Annexes

Annex 1. Nomenclature

Energy Flows Nomenclature

This section summarizes the nomenclature for the main energy flows used in the examples (Section 3.6).

W_{GRID}	Electrical energy from grid.	Represents the electrical energy purchased from the electrical grid.
W_{PV}	Electrical energy generated by the on-site photovoltaic plant.	Represents the electrical energy delivered to the data centre by the on-site photovoltaic plant.
W_{CHP}	Electrical energy generated by the on-site combined heat and power plant.	Represents the electrical energy delivered to the data centre by the on-site combined heat and power plant.
$W_{\text{E,SUB}}$	Electrical energy in the electrical substation.	Represents the electrical energy which enters to the electrical substation.
$\zeta_{\text{E,SUB}}$	Electrical losses in the electrical substation.	Represents the electrical losses due to the conversions and inefficiencies of the systems contained in the electrical substation (transformers, switch gears, etc.)
$W_{\text{E,PDTS}}$	Electrical energy in the power distribution system.	Represents the electrical energy which enters to the data centre facility after the conversions and losses in the electrical substation.
$W_{\text{E,MISC}}$	Electrical energy consumption of the miscellaneous systems.	Represents the electrical energy consumed by the miscellaneous systems in the data centre (lighting, appliances, etc.)
$W_{\text{E,MTS}}$	Electrical energy consumption of the mechanical technical systems.	Represents the electrical energy consumed by the cooling equipment (VCCH, ABCH etc.) of the data centre and as well the electrical consumption of the auxiliary cooling systems such as fans, pumps and controls. If the system uses free cooling strategy the energy consumption for free cooling must be also considered.

(Continued)

241

Annex 1. Continued		
$\zeta_{\mathrm{E,PDTS}}$	Electrical losses in the power distribution systems.	Represents the electrical losses due to the conversions and inefficiencies of the power distribution systems contained in the data centre.
$W_{\mathrm{E,IT}}$	Electrical energy consumption of the IT equipment.	Represents the electrical consumption of the IT equipment in the data centre.
$Q_{\mathrm{C,chw,1}}$	Cooling energy delivered by the cooling equipment.	Represents the heating removed due to the cold produced by the cooling equipment of the data centre such as VCCH, ABCH, HP etc.
$Q_{\mathrm{C,chw,2}}$	Cooling energy delivered by the district cooling network.	Represents the heating removed due to the cold purchased in the district cooling network.
$\xi_{\mathrm{th,MTS}}$	Thermal losses in the mechanical technical systems.	Represents the thermal losses due to the thermal inefficiencies introduced by conversion and transport of cooling (such as losses in CRAC, CRAH, pipes, extra pumps or fans) and inefficiencies due to air management in IT rooms
$Q_{\mathrm{C,FC}}$	Cooling energy delivered by the free cooling strategy.	Represents the heating removed in the IT room with the outside air when the free cooling strategy is applied.
$Q_{\mathrm{C,IST}}$	Cooling energy stored in the ice storage tank.	Represents the cooling stored, for future use in the data centre, by the ice storage tank.
$Q_{\mathrm{C,IT}}$	Cooling energy delivered in the IT room.	Represents the final heating removed in the IT room due to the cooling equipment.
$Q_{\mathrm{H,ABCH}}$	Heating energy delivered to the cooling equipment.	Represents the heating delivered to produce cold with an absorption compression chiller.
$Q_{\mathrm{H,DH}}$	Heating energy exported or imported to a district heating network.	Represents the heating exported or imported by the data centre to the district heating network.

Annex A. Subsystems for Advanced Technical Concepts of Cooling and Power Supply

A.1 Introduction

In the present annex, descriptions of the subsystems for advanced technical concepts of cooling and power supply are provided. The subsystems are divided into the following categories: power generation, cooling production, energy storage, heat production and waste heat recovery.

Detailed information on the various technologies can be found in the deliverable 4.1 of the project RenewIT (*Report of different options for renewable energy supply in Data Centres in Europe* [42]).

A.2 Power Generation

A.2.1 Photovoltaics

General Description

The key components of a photovoltaic (PV) power system are various types of PV cells (also known as solar cells), which are interconnected and encapsulated to form a PV module (the commercial product), the mounting structure for the module or array, the inverter (essential for grid-connected systems and required for most off-grid systems), the storage battery and charge controller (for off-grid systems but also increasingly for grid connected ones).

The PV modules have to be integrated through structures that can be mounted directly onto roofs or integrated in the buildings (building integrated PV, BIPV), including PV facades, integrated (opaque or semi-transparent) glass–glass modules and "PV roof tiles". Tracking systems have recently become more and more attractive, particularly for PV utilisation in countries with a high share of direct irradiation. By using such systems, the energy yield can typically be increased by 25–35% for single-axis trackers and by 35–45% for double-axis trackers compared with fixed systems. However, falling costs in PV cells and maintenance criteria might not make them the best option.

Scheme

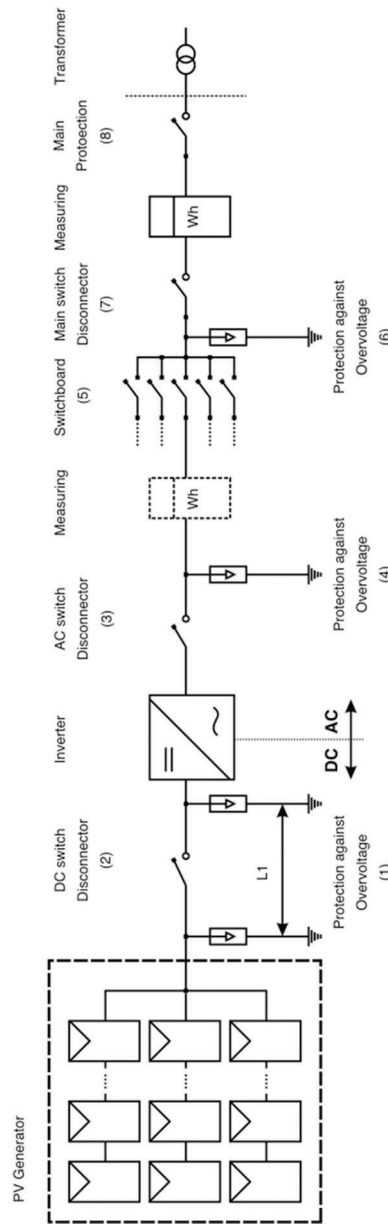The scheme of grid-connected PV system and overvoltage protection is shown in Figure A.1.

Figure A.1   Example of grid-connected PV system and over-voltage protections. PV solar system connected to the local switchboard enables self-consumption of PV solar electricity.

Control

A PV system can be connected to the grid (grid tie) or be independent (off-grid). In both cases, a control system is required to regulate and convert the generated power. The main element responsible for this task is known as inverter. Grid-connected inverters must supply electricity in sinusoidal form AC, synchronised to the grid frequency, limit feed-in voltage to not be higher than the grid voltage and disconnect from the grid if the grid voltage is turned off. Islanding inverters only need to produce regulated voltages and frequencies in a sinusoidal wave-shape as no co-ordination or synchronisation with grid supplies is required.

Calculation

The operation of PV systems depends on the solar irradiation of the site and the technical conditions of the system. Below, a simple methodology for the calculation of grid-connected PV systems is described.

The nominal power of a photovoltaic system is the sum of the nominal power of the modules. The nominal power is the power delivered by the modules at AM1.5 (1000 W/m^2) radiation and 25°C of module operation temperature.

If a module is irradiated by H kWh/m^2, the energy of the radiation received by the module is equivalent to H hours of normal AM1.5 radiation. Therefore, a first simple estimation of the production can be made by the following equation:

$$E = P_{\mathrm{nom}} \cdot H$$

The equivalent number of hours of normal radiation is available for a large number of locations [28].

The area required to achieve the desired nominal power depends on the efficiency of the PV module in the range of 110 to 145 W_{p}/m^2.

However, the performance of a system under real operation conditions differs from the nominal efficiency of the modules. This performance ratio (*PR*) of the system can be separated in two factors: the performance ratio of the module (PR_{mod}) and the performance ratio of the balance of system (PR_{BOS}). With the performance ratios, the electric energy (E) produced by the system can be calculated by the following equation:

$$E = P_{\mathrm{nom}} \cdot PR \cdot H = P_{\mathrm{nom}} \cdot PR_{\mathrm{mod}} \cdot PR_{\mathrm{BOS}} \cdot H$$

Due to sun radiation, the modules operate at a higher temperature than ambient temperature and it is necessary to introduce a temperature correction of PR.

The variation of the module power due to an operating temperature different from standard test conditions temperature (25°C) can be determined by using the temperature coefficient of the module power (α_{PT}):

$$PR_{\mathrm{mod}} = 1 + \alpha_{\mathrm{PT}} \cdot (T_{\mathrm{amb}} - 25 + T_{\mathrm{NOCT}} - 20)$$

The rest of the system components (BOS) also introduce losses. Cabling is responsible for resistive energy losses that usually are kept lower than 1% during the design phase. The modern inverters are very efficient and present a small amount of losses in the range of 2% to 6%. If there are transformers to change voltages, it is also usual to have 2.5% losses for every transformer step. Differences in the performance of the modules produce a mismatch loss that is usually in a 1 to 3% range. In a linear approximation, all these effects can be introduced as a constant PR_{BOS} usually in the 0.85 to 0.90 range.

Limits of Application

PV systems do not have any specific limitation, except for the space required for its installation. However, this technology makes sense only in those locations where the radiation levels justify the investment.

Economic Aspects

The cost in the case of PV largely depends on the size of the plant to be installed. The information regarding the differences in costs between the type of system installed and the cost of the different components in the global system cost is given in [18]. It can be noticed that the percentage of cost of the module in the global cost oscillates between a 30% and a 40% of the global cost (0.8–2.3 €/Wp), and the trend in the last years is a continuous reduction in costs. In the case of Data Centres, when talking about either commercial rooftop or utility mounted on the ground (either fixed tilt or one axis tilt), costs can oscillate between 2.3 and 3.4 €/Wp.

A.2.2 Wind Turbines

General Description

Wind energy is the conversion of the kinetic energy of wind into a useful form of energy, like mechanical energy (pumping) or electricity (through the use of wind turbines integrated with electric generators). Wind turbines are the

main element harvesting this kinetic energy. These can be classified into the following two groups:

- Horizontal axis machine (HWTs): Rotation axis is parallel to wind direction, in a similar way as the classic windmills.
- Vertical axis machine (VWTs): Rotation axis is perpendicular to wind direction. The most common types are the Savonius and Darrieus wind turbine.

Actually, horizontal axis generators are most common as electricity generators in big wind farms.

On the other hand, wind turbines placed in urban locations are characterised by a lower annual mean wind speed (AMWS) compared with rural areas, and more turbulent flow [2]. The lower velocity is caused by the obstructions around the turbine that do not allow the wind to increase its velocity. Wind flow becomes turbulent because of these obstructions.

In order to supply energy to a Data Centre, it is important to consider the location of the energy production plant. It is clear that HWTs are more efficient than VWTs in clear spaces with laminar flow. However, lower wind speeds, turbulent flow and variable wind direction (city conditions) can favour the use of VWTs.

Control

Flexibility of operation is conditioned to the wind resource at any moment. Wind turbines have modern control systems that allow a wide wind speed range with a similar power ratio, so there are fewer turbine limitations in flexibility terms. Anyway, all the wind turbines present a cut in and cut out speed to work, so flexibility is compromised by wind sources.

Control of the rotational speed of the turbine is done through resistors, disorientation or changing the blade angle to avoid accidents if the wind exceeds recommended limits. Modern turbines with blades are usually pitch active controlled. That means that blades change their pass angle to reduce wind harvesting. There is also another control type that is based in the aero dynamical design of the blades, known as stall control.

Calculation

Wind energy depends basically on the capacity of the turbine for harvesting the wind power, the maximum amount of power being the amount of kinetic energy of the wind, which depends on the area covered by the turbine blades

(A_R), the density of the air (ρ), the velocity of the wind (V) and the power coefficient (C_p):

$$P = \frac{1}{2}C_P\rho A_R V^3$$

However, not all the kinetic energy of the wind can be harvested. The maximum physical efficiency of the system according to Betz's law is 59% of the total kinetic energy of the wind.

High-speed turbines with horizontal axis have a maximum C_p value about 0.4 at wind speeds 7 or 10 times greater than for low-speed turbines. A VWT Savonius rotor has a maximum C_p value about 0.3 at about 1 m/s wind speed. Darrieus rotor has a maximum C_p value greater than Savonius at about 4–6 m/s wind speed.

In addition to this power coefficient, losses due to mechanical friction and electronic converter must be added. The gearbox performance (η_t) is over the 80%, and the electric generator (η_m) is over the 95%. This means that final electric conversion efficiency is between 25 and 33% in most cases.

In order to know the wind speed on a location, it is necessary to have a probability distribution. A variety of probability density functions have been used in literature to estimate wind energy potential, but the Weibull function is most widely adopted.

Using the above expression and the values of Figures A.2 and A.3, it is possible to calculate the power generated during a year.
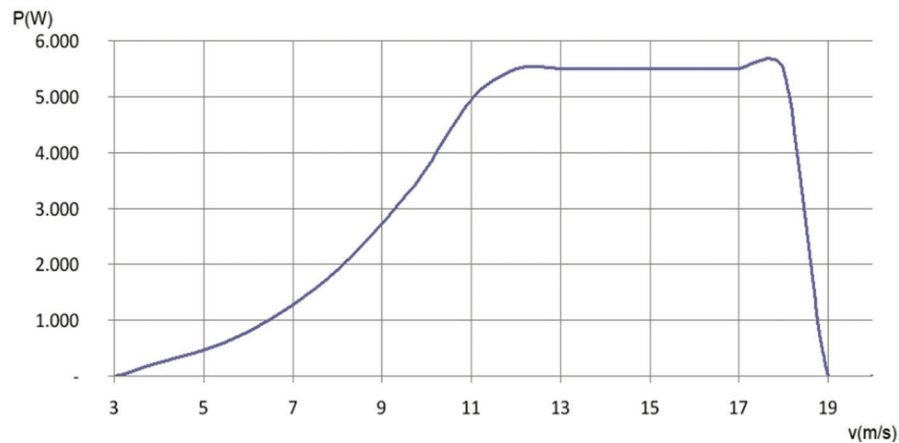

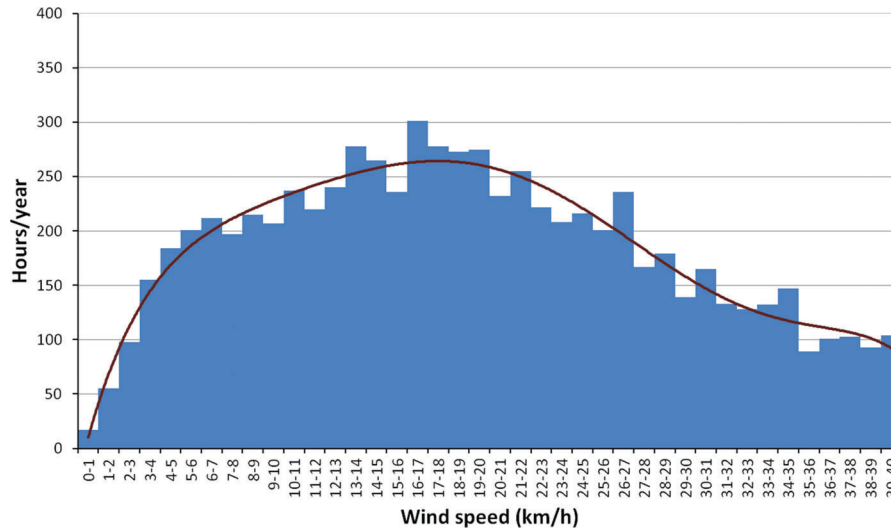**Figure A.2** Performance of a micro wind turbine Tornado (5 kW) [48].

Figure A.3   Wind speed distribution in a station of Montjuïc (Barcelona) [1].

Limits of Application

The location of the wind turbine has a big influence on the power range. The mean ratio power of the urban HWT is about 9 kW with a rated wind speed about 12 m/s. For the urban VWT, the mean ratio power is a bit lower, about 7 kW with a higher rated wind speed of 13 m/s.

The mean ratio power of open source HWT is about 2.3–3.0 MW with a mean rated wind speed of 12 m/s. Mean cut in speed is about 3 m/s, and cut out speed is about 24 m/s.

Offshore HWT mean power ratio is from 3.0 to 8.0 MW. The mean rated wind speed is similar than HWT on shore, about 12–13 m/s. The same for the cut in and cut out speed, being the main differences not in operation but in structural placement and costs.

Economic Aspects

The cost of wind power plants depends on the type of placement (onshore/offshore) [33]. For onshore technology, estimated investment cost is about 1,450 €/kW + 25% [33]. Cost improvements of this maturing technology through 2050 are not expected. Performance improvements due to new technologies in the wind turbine are expected until 2030; further improvements are not assumed to be achievable after 2030 (Table A.1).

Table A.1   Summary of available wind turbine power ranges

Location	Name	Power Range (kW)
Onshore	Micro turbine (very low power)	0–3
	Mini turbine (low power)	3–50
	Meso turbine (medium to high power)	50–1000
	Macro turbine (very high power)	1000–3000
Offshore	Meso turbine (medium to very high power)	50–1000
	Macro turbine (very high power)	1000–8000
Urban	Urban turbines vertical axis	0.025–100
	Urban turbines horizontal axis	0.4–30

For fixed bottom offshore technology, estimations of investment costs are 2,400 €/kW + 35% [33]. Until 2030, performance and 10% of cost improvement are assumed to be achievable.

The offshore wind technology with floating platforms are suitable in deep water because a tower and foundation are not cost effective in this case. This technology is under development right now and allows high power production. In 2020, investment cost is expected to be 3,000 €/kW + 35% [33]. Cost and efficiency improvements of 10% are expected through 2030.

Urban wind turbines are not as common as the ones described before, so it is more difficult to collect cost data. It is assumed that urban wind turbine costs ranges from 6,000 €/kW to 10,000 €/kW [8]. Costs can be very variable depending on the connection configuration of the urban wind turbines, if their installation is part of a stand-alone system, or it is necessary to pay for a grid connection.

A.3 Power and Heat Production

A.3.1 Fuel Cells

General Description

Fuel cells (FC) are electrochemical devices that convert the chemical energy of fuel, such as natural gas or hydrogen, into direct current and heat energy without any combustion (but oxidation) process. The produced electricity can be used to power Data Centres, and heat can be used to produce steam for CHP plant or for cooling purposes through absorptions chillers.

The working temperature of fuel cell varies from $-10°C$ [24] to $1000°C$ [25], and the total efficiency can reach up to 90% if heat is used, depending on the application [19]. The basic elements of fuel cells comprise of anode, which requires H_2 fuel, cathode, which brings O_2, and electrolyte, where exchange of ions takes place [22, 23, 29].

There are different fuel cell typologies depending on its electrolyte. The most common types include [43] proton exchange membrane (PEM), phosphoric acid fuel cell (PAFC), direct methanol fuel cell (DMFC), alkaline fuel cell (AFC), direct carbon fuel cell, solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC).

Some companies, such as Bloom Energy, Hydrogenics Corp, and United Technologies and Fuel Cell Systems (UPS Systems), produce fuel cells for Data Centres [4]. There are several ways to place fuel cells in the Data Centre. For example, that can be at the utility power level, at the rack level and at the server level [43]. However, their energy source (natural gas) is generated off-site and distributed by a utility [4]. For the smooth operation of fuel cell, the reliable supply of fuel is utmost important and additional equipments such as reformers, battery systems, start-up systems and auxiliary circuits are needed [43]. Figure A.4 illustrates different processes in obtaining hydrogen from different carbon-based fuels.
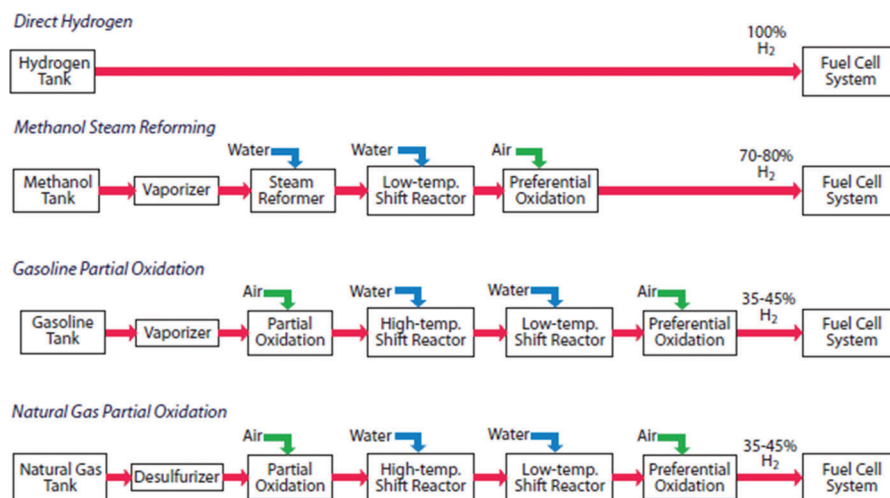
Figure A.4 Fuel sources for fuel cell system [47].

Hydraulic Scheme

Figure A.5 represents the hydraulic scheme of a fuel cell system.
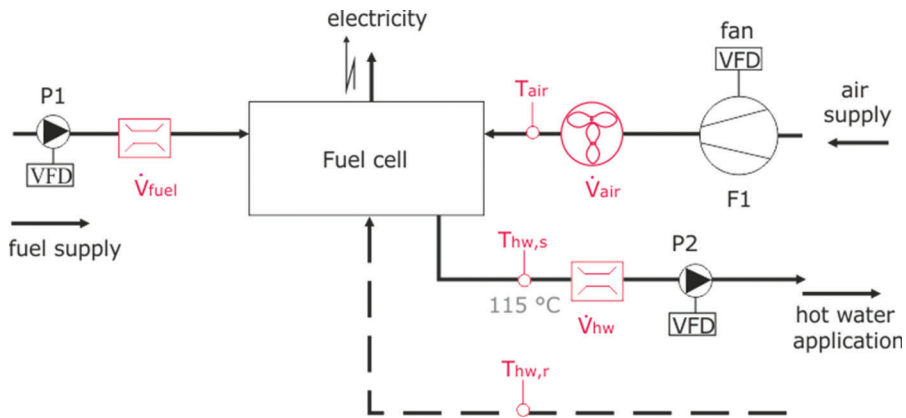

Figure A.5 Hydraulic scheme of a fuel cell (example temperature).

Calculation

Given below are some of the important performance parameters of fuel cells.

The energy conversion efficiency of the fuel cell can be calculated using the following equation [46]:

$$\eta_{FC} = \frac{P_{FC}}{\dot{m}_{fuel}\ LHV}$$

Here, P_{FC} is the electrical power output, $\dot{m}_{fuel}$ is the flow rate, and *LHV* is the lower heating value of H_2.

Capacity factor of a fuel cell shows the ratio of the electricity generated, for a certain period, to the energy generated at full power operation during the same period [29]. Thermal efficiency of a fuel cell shows the ratio of thermal heat available to the total amount of energy put in.

Table A.2 lists characteristics of two promising types of fuel cells, SOFC and PEM.

Control

A satisfactory transient behaviour of fuel cell is very crucial for its smooth operation in Data Centre. Four main subsystems of fuel cell plants are reactant

Table A.2 SOFC and PEM characteristics [34, 35, 43]

	SOFC	PEM
Size range	2 kW–200 MW	2 kW–200 kW
Catalyst	Peroktives	Platinum
Electrolyte	Ceramic	Ion exchange membrane
Fuel	Natural gas, H_2, coal-derived gas	Pure H_2
Electric efficiency	50%–60%	40%
Operating Temperature	800–1000°C	80–150°C
Typical application	High-power generation, stationary, transport	Low-power generation, space, transport, stationary
Advantages	high efficiency, CHP	rapid start-up, fast on/off

supply; heat, temperature, pressure and humidity control; water management; and power management [43]. A control system manages correctly these subsystems in stack [43].

Part Load Characteristics

Figure A.6 shows the variation of overall energy efficiency under different load conditions. At little load, the efficiency is too low, and as load increases,
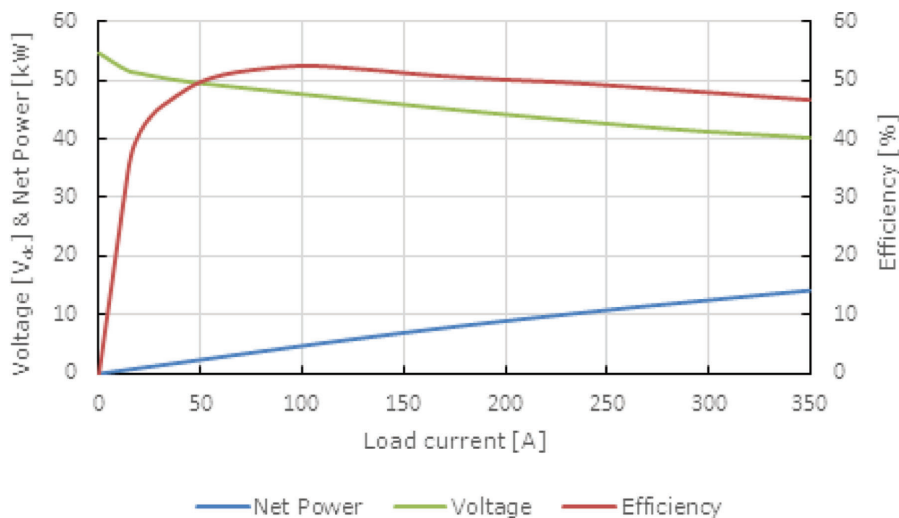

Figure A.6 Voltage, net power and efficiency of a 10 kW PEM under different load conditions [43].

efficiency decreases marginally. Therefore, FCs operate insufficiently at too little and too much load [43]. The power consumption of Data Centres fluctuates with the variation of workload and server on/off [43]. SOFC has very slow response time (e.g., 200 W/min) [5]. Therefore, to cope with this variation, FCs need to be over-provisioned or powered by external batteries [43].

Limits of Application

The main limitations of this technology are the fuel availability and the space required to store it.

Economic Aspects

The cost of FCs at present is high due to the limited production, around 25,000 units/year globally [43]. Reduction of cost is expected due to the invention of cheaper material and mass production. The conservative cost range of fuel cell is 3–5 $/W (2.2–3.6 €/W)[1] [43].

A.3.2 Reciprocating Engine CHP
General Description

Reciprocating internal combustion engines are a widespread and well-known technology. There are two basic types of reciprocating engines for CHP uses: spark ignition (otto cycle) and compression ignition (diesel cycle). Both use a cylindrical combustion chamber with a piston. After ignition, the piston is pushed by the gases and moves the crankshaft, converting the linear movement into a circular one. The main difference between the two designs is that otto cycle needs to ignite the mixed fuel with a spark, and the diesel ones make ignition due to high pressure and temperatures of the chamber.

There are four sources of usable waste heat from a reciprocating engine: exhaust gas, engine jacket cooling water, lube oil cooling water and turbocharger cooling. Recovered heat generally is in the form of hot water. The high-temperature exhaust can generate medium pressure steam, but the hot-exhaust gas contains only about one half of the available thermal energy from a reciprocating engine. Some industrial CHP applications use the engine exhaust gas directly for process drying. Generally, the hot water produced by reciprocating engine CHP systems (Figure A.7) is appropriate

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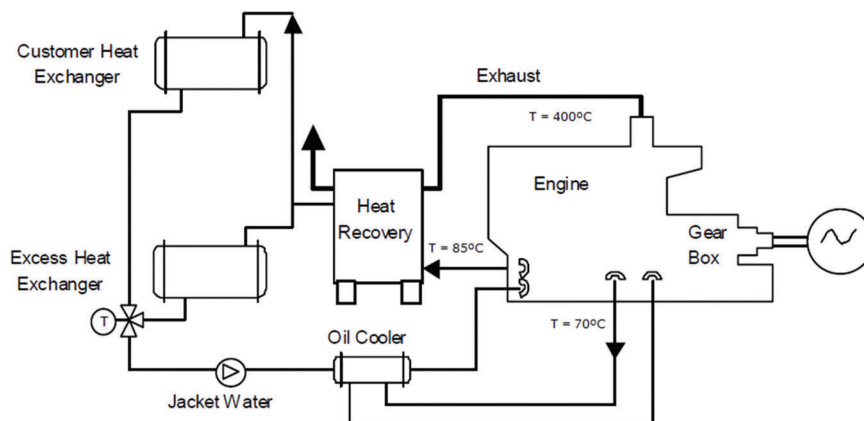[1]1$ = 0.73 € (Exchange rate as on 26 March 2014).

Figure A.7 Closed-loop heat recovery system in a reciprocating engine (example temperatures) [51].

for low-temperature process needs, space heating and potable water heating, and to drive absorption chillers providing chilled water, air conditioning or refrigeration.

Control

Reciprocating engines are controlled by the amount of fuel injected in the CHP system. The control depends on which is the priority demand to supply. However, thermal and electrical demand can be supplied simultaneously. If thermal energy is needed during CHP operation, there is no problem. Heat demand is supplied while electricity can be delivered to the grid or can be consumed by the process or the building. If thermal demand is not needed during CHP operation, there must be a heat storage device. Heat transportation is expensive and has a reduced efficiency due to the thermal losses. Other way, this heat storage device has a limited capacity. If there is no heat demand and the heat storage device is already full, CHP system may stop its operation in order not to waste heat. Mostly, an emergency or auxiliary cooler is installed for operational safety.

Calculation

The total efficiency of the plant is defined as follows:

$$\eta_{\mathrm{CHP}} = \frac{\dot{Q}_H + P_{\mathrm{el}}}{\dot{m}_{\mathrm{fuel}}\,\mathrm{LHV}}.$$

where P_{el} is the electric power, $\dot{Q}_H$ is the useful rate of heat, $\dot{m}_{\text{fuel}}$ is the rate of supplied fuel, and *LHV* is the lower heating value of the fuel. The total efficiency is often divided into the two parts, instantaneous electric efficiency $\eta_{\text{el,CHP}}$ and thermal efficiency $\eta_{\text{th,CHP}}$ with $\eta_{\text{CHP}} = \eta_{\text{el,CHP}} + \eta_{\text{th,CHP}}$:

$$\eta_{\text{el,CHP}} = \frac{P_{el}}{\dot{m}_{\text{fuel}}\ \text{LHV}}; \quad \eta_{\text{th,CHP}} = \frac{\dot{Q}_H}{\dot{m}_{\text{fuel}}\ \text{LHV}}.$$

Limits of Application

The CHP plant requires a certain amount of annual operating hours in order to make economic sense. Thus, there must be an appropriate heat demand available close to the Data Centre, which absorbs the rejected heat especially during winter, when the Data Centre is cooled by means of indirect air free cooling.

Economic Aspects

The investment costs (without gas processing) of a reciprocating engine for biogas CHP can be estimated by [6]

$$c_{\dot{Q}} = f_{\text{RPI}}^{(y-2011)}(15648\ P_{el}^{-0,536})$$

where $c_{\dot{Q}}$ und P_{el} represent the specific investment costs in €/kW and the electric power in kW, respectively. The factor f_{RPI} indicates the mean annual rate of cost increases (e.g., 1.03) from 2011 to the current year y.

A.4 Cooling Production

A.4.1 Absorption Chiller

General Description

An absorption chiller produces chilled water by transferring heat from the chilled water circuit to the re-cooling circuit (closed cycle). The absorption cycle is driven by heat supplied to the generator.

The main components of an absorption chiller are evaporator, condenser, generator and absorber as well as expansion devices and a solvent pump as shown in Figure A.8. For HVAC applications and chilled water production, water and lithium bromide are most commonly used as refrigerant and solvent, respectively [53]. Absorption chillers are available as single-effect,
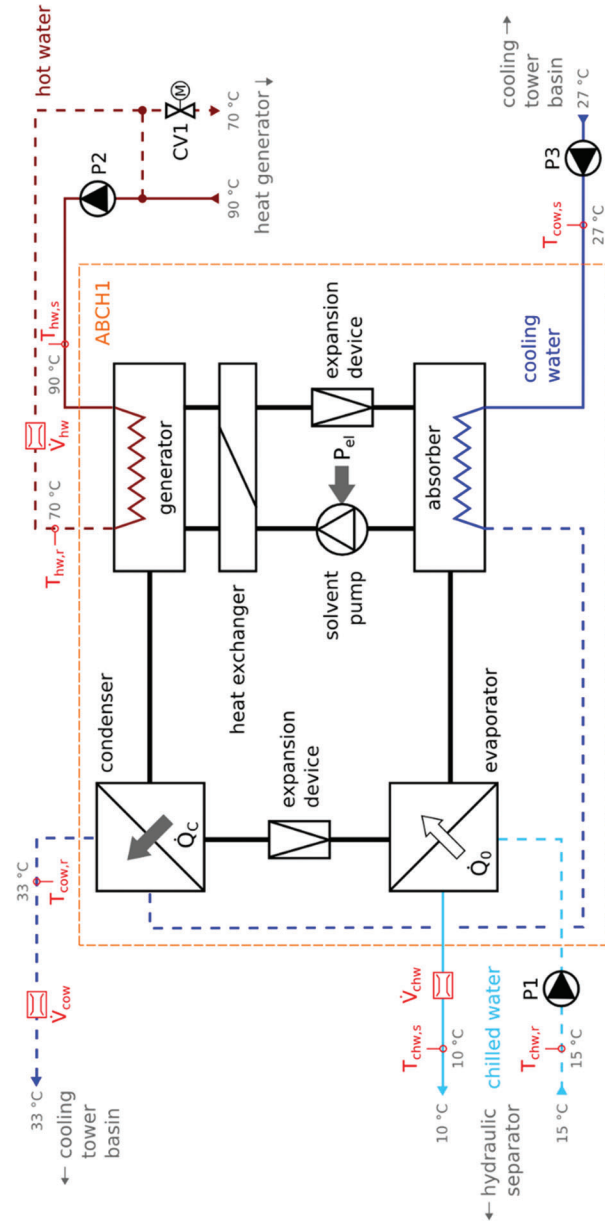
Figure A.8 Hydraulic scheme of a single-effect absorption chiller (H_2O-LiBr) for water cooling; re-cooled with water (example temperatures; scheme based on [53]).

double-effect or triple-effect machines. Double- or triple-effect chillers can be applied when high driving temperatures are available and lead to higher *COP*s compared to single-effect absorption chillers.

In addition to the chiller itself, the three pumps P1, P2 and P3 shown in Figure A.8 are considered as parts of the subsystem.

Hydraulic Scheme

The hydraulic scheme of a single-effect absorption chiller is shown in Figure A.8.

Control

Cooling power of the chiller is controlled internally for reaching the set point of chilled water supply temperature $T_{chw,s}$. Constant flow through the shell-and-tube heat exchangers is recommended. Thus, it is proposed to run an absorption chiller with constant cooling power and use a thermal energy storage for levelling fluctuating loads.

In the hot water circuit, a variable supply temperature $T_{hw,s}$ can be reached by controlling the addition of return water to the supply by means of a control valve CV1.

Calculation

The heating power $\dot{Q}_H$ needed to produce a given cooling power $\dot{Q}_0$ can be calculated from the coefficient of performance (*COP*):

$$\dot{Q}_H = \frac{\dot{Q}_0}{COP}$$

The *CoP* depends, for example, on the construction type of the chiller, on the current usage rate and on the media used as refrigerant and solvent. Typical *COP* values are shown in Table A.3. Detailed rating values are available from literature, e.g. [13].

Absorption chillers are characterised by a beneficial part load behaviour. Normally, cooling power can be reduced to 10% of the rated power as shown in Figure A.9.

As it is shown by the energy flow scheme in Figure A.10, the heat flow $\dot{Q}_{con} + \dot{Q}_{Abs}$ which is to be removed by the re-cooling circuit amounts to

$$\dot{Q}_{con} + \dot{Q}_{Abs} = \dot{Q}_0 + \dot{Q}_H.$$

Table A.3 Characteristics data of absorption chillers for the production of chilled water and process cooling [53]

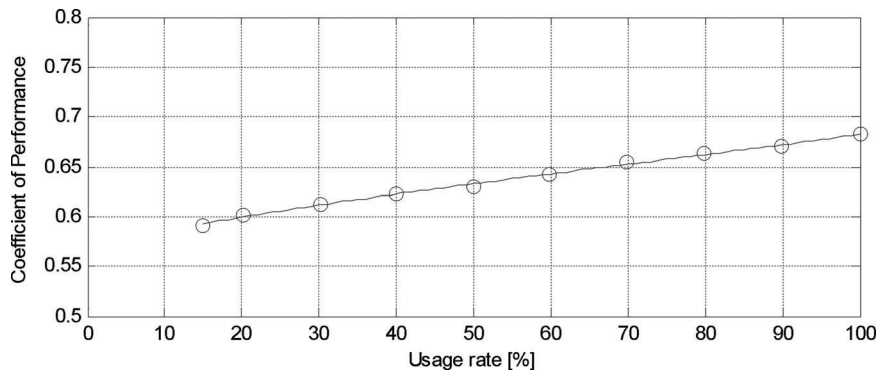|	H_2O–LiBr ABCH (SE)	H_2O–LiBr ABCH (DE)	NH_3–H_2O ABCH
Application	Chilled Water	Chilled Water	Process Cooling
Chilled water outlet temperature [°C]	5–25	5–25	–50–5
Cooling water inlet temperature [°C]	16–45	16–45	
Inlet temperature of heating medium [°C]	75–140	140–170	100–160
COP	0.55–0.75	0.8–1.2	0.35–0.65

Figure A.9 Typical part load behaviour of LiBr-H_2O absorption chillers (single-effect) [21].
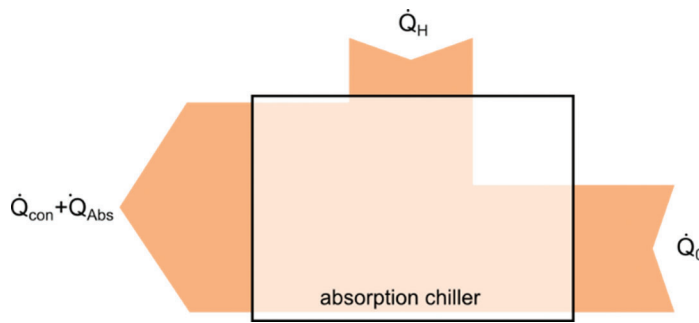

Figure A.10 Scheme of heat flow in an absorption chiller.

The specific internal auxiliary energy demand for pumps accounts for $E_{\mathrm{aux}} = 15 \ \mathrm{Wh/kWh_C}$ [13].

Pumping hot water, chilled water and cooling water through the chiller requires electrical energy. The power P_{Pump} required for a given volume flow rate $\dot{V}$ can be calculated using the following equation:

$$P_{\mathrm{pump}} = \frac{\dot{V}_{\mathrm{chw}} \cdot \Delta p_{\mathrm{chw}}}{\eta_{\mathrm{pump}}} \tag{A.1}$$

Limits of Application

Absorption chillers cover a wide range of cooling power from some kW to some MW. Their application is mainly limited by the availability of a suitable heat sink for re-cooling. For driving the chiller, cheap heat must be available with a temperature of at least 75°C or 140°C (single-effect or double-effect H_2O-LiBr chiller, respectively [53]). Generally, absorption chillers should be used when at least 90°C are available while adsorption chillers are recommended for lower temperatures. The cooling water supply temperature must not drop below 25°C [45].

Economic Aspects

The investment costs of a single-effect absorption refrigerator (without re-cooling plant) can be estimated by [20]

$$c_{\dot{Q}} = f_{\mathrm{RPI}}^{(y-2002)} \left(14{,}740.2095 \ \dot{Q}_0^{-0.6849} + 3.29 \right)$$

$$\left(\text{valid for } 50 \ \mathrm{kW} \leq \dot{Q}_0 \leq 4{,}750 \ \mathrm{kW} \right)$$

where $c_{\dot{Q}}$ and $\dot{Q}_0$ represent the specific investment costs in €/kW and the cooling power in kW, respectively. The factor f_{RPI} indicates the mean annual rate of cost increases (e.g., 1.03) from 2002 to the current year y.

For a double-effect machine, the cost function reads [20]

$$c_{\dot{Q}} = f_{\mathrm{RPI}}^{(y-2002)} \left(231975.0507 \ \dot{Q}_0^{-1,1422} + 90.09 \right)$$

$$\left(\text{valid for } 400 \ \mathrm{kW} \leq \dot{Q}_0 \leq 5270 \ \mathrm{kW} \right) .$$

A.4.2 Vapour-Compression Chiller

General Description

A vapour-compression chiller produces chilled water by transferring heat from the chilled water circuit to the re-cooling circuit. The vapour-compression cycle is driven by electrical energy supplied to the compressor. Re-cooling can be realised either by water-cooling or by air-cooling.

The main components of a vapour-compression chiller are evaporator, compressor, condenser and expansion device as shown in Figure A.11. Many different construction types are available; an overview is given for example in [14].

In addition to the chiller itself, pumps are needed for the chilled water and the cooling water circuit.

Hydraulic Scheme

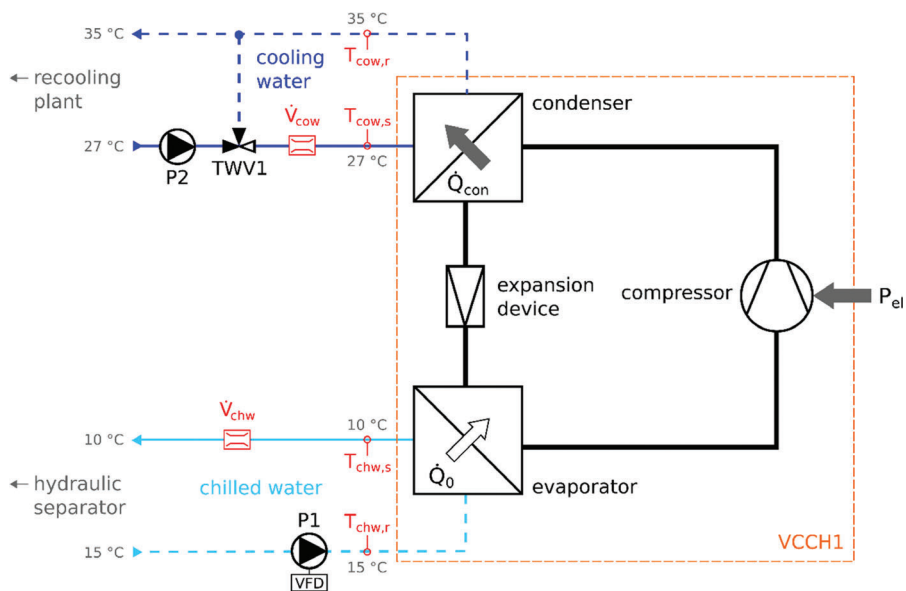The hydraulic scheme of a vapour-compression chiller is shown in Figure A.11.

Figure A.11   Hydraulic scheme of a vapour-compression chiller for water cooling; re-cooled with water (example temperatures; scheme based on [53]).

Control

The cooling power is controlled internally in order to reach the set point of the chilled water supply temperature $T_{\text{chw,s}}$. A variable speed pump P1 can be used for adjusting the chilled water flow to the cooling load. With state-of-the-art chillers, manufacturers allow variable evaporator flow as long as minimum and maximum flow velocities as well as a maximum rate of chilled water flow variation are met [7]. If the evaporator flow rate becomes too small, heat transfer may drop severely.

For achieving a constant cooling water supply temperature $T_{\text{cow,s}}$ which is not too low, a three-way valve TWV1 can be used for admixing return water to the supply.

Calculation

The electrical power P_{el} needed to produce a given cooling power $\dot{Q}_0$ can be calculated from the coefficient of performance:

$$P_{\text{el}} = \frac{\dot{Q}_0}{COP}.$$

The coefficient of performance depends, for example, on the construction type of the chiller and on the current usage rate and generally has a value of 3 to 8 in HVAC applications [20]. Detailed rating values for different compressor types, refrigerants and so on are available from literature, e.g., [13].

Cooling power of vapour-compression chillers can be reduced to 20% of the rated power or less, but *COP* decreases as well in this case as shown in Figure A.12.

As it is shown by the energy flow scheme in Figure A.13, the heat flow $\dot{Q}_{\text{con}}$, which is to be removed by the re-cooling circuit, amounts to

$$\dot{Q}_{\text{con}} = \dot{Q}_0 + P_{\text{el}}.$$

As far as the pump energy demand is concerned, please refer to Section A.4.1.

Limits of Application

Vapour-compression chillers cover a wide range of cooling power from some kW to some MW. Their application is mainly limited by the availability of a suitable heat sink for re-cooling. The cooling water supply temperature must not be too low. The minimum value depends on the process and the machine as well as the refrigerant.

Economic Aspects

The investment costs of a vapour-compression chiller (without re-cooling plant) can be estimated by [20]

$$c_{\dot{Q}} = f_{\text{RPI}}^{(y-2002)} \left(4{,}732.2487 \, \dot{Q}_0^{-0.7382} + 109.30 \right)$$

$$\left(\text{valid for } 10 \text{ kW} \leq \dot{Q}_0 \leq 10{,}000 \text{ kW} \right)$$

where $c_{\dot{Q}}$ and $\dot{Q}_0$ represent the specific investment costs in €/kW and the cooling power in kW, respectively. The factor f_{RPI} indicates the mean annual rate of cost increases (e.g., 1.03) from 2002 to the current year y.
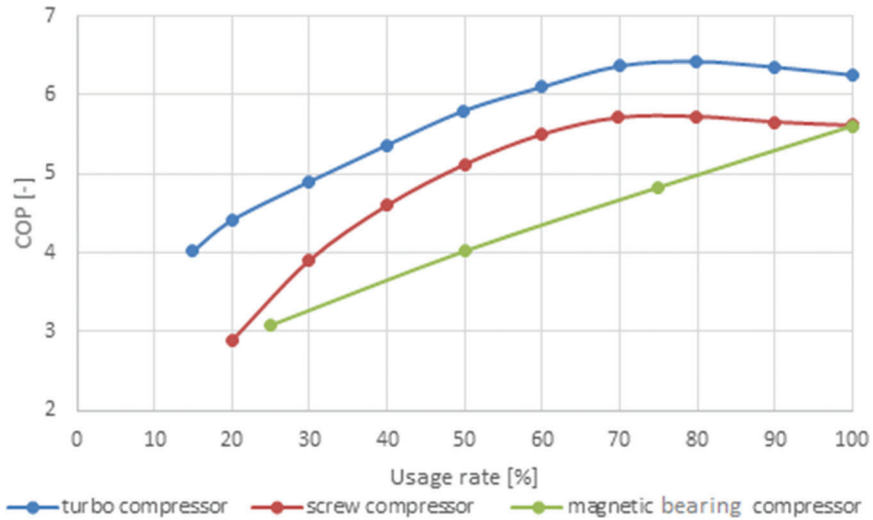

Figure A.12 Typical part load behaviour of vapour-compression chillers depending on the compressor type [11, 21].
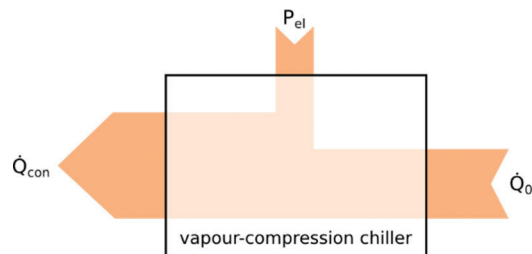

Figure A.13 Scheme of energy flow in a vapour-compression chiller.

A.4.3 Evaporative Cooling

General Description

Evaporative cooling process (adiabatic cooling) is commonly used in cooling water towers, air washes, evaporative condensers and fluid cooling and to soothe the temperature in places where several heat sources are present. It is a simple and effective way of cooling an air stream.

Evaporative cooling equipment can be direct evaporative cooler or indirect cooler. In a direct evaporative cooler (DIEC), the air stream to be cooled is in direct contact with a liquid water film and cooling is accomplished by the adiabatic heat exchange between the air stream and the liquid water film. The evaporation of water in the air stream leads to a reduction in the dry-bulb temperature. However, this will also concurrently cause an increase in the humidity ratio of the air stream. Generally, the maximum possible reduction in air dry-bulb temperature depends on the difference between the dry-bulb and the wet-bulb temperature of the air stream. In many applications, like Data Centres, the increase in humidity in the supply air stream is not desirable. In this case, an indirect evaporative cooling system can be employed.

In an indirect evaporative cooling system, the process air (primary airflow) transfers heat to a secondary airflow or to a liquid that has been cooled by evaporation. By using a cross-fluted heat exchanger, the water never comes in contact with the air. In this case, both dry-bulb and wet-bulb temperatures are reduced.

Using evaporative cooling (DIEC) for the first stage of cooling make-up air reduces energy costs. The second stage is handled by conventional air conditioning. The use of an indirect evaporative cooling system in conjunction with a mechanical air conditioning system offsets cooling loads and significantly reduces energy consumption during peak design conditions.

Hydraulic Scheme

The scheme of an indirect evaporative cooling system is shown in Figure A.14.

Control

The direct evaporative cooler component provides an added cooling benefit only when the ambient dry-bulb temperature is less than the desired supply air temperature. This is because a direct evaporative cooler adds moisture to the supply air as it cools. Similarly, indirect evaporative cooler provides a cooling
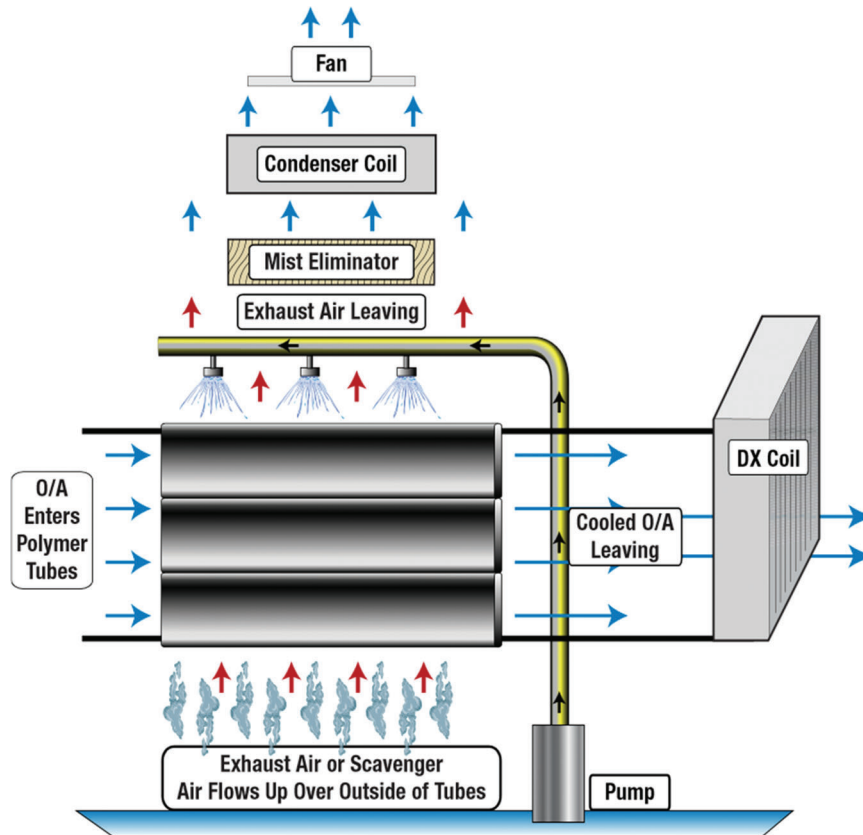
Figure A.14   Hydraulic scheme of an indirect evaporative cooling system [32].

benefit only when the return air wet-bulb temperature is less than the dry-bulb temperature of the outdoor air entering the indirect evaporative cooler. Thus, the system controls typically turn off direct evaporative cooler when the ambient dry-bulb is greater than 13°C, and indirect evaporative cooler is normally disabled when the ambient dry-bulb is less than 17°C to 18°C [44].

Face and bypass dampers on the air-to-air heat exchanger are essential for best control of any two-stage evaporative cooling system, as they allow for economizer cooling and full modulation of indirect evaporative cooler, while similarly allowing for optimal direct evaporative cooler control by regulating the amount of heat recovery as needed to achieve tighter supply air temperature control.

Calculation

The performance of this system is always associated with the other elements of the cooling system. Specific software tools have to be used for selecting the adequate dimension and number of cooling towers for given temperatures and cooling capacity.

Limits of Application

Annual dry- and wet-bulb temperatures at the specific location have to be suitable for the application of evaporative cooling. Additionally, make-up water has to be available.

Economic Aspects

DIEC modules are relatively inexpensive, typically costing 0.37 € per l/s to 0.73 € per l/s for a high-quality unit [36].

A.4.4 Dry Cooler
General Description

A dry cooler (DRC) is a heat exchanger used for transferring heat from a liquid circuit (water or brine) to the ambient air. As shown in Figure A.15, fans are used for blowing the air through the heat exchanger.

Dry coolers can be used for re-cooling the brine circuit of chillers as well as free cooling of chilled water circuits.

Hydraulic Scheme

The hydraulic scheme of a dry cooler plant is shown in Figure A.15.

Control

A set point is given for the brine supply temperature $T_{\mathrm{cow,s}}$. The cooler fans are driven with variable frequency or at least switched between off and two stages (e.g., depending on the ambient temperature). The single coolers with their pumps are switched on and off according to the required cooling power (cascade).

Calculation

The required re-cooling power (heat rejection rate) $\dot{Q}_{\mathrm{Con}}$ is calculated, e.g., for the chiller plant. Design cooling water temperatures can be calculated
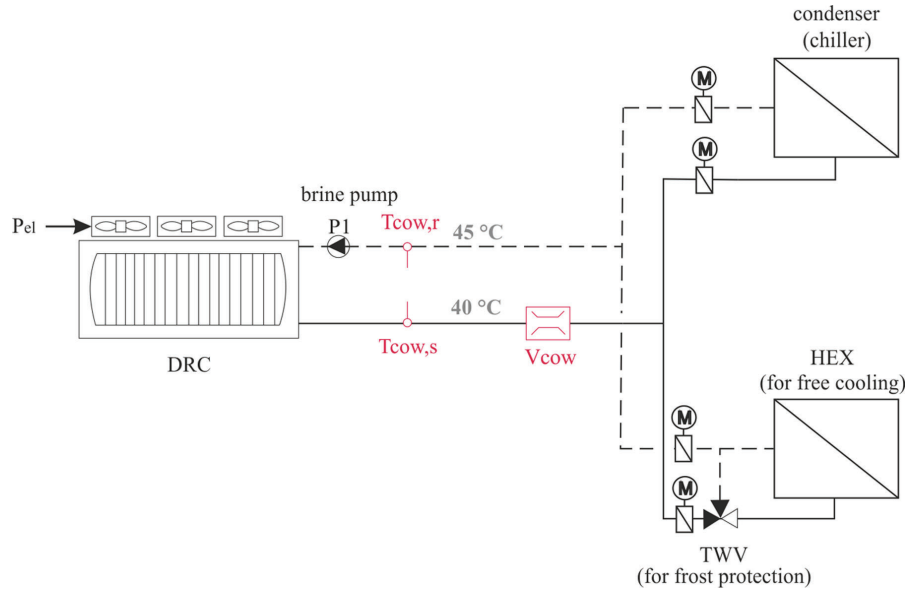
Figure A.15   Hydraulic scheme of a dry cooler plant (example temperatures).

as follows: the design dry-bulb temperature $T_{\mathrm{db,d}}$ depends on the location. Cooling water supply temperature $T_{\mathrm{cow,s}}$ is then known from a given approach (temperature difference between water exiting the cooler and ambient air) which generally is 4–7 K [21]. Fixing the range (temperature difference between water inlet and outlet; typical values are 5–7 K [21]) gives the design water return temperature $T_{\mathrm{cow,r}}$.

   Key data of the cooler are the overall heat transfer coefficient U_0 (design value) and the heat exchanger surface area A. The product UA required for the design cooling capacity $\dot{Q}_0$ can be calculated from [50]

$$\dot{Q}_C = \left(1 - \exp\left[\left(\frac{C_{\mathrm{max}}}{C_{\mathrm{min}}} \right) \left(\frac{UA}{C_{\mathrm{min}}} \right)^{0.22} \right.\right.$$
$$\left.\left. \left\{ \exp\left[-\frac{C_{\mathrm{min}}}{C_{\mathrm{max}}} \left(\frac{UA}{C_{\mathrm{min}}} \right)^{0.78} \right] - 1 \right\} \right] \right) C_{\mathrm{min}} \left[T_{\mathrm{cow,r}} - T_{\mathrm{air,in}} \right]$$

with C_{max} and C_{min} representing the maximum and the minimum value of the capacity flow, respectively. Capacity flow C is calculated as $C = \dot{m}c_p$ from mass flow $\dot{m}$ and specific heat capacity c_p.

Limits of Application

The maximum dry-bulb temperature at the location must not be too high for providing the cooling water temperature required by the process (e.g., vapour-compression chiller).

Economic Aspects

The investment costs for a horizontal dry cooler with fan motor with star connection can be estimated from [20]

$$C[\text{€}] = f_{\text{RPI}}^{(y-2002)} \left(46.169 \cdot \dot{Q}_{\text{rating}} \ [\text{kW}] + 525.02 \right)$$

$$(\text{valid for } 20 \ \text{kW} \leq \dot{Q}_{\text{rating}} \leq 950 \ \text{kW})$$

with $\dot{Q}_{\text{rating}} = \dot{Q}_0 / f_{\text{t}}$ and the correction factor

$$f_{\text{t}} = -0.1 \ t_{\text{air}} \ [^\circ\text{C}] + 3.5 + \left(\frac{t_{\text{brine,in}} \ [^\circ\text{C}] - 40}{10} \right).$$

The power demand of fans and brine pumps can be estimated from the following key figures [20]:

- Fan power: $P_{\text{fan}} = 0.0285 \ \dot{Q}_{\text{rating}}$
- Pump power: $P_{\text{pump}} = 0.0061 \ \dot{Q}_{\text{rating}}$

A.4.5 Wet Cooling Tower

General Description

An open wet cooling tower (WCT) is a heat exchanger used for transferring heat from a water circuit to the ambient air. As the water is in contact with the air, evaporation takes place, which dominates the heat transfer process. As shown in Figure A.17, fans are used for blowing the air through the cooling tower.

A typical wet cooling tower plant consists of several cooling tower cells, which are connected to cooling water basins collecting the warm and the cooled water. Equipping each cell with a cooling water pump is recommended for running arbitrary combinations of cooling tower cells according to demand.

Wet cooling towers can be used for re-cooling the cooling water circuit of chillers as well as free cooling of chilled water circuits.

The enthalpy (*h-x*) chart (Figure A.16) shows the heat transfer processes between air and cooling water in a wet cooling tower.
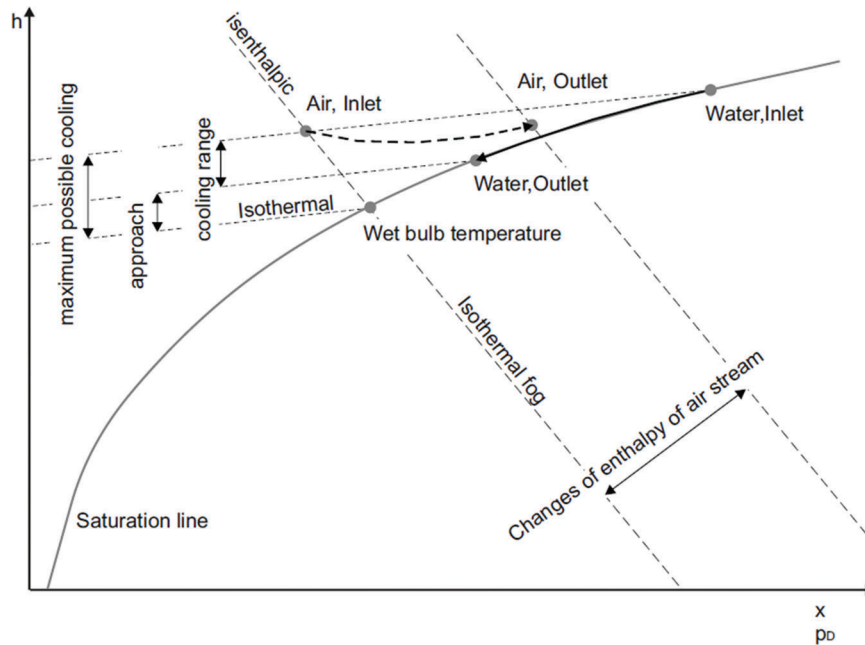
Figure A.16   Schematic representation of change of state of moist air and cooling water in
h-x chart for moist air for an open wet cooling tower [53].

In this chart, a cooling limit represents the theoretically possible cooling
of water in a wet cooling tower. When the air is dryer (a lower wet-bulb
temperature), it can decrease the temperature of the cooling water more
through evaporation. Cooling range represents the actual cooling of the water,
and the approach defines the distance to cooling limit. These terms assist in
evaluating the quality of a cooling tower.

Hydraulic Scheme

The hydraulic scheme of a wet cooling tower plant is shown in Figure A.17.

Control

A set point is given for the cooling water supply temperature. The airflow
through the cooling tower cell is controlled by switching between different
fan power stages or by using variable-frequency drives for the fans. When
the fan of one cell has reached its maximum power and the cooling water
supply temperature is still too high, the next cooling tower cell is switched on
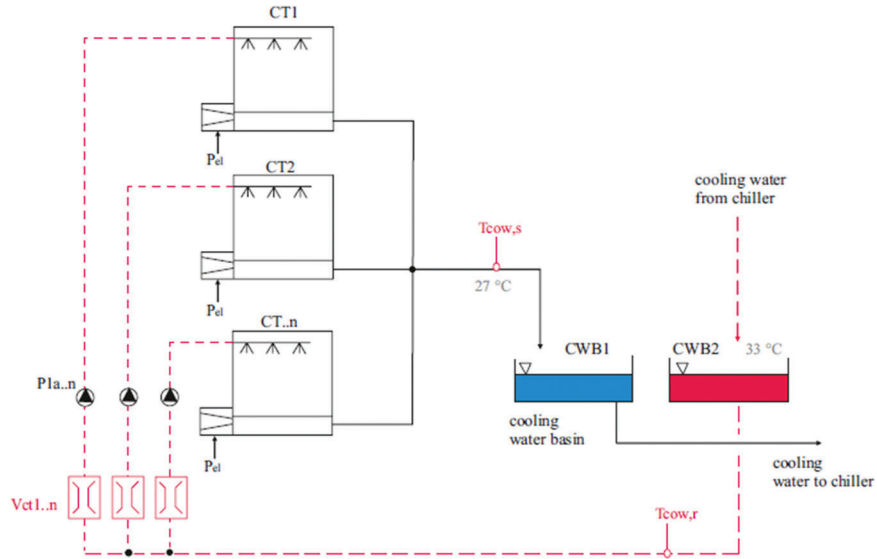beginning with the lowest fan power.

Figure A.17 Hydraulic scheme of a wet cooling tower plant (example temperatures, scheme based on [53]).

An advantage of the basins is their capability to balance fluctuating cooling water temperatures. As a result, a relatively constant cooling water temperature is supplied to the chillers.

Calculation

Obtaining the required cooling capacity and design temperatures is conducted as described in Section A.4.3. As the minimum temperature which can be reached is the wet-bulb temperature, wet cooling tower design is based on a design value of this temperature. It can be, for example, 22°C in Chemnitz, Germany and 26°C in Barcelona, Spain. Typically, the approach and the cooling water range are 4–6 K and 5–7 K, respectively.

Manufacturer software tools have to be used for selecting the adequate cooling tower for given temperatures and cooling capacity.

The power demand P_{fan} of the fans can be estimated depending on the fan type [20]:

$$P_{\text{fan}} = \begin{cases} 0.0043\, \dot{Q}_{\text{C}}^{1.2336} & \text{for centrifugal fans} \\ 0.0105\, \dot{Q}_{\text{C}}^{0.9613} & \text{for axial fans} \end{cases} \tag{A.2}$$

The power demand of the cooling tower pump can be calculated from Equation (A.2) depending on the pressure height Δp.

Limits of Application

Make-up water availability is a requirement for wet cooling tower application. The total water loss sums to about 2.5 to 4.5 l/kWh cooling [27]. Local legislation may restrict the application of wet cooling towers. The effectiveness of re-cooling the cooling water decreases with increased ambient air humidity.

Economic Aspects

The specific investment costs of wet cooling towers can be estimated as [20]

$$c[\text{€}/\text{kW}] = f_{\text{RPI}}^{(y-2002)} \left(2348.2 \, \dot{Q}_C \, [\text{kW}]^{-1.0398} + 26.15 \right)$$
$$\left(\text{for } 50 \text{ kW} \leq \dot{Q}_C \leq 1.2 \text{ MW} \right).$$

A.5 Energy Storage

A.5.1 Electrical Energy Storage

A.5.1.1 Electrochemical batteries

Power stability and power bridging are the two roles covered by electrical energy storages commonly available in Data Centres. An increased energy storage capacity together with advanced control algorithms can enhance energy management strategies easing the integration of renewable energy sources in Net Zero Energy Data Centres.

The commonest electrical storage systems are based on batteries even if flywheels and ultra-capacitors have been tested to store energy in Data Centre environments. Accordingly, following sections concern basic descriptions and key aspects for assessing the modelling of the aforementioned electrical storages.

General Description

A battery is an electrochemical device that stores energy and then supplies it as electricity to a load circuit. Batteries are typically organized in strings and can be connected in series, in parallel or in combination of both, in order to provide the required operating voltage and current.

Electrical Scheme

The electrical scheme of an energy storage system can vary according to the Data Centre energy supply architecture and according to the different types of loads which the energy storage system has to supply. If the energy storage is supposed to supply just the IT load, the electrical storage system can be seen as an additional energy capacity that increases the autonomy of the traditional UPS battery. Otherwise, the electrical storage system should be able to supply both normal and UPS loads.

Control

Charging and discharging processes for the battery are controlled by the AC/DC power converters connecting the storage device with the rest of the electrical system of the Data Centre. In particular, one common practice is to use the DC/AC inverter based on controlled transistors (right converter in Figure A.18) to actively control the currents flowing from/to the battery cell to feed the electrical loads of the Data Centre. This controller can be a proportional type ensuring constancy of the electrical frequency within the electrical grid of the Data Centre. In turn, the left-side converter in Figure A.18 can be non-actively controlled, i.e. based on passive diodes. That is because its duty is just to rectify AC voltage from the main grid to be able to connect the direct current terminals of the battery cell. This converter does not control power flows. However, considering bidirectional power flows between Data Centre and the main grid, both converters should have to be controlled, so they are to be based on transistors.

Calculation

The efficiency of the energy storage system is the key parameter characterising its performance. Round-trip efficiency is affected by both charging and
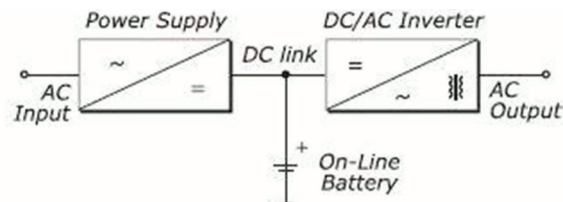

Figure A.18   Battery connected to the DC link of an AC/DC/AC power conditioning unit (topology usually concerned for UPS applications).

discharging operations. In addition, auxiliary loads affect the round-trip efficiency of the system that can be defined as follows:

$$\eta = \frac{E_{\text{out}}}{E_{\text{in}}}$$

where E_{in} is the energy absorbed from an energy source or from the grid while E_{out} is the energy supplied to the grid or to a load. Round-trip efficiency can vary from 95% to 60% according to the cell type.

Limits of Application

Energy storage systems based on batteries are characterised by their great scalability and modularity. This way, designed solutions can be scaled up to several tens of megawatts of power with energy capacity enough to provide energy for several hours at full power. The application of electrical storage in Data Centres is thus not constrained technically, at performances and operating conditions fit with requirements of such installations. Major limits of application are related to economic aspects, as in general terms batteries are expensive components and detailed cost analyses are needed to assess their installation.

Economic Aspects

Table A.4 lists average cost of an electrical energy storage system based on different battery technologies.

Academic work reported by [37] proposes a mathematical expression to estimate the investment cost of electrical energy storage systems. This describes investment cost as a function of power and energy capacities as

$$C[€] = \text{ce}\left[\frac{€}{\text{kWh}}\right] \cdot E[\text{kWh}] + \text{cp}\left[\frac{€}{\text{kW}}\right] \cdot P[\text{kW}],$$

where *ce* is the cost in terms of energy capacity. It mainly refers to the cost of the "container" of the energy stored, i.e. the electromechanical cell in secondary

Table A.4 Cost parameters for different types of batteries [15, 19]

	Li-Ion	Lead-Acid
Investment cost per unit installed power [€/kW]	200	150
Investment cost per unit energy (cost/capacity/efficiency) [€/kWh]	500	200

batteries. *E* is the energy capacity of the storage system and *cp* is the specific cost in terms of power capacity. It mainly refers to the power conditioner unit for the electrical power exchanged by the storage device at its connection point. *P* is the power capacity of the system.

A.5.1.2 Rotary UPS (flywheels)

General Description

Rotary UPS systems are based on flywheels. Flywheels are electromechanical energy storage systems, which store kinetic energy in a rotating disk being mechanically coupled to an electrical machine spinning at high velocity. When energy is required for the loads, the flywheel is slowed down. Thus, part of the stored kinetic energy is translated into electrical energy through the electrical machine. Conversely, when charging the storage device, the flywheel is accelerated so that the electrical energy consumed by the electrical machine during this acceleration is translated into an increment in the rotating speed of the disk. An electronic power converter drives the electrical machine to control its rotating speed, i.e. to control the state of charge of the energy storage device.

Flywheels are characterised by presenting high cyclability, high ramp power rates, short time responses and high power capacity. On the other hand, the energy capacity of flywheels is very limited and they present high standing losses.

Since the energy capacity of flywheels is relatively low, they are able to exchange their rated power for no more than a few seconds at most until being completely discharged.

Rotary UPS systems mainly concern two major design concepts:

a. The rotary UPS and the generator are separated. In this case, the rotary UPS can have a flywheel as a backup.
b. Combined machine of the diesel generator and the flywheel; DRUPS concept/diesel rotary UPS.

In general, diesel generators are placed as close to the Data Centre as possible, mainly to limit the cable length (limits costs, resilience and vulnerability). It should be taken care of that the generator does not cause any vibrations that influence the Data Centre negatively. The generator should be placed inside a compartment that is fire resistant for 60 min. Finally, it is worth noting that the generator is preferably coupled to the Data Centre on the low voltage level.

Electrical Scheme

According to [37], while applied in UPS systems, a flywheel usually provides the energy required for the transition between the mains failure and the starting of long-term backup systems such as diesel generators. This will permit to maintain electrical frequency within admissible limits ensuring proper security of supply for the loads. As previously noted, diesel generators can optionally be part of flywheel-based UPS systems (DRUPS concept).

For short disturbances (up to a few seconds), the flywheel provides the required energy to the loads. Since most of the mains failures last for no more than a few seconds, diesel systems are activated very few times during the life span of the system, prolonging the life of electromagnetic clutches and other critical components. The electrical scheme is shown as follows. Optional components (electrical motor generator, the clutch and the backup diesel generator) are shown in grey.

As shown, in the simplest configuration, the flywheel is composed by the rotating disk coupled to a permanent magnet synchronous machine and an AC/AC power-conditioning unit. This can be directly connected to the power distribution system of the Data Centre or to a motor generator that in turn can be activated by a backup diesel generator, when the energy stored in the flywheel is exhausted. The aim of the electrical motor generator, apart from translating the mechanical energy of the axis of the diesel generator into electrical power, is to protect the power electronics of the flywheel system against short-circuit currents and to improve the quality of the power exchanged with the rest of the system filtering harmonics and correcting power factor, among other aspects.

Control

UPS system is always connected for safety and regulatory issues. Only non-critical loads are directly connected to the main grid. For those loads fed by UPS, and in normal operating conditions, electrical power flows from the main grid, the safety breaker and through the passive filter for power quality issues, as indicated in Figure A.19. Thus, no power flows from/to the flywheel but it is always in charged state, so spinning steadily. Nevertheless, active filtering of power supply can also be performed by controlling fast power exchange by the flywheel at its point of connection.

In case of a mains failure, the safety breaker (see Figure A.19) is rapidly opened and the flywheel feeds the loads. In this case, flywheel is commanded to be discharged, so it slowed down for several seconds until the connection of backup diesel generators [37].
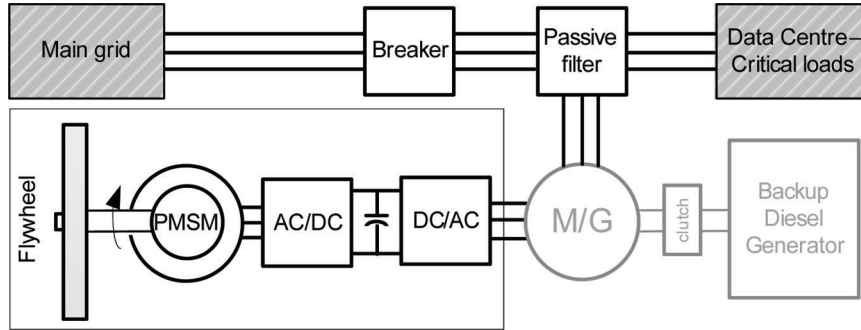
Figure A.19   Flywheel-based UPS system (simplest configuration in black, addition of a backup diesel generator is optional).

Regarding the control of the electronic power converters of the flywheel, it is worth noting that the left-side AC/DC converter in Figure A.19, commonly called machine side converter, is in charge of regulating the speed of the flywheel, i.e. its state of charge. Therefore, it is in charge of controlling the power exchanged by the flywheel. The right-side DC/AC converter is in charge of simply maintaining a constant voltage in the DC link of this set of converters. Thus, both converters have to be based on controlled transistors.

Calculation

For energetic balances, the efficiency of the energy storage system is a key parameter. In this sense, the term "round-trip efficiency" considers both charging and discharging processes and is calculated as

$$\eta = \frac{E_{\text{out}}}{E_{\text{in}}}$$

where E_{in} is the energy absorbed from an energy source or from the grid while E_{out} is the energy supplied to the grid or to a load. For flywheel-based UPS systems, round-trip energy efficiency reaches up to 95%. The simplest configuration for flywheel-based UPS is considered here and corresponds to what is drawn in black in Figure A.19.

Limits of Application

Energy storage systems based on flywheels are characterised by their great scalability and modularity. In addition, the high specific power of flywheels

reduces footprint; so designed solutions can reach several MW of rated power even in limited spaces.

Concerning their application in Data Centres, flywheel-based UPSs should be water-cooled or air-cooled, even connected to the building's chiller water supply. Although cooling requirements are marginal for high-tech units, this is something to take into account.

However, as in the case of electrochemical batteries, major limits of application are related to economic aspects, due to the relatively high cost of the system.

Economic Aspects

Table A.5 presents cost estimations for flywheel systems. The simplest configuration (Figure A.19) for flywheel-based UPS is considered here.

According to an industrial benchmark, a 100 kW UPS based on flywheel system (simple configuration, without diesel generator) with energy capacity of about 300 Wh can cost around 60,000 € . A flywheel system equipped with a backup diesel generator with rated power of about 400 kW can cost around 200,000 € .

A.5.1.3 Static UPS

General Description

The static UPS is called "static" because, throughout its power path, it has no moving parts. The UPS raises the level of safety of the IT equipment. The static UPS has three major subsystems: rectifier, batteries and inverter.

UPSs vary greatly in physical size, weight, capacity, supported input power source, technological design and cost. The four main systems are [38] as follows:

- Standby systems – used for power range of 0–5 kVA
- Line interactive UPS – used for power range of 0–5 kVA
- Online UPS double conversion – used for power range of 5–5000 kVA
- Online UPS delta conversion – used for power range of 5–5000 kVA

Table A.5 Cost parameters for flywheel systems [12]

	Flywheels
Investment cost per unit installed power [€/kW]	600
Investment cost per unit energy (cost/capacity/efficiency) [€/kWh]	1200

Here, only the two last-mentioned systems are described in order to compare 3-phase UPSs that can support Data Centres.

In double conversion UPS (Figure A.20), the critical load is provided with fully conditioned mains power, converting AC to DC and back into clean AC energy. The rectifier and inverter constantly convert all the power required by the load. When a failure of the input AC occurs, this does not cause an activation of the transfer switch, because the input AC is charging the backup battery source that provides power to the output inverter. Thus, during an input AC failure, online operation results in no transfer time and the output voltage is of high quality.

The delta conversion UPS (Figure A.21), under conditions of AC failure or disturbances, exhibits behaviour identical to the double conversion, and it was introduced to eliminate its drawbacks. The inverter powers the load constantly, but the delta converter helps to provide power, drawing it from the main power. In this way, the input voltage is treated and integrated with what is missing at the desired value. The delta converter controls the input power characteristics and controls input current in order to regulate charging of the battery system. Delta conversion provides dynamically controlled a power factor corrected input without the inefficient use of filter banks associated with traditional solutions. The most important benefit is a significant reduction in energy losses.
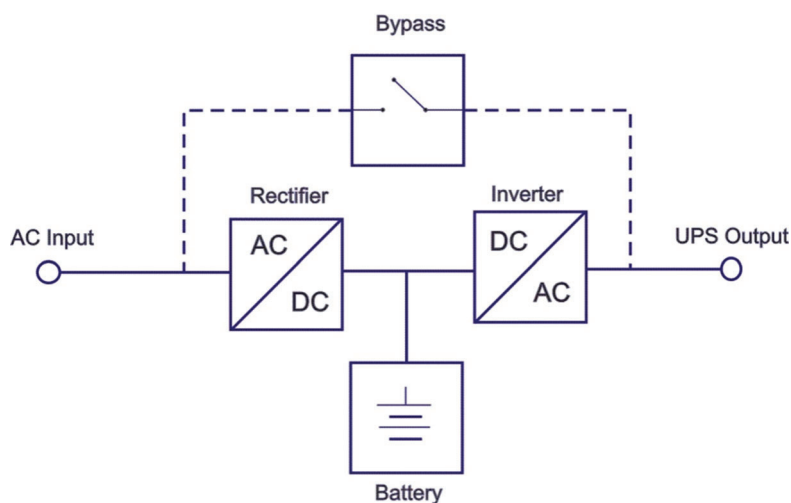

Figure A.20   Double conversion UPS scheme: rectifier and inverter constantly convert all the power required by the load; bypass line is used in case of UPS failure or maintenance.
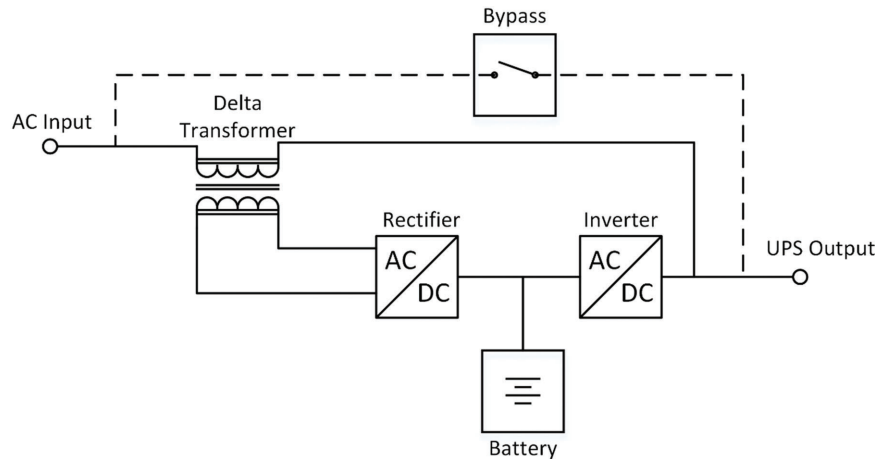
Figure A.21 Delta conversion UPS scheme: rectifier and converter constantly convert all the power required by the load; delta transformer helps to provide power, drawing it from the main power; bypass line is used in case of UPS failure or maintenance.

These systems have several possible configurations. The five most popular UPS configurations are [30] as follows:

- (N) System: The UPSs are one or more in parallel, but the overall capacity is never greater than the load to serve. UPSs can be different.
- Isolated redundant: It has two UPSs: one primary that powers the load alone and a secondary that powers the bypass of the primary. This configuration is redundant, when the primary's bypass is activated, and the secondary should be able to support the entire load instantaneously. UPSs can be different.
- Parallel redundant or ($N + 1$) system: More identical UPSs modules in parallel on a single-bus output. It needs a logic control, because it must have synchronised outputs. For this reason, UPSs have to be identical. The load is uniformly distributed among the modules, and if they work at high percentages of load, the total efficiency increases. Every module can be hot swappable. The bus can be a single point of failure.
- Distributed redundant: Three or more UPS modules with independent input and output power lines. If using static transfer switch (STS), the outputs of the UPS must be synchronised. The STS has two inputs and one output to the PDU. UPSs need a controller, because there is a risk during battery operation that the outputs are out of phase. Every module can be hot swappable. STS is a single point of failure.

- System plus system: This double parallel redundant system $(2 \cdot (N + 1))$ eliminates all single points of failure and maintains redundancy even when maintenance is performed. The two power supply lines must follow separate paths. The parallel UPS must be placed in distant locations.

Each configuration provides different levels of availability, performance and costs.

Electrical Scheme

The electrical schemes of the double and delta conversion UPS are shown in Figures A.20 and A.21, respectively.

$$\eta = \frac{E_{\text{out}}}{E_{\text{in}}}$$

Calculation

Evaluation parameters to size a UPS are operating parameters, availability and performance (efficiency).

The operating parameters are as follows:

- Nominal apparent power S must always be equal or higher than that total load.
- Nominal active power P must always be equal or higher than that total load.
- Overload, necessary to quantify and verify that the UPS can support it.
- Operating temperature tries to predict the temperature rise with the UPS at full load.

The availability defines the ability of the UPS to provide power to the loads continuously and is defined by the following formula:

$$A = (1 - \text{MTTR/MTBF}) * 100$$

where MTTR is mean time to repair and MTBF is mean time between failures [10].

The efficiency η defines the relation between the output and the input active power at the UPS (Figure A.22).
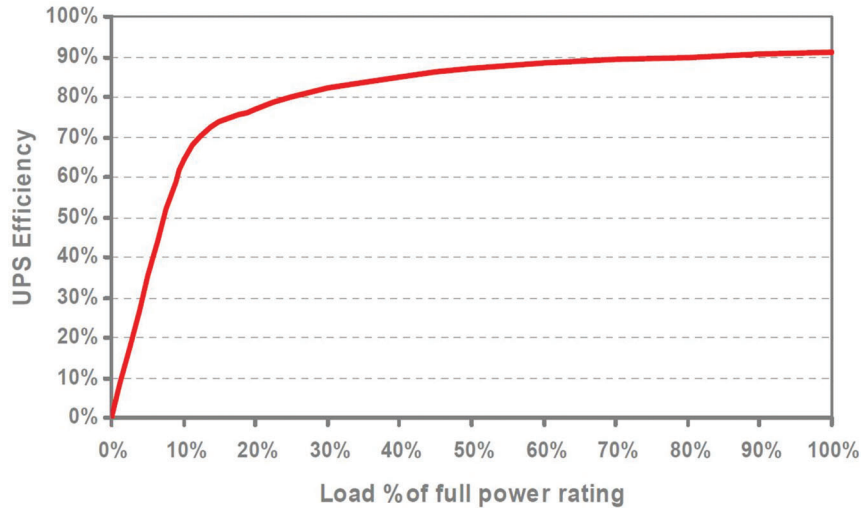
$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}}$$

Figure A.22 UPS efficiency decreases with decreasing load, thus better design and install modular UPS.

Limits of Application

There are some limits to be considered, for example, the noisiness. The noise level produced by the UPS should not exceed the allowable average noise level. The inclusion of the UPS in a specific environment must not alter the living conditions of that area.

The size of a UPS is also an important factor. The space required for the installation of UPS is an important parameter for maintainability, and it is a function of space cost per m^2.

The battery life depends on the ambient temperature, the charging parameters and the number of cycles of charge and discharge.

Economic Aspects

A basic utility cost model of a static UPS is described below (Table A.6):

$$\text{Cost of Energy} = P \cdot \left(\frac{1}{\eta} - 1 \right) \cdot t \cdot c$$

where P is the active power (kW) supplied to the loads, η is the UPS efficiency reported to a given load level and, therefore, not necessarily the rated efficiency of the machine, t is the time in hours per year of service, to the same load level, and c is the unit cost of electricity per kWh.

Table A.6   Cost parameters for batteries systems [12]

	Batteries
Investment cost per unit installed power [€/kW]	400
Investment cost per unit energy (cost/capacity/efficiency) [€/kWh]	200

A.5.2 Thermal Energy Storage

It is well known that thermal energy storage (TES) could be the most appropriate way to close the gap between thermal energy demand and supply. TES can be based on four principles: temperature difference (sensible TES), phase change (latent TES), sorptive processes and reversible chemical reactions. The energy density in sensible heat storages is determined by the specific heat capacity of the storage material and the temperature difference, while in the latent storage, it is determined by the latent heat (enthalpy of fusion). Due to the still low degree of maturity of sorptive and chemical storages, this study only focuses on using sensible and latent heat storage materials.

There are two kinds of storage: short- and long-term storage. Hence, two different storage strategies can be studied:

Short-Term Storage

The cold is stored for some hours (i.e. during the night and the early morning free air cooling is used to cool the Data Centre, while the TES system is storing cold at the same time). When the outside air conditions do not allow operating in free cooling mode, the cold stored is used to reduce partially or totally the Data Centre cooling demand (Figure A.23a).

Moreover, another strategy is to run chillers when their *COP* is high (the lower the outside temperature, the higher the *COP*) or when the electricity cost is low (during peak-off tariff rates) to produce cold and charge the TES. Notice that from using this strategy, not only energy savings can be accomplished (higher *COP* rates), but also lower operational costs since cheap electricity is used.

Seasonal (Long-Term) Storage

The cold is stored for many weeks or months during the cold season, and it is released into Data Centres during warm/hot periods (Figure A.23b). Although long-term storage has greater potential in practical applications, it is more technologically challenging than short-term storage since it requires large storage volumes and has greater risks of heat losses. Moreover, the storage material must be economical, reliable and ecological.
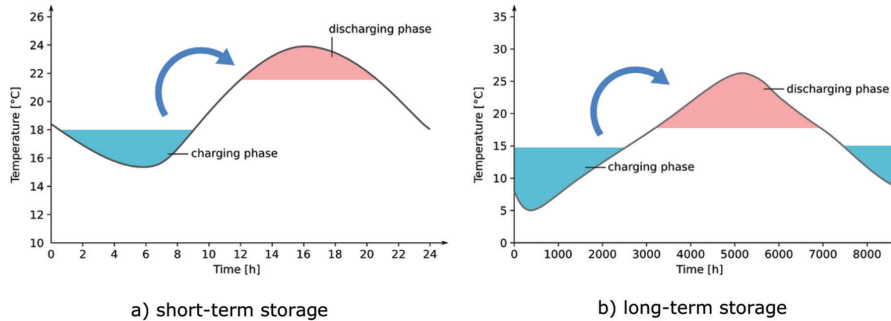
a) short-term storage

b) long-term storage

Figure A.23 Average outside air temperature and TES charging/discharging periods in Barcelona (Spain): spring day with short-time storage (a) and whole year with long-term storage (b).

A.5.2.1 Thermal Energy Storage – Water

General Description

A thermal energy storage (TES) can be applied for short-term storing of chilled or hot water, i.e. as cold or heat storage, respectively. Thermal stratification is important for efficient storage operation. The temperature-depending density of water is used to maintain layers with different temperatures within the storage tank (water temperature decreases from top to bottom). There are different possibilities for storage construction [53]. Here, flat-bottom tanks are assumed for the storage of chilled water.

The storage system consists of the storage tank itself as well as pumps and valves for charging and discharging the storage (see Figure A.24). Connecting the storage to a hydraulic separator between the supply system (chillers for the case of cooling) and the consumer circuit (e.g., cooling distribution system) is favourable.

Hydraulic Scheme

The hydraulic scheme of a chilled water thermal energy storage is shown in Figure A.24.

Control

The parallel pumps (cascade) which are equipped with variable-frequency drives control charging or discharging power. Valves are used for shifting between charging and discharging (these valves are not shown in Figure A.24).
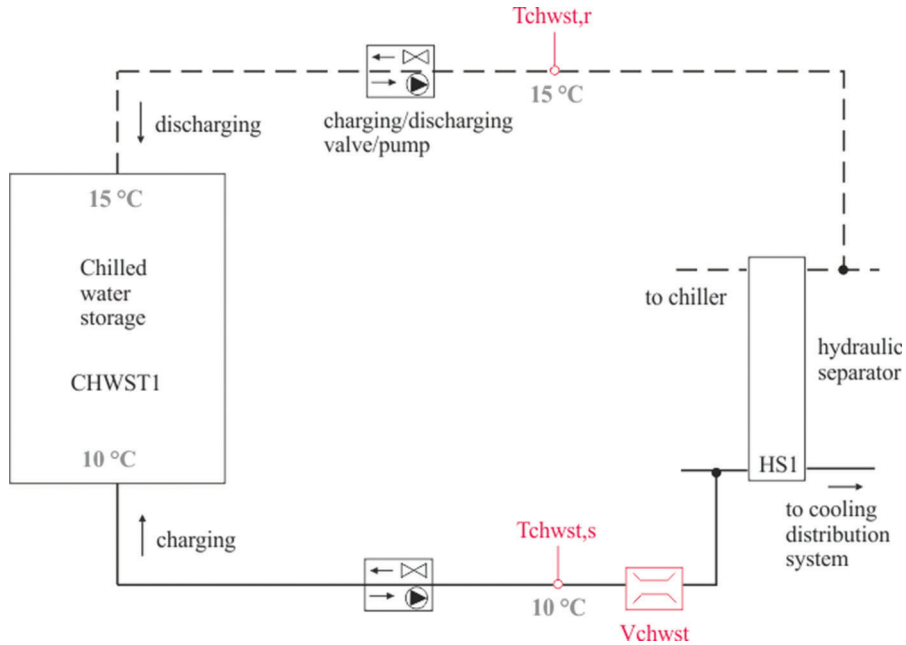
Figure A.24   Hydraulic scheme of a chilled water thermal energy storage (example temperatures) based on [53].

Calculation

For sizing the storage, the required discharging or charging power $\dot{Q}_{\mathrm{CDS}}$ has to be defined as well as the time t_{CDS} which has to be covered until the storage is fully charged or discharged. From $\dot{Q}_{\mathrm{CDS}}$, the design charging/discharging volume flow $\dot{V}_{\mathrm{CDS}}$ can be calculated as

$$\dot{V}_{\mathrm{CDS}} = \frac{\dot{Q}_{\mathrm{CDS}}}{\Delta T \ \rho \ c_p}$$

with the temperature difference ΔT, water density ρ and specific heat capacity c_p. The required storage volume is obtained from $V_{\mathrm{TES}} = \dot{V}_{\mathrm{CDS}} \ t_{\mathrm{CDS}}$.

The power demand of the charging/discharging pump can be calculated from Equation (A.1) on page 13. The pressure difference Δp depends, for example, on the static pressure in the cooling supply system. For a typical chilled water storage ($V_{\mathrm{TES}} = 2700$ m^3, $\dot{V}_{\mathrm{CDS}} = 315$ m^3/h), the required pressure difference is $\Delta p_{\mathrm{pump}} = 0.4$ bar (static pressure 1.5 bar in hydraulic separator).

Limits of Application

Chilled water storages are limited to a minimum water temperature of 4°C due to density rise below this value. Unpressurised hot water storages as considered here are limited to a maximum temperature of 95°C.

Economic Aspects

The specific investment costs of chilled water storage systems ($100 \text{ m}^3 \leq V_{\text{TES}} \leq 6000 \text{ m}^3$) can be estimated as [52].

$$c[\text{€}/\text{m}^3] = f_{\text{RPI}}^{(y-2008)} \left(-119.74 \, \ln \left(V_{\text{TES}} \, \left[\text{m}^3 \right] \right) + 1291.1 \right).$$

A.6 Waste Heat Recovery

A.6.1 (Low-Ex) Heating System

General Description

A building heating system can make use of the heat produced in the Data Centre for space heating, e.g., in offices related to the Data Centre or in other facilities close to it. The heating system is a heat sink characterised by a heat demand and certain supply and return temperatures. Favourable are Low-Ex systems with supply temperatures being close to the ambient temperature.

As shown in Figure A.25, different solutions are possible depending on the IT cooling system:

a. If heat is absorbed from the IT hardware by direct liquid cooling system, the water of the cooling circuit can be used for space heating (heat sink HSI1). A heat storage could be included in the heating system for balancing the difference between heat supply and demand as well as smoothing fluctuating water temperatures.
b. For the case of air-cooled IT, the heated air can be passed directly to the rooms that require heating.

Hydraulic Scheme

The hydraulic schemes of heating systems using heat from the Data Centre for the cases of IT direct cooling and air-cooling are shown in Figure A.25.
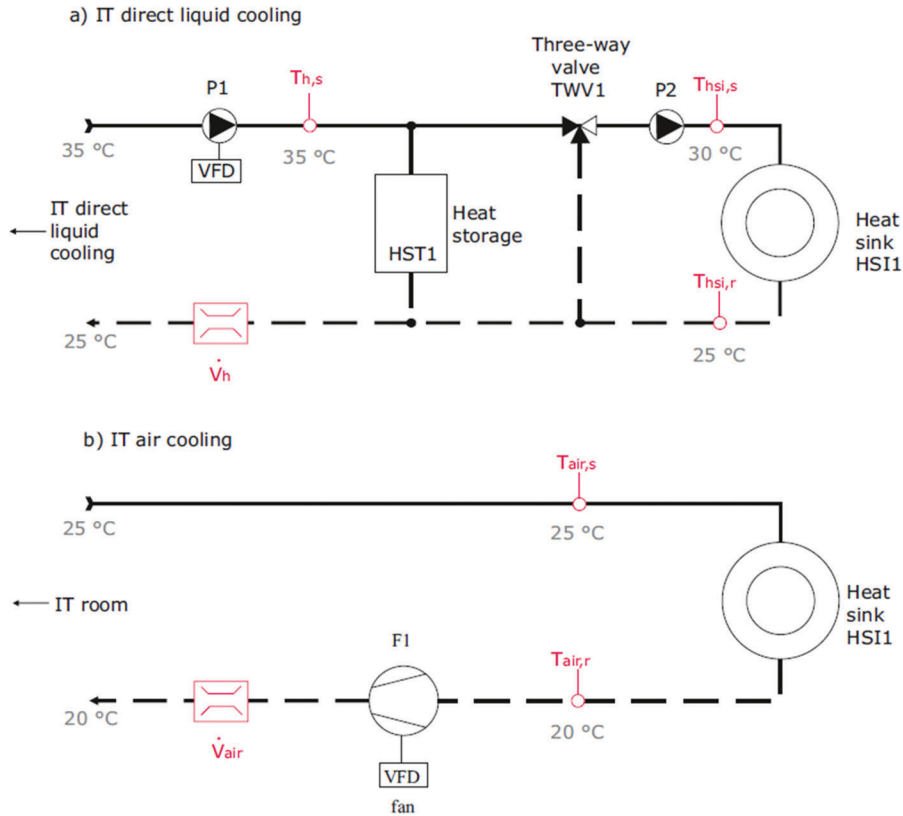
a) IT direct liquid cooling

Three-way
valve

P1   T$_{h,s}$ TWV1   P2   T$_{hsi,s}$

35 °C   35 °C   30 °C

VFD

IT direct
← liquid
cooling

Heat
storage

HST1

Heat
sink
HSI1

T$_{hsi,r}$

25 °C   25 °C

$\dot{V}_h$

b) IT air cooling

T$_{air,s}$

25 °C   25 °C

← IT room

Heat
sink
HSI1

F1   T$_{air,r}$

20 °C   20 °C

$\dot{V}_{air}$

VFD

fan

Figure A.25 Hydraulic scheme of heating systems using heat from the Data Centre for the case of IT direct cooling (a) and air cooling (b); example temperatures.

Control

a. Water-heating system

The heating circuit is run with variable flow (pump P2) for energy-efficient operation. The pump control is adapted to the heating system. A three-way valve TWV1 is controlled for maintaining the set point supply temperature $T_{hsi,s}$ (depending on ambient temperature) by admixing return water.

b. Air-heating system

The air volume flow supplied to the heat consumer can be controlled by means of a variable-frequency driven fan.

Calculation

Heat sink inlet and outlet temperatures $T_{\mathrm{hsi,s}}$ and $T_{\mathrm{hsi,r}}$, respectively, are connected to the heating power $\dot{Q}_h$ by

$$\dot{Q}_h = \dot{V} \rho c_p \left(T_{h,s} - T_{h,r} \right)$$

with the heat carrier's flow rate $\dot{V}$, its density ρ and its specific heat capacity c_p. Design temperatures can be for example

- $T_{\mathrm{hsi,s}} = 70°\mathrm{C}/T_{\mathrm{hsi,r}} = 55°\mathrm{C}$ (low-temperature radiator heating system)
- 55/45°C (radiator heating system with reduced temperatures)
- 35/30°C (Low-Ex underfloor heating system)
- 28/22°C (wall and/or underfloor heating system)

Limits of Application

A significant heat demand is required close to the Data Centre. The design temperatures of the IT cooling system and the space heating system have to be harmonised.

A.6.2 Heat Pump

General Description

The main function of a heat pump is raising heat to a higher temperature level in order to supply a heat demand. The main components of an electrically driven heat pump are compressor, condenser, expansion valve and evaporator as shown in Figure A.26. The heat pump cycle is identical to the vapour-compression refrigeration cycle. The basic difference between a heat pump and a refrigerator (chiller) is that in a refrigeration system, cooling of the fluid flowing through the evaporator (primary circuit) is the main purpose, while heating of the fluid in the condenser (secondary circuit) is aspired in heat pump application.

Here, both cooling of the primary circuit and heating of the secondary circuit are beneficial. A water–water high-temperature heat pump is used for cooling the water coming from the white space. The condenser heats water up to, e.g., 70°C for application in space heating systems or feed into a district heating system.
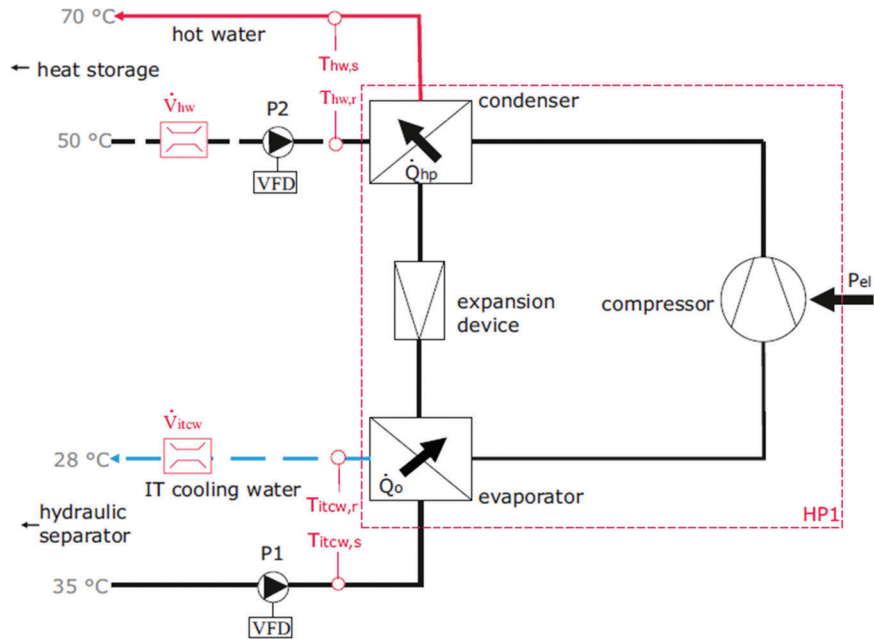
Figure A.26   Hydraulic scheme of a heat pump for water cooling (example temperatures).

Hydraulic Scheme

The hydraulic scheme of a heat pump is shown in Figure A.26.

Control

A set point is presumed for the hot water outlet temperature of the condenser. A pump equipped with variable-frequency drive (VFD) regulates the flow of water flowing through evaporator and condenser accordingly. Controlling of the temperature, load and pressure difference is possible within the allowable limits of the heat pump. Also, desired temperature difference between inlet and outlet of evaporator and condenser could be obtained with the VFD pump.

As cooling supply is very important in Data Centres, controlling the heating power of the heat pump must not result in too low cooling power in the primary circuit.

The coefficient of performance (*COP*) of a heat pump is defined as

$$COP_{\mathrm{hp}} = \frac{\dot{Q}_{\mathrm{hp}}}{P_{\mathrm{el}}} \, ,$$
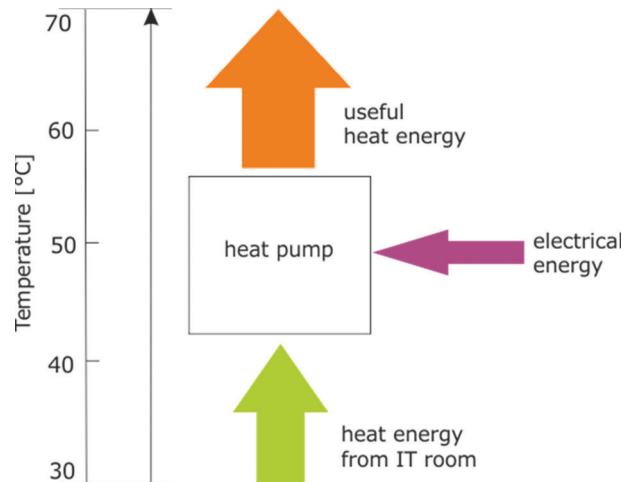
Figure A.27 Schematic energy flow of a heat pump.

where $\dot{Q}_{hp}$ is the thermal output and P_{el} is the power consumption of the unit. In most applications, the *COP* is between 2 and 6 [31]. The *COP* value depends, for instance, on the temperature difference between heat source and heat sink as well as on the type of heat pump. Its value decreases as the temperature difference increases [26].

Figure A.27 shows the energy flow of a heat pump. The thermal output $\dot{Q}_{hp}$ equals the sum of thermal input $\dot{Q}_0$ (cooling power) and electrical energy supply $P_{el} : \dot{Q}_{hp} = \dot{Q}_0 + P_{el}$.

Limits of Application

Water-to-water heat pumps are available in the market from 1 kW to 10 MW [3]. Thermea Energiesysteme [49] offers high-temperature heat pumps with CO_2 as refrigerant in the range from 45 kW to 360 kW (reciprocating compressor) as well as 1 MW (screw compressor). These heat pumps have allowable temperatures at the inlet and outlet of the evaporator from 8 to 50°C and from 2 to 35°C, respectively, and at the condenser from 10 to 50°C and from 40 to 90°C, respectively. The working fluid is water.

Economics Aspects

From budget prices provided by Thermea, the following function was derived describing the investment costs for a high-temperature heat pump (CO_2):

$$c_{\dot{Q}}[\text{€}/\text{kW}] = 98370.2 \ \dot{Q}_{hp}[kW]^{-1.2183} + 178.06$$

$$\text{valid for } 45 \text{ kW} \leq \dot{Q}_{hp} \leq 1000 \text{ kW}).$$

Here, $c_{\dot{Q}}$ and $\dot{Q}_{\text{hp}}$ represent the specific investment costs and the heating power, respectively. The cost data used for deriving the equation were based on heat source and heat sink temperatures of 35/28°C and 70/40°C, respectively.

A.6.3 Feed into District Heating System

General Description

Heat produced in a Data Centre can be fed into a district heating (DH) system when a DH network is available and suitable temperatures can be reached from direct liquid cooling (with heat pump if necessary). The main component is a heat exchanger (HEX1 in Figure A.28) which separates the Data Centre cooling system from the DH system.

Hydraulic Scheme

The hydraulic scheme of a transfer system for feeding heat into a district heating system is shown in Figure A.28.
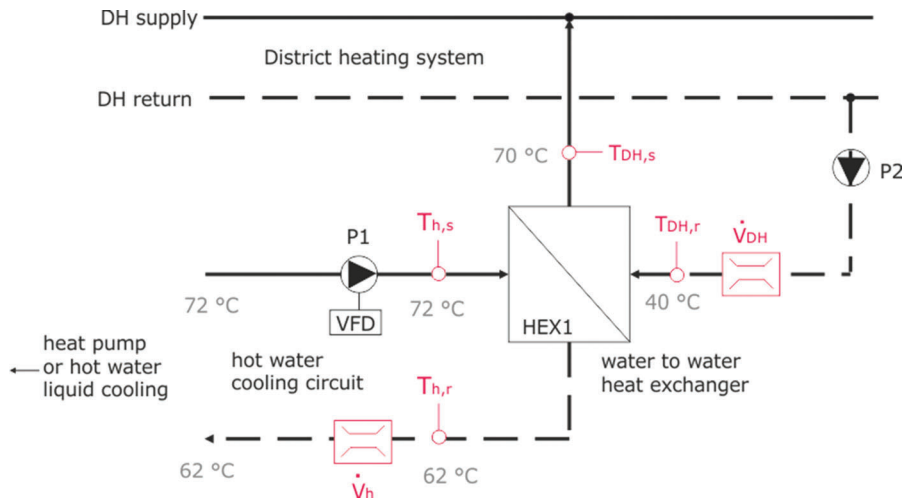

Figure A.28 Hydraulic scheme of a transfer system for feeding heat into a district heating system (example temperatures).

Control

A variable-frequency-driven pump P1 in the hot water "cooling" circuit can be used for keeping the hot water supply temperature at a given set point. However, running the "cooling" circuit according to the supply temperature at the DH heat exchanger must not interfere with IT operation.

Calculation

For a plate heat exchanger operating under counter-flow conditions, the required product of total heat transfer coefficient U_0 and heat transfer surface area A_{HEX} can be calculated from the heat transfer rate $\dot{Q}_{\mathrm{HEX}}$ and the mean temperature difference ΔT_{m}:

$$U_0 A_{\mathrm{HEX}} = \frac{\dot{Q}_{\mathrm{HEX}}}{\Delta T_{\mathrm{m}}} \ \text{ with}$$

$$\Delta T_{\mathrm{m}} = \frac{(T_{\mathrm{hot,in}} - T_{\mathrm{cold,out}}) - (T_{\mathrm{hot,out}} - T_{\mathrm{cold,in}})}{\ln\left[(T_{\mathrm{hot,in}} - T_{\mathrm{cold,out}})/(T_{\mathrm{hot,out}} - T_{\mathrm{cold,in}})\right]}$$

With the temperatures indicated in Figure A.28, the equation for ΔT_{m} reads

$$\Delta T_{\mathrm{m}} = \frac{(T_{\mathrm{h,s}} - T_{\mathrm{DH,s}}) - (T_{\mathrm{h,r}} - T_{\mathrm{DH,r}})}{\ln\left[(T_{\mathrm{h,s}} - T_{\mathrm{DH,s}})/(T_{\mathrm{h,r}} - T_{\mathrm{DH,r}})\right]}.$$

A typical approach temperature (temperature difference between hot outlet and cold inlet) of water/water heat exchangers is 5 K. However, here a large heat exchanger with an approach of, e.g., 2 K should be used. Thus, the temperature that has to be produced in the hot water "cooling" circuit by the IT hardware or a heat pump is reduced.

Typical design overall heat transfer coefficients of liquid/liquid plate heat exchangers are $U_0 = 1200\ldots4500 \ \mathrm{W/m^2 \cdot K}$ [54]. U_0 decreases when the volume flow rates through the heat exchanger are reduced during part-load condition as can be seen from Figure A.29.

Limits of Application

Feeding heat from the Data Centre into a district heating system requires a network being available or built. The hot water produced in the Data Centre needs to have a suitable temperature.
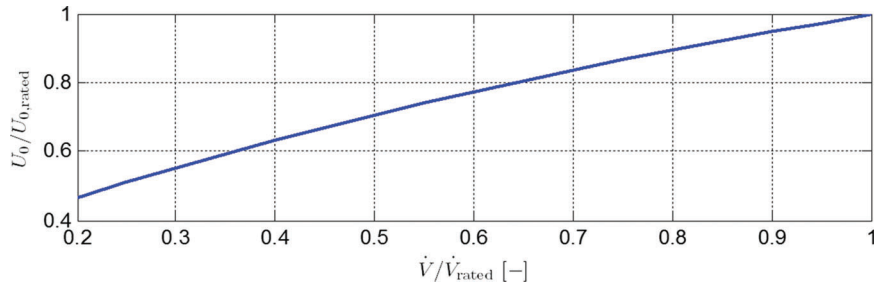
Figure A.29   Relative overall heat transfer coefficient of a water-water plate heat exchanger depending on the relative water flow rate (equal flow rates on primary and secondary side).

Economic Aspects

The investment costs for a gasketed plate heat exchanger can be estimated from [20]

$$C[\text{€}] = f_{\text{RPI}}^{(y-2002)} \left(151.7017 \; A_{\text{HEX}}[\text{m}^2]^{0.8829} + 421.17 \right)$$
$$\left(\text{valid for } 1 \leq A_{\text{HEX}} \leq 550 \text{ m}^2 \right).$$

The cost function was derived for stainless steel plates with EPDM-HT gaskets, maximum temperature and pressure being 160°C and 10 bar, respectively.