6

Advanced Technical Concepts for Power and Cooling Supply with Renewables

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6.1 Introduction

The next step after load minimisation by means of energy efficiency measures as described in Chapters 4 and 5 is to supply the electrical and cooling load efficiently with a high share of renewable energy resources. Six advanced technical concepts containing promising energy-efficiency strategies are proposed in this chapter, which have the potential to minimise the non-renewable primary energy demand for supplying both cooling and power or only cooling to Data Centres.

At first, four scenarios of Data Centres defining sizes and redundancy levels are presented. Advanced technical concepts are assigned to these scenarios in order to cover a wide range of Data Centre types. A brief description of each concept including thermal[1] and electric schemes along with the main components is presented. As far as thermal and electrical storages are concerned, operation and management strategies are required for optimal integration into Data Centres and in order to reach high-energy efficiency. These strategies are incorporated in the concepts as well. Energy flows per year using a Sankey chart are presented for selected scenarios with the objective to present how energy is distributed within the different subsystems.

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[1] The schemes are simplified and do not consider safety equipment and other parts which are required in practice.

6.1.1 Concepts Overview

The advanced technical concepts are defined as a combination of known technologies that are adapted to the specific requirements of Data Centres. It is derived from the integration of innovations under a holistic approach with the aims to provide power, cooling, or both for a Data Centre and to ensure a high share of renewables. Thus, the integrated solutions of the concepts are evaluated and not the sum of the individual subsystems.

The concepts have been chosen based on the following premises:

- The concepts should cover the whole size range of Data Centres.
- The concepts should cover the variety of geographical and climatic conditions in Europe as well.
- The concepts should have the potential to reach a high share of renewables and efficient supply of Data Centres in urban locations.
- The concepts should be economically feasible at present or supposed to become feasible within the next years.

As the most promising solutions, six thermal and electrical power supply concepts for Data Centres have been chosen to be presented in this chapter (Table 6.1). Three of the proposed concepts (1, 5 and 6) cover both cooling and power supply including power generation technologies. These could supply the cooling load as well as a high share of the total electric energy demand of the Data Centre (if necessary, additional electricity might be purchased from the grid). Concept 4 is based on electricity purchased from the grid, but includes thermal and also electric storages for optimal utilisation of the grid power (for example, the storage can be charged when the current electricity price is low or when a lot of renewable energy is fed into the grid leading to a high share of renewables). The other two concepts 2 and 3 are pure thermal concepts, which do not include power supply. Purchasing green electricity from the grid is recommended when implementing these concepts in order to minimise the Data Centre's non-renewable primary energy demand.

Four locations, Barcelona (Spain), Frankfurt (Germany), Amsterdam (Netherlands) and Stockholm (Sweden), representing different climate conditions around Europe, were chosen as examples for evaluating the concepts. It is important to keep in mind that these locations do not represent the climate conditions of the entire country, but are an example for the conditions in the climate zone they are located. The assumed location determines the number of annual hours which allow free cooling, the availability of renewable resources such as solar radiation and wind, the share of renewable energy in the national

Table 6.1 Characteristics of energy supply systems for Data Centres [39]

No. of Concept/Scheme		1	2	3	4	5	6
Liquid-cooled server			x				
Free Cooling	Air	x	x	x	x	x	x
	Cooling Tower			x			x
Chiller	Compression	x		x	x		
	Absorption					x	x
Cold Storage	Buffer, Cold Water	x		x		x	x
	Cold Water				x		
District Cooling	District Cooling		x				
National Power Grid	National Power Grid	x	x	x	x	x	x
Battery Storage	Lead Acid	x					
	Lithium Ion				x		
Renewable Energy sources for Power and Possible Heat Production	PV	x					
	Wind	x					
	CHP with Biomass					FC	CHP
Heat Storage (Buffer, Warm Water)						x	x
Heat Feed-In			x			x	x
Heat Pump for Temperature Rise			x				

grid and the electricity price. Free cooling has been considered in all supply concepts, because it makes sense from the point of view of the primary energy demand at least during winter in all locations.

6.1.1.1 Sankey charts analysis

Within the concept description, the simulation results in terms of Sankey charts illustrate the distribution of average energy flows per year within different subsystems for different scenarios (Table 6.2).

The dynamic simulation tool TRNSYS 17 is used for modelling the six concepts. Each model consists of a group of macros that are connected and create an energy model. The workload has been assumed as the HPC workload (constant over time) for each concept during the simulation. The design IT power of the systems ranges from 120 kW to 2000 kW. The actual IT power consumption of the system is smaller than the design IT power. In general, the IT power consumption of the Data Centre depends on many factors, such as the server type, physical properties of the cooling medium (such as the temperature, flow rate), workload and the occupancy rate. Therefore, in reality, the IT load of the system can never reach the value of the design IT power. This is also regulated by the safety margin.

6.2 Description of the Proposed Advanced Technical Concepts

In this chapter, a brief description of the aforementioned concepts including thermal[2] and electric schemes along with the main components is presented. Furthermore, operation and control of the concepts as well as their limits of

Table 6.2 Data Centre scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Type of facility (example)	Server room	Very small enterprise Data Centre	Small enterprise Data Centre	Cloud Data Centre
Localisation	In house	In house	Building for the DC in a build environment	
Assumptions for concept development	24 kW Redundancy level I	120 kW Redundancy level II	400 kW Redundancy level III	2000 kW Redundancy level III

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[2] More detailed hydraulic schemes of the subsystems as well as information about their control, requirements and costs can be found in annex A. The schemes are simplified and do not consider safety equipment and other parts which are required in practice.

application and geographic restrictions are described. Simulation results in terms of Sankey diagrams illustrate the specific energy flow of each concept.

Emphasis is placed on the thermal systems (for cooling supply) because they are more complex than the power supply system due to energy conversion and heat transfer processes. Furthermore, the grid is always available for purchasing additional electricity or feeding excess power from own generation, whereas the cooling load has to be supplied just in time by own generation or storage discharging. However, the importance of an optimised and efficient power supply system should not be neglected.

In order to guarantee the reliable operation of Data Centres, redundancy and backup equipment are considered in the concepts according to the assumed redundancy levels of the scenarios.

6.2.1 Photovoltaic System and Wind Turbines with Vapour-Compression Chiller and Lead-Acid Batteries

General

In concept 1, vapour-compression chillers along with a dry cooler are used to produce cooling energy during summer. Figures 6.1, 6.2 and 6.3 depict the thermal and electric scheme of this concept. The electrical power required to drive the chiller and to run the IT hardware can be generated by a photovoltaic system and wind turbines installed near the building; additional power is purchased from the grid. Lead-acid batteries are used for decoupling power generation from power consumption and cooling demand. Thus, batteries are charged for example when renewable electric generation is high or when the cost of electricity is low. This strategy allows adopting the Data Centre's

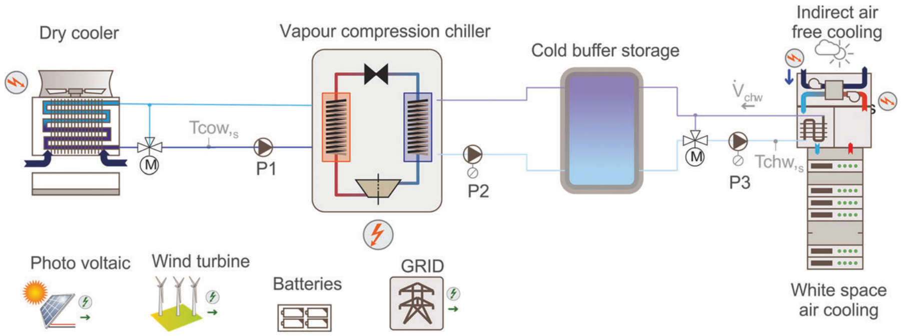

Figure 6.1 Thermal scheme of concept 1.

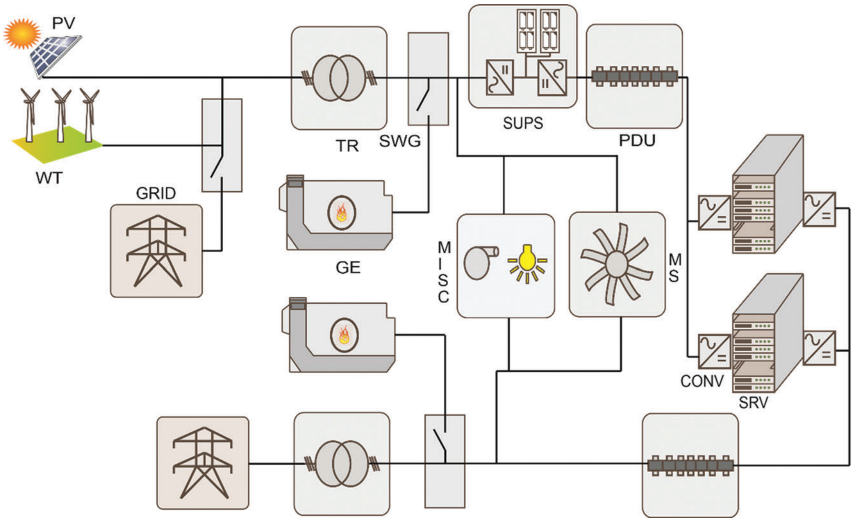

Figure 6.2 Electric scheme of concept 1 with the off-site generation.

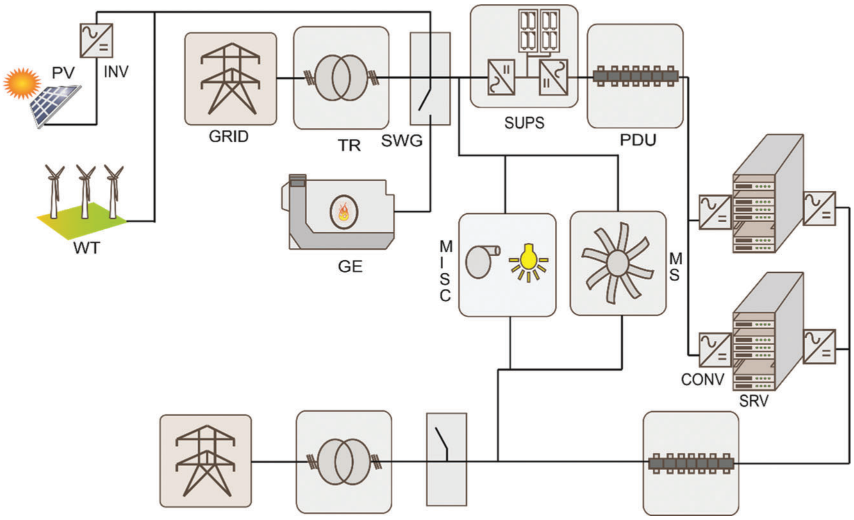

Figure 6.3 Electric scheme of concept 1 with the on-site generation.

total energy draft from the grid to the fluctuating parameters (e.g., cost and share of renewables) in order to optimise the Data Centre energy supply. Additionally, time shifting of the IT workload should be applied in this concept (see Chapter 4).

In winter, indirect air free cooling is performed for efficient cooling supply to the Data Centre.

Operation and Control

Figure 6.4 depicts the control strategy of concept 1. The cooling control strategies vary depending on the operating parameters such as the ambient air temperature, wind and solar power availability, share of renewable power in the grid, cost of electricity and the state of charge of the battery. The operating mode of the concept is selected based on the availability of one of the following order of the operating parameters; first, the availability of the wind and solar power, secondly high share of renewable power in the grid and third cheap electricity. In some scenario, there is a possibility of the availability of more than one operating parameter. The set point values for the supply temperatures of the chilled water ($T_{chw,s}$) and the cooling water ($T_{cow,s}$) used in this concept are 10°C and 27°C, respectively. The pump used for the cooling water circuit (i.e. P1) could be operated with constant speed, whereas the pumps (i.e. P2 and P3) could be operated with variable speed. The flow rate of fluid through the chiller water pump P3 ($\dot{V}_{chw}$) is controlled in order to maintain a specific supply air temperature of 20°C into the white space.

For efficient part load operation of the cooling system, chillers as well as cooling tower units should be sequenced.

Limits of Application

This concept is suitable for all kinds of Data Centres. However, this expensive combined solution requires relatively high levels of radiation and high availability of wind resources to justify the extra investment which is needed. Additionally, sufficient space is required for both the PV panels and the wind turbines.

Backup and Redundancy

As a redundancy, $N + 1$ compression chillers and wet cooling towers are used to attain redundancy level III. All components are connected by two independent paths (Table 6.3).

Sankey Analysis

For the simulation of the concept, a 400 kW IT power capacity Data Centre located in Barcelona has been used. Moreover, the parameters such as IT power

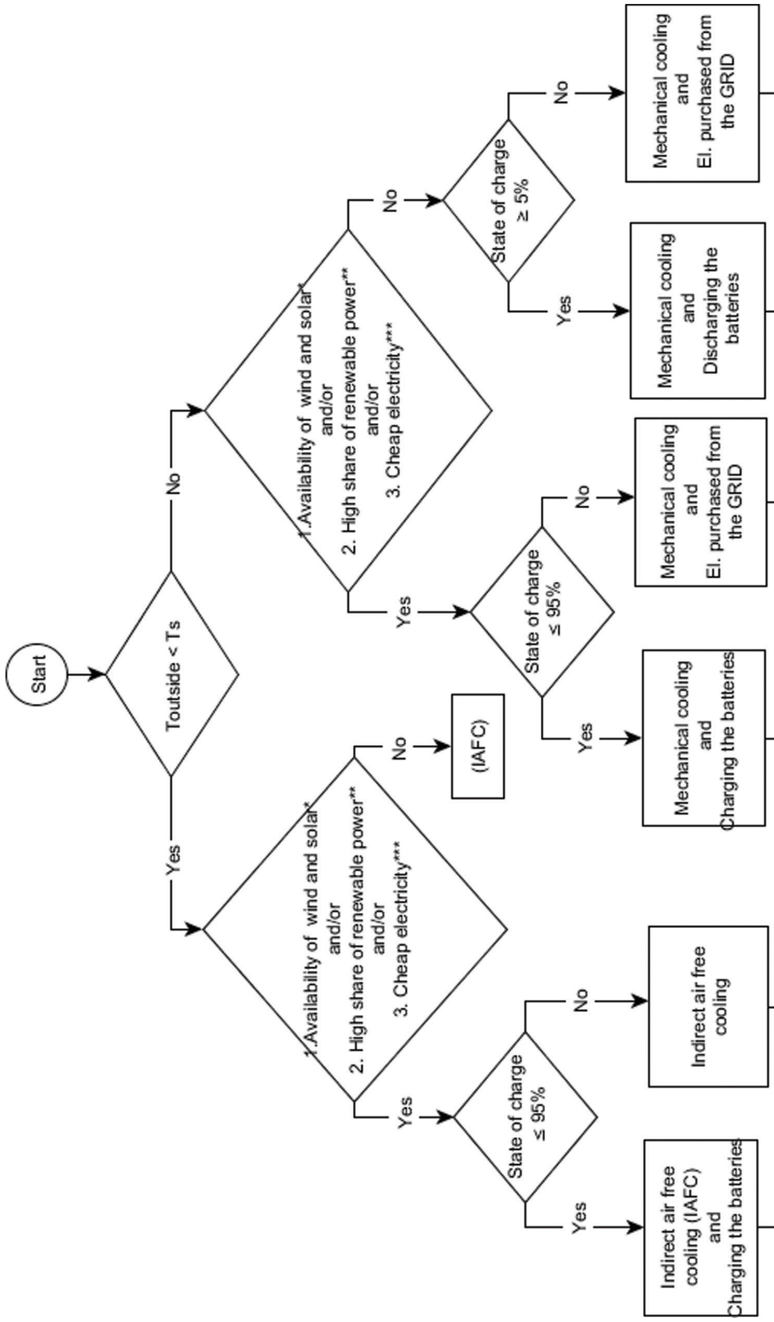

Figure 6.4 Flow chart for the control strategy of concept 1.

Table 6.3 Subsystems in concept 1

Subsystem	Comments
PV power system	Grid-tie photovoltaic power system installed near the building
Wind turbine system	Grid-tie wind turbines installed near the building
Lead-acid battery	Sized according to the required electrical power for IT and cooling distribution as well as the envisaged charging and discharging time
Vapour-compression chiller	Highly efficient machine, e.g., with screw compressor
Dry cooler	Sized according to the chiller capacity
Cold buffer storage	Allowing for optimal operation of both the cold generator (compression chiller) and the cold consumer (e.g., CRAH) by smoothing temperature fluctuations
Indirect air free cooling	Could include adiabatic cooling; run as often as possible

capacity, location and the redundancy level from the scenario 3 (Table 6.2) are applied. The yearly average value of the share of renewable energy in the national grid (RES) is 0.36 during 2013 [16, 17]. Figure 6.5 depicts

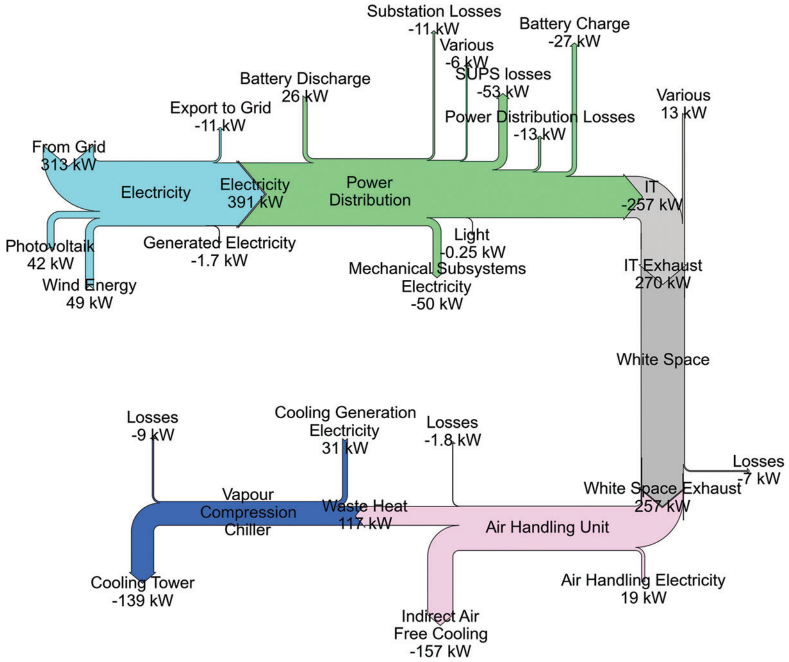

Figure 6.5 Sankey chart showing the distribution of average energy flows per year within different subsystems of concept 1 for scenario 3 (Boundary condition: Barcelona, 400 kW IT power capacity, RES = 0.36).

the distribution of the average energy flows per year within the different subsystems of concept 1. The electricity generated by the PV system and the wind turbines is not sufficient and therefore purchased from the national grid. In the case when the electricity generated is not self-consumed, it is exported to the grid. The concept uses a battery, and about 7% of the electricity is stored temporarily in the battery. It is visible that the free cooling covers only 57% of the cooling load of the Data Centre and the rest is supplied by the chiller.

6.2.2 District Cooling and Heat Reuse

General

In concept 2, chilled water for air cooling is supplied by a district cooling system. Additionally, heat from direct liquid cooling is reused for space heating by means of a heat pump.

Figures 6.6 and 6.7 show the thermal and electric schemes of this concept, respectively. During summer, chilled water from the district cooling system is used to cool the air flowing into the Data Centre, and during winter, indirect free air cooling is conducted. The water for direct liquid cooling is cooled by a heat pump, which provides heat for space heating and domestic hot water. A dry cooler could be used if there is no heat demand.

A district cooling water network with a high share of cooling from renewable sources is required for implementing this concept, but there are no geographical restrictions. The concept might be applied to very small as well as very large Data Centres (50 kW to >10 MW) if a suitable heat sink for heat reuse is available. As the concept does not cover power generation, the required electrical energy can be purchased from the national grid for instance.

Main Components

The main components for this concept are listed in Table 6.4.

Operation and Control

Figure 6.8 depicts the cooling control strategy for both the air-cooled and direct liquid-cooling mode of concept 2. The chilled water volume flow on the primary side of HEX is controlled according to the air-cooling demand[3],

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[3] The flow rate of fluid through the pump P1 ($\dot{V}_{\mathrm{chw}}, 1$) is controlled in order to maintain a specific supply air temperature of 20°C into the white space.

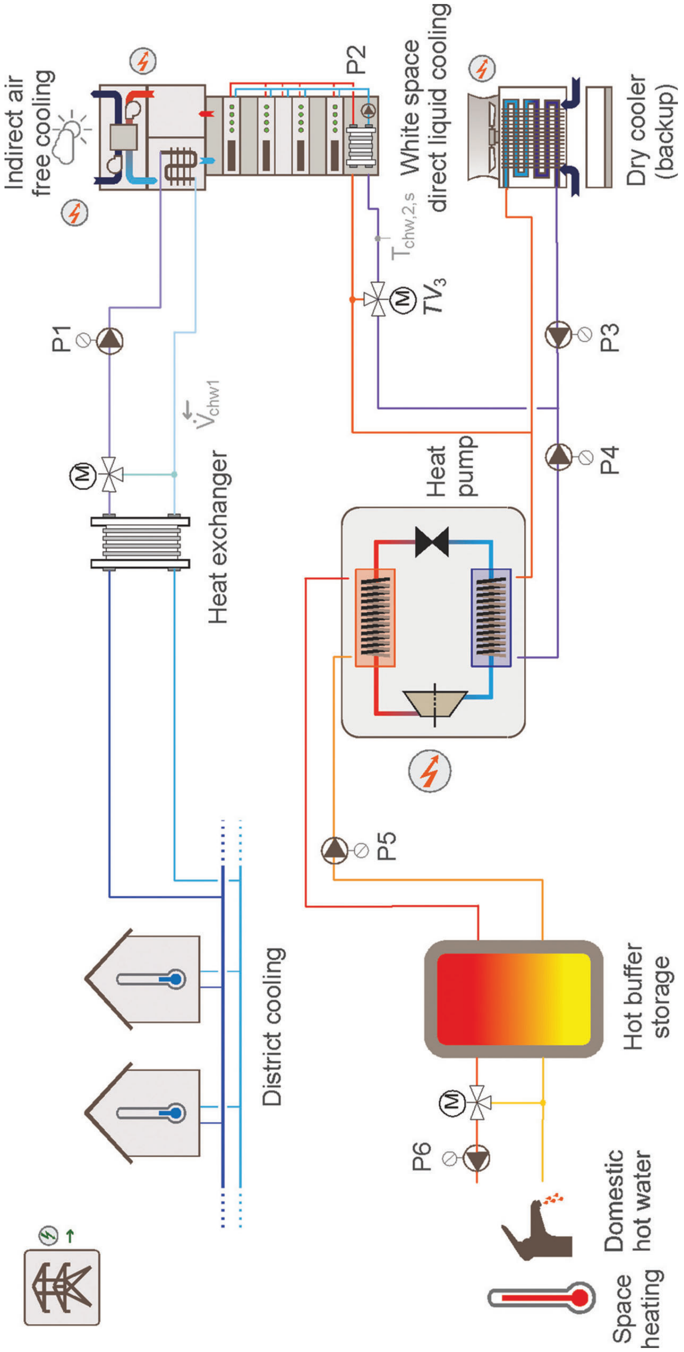

Figure 6.6 Thermal scheme of concept 2.

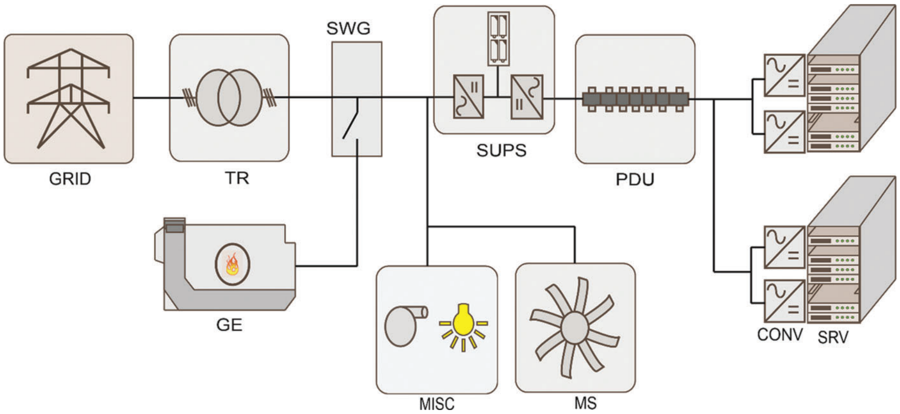

Figure 6.7 Electric scheme of concept 2.

Table 6.4 Subsystems in concept 2

Subsystem	Comments
District cooling system	Supplies water with temperature of, e.g., 5/10°C (higher temperature is preferable for efficiency reasons, e.g., 10/16°C)
Heat exchanger	Water/water plate heat exchanger; sized according to the mean temperature difference and required air cooling power
Heat pump	CO_2 high-temperature heat pump; sized according to water cooling power demand; might not be necessary in a Low-Ex heating system without domestic hot water production
Hot buffer storage	Allowing for optimal operation of both the heat generator (heat pump) and the heat consumer (domestic hot water and space heating) by smoothing temperature fluctuations; works as hydraulic separator between generator and consumer circuit
Space heating system	Design supply temperature as low as possible, e.g., Low-Ex system (40/35°C)
Indirect air free cooling	Could include adiabatic cooling; run as often as possible

while the heat pump is operated depending on the liquid cooling demand. Both the hot and the cold water supply temperatures of the heat pump have to be maintained in a given range. A set point value is defined for one of the temperatures, while the other one is monitored. In concept 2, temperature of the cold water supply (i.e. $T_{chw,2,s}$) is set as 40°C. All the pumps used in concept 2 could be operated with the variable speed.

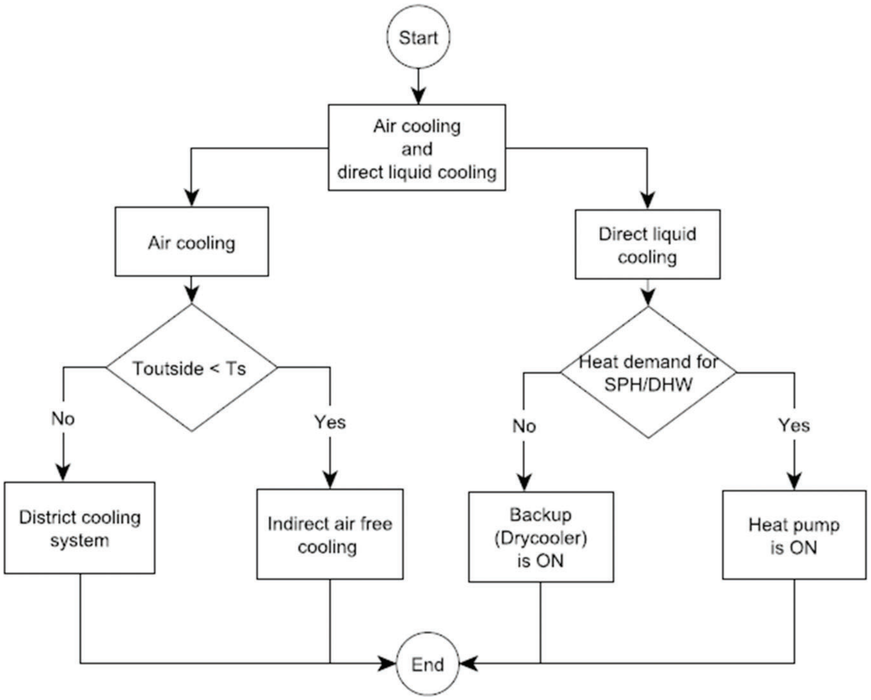

Figure 6.8 Flow chart for the cooling control strategy of concept 2.

Limits of Application

The availability of a district cooling system limits the use of the proposed concept (only urban location). Furthermore, there must be an appropriate heat demand for reusing the heat from direct liquid cooling.

Backup and Redundancy

Redundancy level II can be attained by installing dry cooling tower units, which dissipate the heat from direct liquid cooling when the heat pump is not operating. Alternatively, the direct liquid cooling circuit could be connected to the district cooling system as well. For this system, a guarantee of >99% availability given by the provider is assumed and no backup is considered at the Data Centre.

Sankey Analysis

For the simulation, a 120 kW IT power capacity Data Centre located in Frankfurt and the parameters from scenario 2 (Table 6.2) are used. Figure 6.9

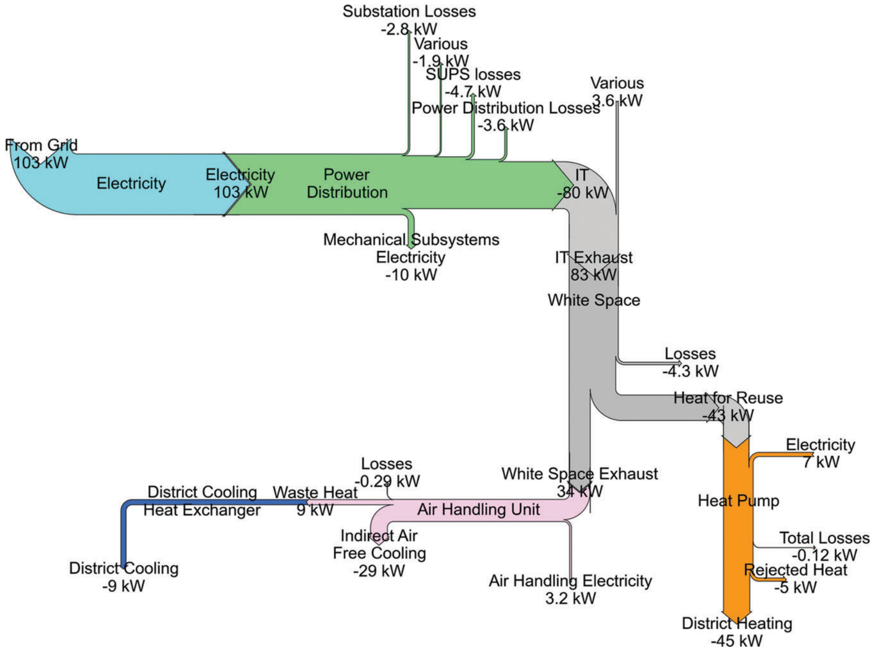

Figure 6.9 Sankey chart showing the distribution of average energy flows per year within different subsystems of concept 2 for scenario 2 (Boundary condition: Frankfurt, 120 kW IT power capacity, RES = 0.26).

illustrates the distribution of the average energy flows per year within the different subsystems of concept 2. Here, the Data Centre is cooled by the air-cooling and the liquid-cooling system. In order to cool the air of the Data Centre in the summer, chilled water from the district cooling system is used, and during the winter, indirect air free cooling is applied. The air-cooling system accounts for 74%, while the liquid-cooling system accounts for 24% of the total cooling load of the Data Centre.

6.2.3 Grid-Fed Wet Cooling Tower Without Chiller

General

In concept 3 (Figure 6.10), wet cooling towers (without chillers) can be used to produce cooling energy. When this evaporative free cooling is not possible, backup vapour-compression chillers along with cooling towers are used. The electrical power required to drive the cooling towers and the backup chillers can be purchased from the national grid. In winter, direct air free cooling

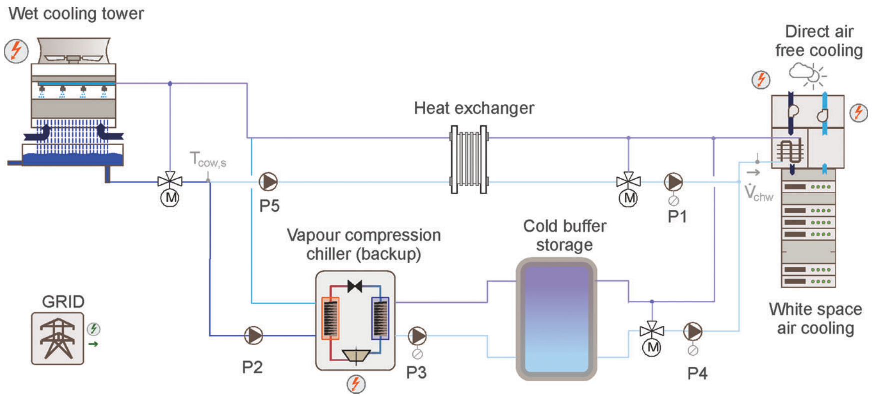

Figure 6.10 Thermal scheme of concept 3.

is performed for efficient cooling supply to the Data Centre. Figure 6.11 depicts the electric scheme of this concept.

This concept might be applied in very small as well as medium-sized Data Centres (50 kW to 1 MW). Table 6.5 gives an overview on the main components (subsystems) shown in Figure 6.10.

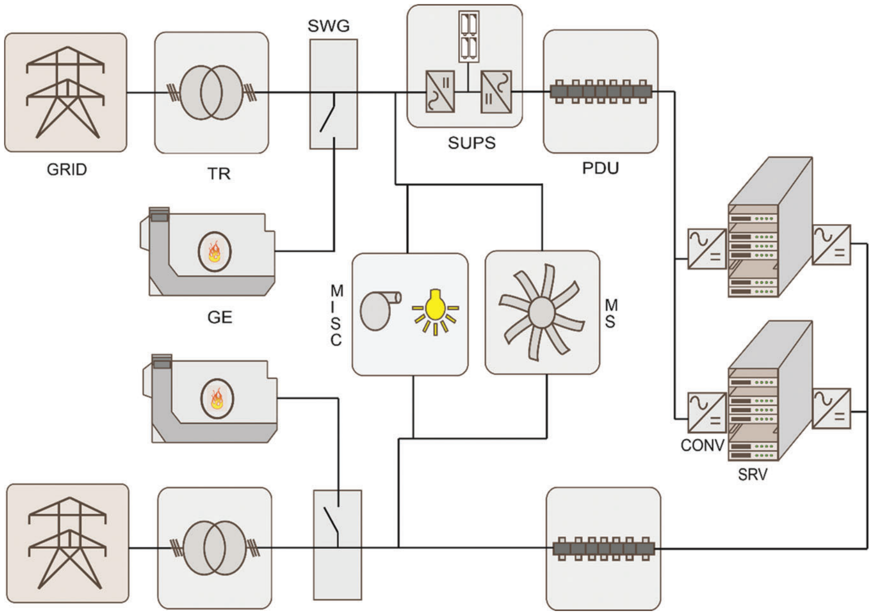

Figure 6.11 Electric scheme of concept 3.

Table 6.5 Subsystems in concept 3

Subsystem	Comments
Wet cooling tower	Used for free cooling and for dissipating the heat from the chiller in summer
Vapour-compression chiller	Backup vapour compression chiller; highly efficient machine, e.g., with screw compressor
Heat exchanger	Water/water plate heat exchanger; sized according to the mean temperature difference and required air cooling power
Cold buffer storage	Allowing for optimal operation both of the cold generator (backup compression chiller) and the cold consumer (e.g., CRAH or cooling coil) by smoothing temperature fluctuations
Direct air free cooling	Run as often as possible

Operation and Control

Figure 6.12 shows the cooling control strategy of concept 3. In case that the outside air temperature is lower than the supplied air temperature to the IT room, the direct air free cooling is used. In other cases when the outside air temperature is higher than the supplied air temperature, the direct air free cooling is not applicable. In this scenario, the cooling tower is used to produce the cooling energy. The operation of the cooling tower control is based on the ambient wet-bulb temperature. This evaporative free cooling is only possible when the outside wet-bulb temperature is lower than the limit set point.[4] In the case when the outside wet-bulb temperature is higher, backup vapour-compression chillers along with dry cooling towers are used. The set point value for the supply temperature of the cooling water ($T_{cow,s}$) used in this concept is 10°C. The pump used for the cooling water circuit of the backup chiller (i.e. P2) is the constant speed pump, and the pumps (i.e. P2, P3, and P4) are variable speed pumps. The flow rate of fluid through the cooling water pump P1 ($\dot{V}_{chw}$) is controlled in order to maintain a specific supply air temperature of 20°C into the white space.

If the implementation of the cooling system has multiple cooling towers and chillers, efficient part load operation sequenced operation strategies should be used.

Limits of Application

The feasibility of this concept depends largely on the number of free-cooling hours and the possibility of adiabatic cooling by direct use of the cooling tower.

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[4] The limit value for the allowable ambient wet-bulb temperature is 6°C.

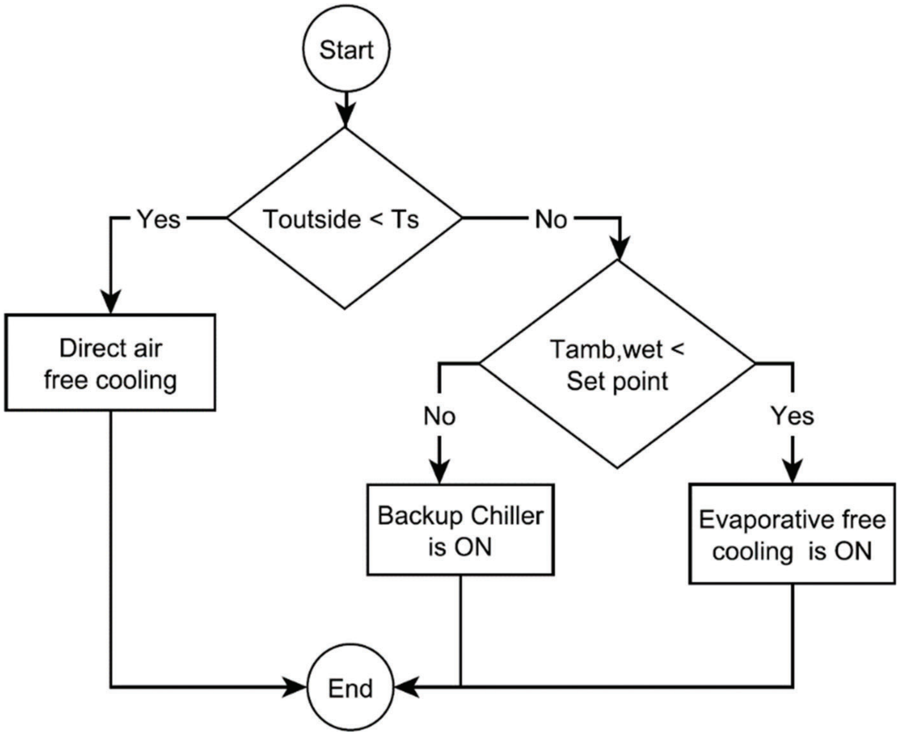

Figure 6.12 Flow chart for the cooling control strategy of concept 3.

For this reason, the maximum wet-bulb temperature at the location must not be too high for providing the chilled water temperature required in the Data Centre.

Plenty of makeup water is required for the application of wet cooling towers. Furthermore, for the application and maintenance of cooling towers and their water circuit in it, certain health and safety regulations need to be fulfilled in some countries. These local regulations may restrict the application of wet cooling towers.

Backup and Redundancy

This evaporative free cooling system needs a backup system when the environmental conditions are not suitable. As a redundancy, $N + 1$ compression chillers and wet cooling towers are used to attain redundancy level III. All components are connected by two independent paths.

Sankey Analysis

Figure 6.13 depicts the distribution of the average energy flows per year within the different subsystems of concept 3. For the simulation, a 400 kW IT power capacity Data Centre located in Stockholm and the parameters from the scenario 3 are used. The simulation results show that 96% of the cooling load of the Data Centre is covered by the direct air free cooling and the wet cooling tower is operated to meet the remaining cooling load.

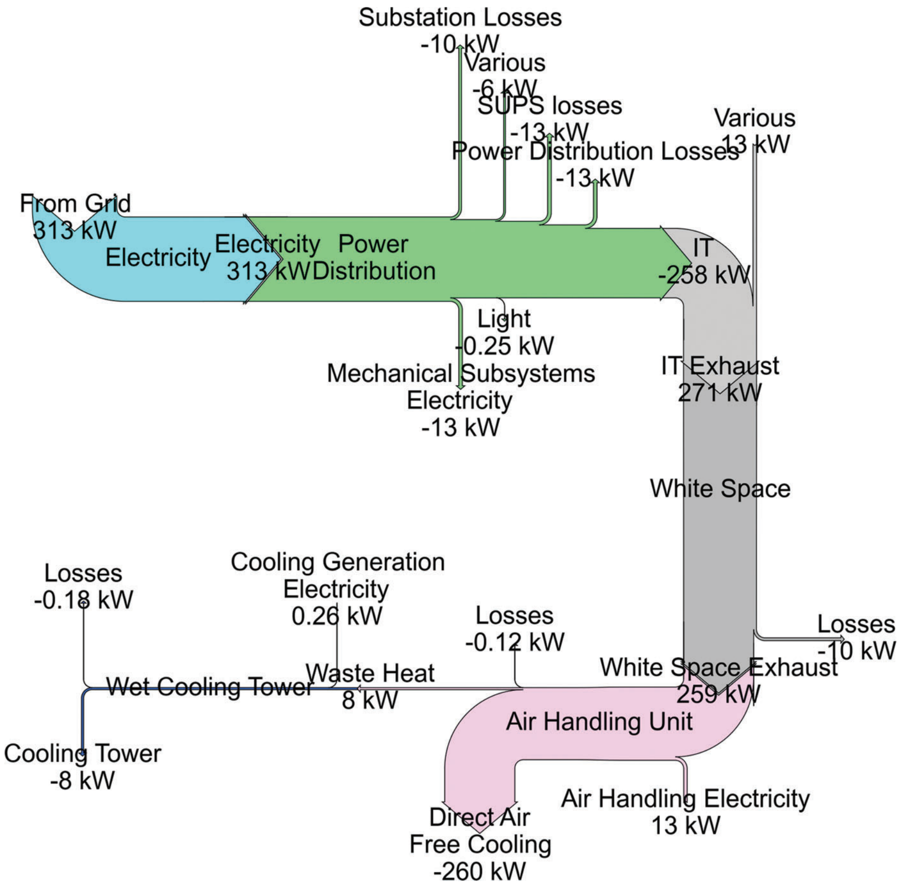

Figure 6.13 Sankey chart showing the distribution of average energy flows per year within different subsystems of concept 3 for scenario 3 (Boundary condition: Stockholm, 400 kW IT power capacity, RES = 0.62).

6.2.4 Grid-Fed Vapour-Compression Chiller with Electrical Energy and Chilled Water Storages

General

In concept 4 (Figure 6.14), vapour-compression chillers along with wet cooling towers are used to produce cooling energy during summer. The electrical power required to drive the chiller can be purchased from the national grid. A large chilled water storage tank (CHWST) for decoupling cooling generation from cooling demand and lithium-ion batteries for storing electrical energy are provided. Thus, both storages are charged, for example when the cost of electricity is low or when the share of renewables is high in the grid. This strategy allows adopting Data Centre's total energy draft from the grid to the fluctuating parameters (e.g., cost and share of renewables) in order to optimise the Data Centre energy supply. Additionally, charging the storage during the colder night might be advantageous especially in warmer regions because cooling tower operation requires less energy when the ambient temperature is lower. During winter, indirect air free cooling is performed for efficient cooling supply to the Data Centre. The concept might be applied in small as well as large Data Centres (50 kW to 10 MW). Figure 6.15 depicts the electric scheme of this concept.

Table 6.6 shows an overview of the main components of the concept.

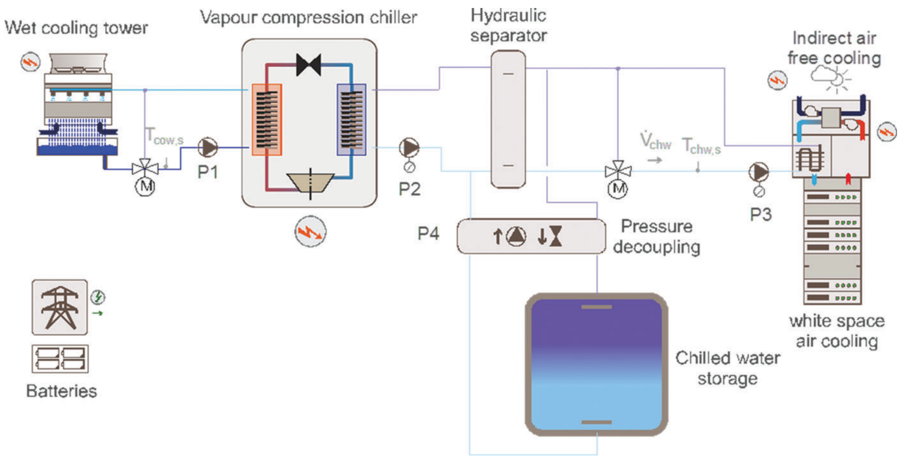

Figure 6.14 Thermal scheme of concept 4.

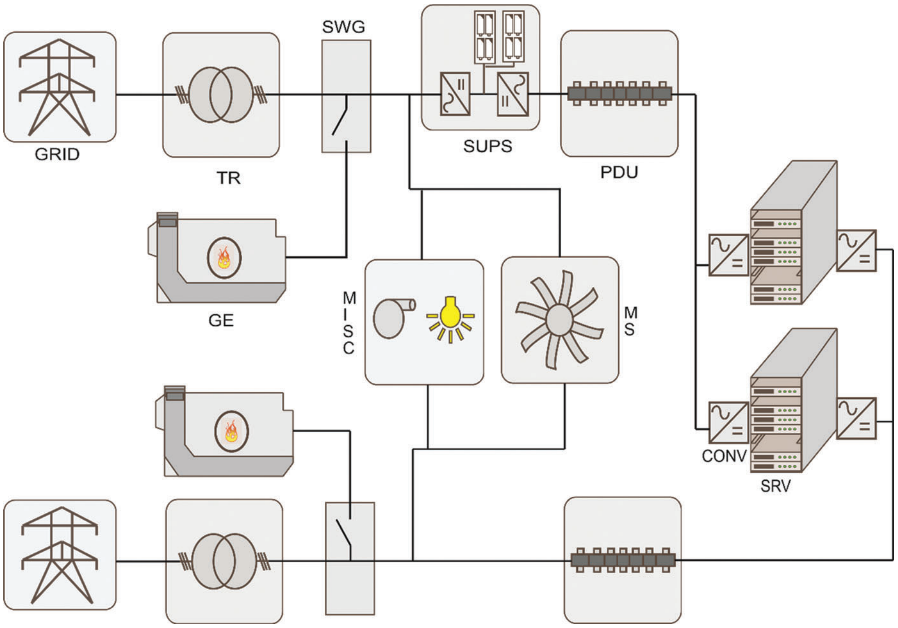

Figure 6.15 Electric scheme of concept 4.

Table 6.6 Subsystems in concept 4

Subsystem	Comments
Lithium-ion battery	Sized according to the required electrical power for IT and cooling distribution as well as the envisaged charging and discharging time
Vapour-compression chiller	Highly efficient machine, e.g., with screw compressor or turbo compressor; backup chiller used for storage charging
Wet cooling tower	Sized according to the chiller capacity
Chilled water storage tank	Non-pressurised tank; contains advanced charging and discharging system for good thermal stratification; sized according to required cooling power and aspired discharging time
Indirect air free cooling	Could include adiabatic cooling; run as often as possible
Hydraulic separator	Separates hydraulic circuits of chillers, storage and consumers (cooling coils)
Pressure decoupling	Decouples storage from network pressure; contains pump for feeding water from the storage into the cooling system and valves for reducing the pressure of water fed into the storage

Operation and Control

Figures 6.16 and 6.17 depict the cooling control strategy and the control strategy of the electrical energy storage of concept 4. Here, the cooling control strategy varies depending on the operating parameters such as the ambient air temperature, electricity price, share of renewable power and the chilled water storage system conditions. The operations of the batteries vary depending on the operating parameters such as cost of the electricity, share of the renewable power and the state of the charge of the batteries. The operating mode of the concept is selected based on the availability of the one of the following order of the operating parameters; first, high share of renewable power in the grid and second cheap electricity. In some scenario, there is a possibility of the availability of more than one operating parameter.

In case that the outside air temperature is lower than the supplied air temperature to the IT room, indirect air free cooling is used. In addition, the chiller can be used to produce chilled water when the share of renewable power is high in the grid or when the electricity cost is low and cold can be stored in the CHWST. In other case that the outside air temperature is higher

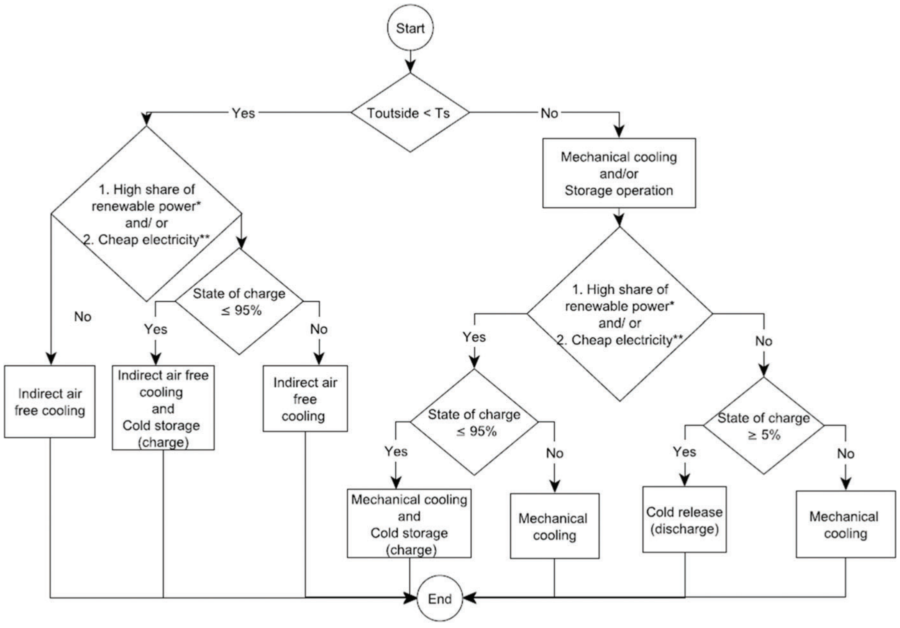

Figure 6.16 Flow chart for the cooling control strategy storage of concept 4.

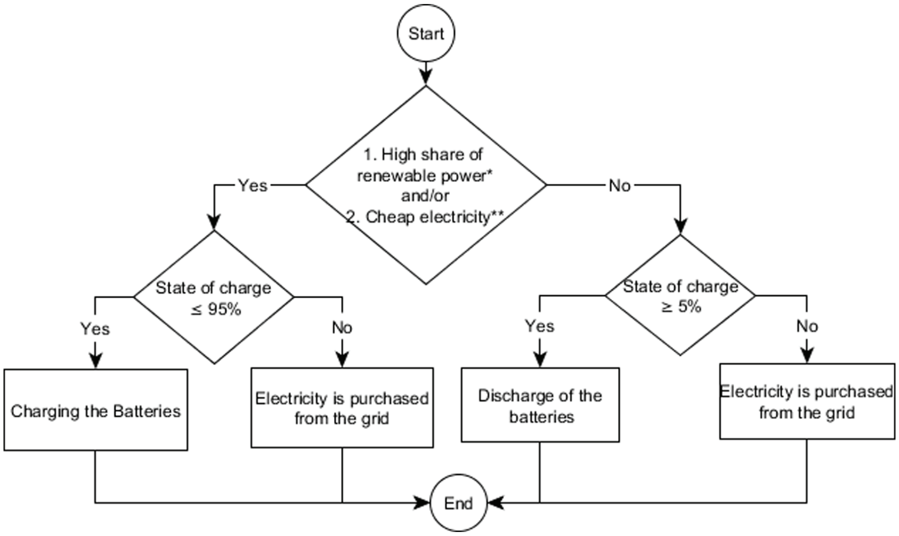

Figure 6.17 Flow chart for the control strategy of the electricity storage of concept 4.

than the supplied air temperature, indirect air free cooling is not applicable. In this scenario, CHWST can partially fulfil the cooling requirements depending on its condition but mainly the vapour-compression chiller produces the cooling energy. Therefore, the vapour-compression chiller is operated interacting with the chilled water storage, based on the cooling energy demand and boundary conditions such as the current electricity cost or share of renewable power, for instance. The set point values for the supply temperatures of the chilled water ($T_{chw,s}$) and the cooling water ($T_{cow,s}$) used in this concept are 10°C and 27°C, respectively. The pump used for the cooling water circuit (i.e. P1) is operated with constant speed, whereas the other pumps (i.e. P2, P3 and P4) are operated with variable speed. The flow rate of fluid through the chiller water pump P3 ($\dot{V}_{chw}$) is controlled in order to maintain a specific supply air temperature of 20°C into the white space.

Limits of Application

Plenty of makeup water is required for the application of wet cooling towers. In addition, local regulation must be considered in order to implement these cooling towers. For the chilled water storage and the electrical storage, sufficient space is required.

Backup and Redundancy

As a redundancy, $N + 1$ compression chillers and wet cooling towers are used to attain redundancy level III. All components are connected by two independent paths.

Sankey Analysis

Here, the location is Frankfurt and the parameters for the simulation from scenario 4 (Table 6.2) are used. It is visible in Figure 6.18 that both the thermal and the electrical storage systems fulfil only the fraction of the total energy required by the Data Centre. About 3% of the imported electricity is stored temporarily in the battery. The share of the indirect air free cooling in the cooling energy demand of the Data Centre is 77%, and the remaining cooling load is supplied by the chiller. About 61%[5] of the energy of the chilled water produced by the chiller is being temporarily stored in the storage, and the rest is used directly to dissipate the waste heat of the AHU unit.

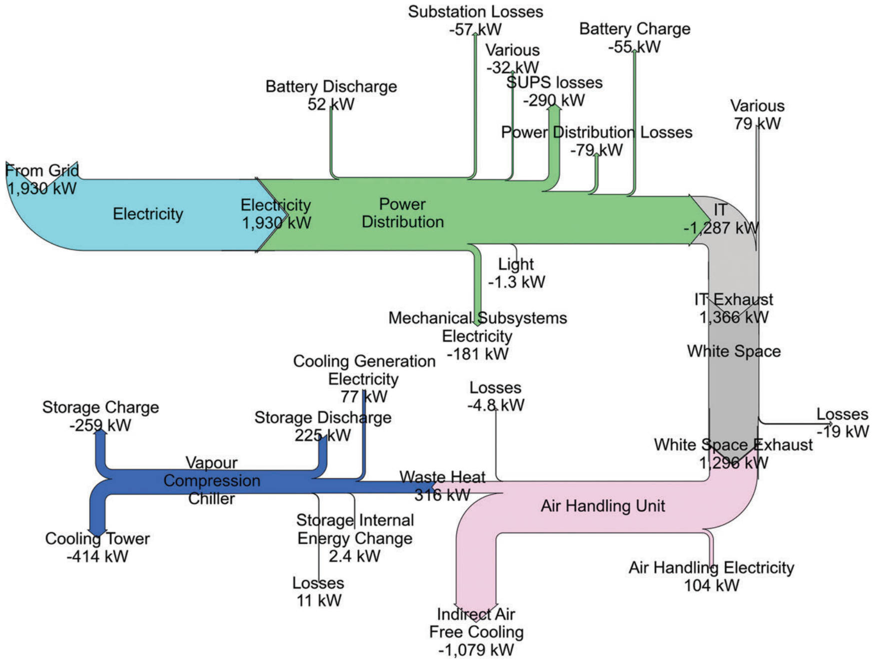

Figure 6.18 Sankey chart showing the distribution of average energy flows per year within different subsystems of concept 4 for scenario 4 (Boundary condition: Frankfurt, 2000 kW IT power capacity, RES = 0.26).

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[5] For this calculation, a *COP* of the vapour-compression chiller of 5.5 is assumed.

6.2.5 Biogas Fuel Cell with Absorption Chiller

General

A biogas-fed fuel cell is applied for generating both power and heat, which is used for driving an absorption chiller during summer (Figures 6.19 and 6.20). In winter, indirect air free cooling avoids the operation of the chillers. Then, the waste heat from the fuel cell can be recovered for space heating or might also be dissipated by a wet cooling tower. Because of the high temperature and pressure of the hot water, shell and tube heat exchanger are used for transferring the heat between the cooling tower and the fuel cell hot water circuit.

The concept can be realised everywhere where biogas is available. It might be applied in small as well as very large Data Centres (50 kW to >10 MW). Table 6.7 shows an overview of the main components of the concept.

Operation and Control

In summer, the fuel cell is operated according to the heat demand of the absorption chiller. Additional electrical energy can be purchased from the grid. In winter, either the fuel cell can be controlled according to the power demand and its waste heat is dissipated by means of cooling towers, or it is controlled according to the demand of a space and domestic hot water heating. As far as the absorption chiller is concerned, a set point value is defined for the chilled water supply temperature.

Table 6.7 Subsystems in concept 5

Subsystem	Comments
Fuel cell	e.g., SOFC; sized according to the heat demand
Absorption chiller	Double effect, heat supply e.g., at 170/140°C
Wet cooling tower	Sized according to the chiller capacity and for dissipating the waste heat from the fuel cell when there is no heat demand
Hot buffer storage	Allowing for optimal operation both of the heat generator (fuel cell) and the heat consumer (e.g., domestic hot water) by smoothing temperature fluctuations; works as hydraulic separator between generator and consumer circuit
Cold buffer storage	See hot buffer storage
Space heating system	Mixing loop for decreasing the supply temperature in the case of high temperature fuel cell
Indirect air free cooling	Could include adiabatic cooling; run as often as possible
Heat exchanger	Shell and tube heat exchanger; sized according to temperatures of the hot water and mean temperature difference

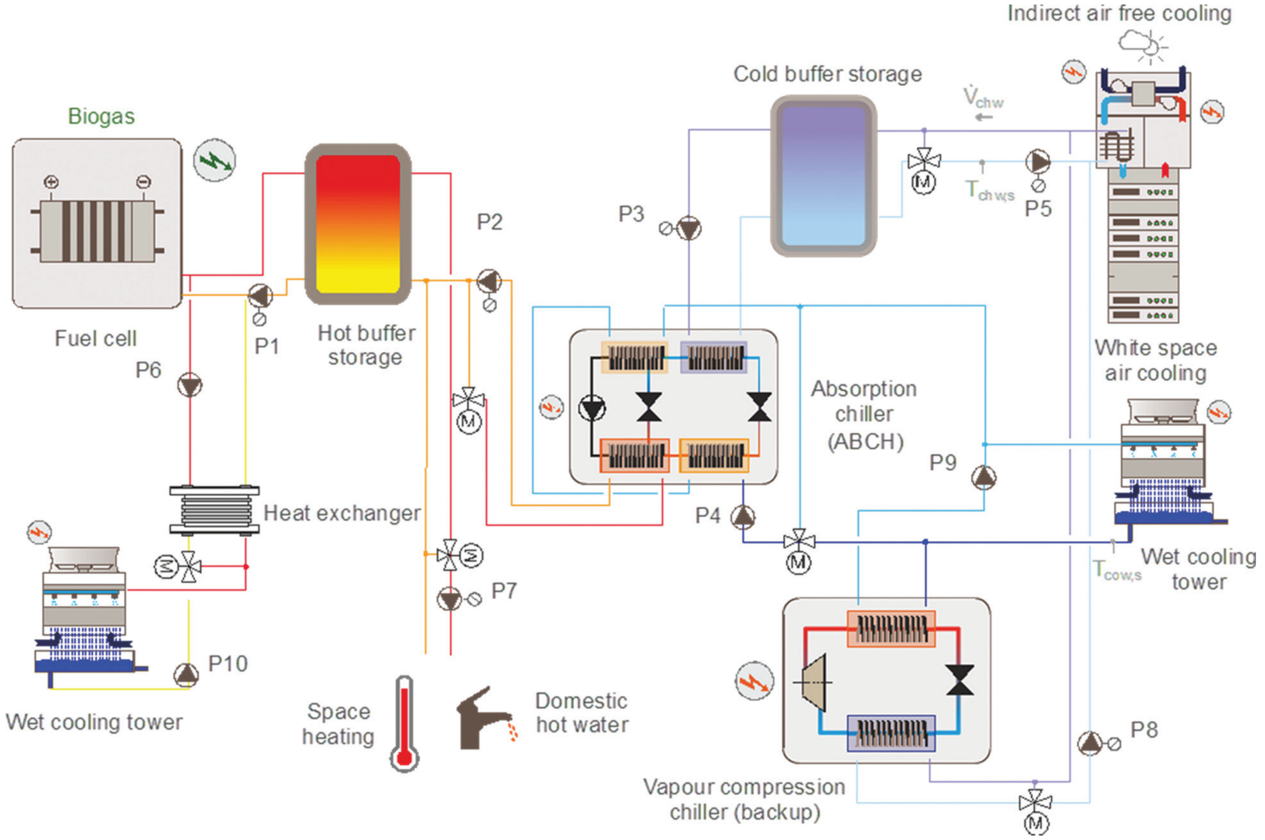

Figure 6.19 Thermal scheme of concept 5.

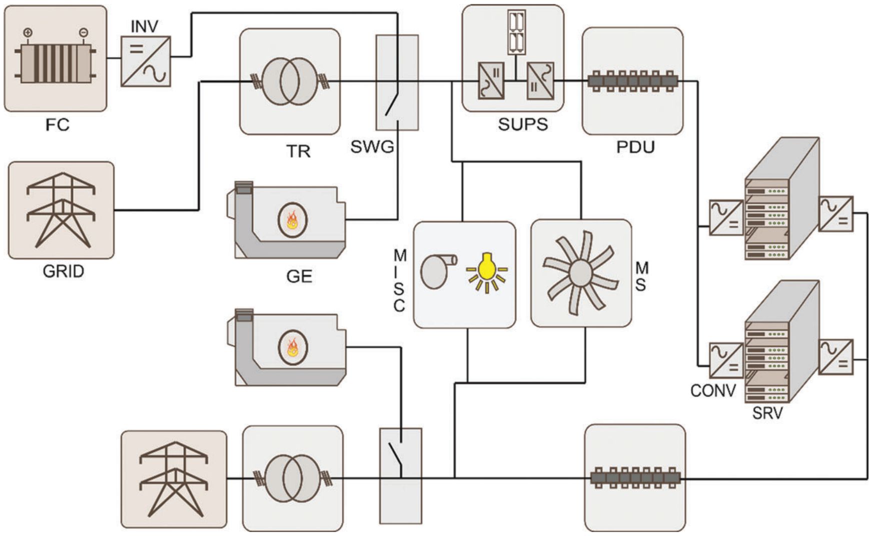

Figure 6.20 Electric scheme of concept 5.

The hot water from the fuel cell is set to 150°C. In addition, set point values are defined for the chilled water supply temperature as well as for the cooling water supply temperature. The set point values for the supply temperatures of the chilled water ($T_{chw,s}$) and the cooling water ($T_{cow,s}$) used in this concept are 10°C and 27°C, respectively. The pumps used for the cooling water circuit (i.e. P4, P6, P9 and P10) are operated with the constant speed, whereas the other pumps are operated with the variable speed pumps. The flow rate of fluid through the chiller water pump P5 ($\dot{V}_{chw}$) is controlled in order to maintain a specific supply air temperature of 20°C into the white space.

The following equations have been used for calculating the amount of the heat and the electricity produced and the fuel consumption of the CHP plant in the simulation of the concept:

$$\dot{Q}_{\mathrm{H,FC}} = \dot{Q}_{\mathrm{H,max,FC}} \cdot \phi_{\mathrm{max}}$$

$$P_{\mathrm{el,FC}} = P_{\mathrm{el,max,FC}} \cdot \phi_{\mathrm{max}}$$

$$\phi_{\mathrm{max}} = \frac{\dot{Q}_{\mathrm{H,Abch}} + \dot{Q}_{\mathrm{H,DHW}}}{\dot{Q}_{\mathrm{H,max,FC}}}$$

$$\dot{Q}_{\mathrm{Fuel}} = \frac{\dot{Q}_{\mathrm{H,FC}} + P_{\mathrm{el,FC}}}{\eta_{\mathrm{FC}}}$$

where $\dot{Q}_{\mathrm{H,FC}}$ represents the heat generated by the fuel cell, $\dot{Q}_{\mathrm{H,max,FC}}$ represents the maximum heat generated by the fuel cell, $P_{\mathrm{el,FC}}$ represents the electricity produced by the fuel cell, $P_{\mathrm{el,max,FC}}$ represents the maximum electricity produced by the fuel cell, $\dot{Q}_{\mathrm{H,Abch}}$ represents the heat required by the absorption chiller to produce the cooling energy, $\dot{Q}_{\mathrm{H,DHW}}$ represents the heat supplied to the space heating, $\phi_{\max}$ is the maximum load factor, $\dot{Q}_{\mathrm{Fuel}}$ is fuel input in CHP system, and η_{FC} is the total efficiency of the fuel cell.

Similarly, the following strategies have been followed for the dissipation of the generated heat by the fuel cell.

$\dot{Q}_a = \dot{Q}_{\mathrm{H,FC}} - \dot{Q}_{\mathrm{H,Abch}}$, where $\dot{Q}_a$ is the excess heat after supplying for the chiller
If $\dot{Q}_a > 0$,
$\dot{Q}_{\mathrm{b}} = \dot{Q}_{\mathrm{a}} - \dot{Q}_{\mathrm{H.DHC}}$, where $\dot{Q}_b$ is the excess heat after supplying for the space heating
If $\dot{Q}_b > 0$,
$\dot{Q}_{\mathrm{H,WCT}} = \dot{Q}_{\mathrm{b}}$, where $\dot{Q}_{\mathrm{H.WCT}}$ is the excess heat dissipated by the cooling tower.

Limits of Application

The applicability of this concept is limited by the availability of biogas and makeup water for the wet cooling tower as well as local legislation for such cooling towers. Because of the high electrical efficiency of fuel cells, a heat demand for heat reuse is not essential.

Backup and Redundancy

Redundancy level III can be reached by installing *N* vapour-compression chillers as backup (in the case of any maintenance or failure of the steam plant or absorption chillers). *N* + 1 wet cooling towers are installed, which are connected to both the absorption chillers and vapour-compression chillers. All components are connected by two independent paths. The required electrical power can be purchased from the national grid when the power from the fuel cell falls short.

Sankey Analysis

The location for the simulation is Frankfurt. The parameters applied for the simulation are used from scenario 4 (Table 6.2). Figure 6.21 shows the

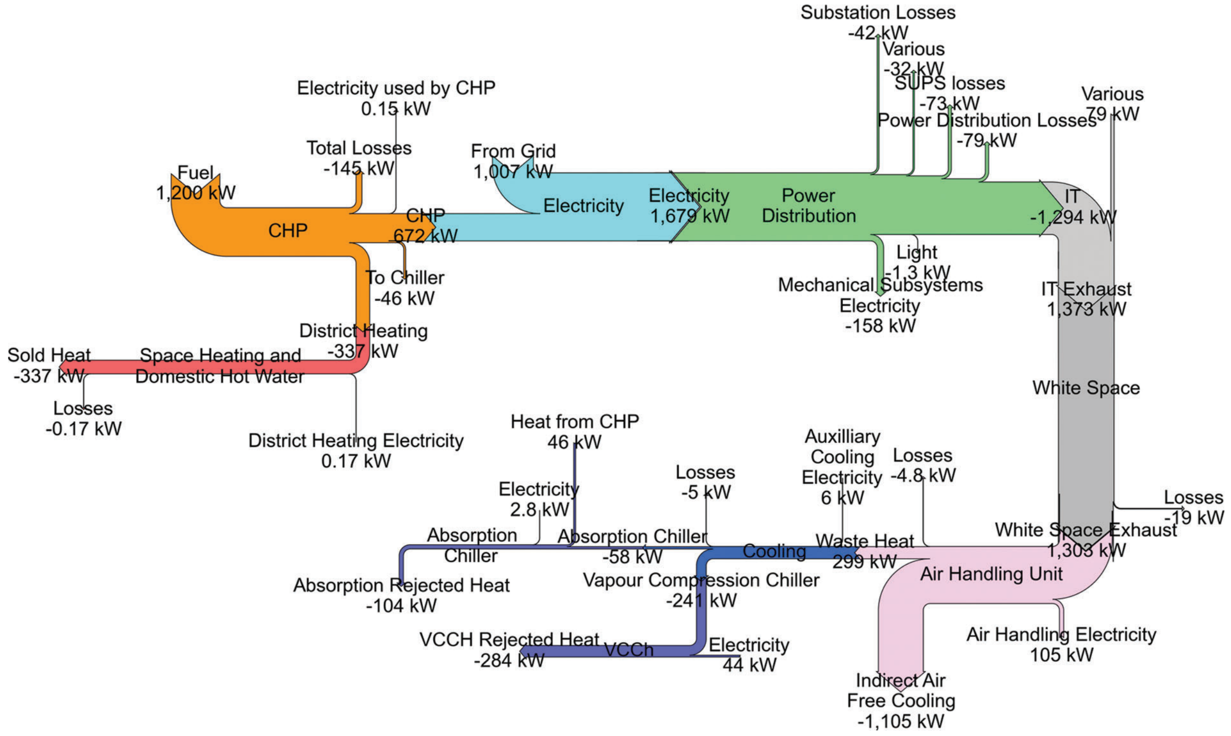

Figure 6.21 Sankey chart showing the distribution of average energy flows per year within different subsystems of concept 5 for scenario 4 (Boundary condition: Frankfurt, 2000 kW IT power capacity, RES = 0.26).

distribution of the average energy flows per year within the different subsystems of concept 5. The excess electricity produced by the CHP system is fed in to the national grid. The CHP plant generates 56% electricity and 32% heat. Only 12% of the useful heat produced by the CHP system is supplied to the absorption chiller to produce the cooling energy and the rest, i.e., 88% of the useful heat, is used for the space heating and domestic hot water. The reason for this is the location, which enables the free cooling to provide a majority of the heat removal, which in turn lowers the cold demand and thereby the heat use by the absorption chiller from the CHP. It is visible that the backup vapour-compression chiller in the system is still needed occasionally to cover certain partial load situations. The free cooling energy covers about 79% of the total cooling energy demand of the Data Centre.

6.2.6 Reciprocating Engine CHP with Absorption Chiller

General

The concept 6 shown schematically in Figures 6.22, 6.23 and 6.24 is based on biogas-fed tri-generation by means of a reciprocating engine CHP plant. The heat from this plant is used for driving a single-effect absorption chiller during summer and supplying space heating for offices or buildings close to the Data Centre during winter. Additionally, indirect air free cooling is implemented for efficient cooling supply to the Data Centre especially during winter. Then, the heat from the CHP plant should be used for space heating and producing domestic hot water if required (generally, hot water demand is quite low in offices).

The concept is not subject to any geographical restrictions and can be realised everywhere where biogas is available. It might be applied in very small as well as large Data Centres (50 kW to 10 MW).

Table 6.8 gives an overview on the main components (subsystems) shown in Figure 6.22.

Operation and Control

Generally, the CHP plant is operated according to the heat demand for driving the chiller or supplying heat for space heating. If the generated power does not match the current power demand of the Data Centre, additional power has to be purchased from the national grid or excess power can be sold to the grid.

If the implementation of the cooling system has multiple cooling towers and chillers, then for the efficient part load operation, sequenced operation

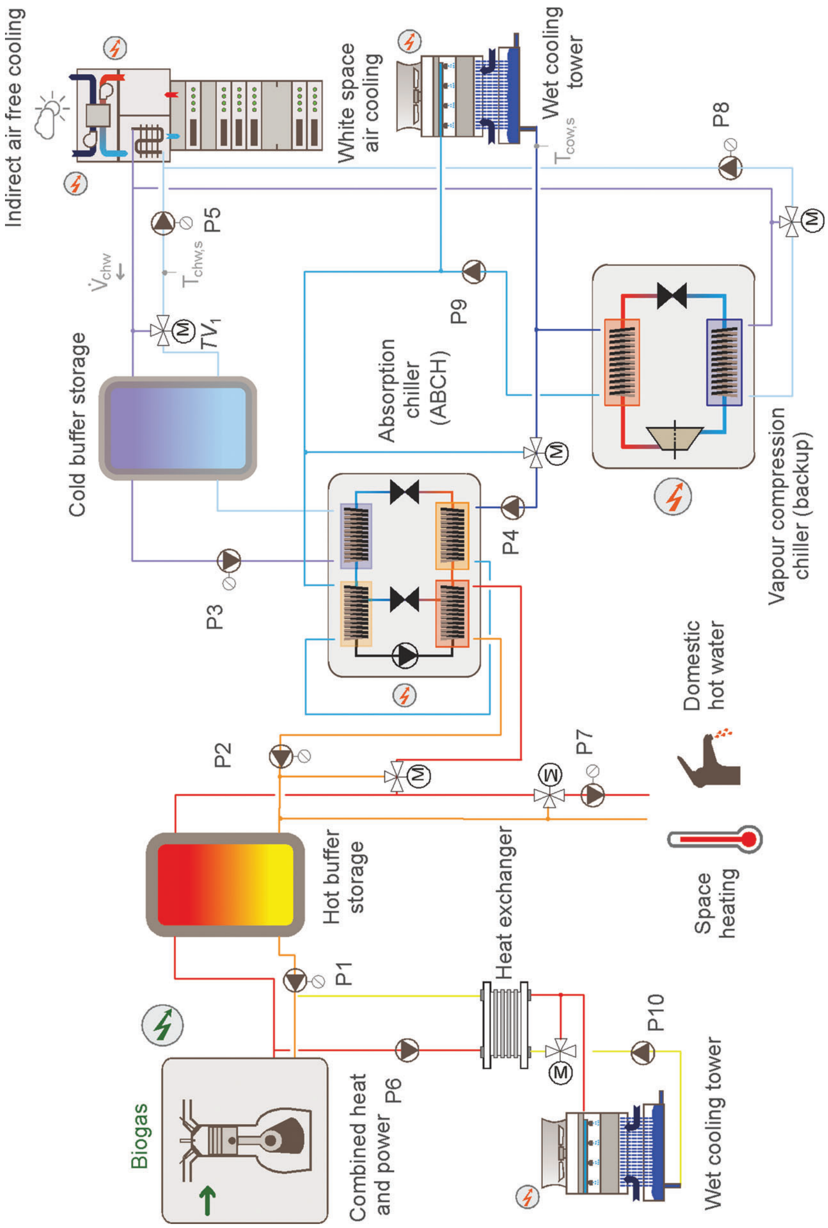

Figure 6.22 Thermal scheme of concept 6.

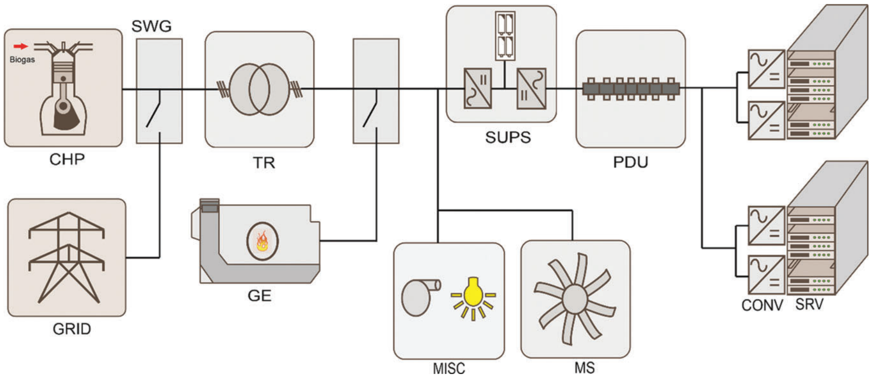

Figure 6.23 Electric scheme of concept 6 with off-site generation.

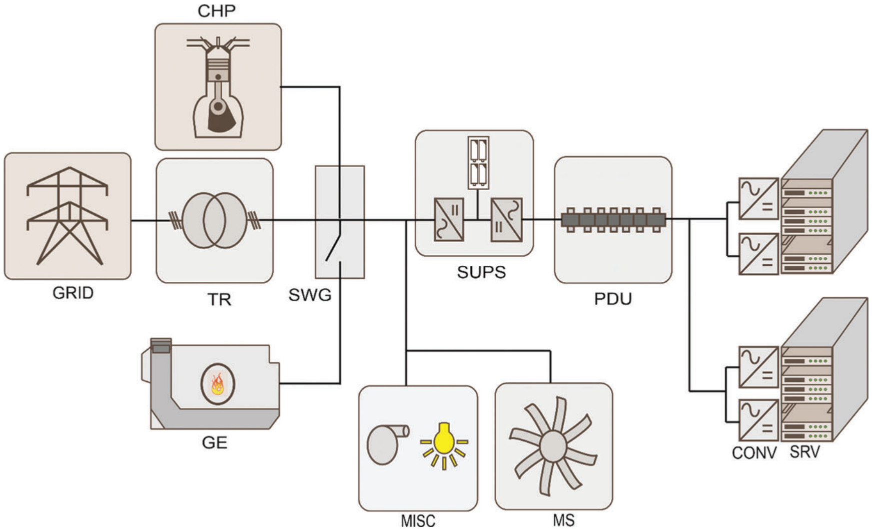

Figure 6.24 Electric scheme of concept 6 with on-site generation.

strategies should be used. Hot water of around 90°C is fed into the chiller. In addition, set point values are defined for the chilled water supply temperature as well as for the cooling water supply temperature. The set point values for the supply temperatures of the chilled water ($T_{chw,s}$) and the cooling water ($T_{cow,s}$) used in this concept are 10°C and 27°C, respectively. The pumps used for the cooling water circuit (P4, P6, P9 and P10) are operated with constant speed, whereas the other pumps are operated with variable speed. The flow

Table 6.8 Subsystems in concept 6

Subsystem	Comments
Reciprocating engine CHP plant	Sized according to the heat demand (supplying absorption chiller in summer and space heating in winter)
Absorption chiller	Single-effect, heat supply, e.g., at 85/70°C
Wet cooling tower	Sized according to the chiller capacity and for dissipating the waste heat from the CHP when there is no heat demand
Heat exchanger	Shell and tube heat exchanger; sized according to temperatures of the hot water and mean temperature difference
Hot buffer storage	Allowing for optimal operation both of the heat generator (CHP plant) and the heat consumer (e.g., chiller) by smoothing temperature fluctuations; works as hydraulic separator between generator and consumer circuit
Cold buffer storage	See hot buffer storage
Space heating system	Design supply temperature adapted to the temperature level provided by CHP, e.g., 70°C
Indirect air free cooling	Could include adiabatic cooling; run as often as possible

rate of fluid through the chiller water pump P5 ($\dot{V}_{\mathrm{chw}}$) is controlled in order to maintain a specific supply air temperature of 20°C into the white space.

The following equations have been used to calculate the amount of heat and electricity produced and the fuel consumption of the CHP plant in the simulation of the concept:

$$\begin{aligned}
\dot{Q}_{\mathrm{H,eff}} &= \dot{Q}_{\mathrm{H,max,CHP}} \cdot \phi_{\mathrm{max}} \\
P_{\mathrm{el,eff}} &= P_{\mathrm{el,max,CHP}} \cdot \phi_{\mathrm{max}} \\
\phi_{\mathrm{max}} &= \frac{\dot{Q}_{\mathrm{H,Abch}} + \dot{Q}_{\mathrm{H,DHC}}}{\dot{Q}_{\mathrm{H,max,CHP}}} \\
\dot{Q}_{\mathrm{Fuel}} &= \frac{\dot{Q}_{\mathrm{H,eff}} + P_{\mathrm{el,eff}}}{\eta_{\mathrm{CHP}}}
\end{aligned}$$

where $\dot{Q}_{\mathrm{H,eff}}$ represents the heat generated by the CHP, $\dot{Q}_{\mathrm{H,max,CHP}}$ represents the maximum heat generated by the CHP, $P_{\mathrm{el,eff}}$ represents the electricity produced by the CHP, $P_{\mathrm{el,max,CHP}}$ represents the maximum electricity produced by the CHP, $\dot{Q}_{\mathrm{H,Abch}}$ represents the heat required by the absorption chiller to produce the cooling energy, $\dot{Q}_{\mathrm{H,DHC}}$ represents the heat supplied to the space heating, ϕ_{max} is the maximum load factor, $\dot{Q}_{\mathrm{Fuel}}$ is the fuel input in the CHP system, and η_{CHP} is the total efficiency of the CHP plant.

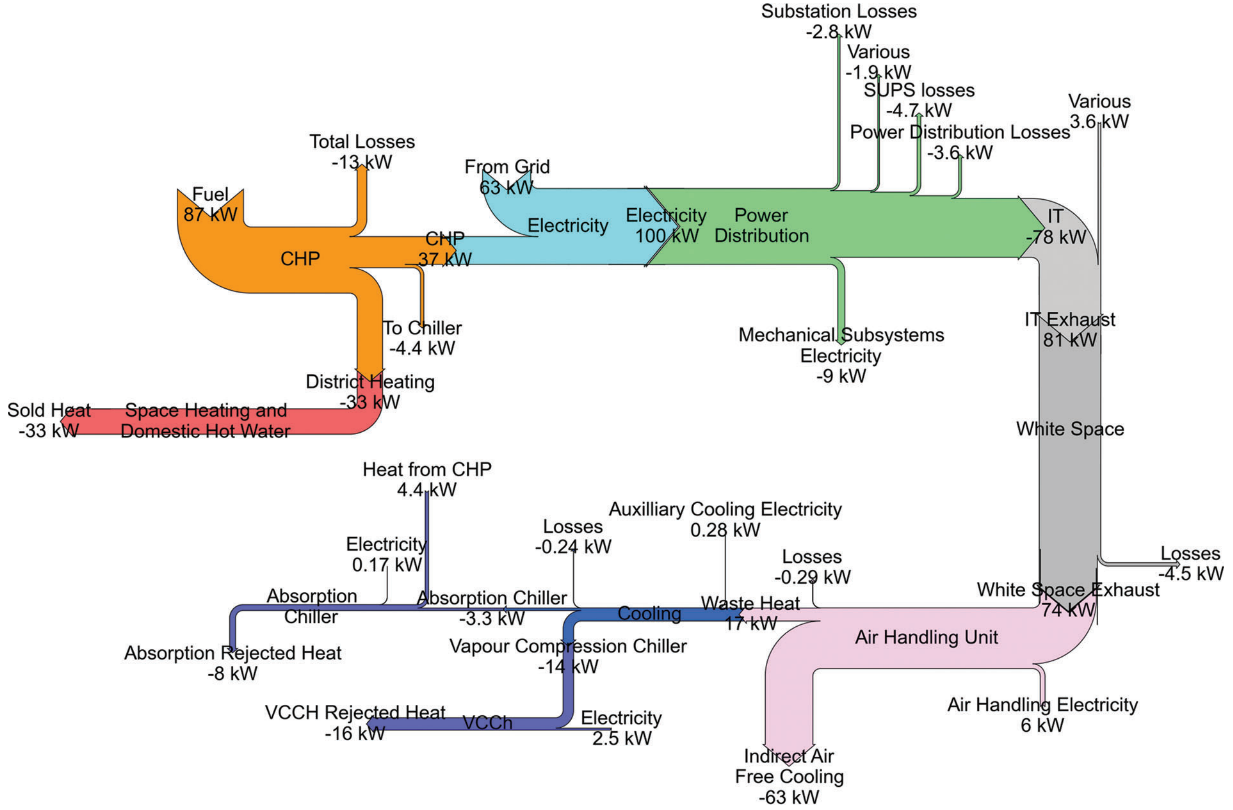

Figure 6.25 Sankey chart showing the distribution of average energy flows per year within different subsystems of concept 6 for scenario 2 (Boundary condition: Frankfurt, 120 kW IT power capacity, RES = 0.26).

Limits of Application

The concept is suitable for all kinds of Data Centres. However, 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 heat especially during winter, when the Data Centre is cooled by means of indirect air free cooling.

Backup and Redundancy

A backup gas boiler can generate heat for the chiller when the CHP plant fails. Redundancy level II can be reached by installing $N + 1$ chillers and cooling tower units.

Sankey Analysis

For the simulation, a 120 kW IT power capacity Data Centre located in Frankfurt and the parameters from the scenario 2 (Table 6.2) are applied. Figure 6.25 shows the distribution of the average energy flows per year within the different subsystems of concept 6. The excess electricity produced by the CHP system is fed into the national grid. The chart shows that the indirect free cooling covers around 79% of the total cooling energy demand of the Data Centre and the rest is covered by the chillers. The CHP plant operates with an electrical efficiency of 43% and a thermal efficiency of 43%. Only 12% of the useful heat produced by the CHP system is used to the absorption chiller to produce cold, and the rest is fed in to the space heating. The operation of the absorption chiller and vapour-compression chiller and the issues are the same as explained for concept 5.

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