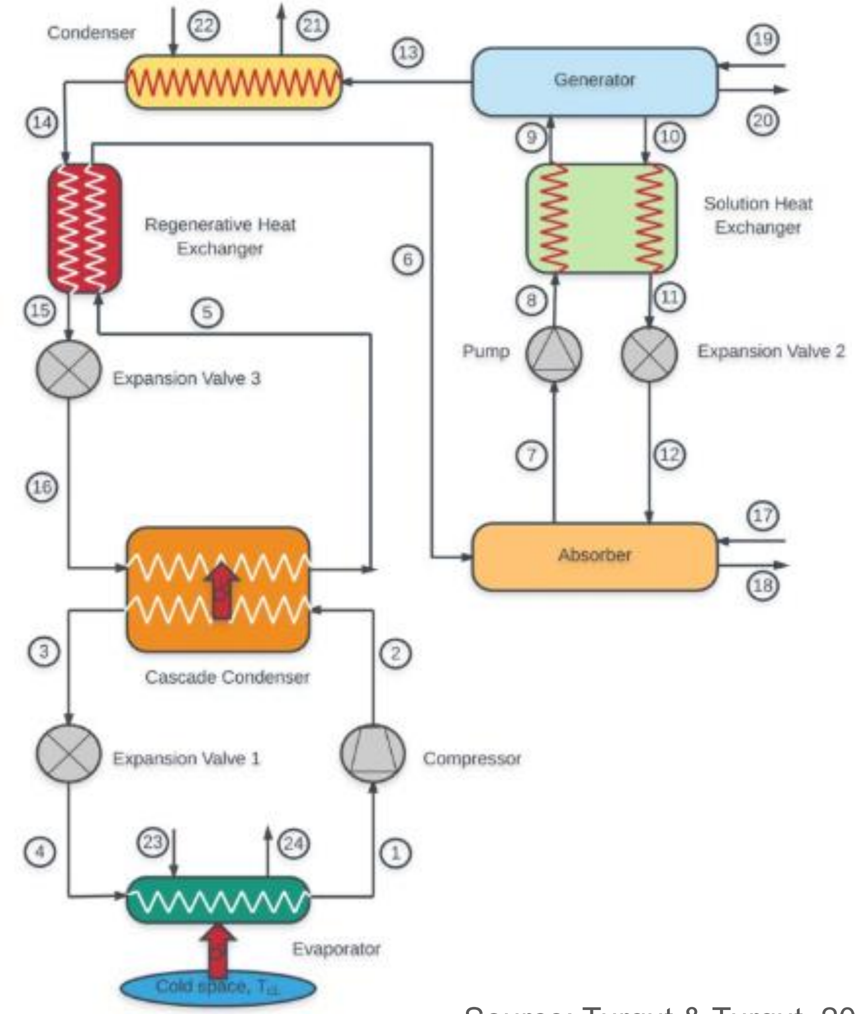
- The environmental impact is reduced because of the reduction of CO_2. Storing the energy and improving operating efficiency with the thermal energy storage tank helps **reduce the CO_2 emissions** of a district cooling system even more.

- 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.

Source: Araner

4. COMBINATION OF MECHANICALLY DRIVEN SYSTEMS AND THERMAL ENERGY-DRIVEN ABSORPTION SYSTEMS

Introduction



Source: Turgut & Turgut, 2019

2.4. COMBINATION OF MECHANICALLY DRIVEN SYSTEMS AND THERMAL ENERGY-DRIVEN ABSORPTION SYSTEMS

Key parameters

In this case, the COP considers the whole system inputs and outputs:

- COP_c: combined coefficient of performance (whole system)
- $Q_{cas,\ cond}$: cascade condenser load
- Q_g: heat load input
- W_c: compressor power consumption
- W_p: pump power consumption

$$COP_C = \frac{Q_{cas,cond}}{(Q_g + W_C + W_P)}$$

Source: Turgut & Turgut, 2019

2.4. COMBINATION OF MECHANICALLY DRIVEN SYSTEMS AND THERMAL ENERGY-DRIVEN ABSORPTION SYSTEMS

Applications of this system

- Industrial Refrigeration
- District Cooling Systems
- Combined Heat and Power (CHP) Plants
- Combined Heating and Cooling (CHC)
- Chemical and Petrochemical Industries
- Data Centers

District Heating and Cooling with Waste Heat Recovery

- Refrigerated Transport
- Ice Rinks and Sports Arenas
- Pharmaceutical and Medical Applications
- 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 present significant differences in advantages and drawbacks.
- COP and EER quantify the nominal operation of the heat pumps and chillers.
- Seasonal COP and EER consider round-season operation, providing a more detailed picture of the actual consumption.
- Absorption chillers activate using heat instead of electricity. They can be gas-fueled, but their sustainability is maximized when combined with renewable, waste heat, or district heating networks.
- Two fluids in absorption chillers must be considered for the particular application.
- Thermal energy storage is considered sensible heat storage (hot water tank). However, phase change materials and thermochemical energy storage are promising in the mid and long-term.
- A combination of vapor compression and absorption systems can maximize cooling generation. This is particularly useful in simultaneous heating and cooling applications for diversifying thermal energy production and peak shifting.

3. REFRIGERANTS

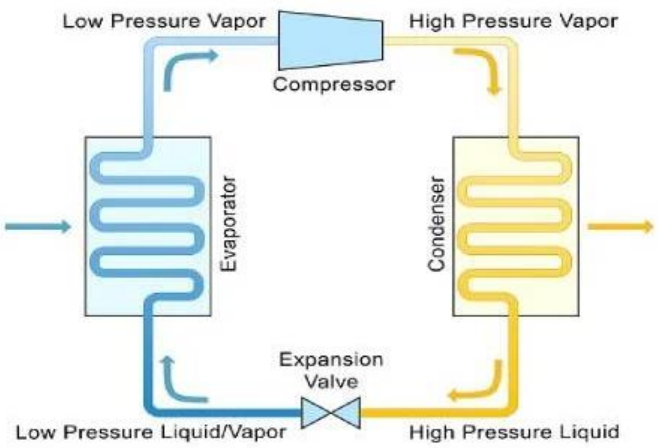
3.1. INTRODUCTION TO REFRIGERANTS

Definition:

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

- **absorb heat at a low temperature and pressure and**
- **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.



Source: Super Radiator Coils

Source: Yueon

Source: Advanced Commercial Group

3.1. INTRODUCTION TO REFRIGERANTS

Primary refrigerant vs. **Secondary refrigerant**

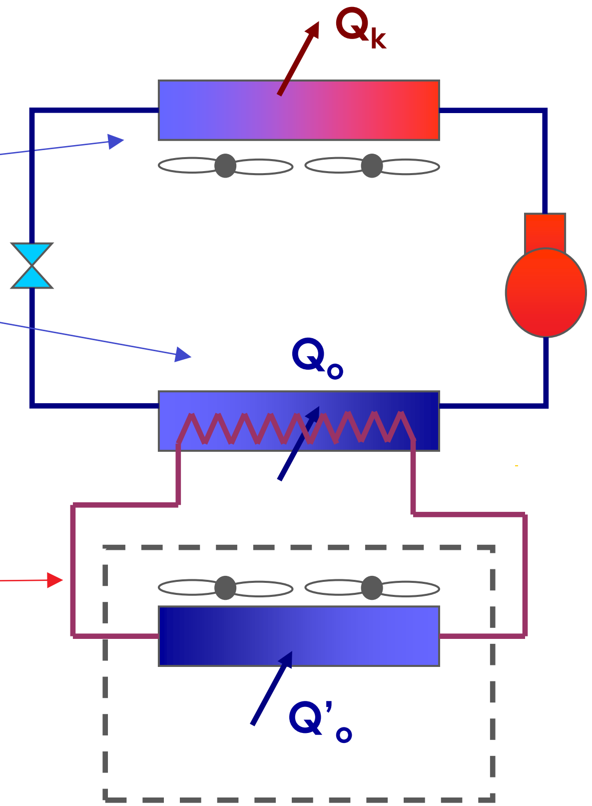
Primary refrigerant, also known as working fluid.

- *Rejects heat at **higher pressure**/temperature*
- *Absorbs it at a **lower pressure**/temperature*

Secondary refrigerant, also known as:

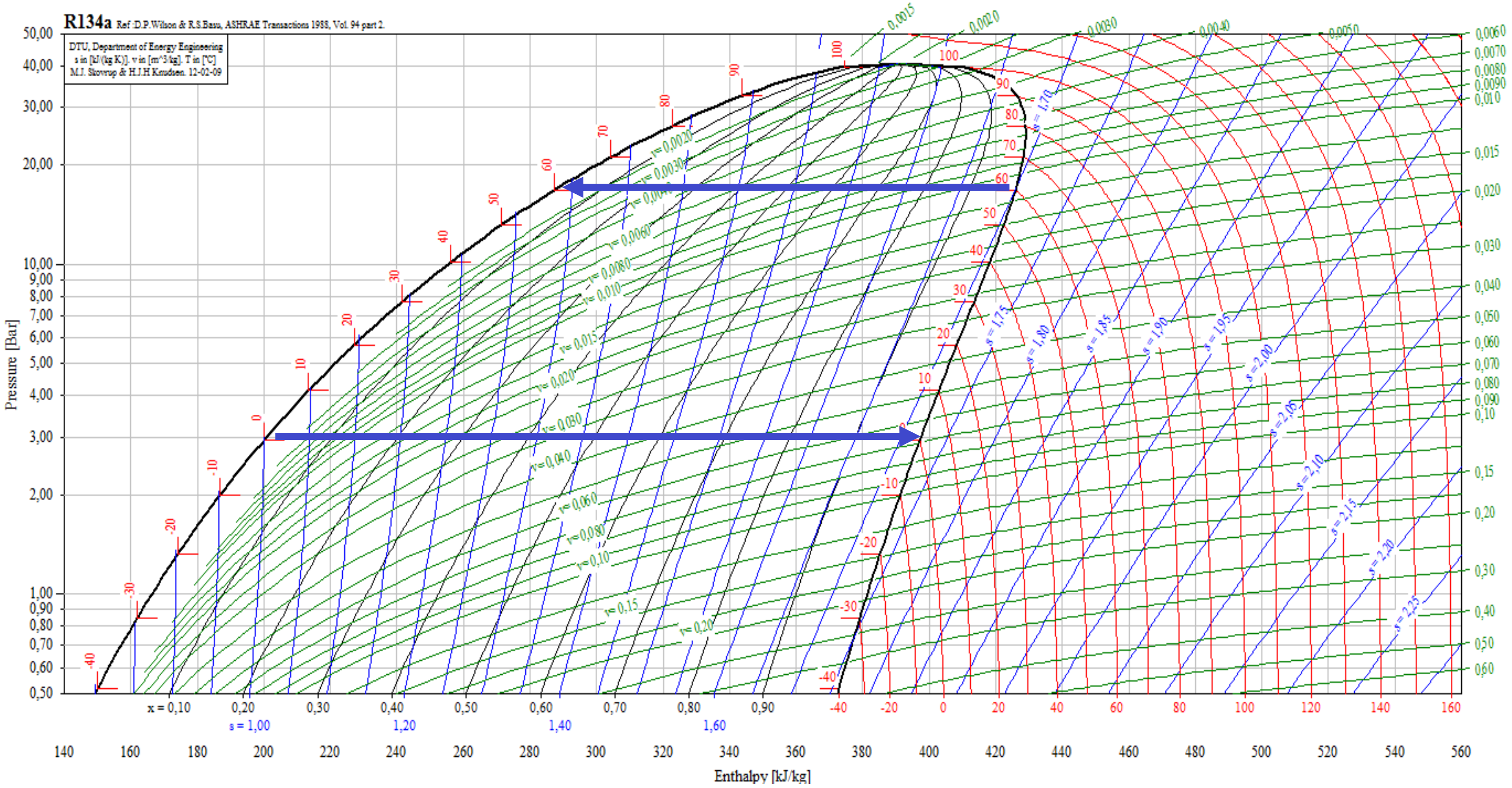
- Secondary fluid
- Seconday coolant
- Heat transfer fluid

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



3.1. INTRODUCTION TO REFRIGERANTS

Basic classification



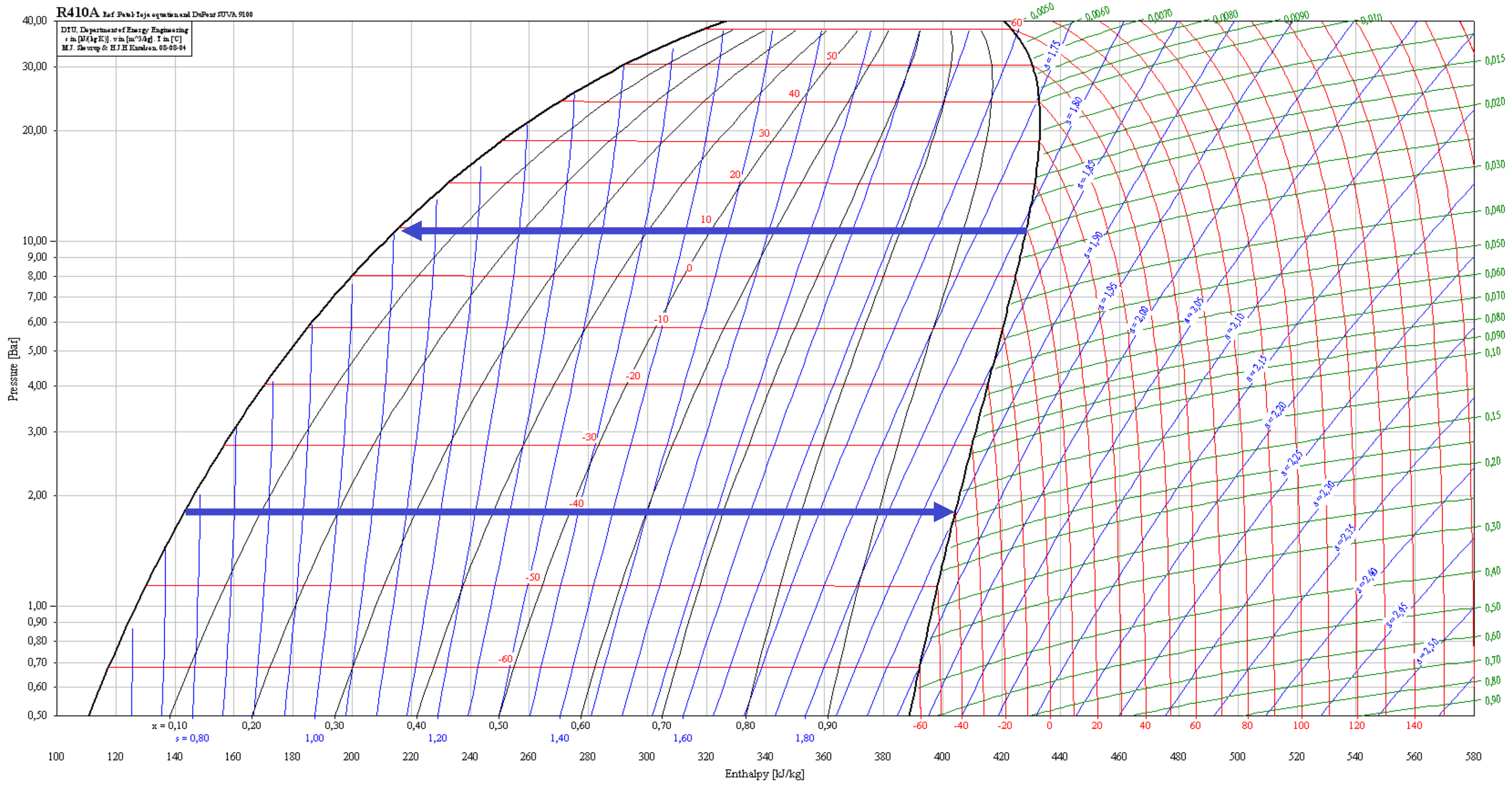
Pure Fluid: Pressure and temperature are constant under phase change, so one can define the other.

During phase change:

P→T and T→P

3.1. INTRODUCTION TO REFRIGERANTS

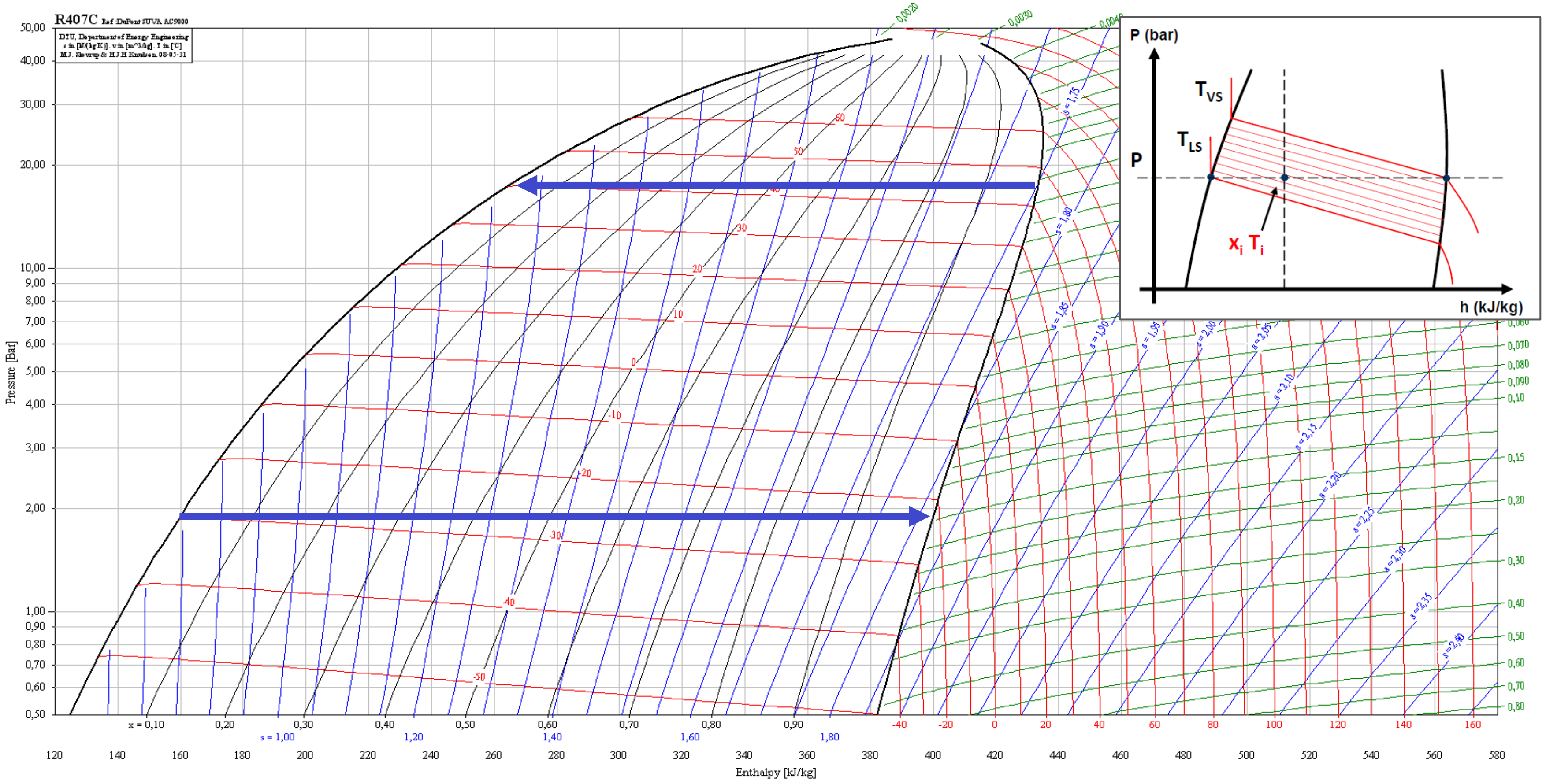
Basic classification



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

3.1. INTRODUCTION TO REFRIGERANTS

Basic classification



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

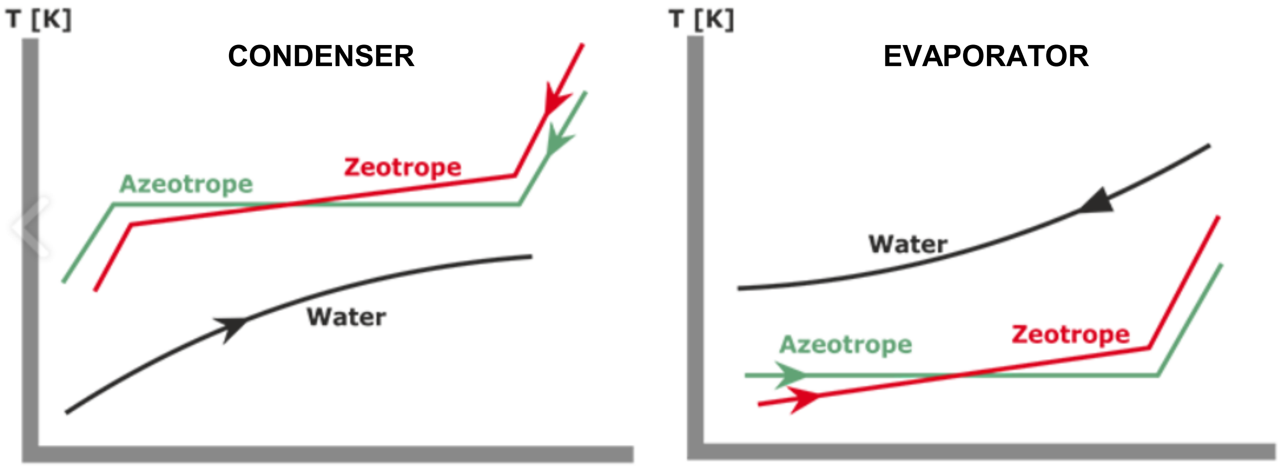
3.1. INTRODUCTION TO REFRIGERANTS

Basic classification

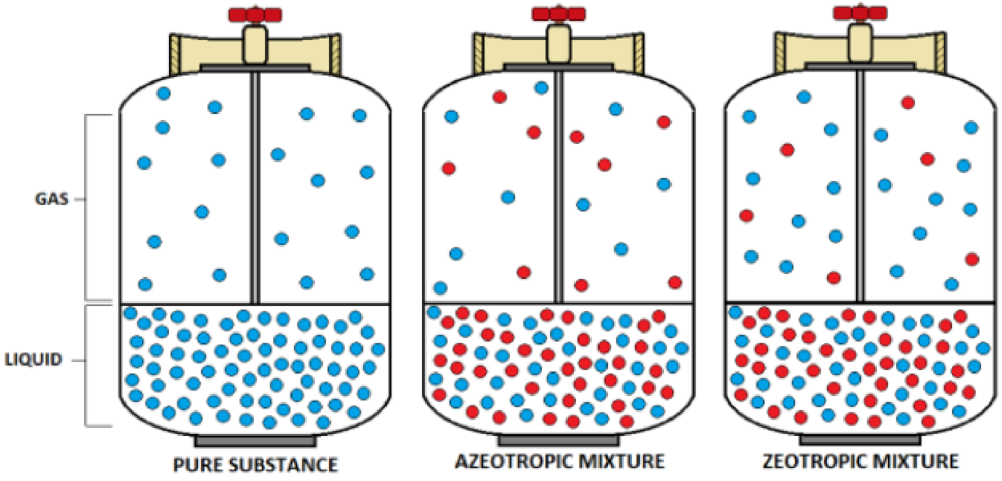
Mixtures:

Zeotropic mixtures requires 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.

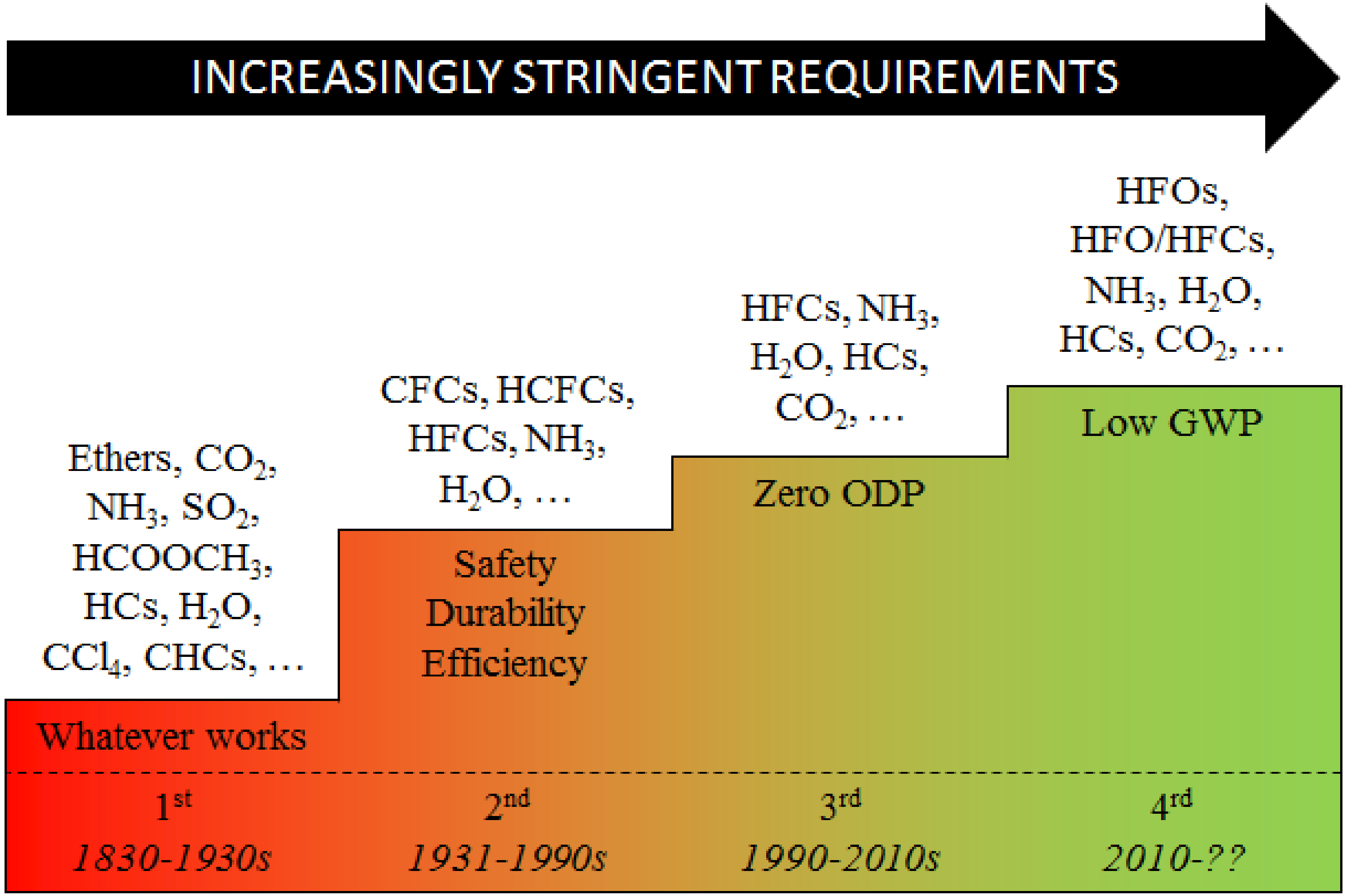


Source: Swep



Source: Silva-Alvarado et al. (2022)

3.2. HISTORY AND EVOLUTION



INCREASINGLY STRINGENT REQUIREMENTS

Ethers, CO_2, NH_3, SO_2, $HCOOCH_3$, HCs, H_2O, CCl_4, CHCs, …

Whatever works

1st

1830-1930s

CFCs, HCFCs, HFCs, NH_3, H_2O, …

Safety
Durability
Efficiency

2nd

1931-1990s

HFCs, NH_3, H_2O, HCs, CO_2, …

Zero ODP

3rd

1990-2010s

HFOs, HFO/HFCs, NH_3, H_2O, HCs, CO_2, …

Low GWP

4rd

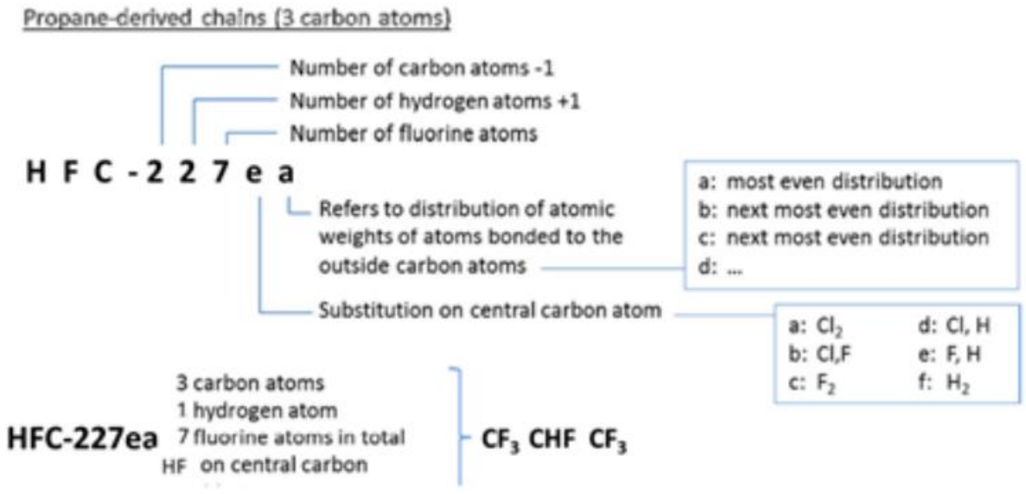
2010-??

Adapted from Calm (2008)

3.3. DESIGNATION AND PROPERTIES

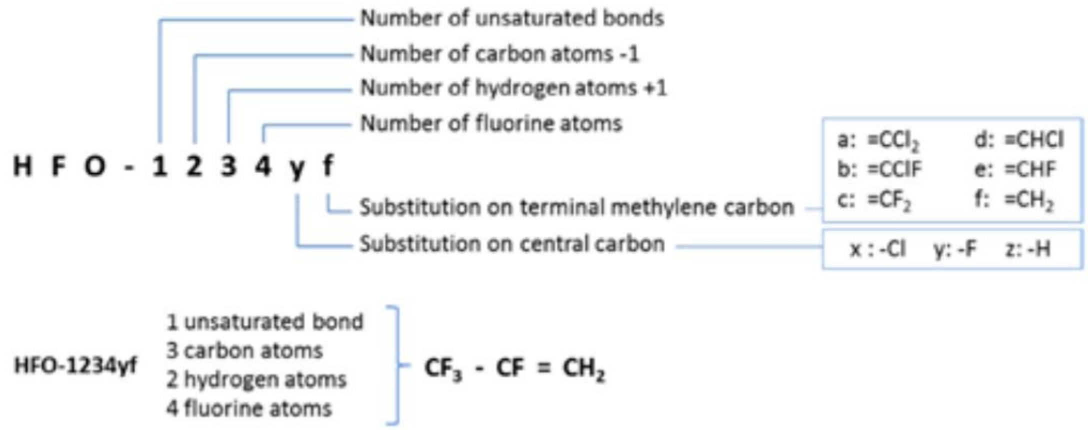
Designation

ASHRAE Standard 34- provides a naming system for common refrigerants and assigns safety classifications to them.



Source: EFCTC (fluorocarbons.org)

Hydrofluoro-olefins, isomers and stereo-isomers



For **double bonds**, **cis** (substitutes on the same the same side of the double bond) and **trans** configurations (substitutes on opposite sides of the double bond) may need to be indicated.

For HFO-1336mzz(Z), the **‘m’ indicates CF3** (letters from a to l indicate other groups) and the **two ‘z’ s indicate H on the central carbon C=C**

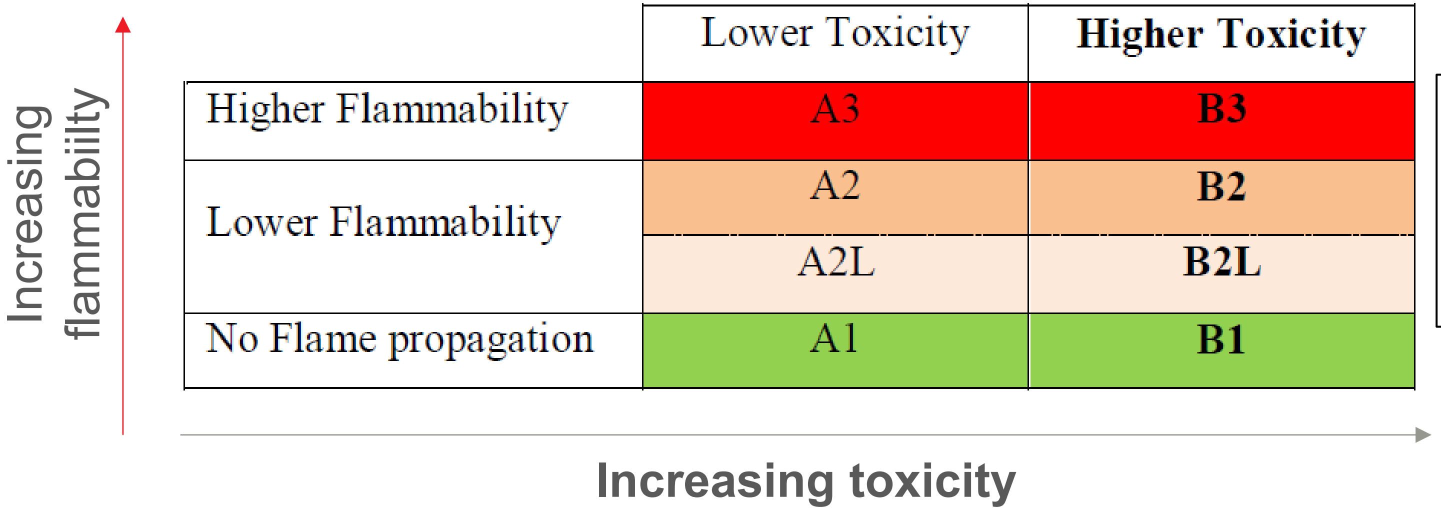
3.3. DESIGNATION AND PROPERTIES

Properties: Safety

Toxicity

Flammability

Defined by ASHRAE 34 (International), then EN378 (Europe), then depends on the country



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

Increasing toxicity

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

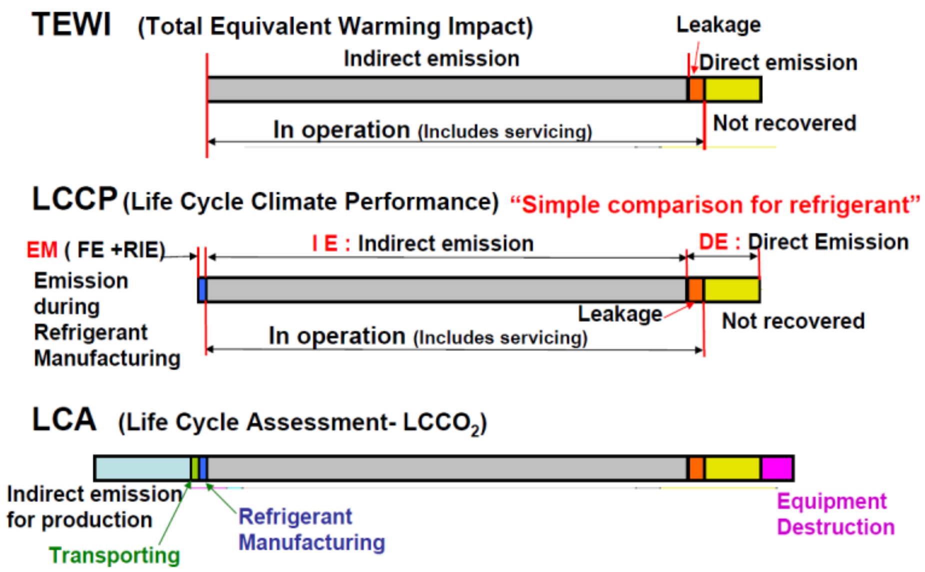
A: Toxicity has not been identified at concentrations ≤ 400 ppm by vol.

3.4. ENVIRONMENTAL IMPACT

Environmental metrics summary

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

Graphical representation for CO_2 equivalent emissions:



3.4. ENVIRONMENTAL IMPACT

GWP

$$\mathrm{GWP}_{\mathrm{gas},t} = \frac{\int_0^t a_{\mathrm{gas}} \cdot C_{\mathrm{gas}}(t)\, dt}{\int_0^t a_{\mathrm{CO_2}} \cdot C_{\mathrm{CO_2}}(t)\, dt}$$

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

TEWI = Direct Emissions + Indirect

$$\mathrm{LCA}_{\mathrm{total}} = \sum_{i=1}^{n} \mathrm{Inventory}_i \times \mathrm{Impact\ Factor}_i$$

3.5. CURRENT REFRIGERANTS AND APPLICATIONS

Most regulations over time

Montreal Protocol (1987)

Kyoto Protocol (1995)

F-gas Regulation and MAC Directive (2006)

F-gas Regulation (2014)

Paris Agreement (2015)

Kigali Amendment to the MP (2016)

F-gas revision (2024)

Ozone protection
HCFC and CFC
HFC

Climate change
HFC
HFO, NatRef

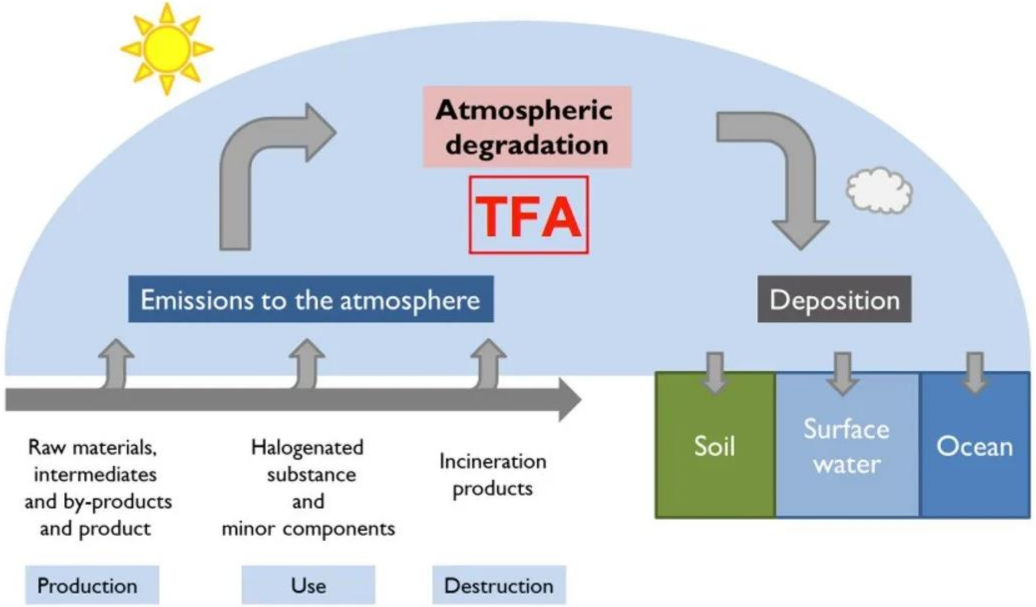
PFAS & TFA
HFO??
NatRef

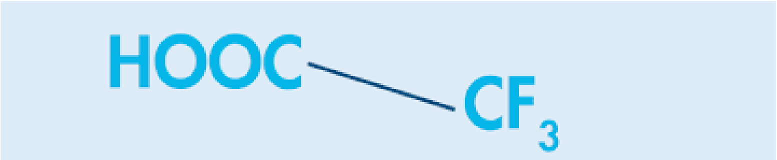
3.5. CURRENT REFRIGERANTS AND APPLICATIONS

TFA

Trifluoroacetic acid (TFA): organofluorine compound CF3CO2H

- Formed from atmospheric decomposition of refrigerants (degradation product).
- Report from the German Federal Environment Agency.
- 5% of human origin (manufacturing, agriculture, wastewater treatment and refrigerants).
- **R1234yf produces 100% TFA, R134a between 7 and 20%, R1234ze(E) less than 10%**
- **R1336mzz(Z) produces less than 20%, R1233zd(E) only 2%.**





3.5. CURRENT REFRIGERANTS AND APPLICATIONS

PFAS

Perfluorinated and polyfluorinated alkyl substances (PFAS)

- Over 4,700 “forever chemicals”
- PFAS can be harmful to human health.
- They cover a range of fluorinated gases, including certain HFCs (R134a, R125, R143a, and R152a) and HFOs (R1234yf, R1234ze(E), and R1233zd(E)) used in HVAC&R applications. TFA is a PFAS (CF3- and CF2-)
- The state of Maine, USA, became the first government to ban the sale of products containing PFAS as of January 1, 2030
- See Report Norwegian Environment Agency

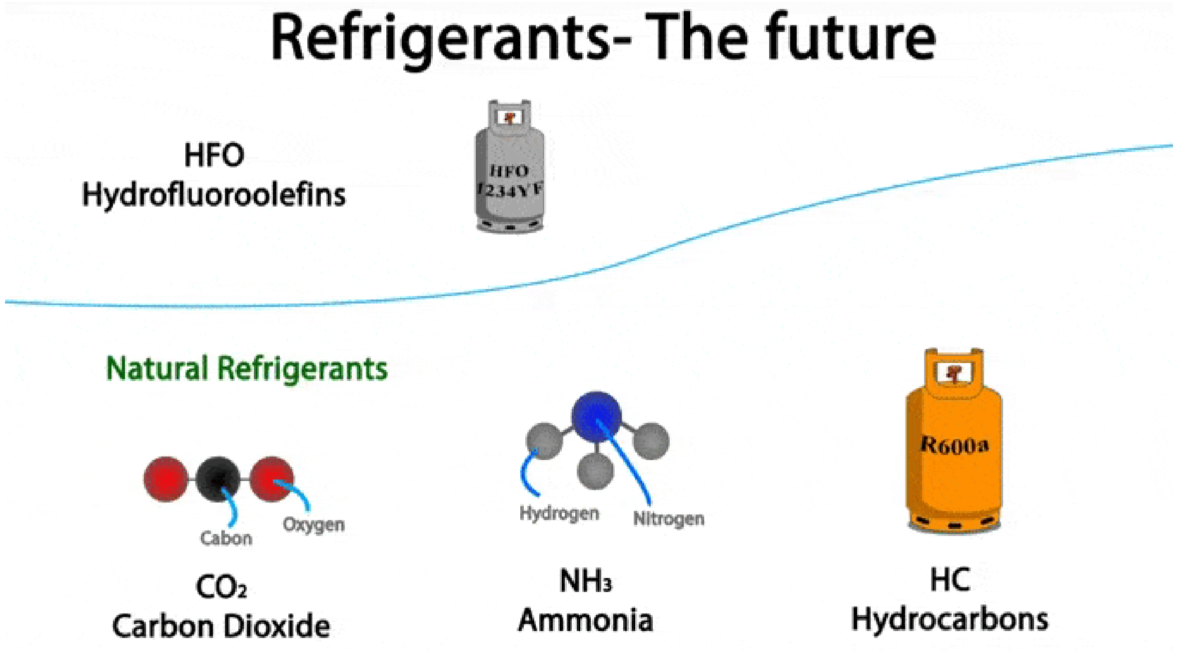
3.5. CURRENT REFRIGERANTS AND APPLICATIONS

Natural refrigerants

Natural refrigerants are seen as a safer and more sustainable option to replace HFOs.

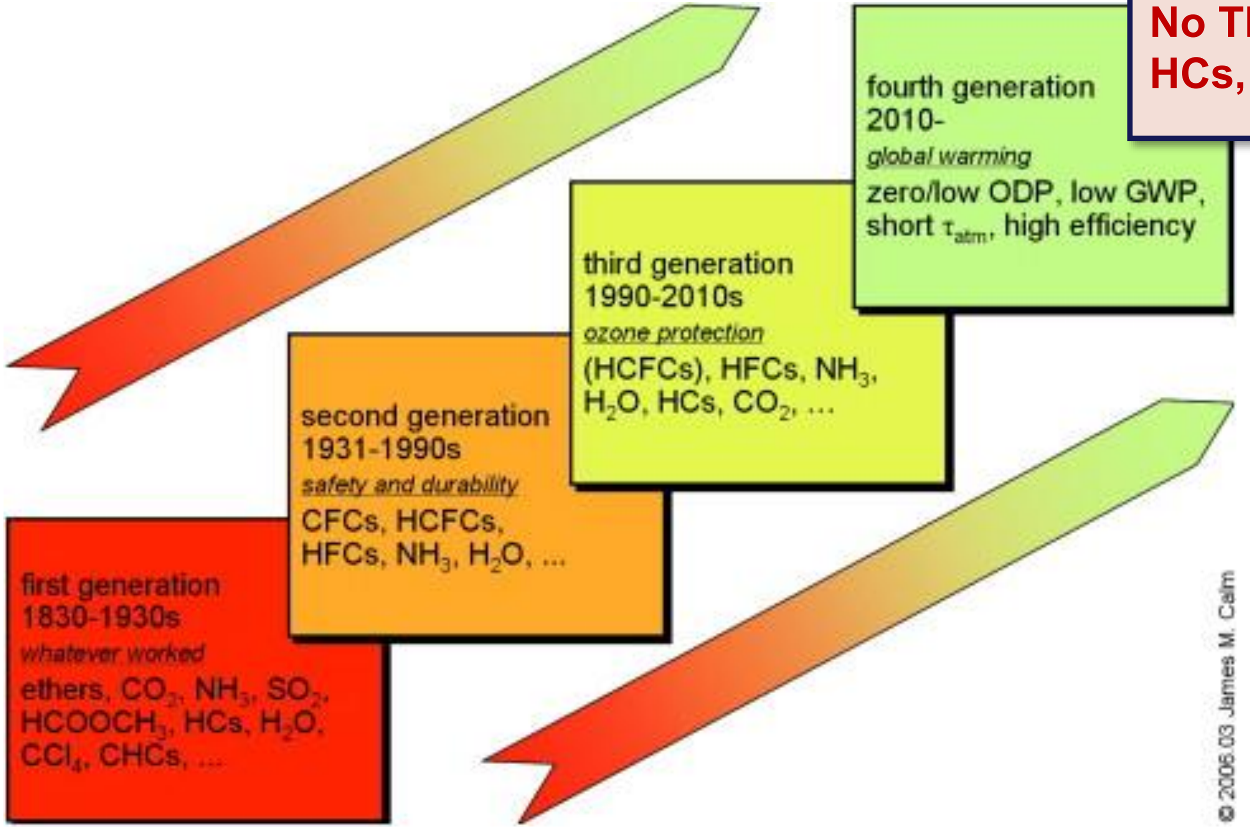
These refrigerants do not generate harmful by-products like TFAs or HF during their breakdown in the atmosphere, and they have no Ozone Depletion Potential (ODP) and a much lower GWP.

The most common ones are: CO_2, NH_3 , and Hydrocarbons.



Source: The Engineering Mindset

3.6. FUTURE OF THE REFRIGERANTS



first generation
1830-1930s
whatever worked
ethers, CO_2, NH_3, SO_2, $HCOOCH_3$, HCs, H_2O, CCl_4, CHCs, ...

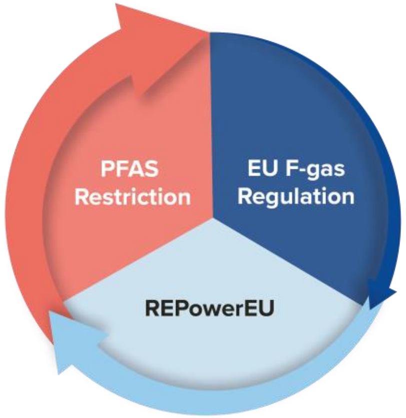
second generation
1931-1990s
safety and durability
CFCs, HCFCs, HFCs, NH_3, H_2O, ...

third generation
1990-2010s
ozone protection
(HCFCs), HFCs, NH_3, H_2O, HCs, CO_2, ...

fourth generation
2010-
global warming
zero/low ODP, low GWP, short τ_{atm}, high efficiency

© 2006.03 James M. Calm

fifth generation
2030-
natural refrigerants
No TFA, no PFAS
HCs, CO_2, H_2O, …



3.5. CURRENT REFRIGERANTS AND APPLICATIONS

Most commonly used refrigerants (synthetic)

Refrigerant	Type	Application	GWP	Safety classification
R-410A	HFC	Common in reversible heat pumps, though its high GWP is leading to its phase-out in favor of lower-GWP refrigerants.	2088	A1
R-32	HFC	Residential and small commercial systems as a lower-GWP alternative to R-410A.	675	A2L
R-134a	HFC	Widely used in commercial applications, though being phased out for its high GWP.	1430	A1
R-513A	HFO/HFC	Used in commercial and industrial applications as a low-GWP replacement for R-134a.	573	A1
R-450A	HFO/HFC	Another low-GWP replacement for R-134a in systems that need dual-purpose heating and cooling.	547	A1
R-1234yf	HFO	Primarily used in automotive air conditioning and increasingly in heat pumps for industrial and commercial systems.	<1	A2L
R-1234ze(E)	HFO	Industrial and commercial systems.	<1	A2L
R-1233zd(E)	HFO	Primarily used in large chillers and heat pumps for industrial and commercial buildings.	1	A1

3.5. CURRENT REFRIGERANTS AND APPLICATIONS

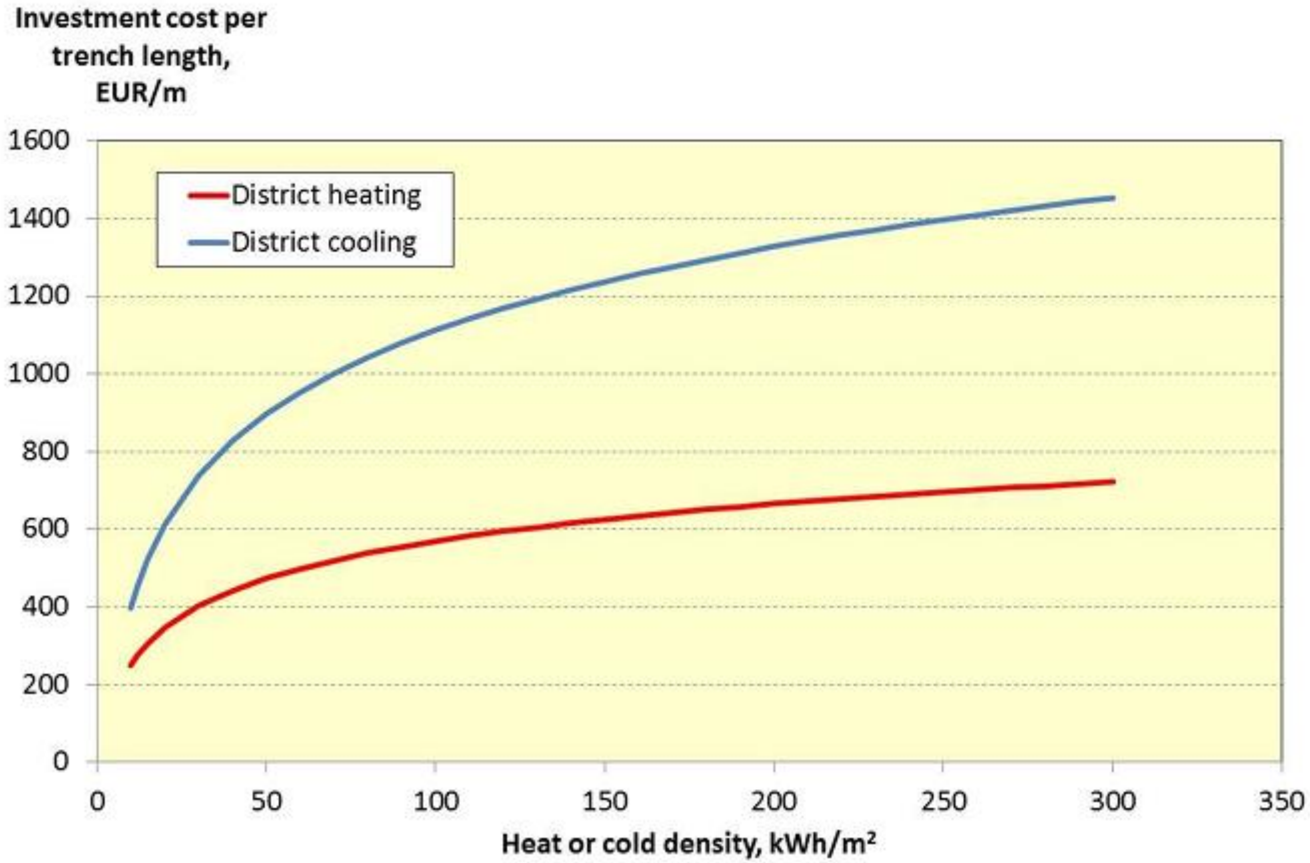
Most commonly used refrigerants (natural)

Refrigerant	Type	Application	GWP	Safety classification
R-744 (CO_2)	Natural	Used in commercial and industrial refrigeration, heat pumps for water heating, and supermarkets. CO_2 is favored for its very low GWP, though its high operating pressure requires specialized system designs.	1	A1
R-290	Natural	Employed in residential and commercial systems for both heating and cooling, particularly in low- to medium-capacity systems.	3	A3
R717 (NH_3)	Natural	Primarily used in large industrial and commercial refrigeration, such as food processing and cold storage	0	B2L
R-600	Natural	Used in small refrigeration appliances, such as domestic refrigerators and some commercial freezers.	3	A3
R-600a	Natural	Commonly used in domestic refrigerators, small commercial freezers, and heat pumps.	3	A3

3.7. CONCLUSIONS

- The history of refrigerants helps us understand standard requirements
- Once commercial refrigeration and heat pump applications were commercialized, most efforts were directed at finding the most sustainable refrigerant.
- For every application, there is one optimum refrigerant. However, the perfect refrigerant does not exist.
- A trade-off between thermodynamic, technical, safety, economic, and environmental perspectives is always required.
- Alternative refrigerants for existing and new systems (drop-in or retrofit) differ. The latter are considered when different safety requirements or operational conditions exist.
- The future will be oriented to natural refrigerants to avoid all environmental concerns.
- DHN and DCN can help transfer heat and use refrigerants with stricter safety requirements, as big and isolated vapor compression systems can be designed.

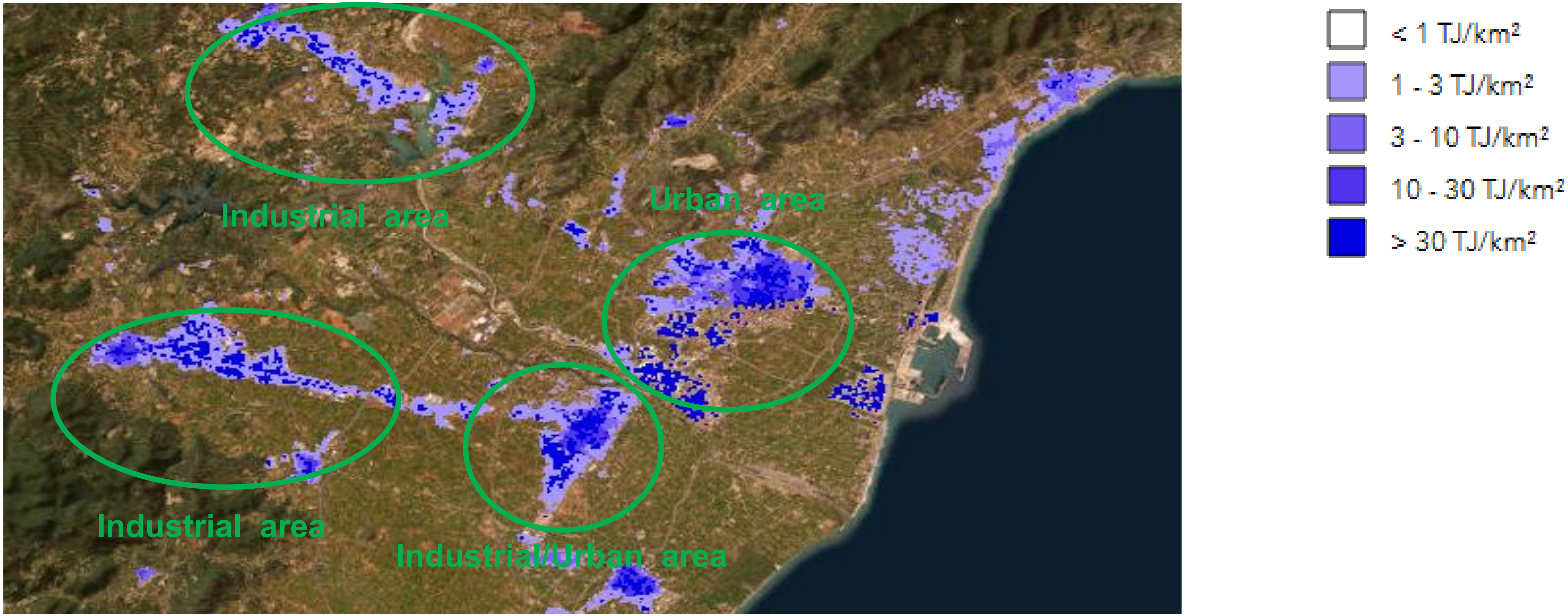
4.1. INTRODUCTION TO ECONOMIC AND ENVIRONMENTAL ASPECTS



Source: Stratego

4.2. DENSITY DEMAND

Cooling demand (2015), Castellón, Spain

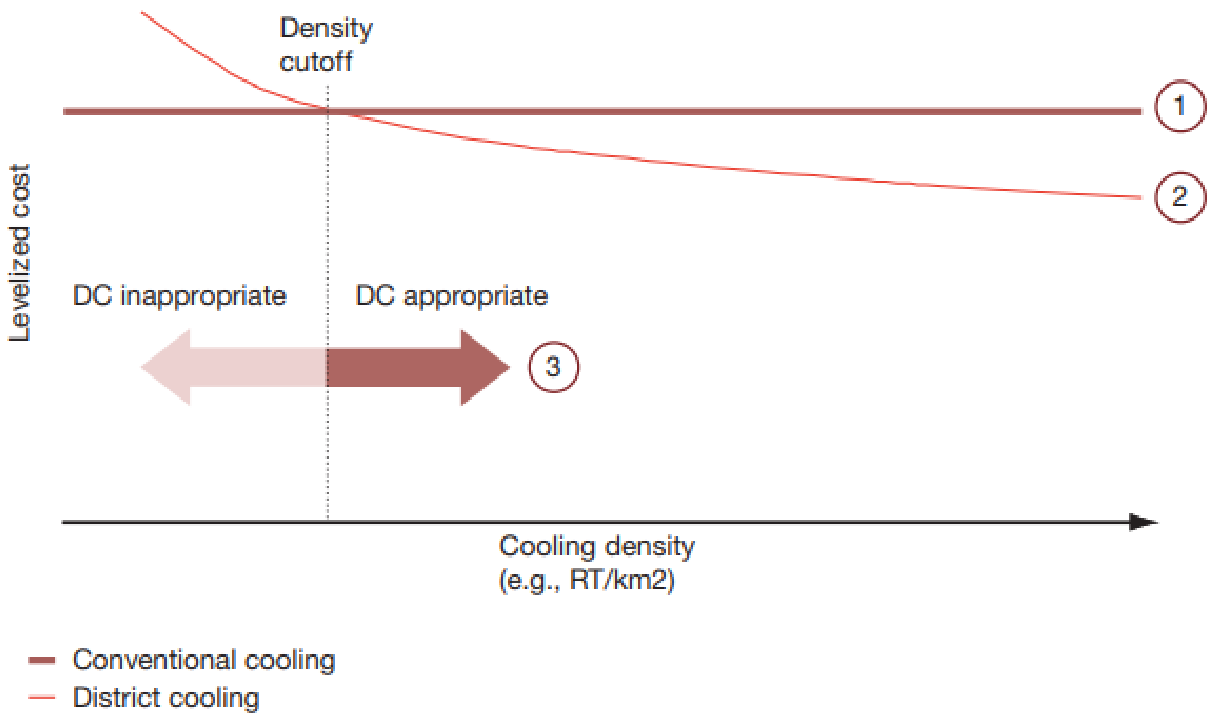


(Pan-European Thermal Atlas 5.2, 2024)

4.2. DENSITY DEMAND

Density cutoff

Cost of Cooling Technologies vs. Cooling Density



①	Conventional cooling costs do not depend on cooling density
②	District cooling costs decrease with increasing cooling density because of lower relative network costs
③	District cooling is more cost effective than conventional cooling only where cooling densities are above the “density cutoff”

Note: RT/km2 = refrigeration tons per square kilometer. Levelized Cost = price required to break even.

Source: Strategy&

4.2. DENSITY DEMAND

Analysis of density demand (1)

1. Data Collection & Preprocessing

- **Building Data**: Types, usage (residential, commercial, industrial), sizes, occupancy, historical demand
- **Climate Data**: Temperature, humidity, solar radiation
- **Energy Patterns**: Peak vs. off-peak consumption profiles

2. Cooling Load Estimation

- **Dynamic Simulation Tools**: e.g., TRNSYS, EnergyPlus
- **Hourly cooling loads** based on envelope, HVAC, internal gains
- **Peak Load Identification**: Crucial for sizing system components

(American Society of Heating, 2013, Ghajar et al., 2017)

4.3. VIABILITY OF DISTRICT COOLING COMPARED TO OTHER TECHNOLOGIES

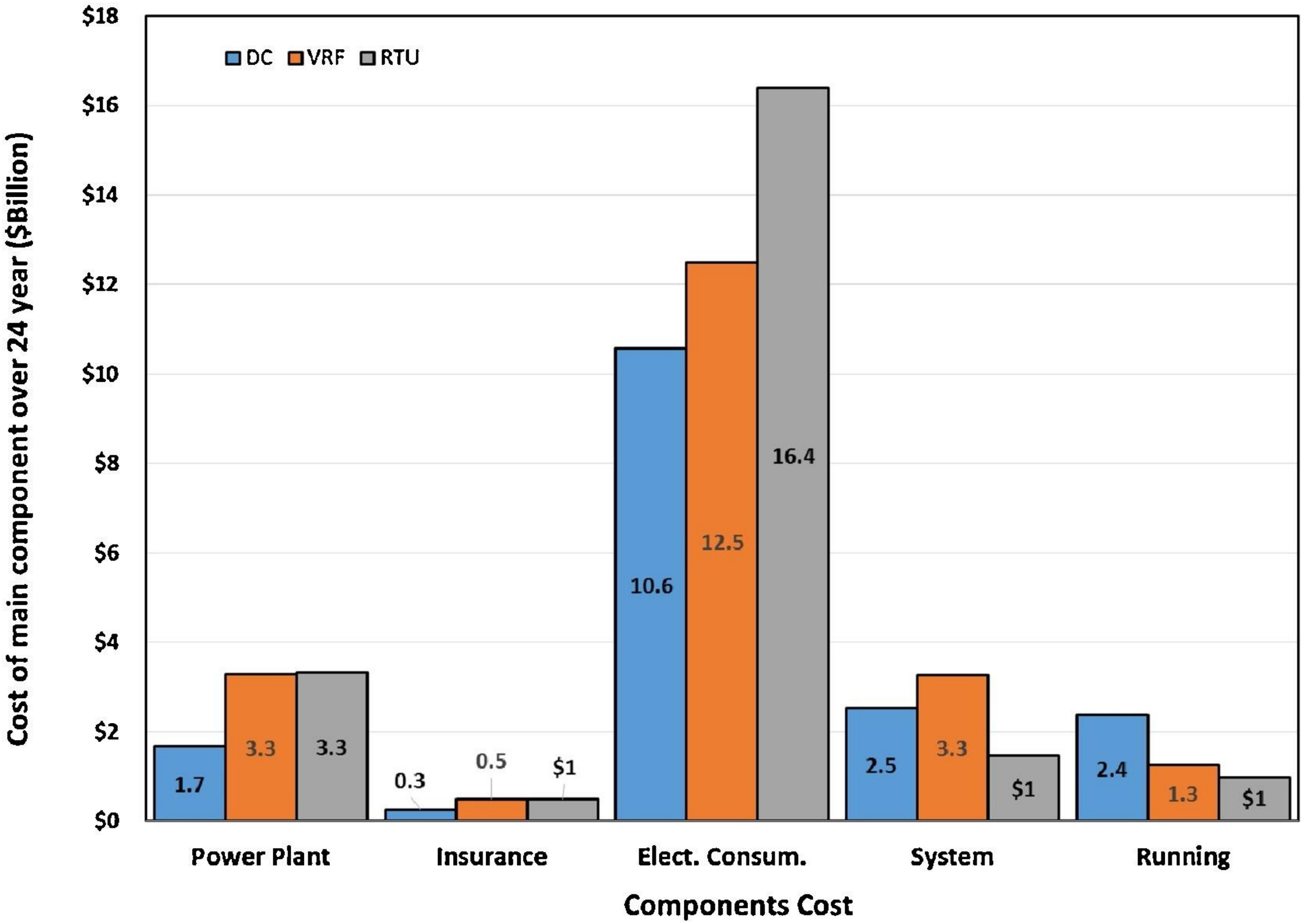
1. **Capital Costs**: DCN systems have high upfront costs, but economies of scale make them cost-effective in dense areas, unlike cheaper standalone systems with duplicated equipment. 😐
2. **Operational Costs**: DCN systems are more energy-efficient and cheaper to maintain due to centralized operations, 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. 🙂

4.3. VIABILITY OF DISTRICT COOLING COMPARED TO OTHER TECHNOLOGIES

Carbon Emissions

Study of Alajmi and Zedan (2020) in Kuwait.

- The total cost is reduced from 22,669 M$ for RTU and 20,829 M$ for VRF systems to 17,395 M$ for the DC system.
- The RTU system needs 660,200 cooling units, the VRF system needs 220,800 cooling units, while the DC system needs only 624 Units. This influences
  - the number of labor hours required to service, maintain, and operate the units
  - space needed by the cooling system on the roof of the residential building.
  - number of spare parts required
  - the risk of refrigerant leakages increases.



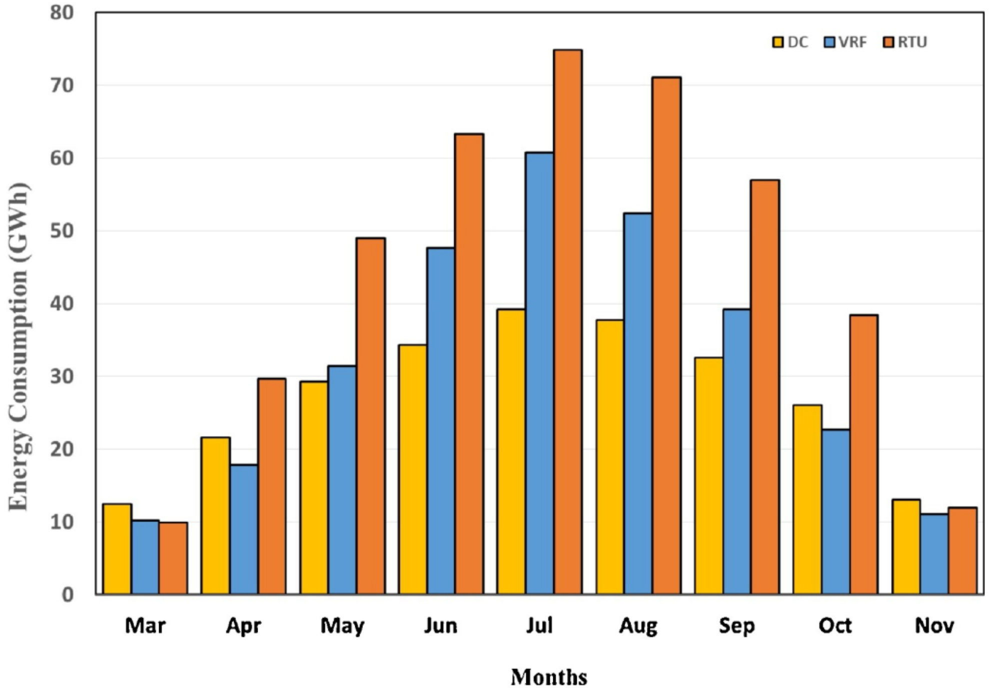
Source: Alajmi and Zedan (2020)

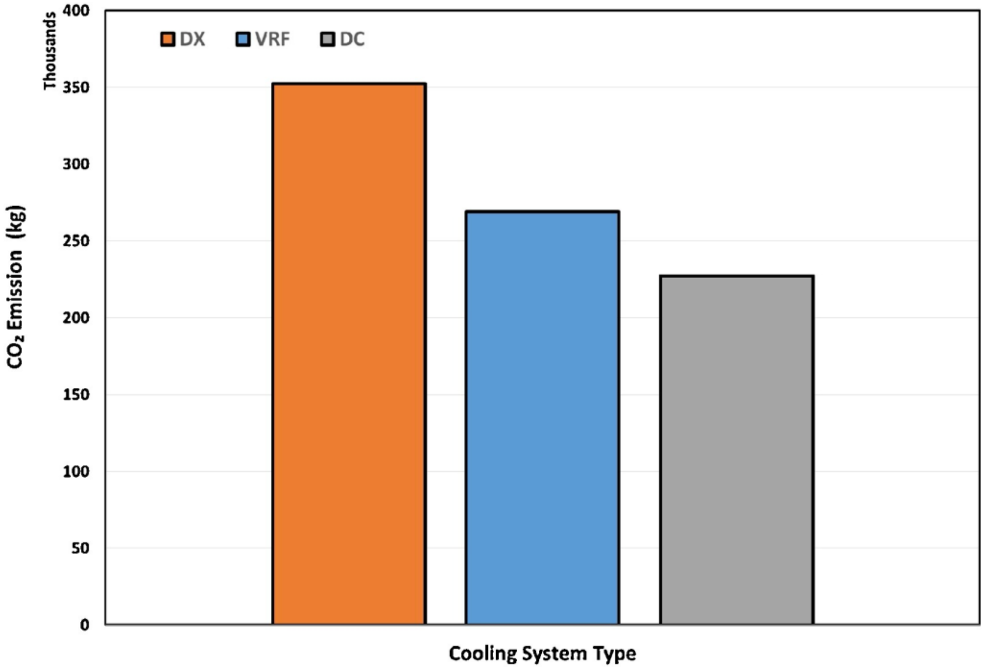
4.4. ENVIRONMENTAL IMPACT OF DISTRICT COOLING

Carbon Emissions (2)

Study of Alajmi and Zedan (2020) in Kuwait.

- **High CO2 emission factor makes even more important high energy efficiency.**



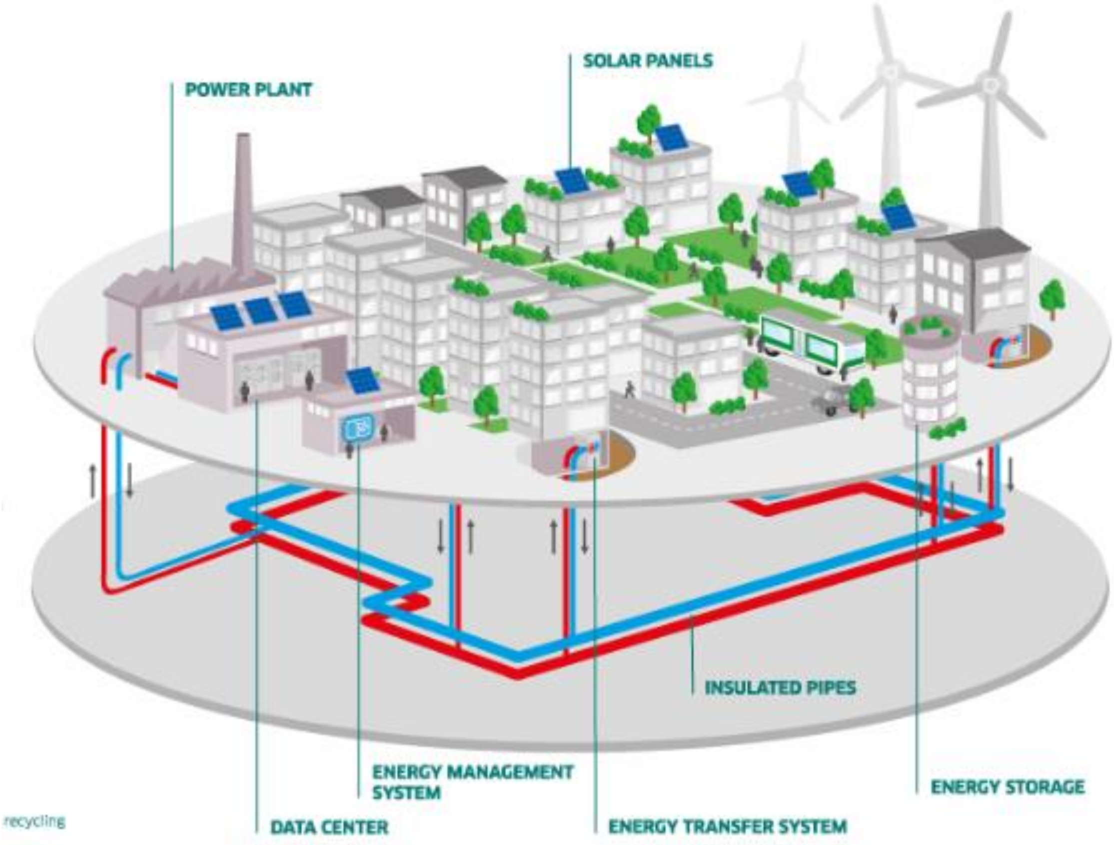


Source: Alajmi and Zedan (2020)

4.5. OPTIMIZATION OF DISTRICT COOLING TECHNOLOGIES

Economic optimization for operational cost reduction

1. Economies of Scale
2. Modular Design
3. Centralized Maintenance



Source: ENGIE

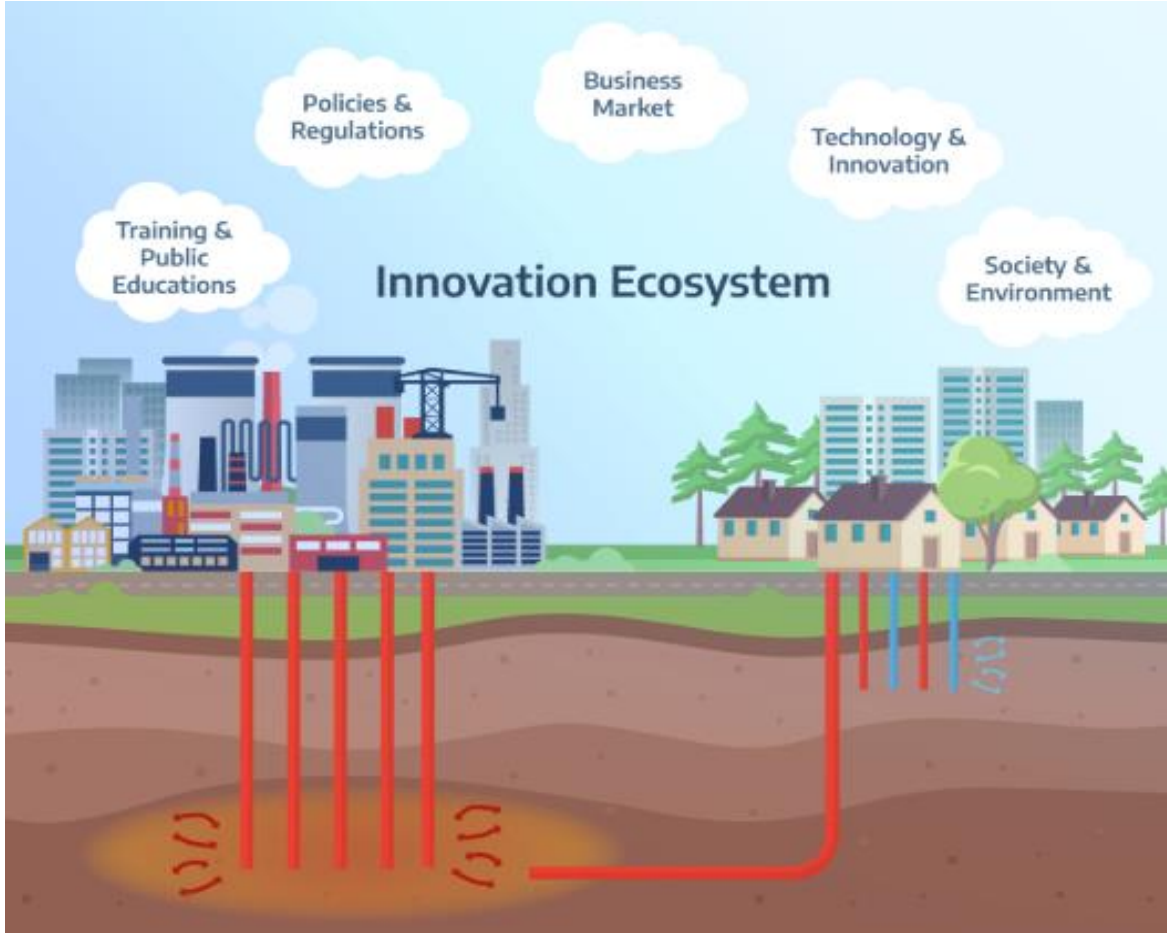
4.5. OPTIMIZATION OF DISTRICT COOLING TECHNOLOGIES

Economic optimization for capital cost reduction

Energy Efficiency

Waste Heat Utilization

Renewable Energy Integration



Source: University of Stravanger

4.5. OPTIMIZATION OF DISTRICT COOLING TECHNOLOGIES

Environmental Optimization

Low-GWP Refrigerants

- Use **natural** or **low-GWP synthetic** refrigerants
- Advanced **leak detection** and **maintenance** to minimize emissions

Decarbonized Energy Supply

- Connect to **renewable-powered grids** (wind, solar, hydro)
- Integrate **on-site renewables** (e.g., solar PV for auxiliaries)

Efficient Water Management

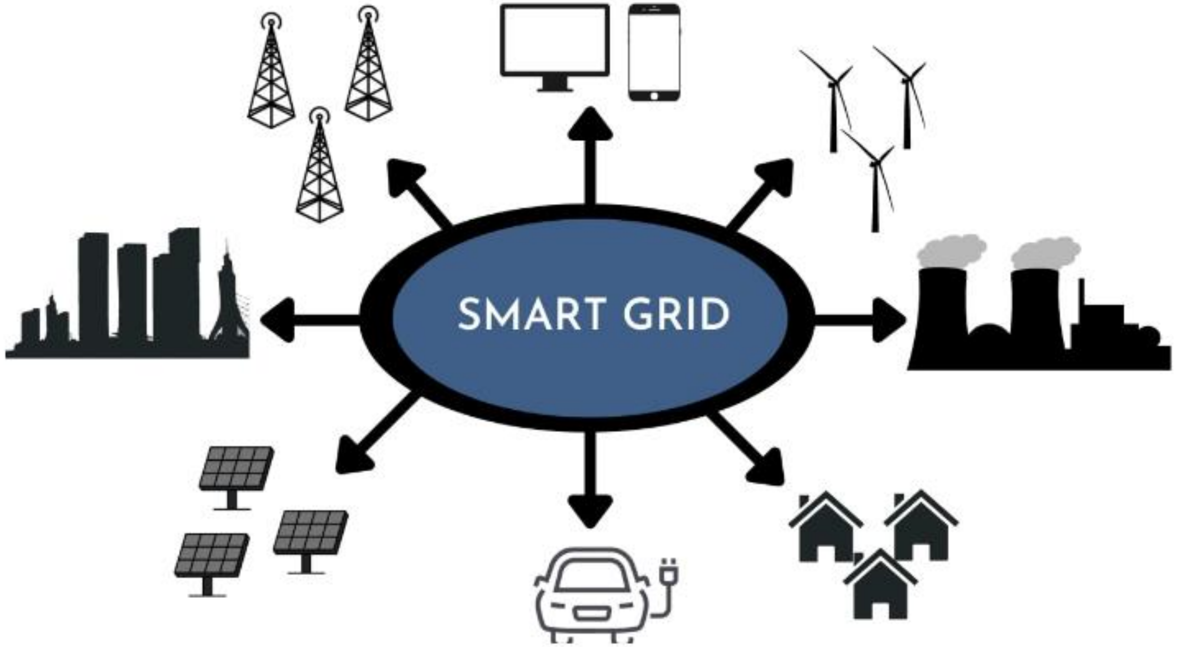
- Implement **closed-loop cooling systems**
- Use **non-potable sources** like treated wastewater

Source: Juhua Group, shutter stock

4.5. OPTIMIZATION OF DISTRICT COOLING TECHNOLOGIES

System Design and Technological Integration

1. Smart Grids & IoT Integration
2. Dynamic load balancing & predictive analytics
3. Demand Response
4. Backup & Resilient Systems



Source:Vikas B

4.6. CONCLUSIONS

- To identify the suitability of the district cooling network, a careful study of density demand must be followed. This study must consider buildings, industrial consumers, and data centers.
- Density demand study involves additional disciplines to conventional HVAC and refrigeration projects, such as GIS.
- If carefully justified and risks minimized, a DCN serving proper density demand will be better than conventional cooling systems. Payback periods could be attractive.
- Contrary to traditional cooling systems, governments must be involved in district cooling networks' development and suitability framework and promote them from many perspectives.
- In addition to the traditional benefits of being a more energy-efficient technology, DCN can help diminish urban heat island effects, reduce waste, and facilitate the integration with sustainable technologies.
- DCN requires a more challenging control optimization to make them profitable and energy efficient, and the latest developments in IoT and communications contribute to it.

5. REALISED PROJECTS AND CASE STUDIES

5.1. BARRIO LA PINADA

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** $\boldsymbol{m^2}$.

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).

	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

5.1. BARRIO LA PINADA

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.

5.1. BARRIO LA PINADA

Network solution

Pipework solution	
Length	6.76 km
Total Cost	1.35 M€
Linear Cost	200 €/m
Losses	1.85 GWh/year
Capacity	3.88 MW

Pipework solution	
Total Capacity Required	3.88 MWp
Output	11.05 GWh/year
Capital cost	2.14 M€
Operating cost: O&M	0.12 M€/year
Operating cost: heat production	0.15 M€/year

Demand solution	
Total Peak Demand	6.16 MW
Demand	9.2 GWh/year
Revenues	0.405 M€/year

5.1. BARRIO LA PINADA

Analysis

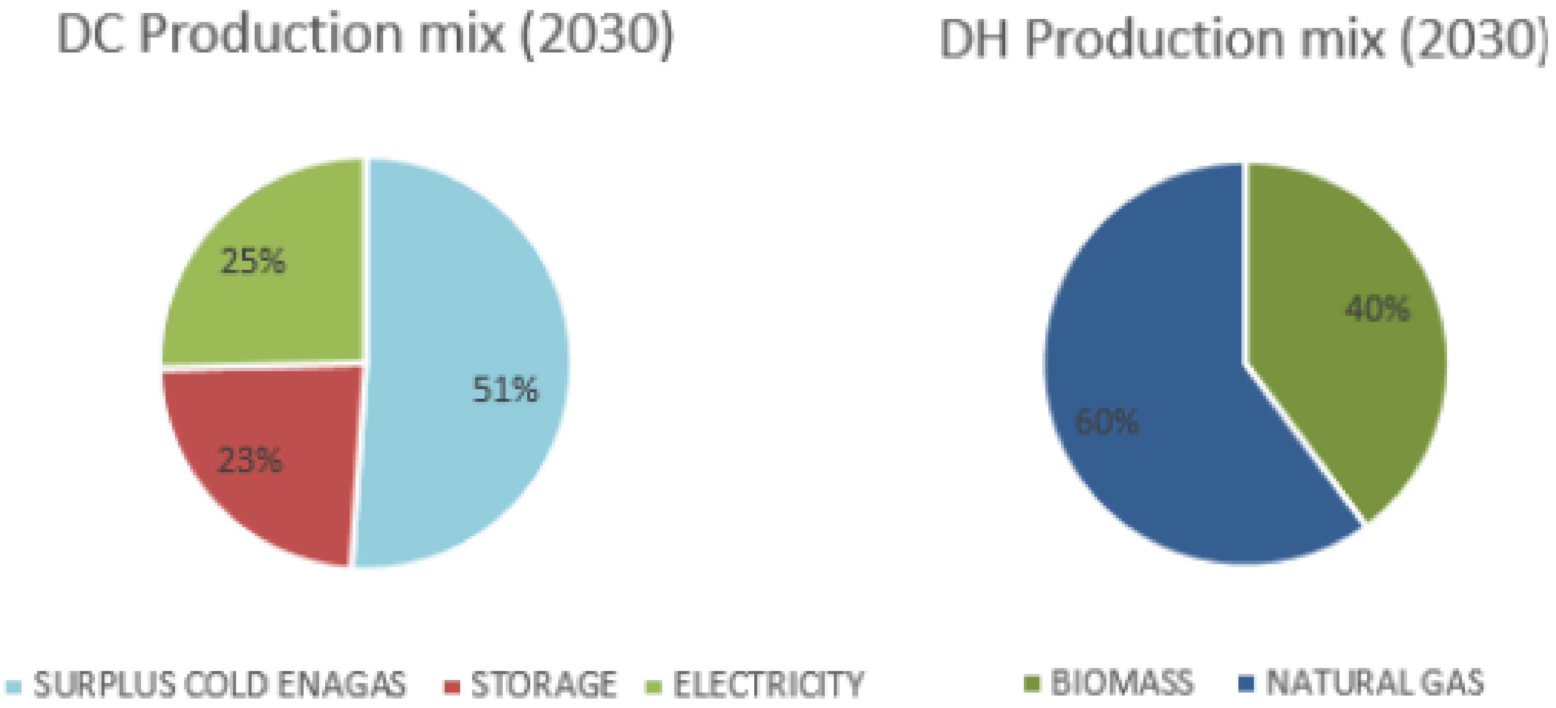
	Capital cost	Operating cost	Operating revenue	NPV
Pipework	-1.35 M€	-	-	-1.35 M€
Heat supply	-2.14 M€	-0.27 M€/year	-	-9.35 M€
Demands	-	-	0.41 M€/year	-10.74 M€
Emissions	Not included at this stage			
Network	**-3.49 M€**	**-0.27 M€/year**	**0.41 M€/year**	**0.06 M€**

5.2. DHC BARCELONA (SPAIN)

Key facts and location

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)

5.2. DHC BARCELONA (SPAIN)



Fuel sources used for DH and DC in Ecoenergies Barcelona 2014

5.2. DHC BARCELONA (SPAIN)

Energy Demand & Supply – Barcelona (Summary)

Climate & Demand

- Subtropical-Mediterranean climate; ~1150 HDD (mild winters).
- Low heating, high and growing cooling demand.

Current Energy Mix

- Heating: Mainly natural gas (individual systems).
- Cooling: Mostly electricity-based.
- Solar Thermal Ordinance (1999): Mandatory solar DHW in new/refurbished buildings.

Energy Consumption

- Existing buildings: ~80 kWh/m²·year
- New buildings: ~45 kWh/m²·year

Market Structure

- Liberalized energy market (consumers choose suppliers).
- 5–6 suppliers cover ~90% of total supply → moderate concentration.

District Heating & Cooling (DHC)

- Regulated by Barcelona City Council via TERSA (public company).
- Prices must remain competitive with conventional energy.

Pricing

- District Heating: €42/MWh, ~10% cheaper than natural gas.
- District Cooling: €38/MWh, 5–12% cheaper than electricity.
- Industrial clients: custom pricing (B2B model).

Case Study – Mercabarna (Ecoenergies)

- Replacing 32 GWh/year electricity with District Cooling.
- Savings:
  - 20% lower electricity costs.
  - 8,730 tCO_2 emissions avoided per year.

5.3. DCN COLD ENERGY RECOVERY FROM LIQUEFIED NATURAL GAS VAPORIZATION

Background

- Buildings consume ~40% of global energy; cooling demand is rising.
- Global residential cooling demand: 300 TWh (2000) → 4000 TWh (2050) → 10,000 TWh (2100).
- Cooling demand is harder to predict than heating, affected by solar radiation, internal gains, and urban heat islands.

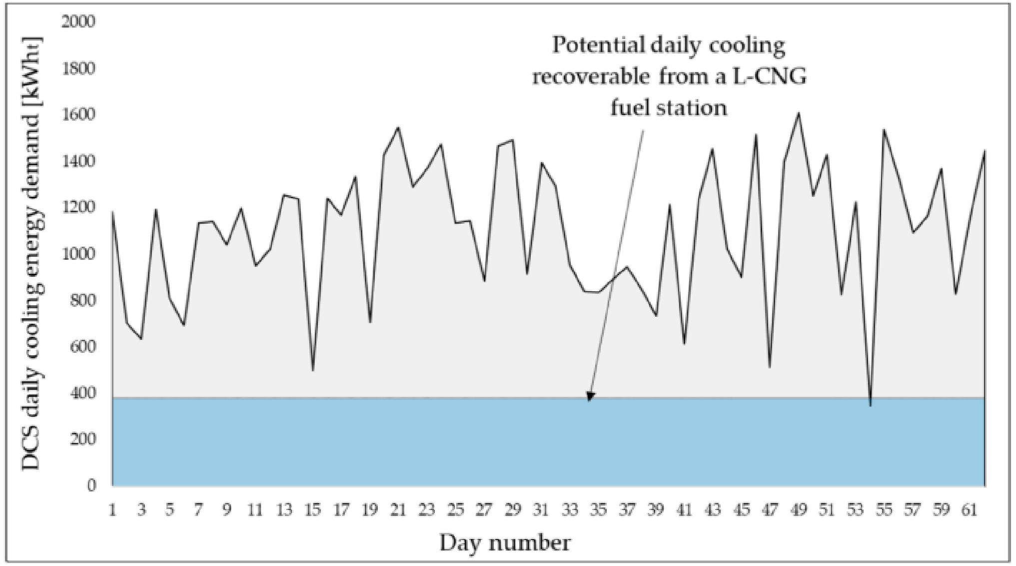
District Cooling Systems (DCSs)

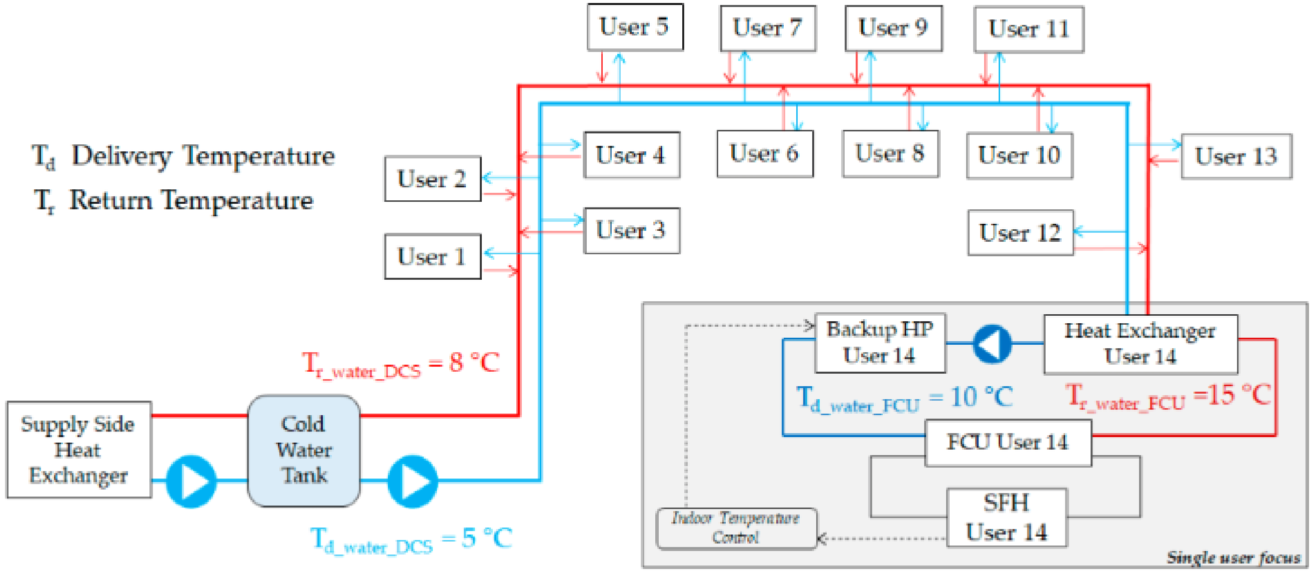
- Centralized cooling solution for multiple buildings.
- Components: Generation unit, distribution network, customers, heat rejection system.
- Recognized as Best Available Technology (BAT) in the EU.

Waste Cold Energy from LNG

- LNG regasification releases significant cold energy (~1245 MWh/year in Italy from L–CNG stations).
- Potential for free cooling, reducing electricity demand in air conditioning.
- No prior studies on coupling DCSs with L–CNG cold energy recovery.

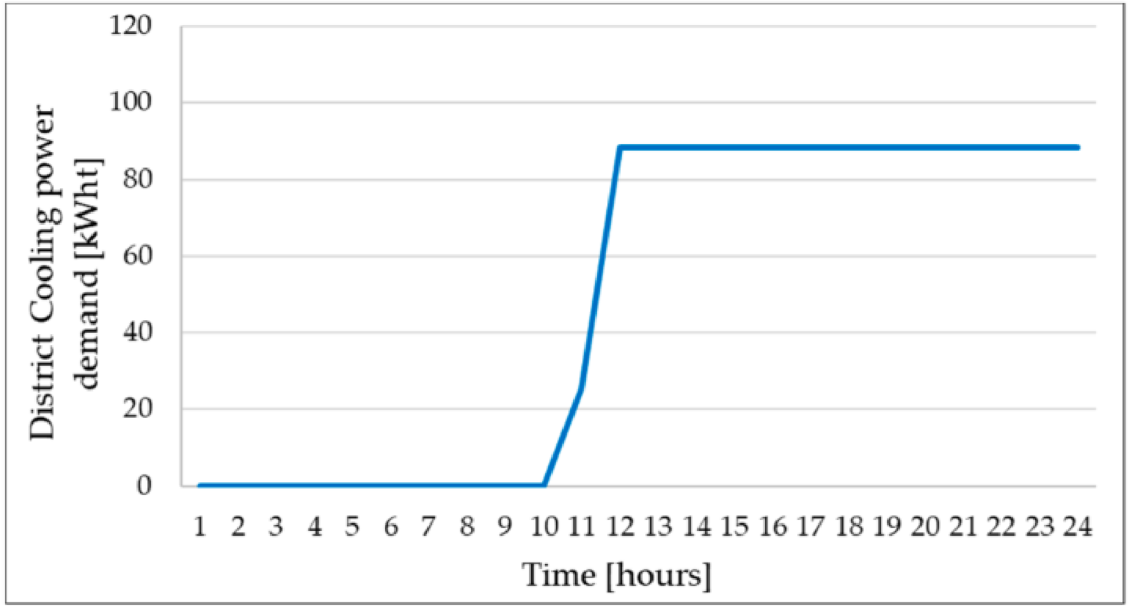
5.3. DCN COLD ENERGY RECOVERY FROM LIQUEFIED NATURAL GAS VAPORIZATION

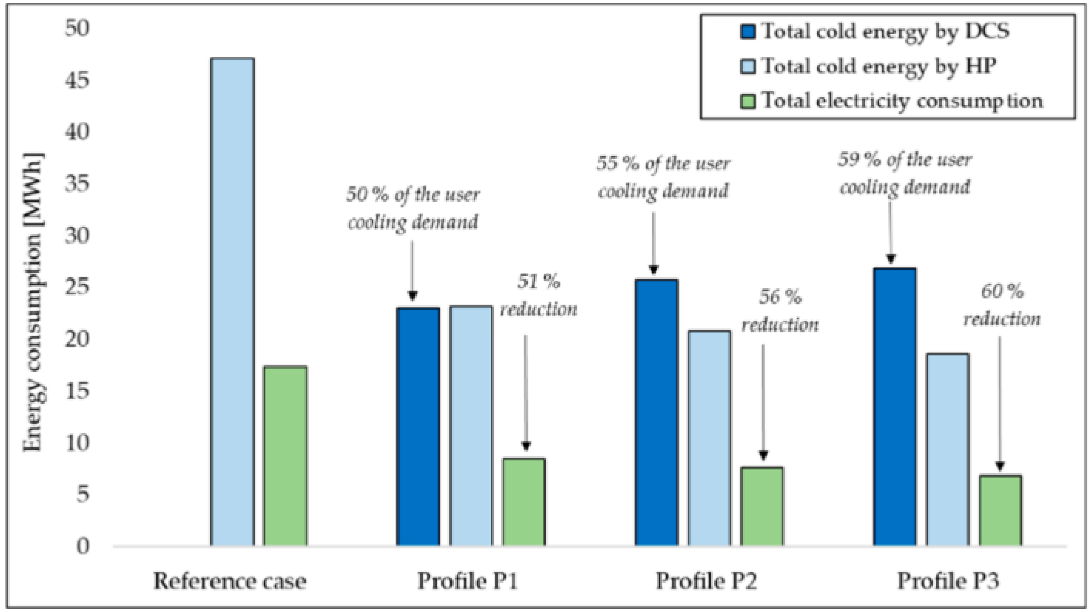




5.3. DCN COLD ENERGY RECOVERY FROM LIQUEFIED NATURAL GAS VAPORIZATION

Simulation Results





5.3. DCN COLD ENERGY RECOVERY FROM LIQUEFIED NATURAL GAS VAPORIZATION

Conclusions

- **DCS Benefits:**
  - Low-cost cold energy supply with reduced CO_2 emissions
  - Integration with renewables, trigeneration, and thermal storage
  - Efficient waste cold energy recovery (ex, L–CNG refueling stations)

- **Case Study:**
  - System: L–CNG refueling station supplying cooling to a residential neighborhood
  - Best Performance: 60% electricity savings (P3 profile + 60 m^3 TES)
  - General Savings: >50% electricity reduction across all scenarios

- **Considerations & Future Work:**
  - Results depend on assumptions about LNG vaporizer energy availability
  - Further studies needed on DCS sizing and user connection optimization

- **Main conclusions:**
  - LNG vaporization can effectively supply residential DCSs
  - Integrating transport and residential cooling enhances urban sustainability

5.4. CONCLUSIONS

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

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