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Advanced Technical Concepts for Low-Exergy Climate and Cooling Distribution

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5.1 Introduction

The objective of this chapter is to describe energy efficiency strategies and advanced technical concepts for Low-Ex climate control with the aim of increasing the return temperature and the temperature difference between the air/water inlet and outlet. Proposed concepts are currently applicable best practices and novel concepts, which can improve supply and distribution of cooling in Data Centres. A quantification of the energetic savings and estimated payback period is presented for each of the concepts which are as follows:

- **Free cooling (Section 5.2):** In these strategies, the cooling demand of the Data Centre is reduced due to the utilisation of the available natural resources as a source of cooling energy.
- **Increasing the maximum allowable temperatures for IT equipment (Section 5.3):** Increasing the Delta T (air temperature difference between inlet and outlet) through the IT equipment directly reduces the required airflow rate through the whitespace. Therefore, energy required by the fans is reduced for circulating the airflow.
- **Hot or cold aisle containment (Section 5.4):** It consists to separate the IT room in hot and cold corridors for a better air management. The objective of these strategies is to avoid that air streams were affected by different phenomena such as bypass, recirculation and pressure air drop,

decreasing cooling efficiency and creating vicious cycle of rise in local temperature.

- **Variable airflow (Section 5.5):** In this concept, the airflow supply into the whitespace is adjusted depending on the required cooling load.
- **Partial loads, component oversizing and using redundant components (Section 5.6):** Using components in partial load can lead to an increasing energy efficiency. It might also be beneficial to use redundant and/or oversizing components.
- **Use of high energy efficiency components (Section 5.7):** Using highly energy efficient components can also lead to the significant reduction in the total energy demand.

5.2 Free Cooling

Free cooling is a cooling design principle, which covers a wide-spread implementation of cooling from natural resources. Free-cooling technologies can be roughly divided into the following:

- Airside free cooling: Makes use of outside air for cooling Data Centres
    - Direct airside free cooling: Drawing the cold outside air directly into the Data Centre (mixing with return air to fulfil the inlet requirements).
    - Indirect airside free cooling: Operating through air-to-air heat exchangers.
- Waterside free cooling: Utilises natural cold source through a chilled water infrastructure (air, ground, river, sea, etc.)
    - Direct water-cooled system: Natural cold water is used to cool the Data Centre. A coolant transfers heat to the seawater (river, ground) through a heat exchanger.
    - Air-cooled system: An air cooler (dry cooler) is used to cool the chilled water circulating through CRAHs when the wet-bulb temperature of the outside air is low enough.
    - Cooling tower system: A cooling tower is used to cool the chilled water circulating through CRAHs and heat exchangers. Two water loops are needed: a cooling (external) water loop and a chilled (internal) water loop.

The possibilities of free cooling depend on climatological and geographical aspects. Therefore, the location of the Data Centre defines the possibilities of applying free cooling.

Table 5.1 shows the annual hours which are suitable for direct air free cooling at different locations around Europe. As can be seen from the Table, the number of hours depends on the Data Centre operational parameters (inlet air temperature to the IT room, also see next section).

As an example, Figure 5.1 shows the estimated reduction in energy required for cooling which can be reached by applying free cooling at Barcelona. Please be aware that the tool [1] used for obtaining the data assumes hot aisle containment for the case of airside free cooling, but no aisle containment for the case of waterside free cooling. Thus, comparability of these two different concepts is limited.

Additionally, a constant chilled water set point of 7.2°C is assumed for waterside free cooling which limits the number of free cooling hours significantly. In practice, higher values are possible especially if the air supply temperature is allowed to exceed 18°C.

Table 5.1 Hours of direct air free cooling for different locations depending on the requested air supply temperature

	Data Centre air Supply Temperature				
Location	18ºC	20ºC	22ºC	24ºC	26ºC
Barcelona (Spain)	4,776	4,918	5,014	5,016	5,072
Chemnitz (Germany)	6,401	6,533	6,612	6,639	6,649
Luleå (Sweden)	7,537	7,651	7,677	7,685	7,685

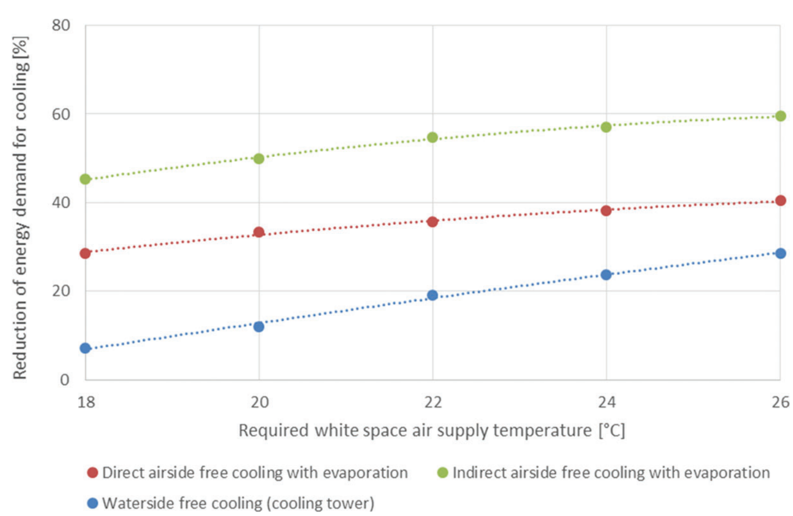

Figure 5.1 Reduction in energy demand for cooling due to free cooling in Barcelona [1].

However, it is obvious from Figure 5.1 that free cooling saves a considerable amount of energy compared to cooling by means of chillers even at the relatively warm location of Barcelona.

Due to applying free cooling, the *PUE* may generally decrease from approximately 1.8 to approximately 1.2. This results in 75% electrical savings for the mechanical installations, which implies a saving of 33% of the Data Centre's total energy demand. The payback period depends on the type of free-cooling technology, but should normally be 1–3 years.

5.2.1 Free Cooling with Direct Ambient Air

General Description

A direct air-cooling system uses outside air for cooling the Data Centre by supplying the external air directly into the Data Centre. The outside air has to be filtered before being supplied to the Data Centre. It is also possible to implement humidification and dehumidification in addition to the direct air cooling system. As a result, it is possible to use only the fan-filter system during a limited period of the year (without additional airconditioning).

During the cold season of the year, the outside air has to be humidified and heated. The reason is to minimise the risk of any damage to the server racks, caused by static electricity. Heating of the outside air is achieved by mixing a part of the recirculation air from the Data Centre with the cold outside air (instead of discharging totally the warm air to the outside). However, the supplied (mixed) air has to be humidified.

During extremely cold outside temperatures, it is necessary to recirculate the air completely. Cooling will be done by means of cooling coils (chilled water). The advantage of using chilled water cooling is a chilled water cooling plant operating 100% on free cooling (no compression cooling with the use of a refrigerant). In addition, the humidification will be considerably less. The disadvantage is the need of an additional cooling system (air-cooled chillers with free cooling mode).

Free cooling units are located adjacent to the white space and to the outside air (facade) and consist of the following components (in the sequence of the direction of the air):

- Air inlet section, including grilles and damper
- Filter section
- Mixing section (for return air)
- Fan section, including sound attenuators

- Return air section, including dampers
- Air outlet damper

In addition, humidification and dehumidification sections can be incorporated in the free cooling units.

Airside free cooling uses outside air for cooling the infrastructure. For this type of cooling, no (chilled) water is required: only air-cooling is applied (direct air or indirect air-to-air). The cooling efficiency of airside free cooling is especially high at locations with low annual average temperatures and low peak temperatures in summer.

Direct Airside Cooling

The available hours of direct airside free cooling depend on the following:

- Temperature of the outside air
- Level of humidity of the outside air
- Data Centre operating requirements

In principle, when the outside temperature is below the required temperature and the air humidity is within the ASHRAE guidelines, direct airside free cooling can be applied. This means that the amount of annual hours with direct airside free cooling can be divided into the following situations (see also Figure 5.2):

- 1A: If the temperature of the outside air is below the specified Data Centre supply temperature and the absolute humidity is within the acceptable range, supply air is composed from mixing recirculated air and outside air.

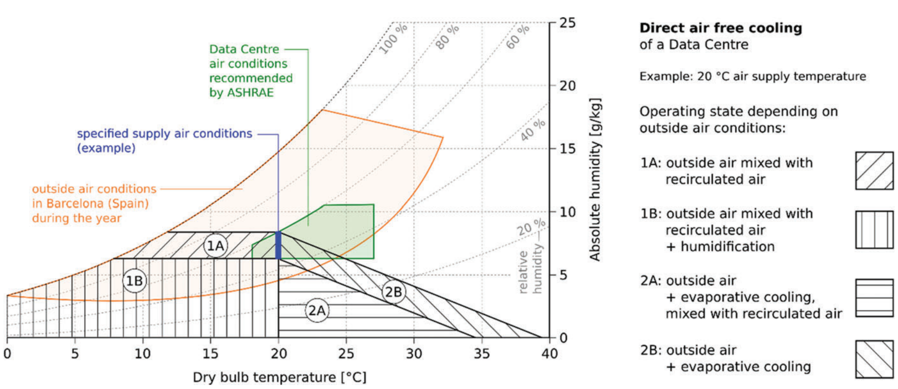

Figure 5.2 Psychrometric chart showing operating states of direct air free cooling depending on outside air conditions.

- 1B: As 1A, but with humidification of the supply air because the humidity of the outside air is too low.
- 2A: Outside air is cooled by evaporative cooling because its dry-bulb temperature exceeds the specified Data Centre supply temperature. Additionally, the outside air is mixed with recirculated air.
- 2B: As 2A, but no mixing with recirculated air is necessary because the temperature and the humidity of the cooled outside air meet the requirements of the white space.

The need for and the amount of evaporative and chiller units depend on the geographic location. At warm regions, both types of cooling are necessary while at colder regions, low temperature outside air and evaporative cooling might be sufficient. However, the relative humidity of outside air determines the applicability of evaporative cooling.

An important point is the heat generation by the supply fan. This will rise the temperature of the outside air. For example, with a temperature difference of 10 K between supply and return temperature of the Data Centre, the fan power will be about 3–5% of the IT power. This will result in a temperature rise of approximately 0.3–0.5 K. With a required white space temperature of 20°C, the maximum required outside temperature then should be 19.5–19.7°C.

Cooling Scheme

The cooling of a Data Centre by means of direct aircooling is shown in Figure 5.3.

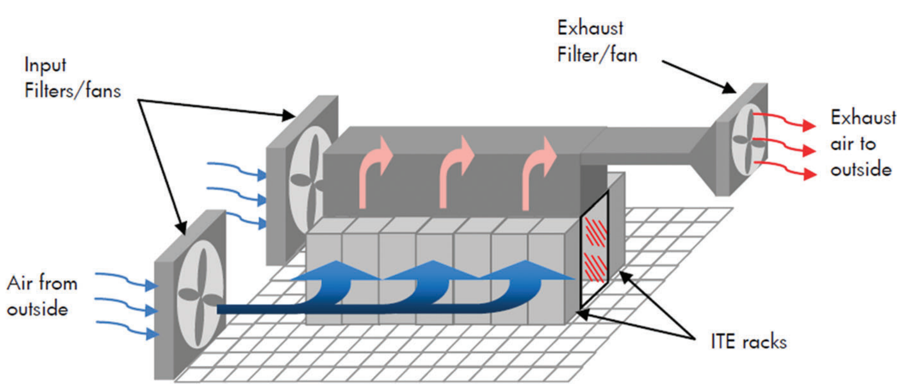

Figure 5.3 Principle of cooling a Data Centre with direct aircooling (without mixing duct) (DEERNS).

Control

During winter, the outside air is mixed with the return air from the white space. When the humidity of the mixed air is below the required humidity, extra evaporative humidification has to be applied. In this case, both the amount of outside air and the amount of humidification have to result in the required supply air temperature and humidity to the white space. Furthermore, in free cooling operation (moderate temperatures), when the evaporative cooling results in a lower supply temperature than required, first the outside air has to be mixed with the return air from the white space, before evaporative cooling is applied. At high outside temperatures, no outside air is used. The return air is cooled by means of a chiller (DX or chilled water).

Limits of Application

There are critical limits of this application, especially concerning humidity control and air quality. A precondition for successfully using direct aircooling is to allow large differences of temperature and humidity in the Data Centre. Otherwise, this concept requires a large chiller system. Since these chillers have minimal operating hours, a decentralised and modular system is possible, keeping system simplicity. However, this increases maintenance costs and results in a higher "day one" investment.

Due to direct provision of very large outside air volumes to IT equipment, the system is very vulnerable for effects from outside (e.g. external smoke, air pollution). Therefore, there is a significant risk if outside air contains harmful contaminants or particles.

Economic Aspects

There are different types of direct air units available in the market, varying from complete air handling units (or containerised units) to fan systems integrated in the building. Generally, all systems consist of filter-fan units, recirculation air and additional cooling and (de)humidification.

Costs are comparable with air handling units. Based on quotations from different suppliers of air handling units, the estimated cost is as follows (sized by m^3/h airflow):

$$C = 20 \cdot \dot{V}^{0.75} \quad \text{with} \quad \dot{V} \in [5,000 \ldots 100,000 \text{ m}^3/\text{h}] \tag{5.1}$$

where C and $\dot{V}$ represent the investment cost in € and the airflow in m^3/h, respectively.

If the starting point of the temperature difference between inlet and outlet temperature of the Data Centre is 12 K (= 4 Watt cooling per 1 m^3/h airflow), this results in the following cost per kW cooling:

$$c_{\dot{Q}} = 1257.4 \cdot \dot{Q}_0^{-0.25} \quad \text{with} \quad \dot{Q}_0 \in [20 \ldots 400\,\text{kW}] \tag{5.2}$$

where $c_{\dot{Q}}$ and $\dot{Q}_0$ represent the specific investment cost in €/kW and the cooling capacity in kW, respectively.

5.2.2 Free Cooling with Indirect Ambient Air

General Description

An indirect air-cooling system uses outside air for cooling the Data Centre. The difference with respect to a direct air cooling system is that the external air is not supplied directly into the Data Centre. This is achieved by means of a separation between the external air and the cooling air inside the Data Centre. The hours of indirect airside free cooling can be divided into two situations:

- Air-to-air cooling
- Additional evaporative cooling (primary side) with air-to-air cooling

There are mainly two principles of indirect air-cooling:

- Using heat recovery wheels
- Using plate heat exchangers (cross flow)

Air-to-air free cooling is also directly related to the outside temperature. However, the use of a heat exchanger between the two airflows results in a higher supply temperature to the Data Centre in relation to the outside air temperature. The temperature difference between the two sides of the heat exchanger is approximately 2–3 K (depending on the design of the heat exchanger).

The fans of the outside and Data Centre airflow can be located in the warm/return airstream. This way, the heat generation of the fans does not affect the supply temperature to the white space.

Since the outside and Data Centre airflows are completely separated, free cooling can be applied for all (suitable) outside temperatures, regardless of the level of humidity of the outside air. As a result, the maximum outside (dry bulb) temperature for free cooling to achieve the required supply temperature without evaporative cooling is 2–3 K below the supply temperature to the

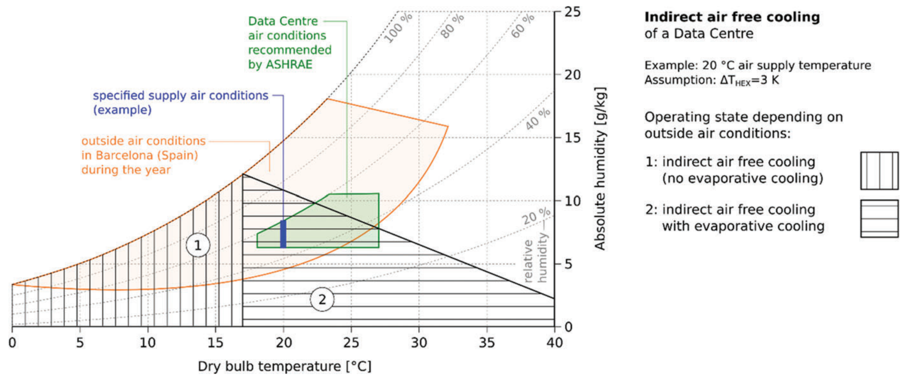

Figure 5.4 Psychrometric chart showing operating states of indirect air free cooling depending on outside air conditions.

Data Centre. An example for the suitable outside air conditions in Barcelona is shown in area 1 of Figure 5.4.

In addition to indirect air-to-air cooling, evaporative cooling can be incorporated. This makes it possible to use outside aircooling with higher outside temperatures without using a chiller. As a result, the (additional) usage of evaporative cooling increases the annual number of free-cooling hours.

When using evaporative cooling, it is possible to cool the outside air to the wet-bulb temperature. So with evaporative cooling, the maximum allowable outside air temperature is based on the wet-bulb temperature. Due to the use of a heat exchanger, the maximum outside wet-bulb temperature for free cooling to achieve the required supply temperaturethen will be 2–3 K below the supply temperature to the white space.

The area 2 in Figure 5.4 shows the outside air conditions in Barcelona which are suitable for indirect airside free cooling with evaporative cooling for the example of 20°C Data Centre supply temperature.

There are different concepts and suppliers available, for example the Green Cooling for Data Centres, or GCDC © concept. The indirect air system is equipped with a number x of fans for the internal airflow and a number y of fans for the external (outside) airflow of the unit, both as a $N + 1$ redundant configuration. The outside air fans operate on full load or partial load, depending on the outside air temperature. This way, the required electrical power of the fans is reduced to an optimum at any lower outside air temperatures. It is possible to make use of redundant components inside the indirect cooling unit. It is also an option to use extra (redundant) units to achieve certain redundancy level.

The GCDC © concept is based on using heat exchangers, cooling the warm return air from the Data Centre by means of outside air. All waste heat is transferred to the outside air.

As already explained before, if sensible temperature of the outside air becomes too high to cool the Data Centre to the required or acceptable temperature (during warm days in summer), additional cooling can be applied to the outside air. This need for additional cooling therefore depends on the location of the Data Centre and the associated climate conditions. This results in the following situations:

- Cold regions without extreme warm conditions:
  - No additional cooling required
- Temperate regions with warm summer conditions (however no extreme conditions):
  - Additional cooling by means of evaporative cooling
- Warm regions with extreme summer conditions:
  - Additional cooling by means of evaporative cooling
  - Mechanical cooling (chilled water or direct expansion)

The GCDC © units (Figure 5.5) consist of two separate airflows:

- *Recirculation air of the Data Centre*: The Data Centre is cooled by cold air supplied from the GCDC © unit. It absorbs the heat of the ICT equipment and flows back to the GCDC © unit.
- *Outside airflow*: The outside air is distributed to the heat exchanger of the GCDC © unit and delivers the required cooling to the recirculation air of the Data Centre.

The GCDC © units are located adjacent to the white space. The system can be incorporated on a double-storey building and is compatible for multiple-storey building configurations. The units consist of two sections with the following components (in the sequence of the direction of the air):

- Outside air section:
  - Air inlet section, including damper
  - Filter section
  - Mixing section (bypass)
  - Adiabatic cooler

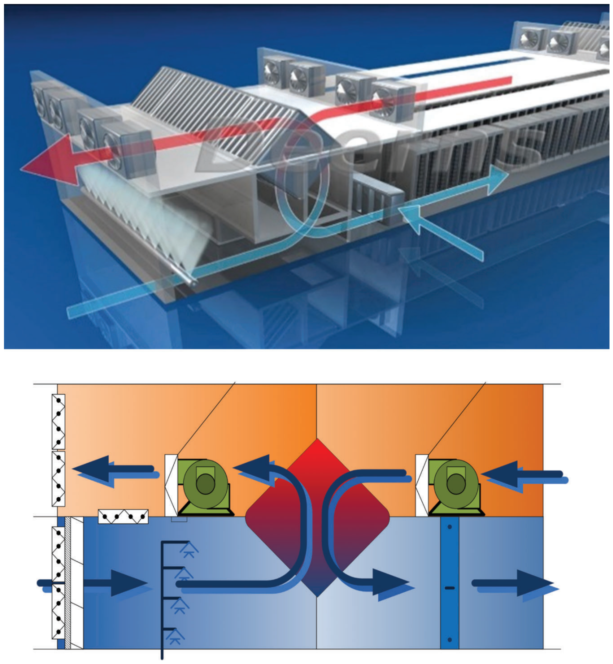

Figure 5.5 GCDC © concept – indirect air cooling using heat exchangers (DEERNS).

  - Plate heat exchanger (cross flow)
  - Heat exchanger chiller
  - Fan section (three fans), including sound attenuators
  - Bypass section, including damper
  - Air outlet damper
- Recirculation air section, for the white space:
  - Air inlet section
  - Mixing section (bypass), for Cloud Control©
  - Fan section (three fans), including sound attenuators
  - Plate heat exchanger (single, for energy efficiency purposes a double heat exchanger is less beneficial)
  - Filter section (for start-up operations)
  - Cooling coil (chilled water), including chiller
  - Bypass, for Cloud Control©
  - Air outlet damper

Hydraulic Scheme (Figure 5.6)

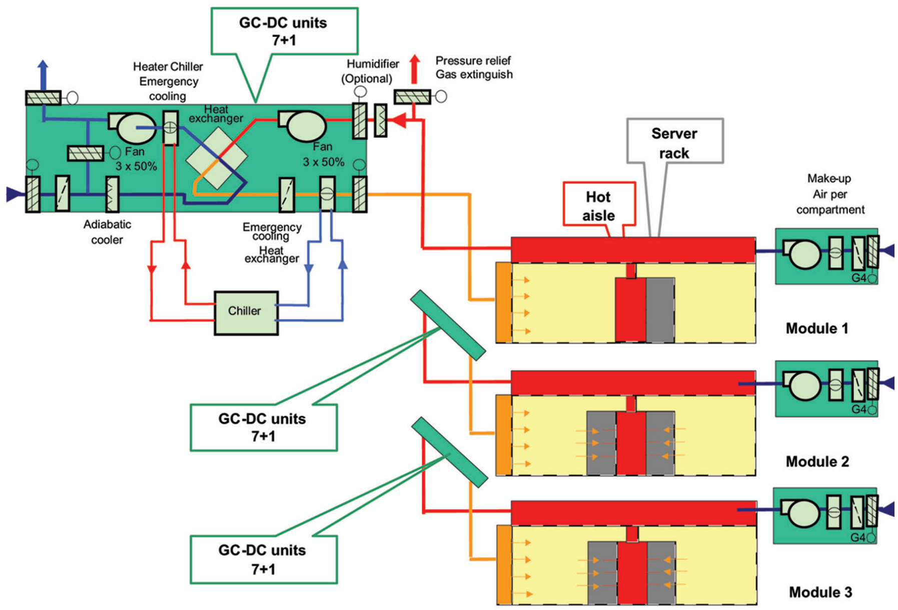

Figure 5.6 System configuration of the GCDC system (DEERNS).

Control

During winter, the system operates in full free-cooling mode. With lower outside temperature, the fan speed is reduced to a minimal required operation. To avoid dehumidification due to the cold air at the heat exchanger, a part of the air is recirculated back on the outside of the heat exchanger. This recirculated air is thoroughly mixed with the outside air to avoid air temperature layers in the supply air. In free-cooling operation, the required cooling is completely supplied with the use of outside air. When the outside temperature becomes higher, the fan speed is increased. With higher outside air temperatures, first the evaporative cooling is put in operation. This will give an amount of additional cooling which depends on air humidity of the outside air. If the evaporative cooling is insufficient, the DX chiller is put into operation, gradually increasing the additional required cooling capacity from the chiller.

Limits of Application

Cooling with outside air depends on the local climate. The maximum extreme temperatures (in summer) and minimum temperatures affect the application of outside aircooling. In winter, below a certain temperature (∼6°C), it is necessary to start mixing warm air with outside air to avoid condensation on the plate heat exchangers. In summer, the required temperature of the cooling air for the Data Centre defines the maximum allowable outside temperature. If the outside temperature exceeds this, adiabatic cooling has to be applied or even chilled water cooling (using chillers).

The GCDC © units can operate in partial load, but are limited to minimal airflow required for the heat exchangers to keep a good level of heat transfer. In addition, the fan efficiency decreases in partial load.

The fresh air supply, overpressure and humidity control of the Data Centre have to be done with a separate installation (comparable to computer room air handling units – CRAH units also use a separate fresh air overpressure system).

Economic Aspects

The indirect cooling unit for Data Centres is a relatively new product in the market. There is some cost information available based on a few quotations of a supplier of the GCDC © units.

The cost of GCDC © unit is approximately as follows (2013), see Figure 5.7:

80 kW: 1,200 €/kW
120 kW: 1,100 €/kW
450 kW: 1,000 €/kW

The costs also depend on the required number of units, resulting in a cost cut of the suppliers of these units.

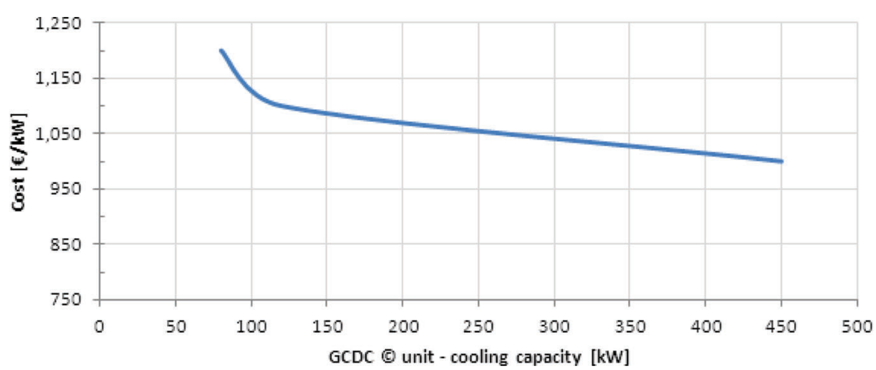

Figure 5.7 Costs of GCDC © unit per kW cooling capacity (DEERNS).

The costs are exclusively for the units, excluding the following:

- Provisions on the building, roof and facade
- Ductwork, air dampers and grilles
- Controls and cabinets
- Electrical provisions

5.2.3 Seawater Air Conditioning System

General Description

Seawater air conditioning systems (SWAC) make use of the cold deep water that can be found within some distance of the coast. At sufficient depth, seawater is not warmed by sunshine nor does heat penetrate there by conduction or convection. This cold water can be used to provide cooling.

The sea server is an inexhaustible source of cold water. The temperature of the water at a particular depth depends on the location. From about 600 m and lower, the seawater temperature reaches what is needed to supply cooling to typical cooling purposes at Data Centres. At 1000 meters and lower, the temperature decline flattens towards the 4°C density peak for water. At very great depths, the pressure causes a shift to even lower temperatures [2]. Generally, the seawater is not applied directly for process cooling. A heat exchanger is used to separate the salty and corrosive seawater from a second loop for Data Centre cooling.

Control

Based on the required cooling water temperature and measured temperature, the seawater pumps are controlled with variable frequency drives. When the temperature of the seawater is lower or equal to the desired chilled water temperature, the chilled water can directly be used for white space cooling by CRAH units.

Seawater cooling can be used through the whole year. An important value is the return water temperature of the seawater. In order to avoid ecological damage to sea life, the outlet temperature must be controlled by mixing the outlet water with cold seawater. The mix ratio is based on the average seawater temperature on outlet depth and the measured temperature of the return water.

Limits of Application

The project needs to be located near the coast. If the location is in a temperate or cold climate, surface seawater can be used, perhaps in combination with a chiller. In that case, the system works similar to aquifer thermal energy storage or cooling with groundwater. If the location is in tropical region, deep-sea water below 600 m is required. Since the cost of the system in this case is determined largely by the piping system in the sea, the limit of application is determined by the distance from the coasts where deep waters are found. This can be within a few hundred meters in some cases, or many kilometres in other cases depending on the location.

Economic Aspects

Costs for a real-world proposed SWAC system have been used to illustrate the economic aspects. The reference system is a 34 MW SWAC with a 220 GWh/year cooling capacity. The seapipe is 8 km out of shore and runs to a depth of 700 m. The seawater is heated by 6 K before being returned to the sea. The electricity cost is 0.26 US$/kWh. Therefore, the cost of sea piping is 33 million US$, the onshore plant (heat exchanger) is 8.6 million US$, electricity cost is 4.6 million US$/year, and operation and maintenance cost is 0.24 million US$. This translates to an investment cost of around 1 $/W for the seawater piping component and 0.25 $/W for the on-shore plant component. Electricity costs and operation and maintenance costs together are 0.02 $ct/kWh. The total investment cost divided simply by 25 years of cooling delivered is 0.008 $ct/kWh.

Location-specific factors contribute greatly to the actual costs. The specific characteristics of the seaside system have a strong influence. Environmental regulations may impose costs on construction of the piping near the shore. The distance to the cold-water resource is another factor. Onshore, issues related to the presence of existing developments can add costs. These all need to be evaluated on a case-by-case basis.

5.2.4 Free Cooling with Groundwater

General Description

Aquifer thermal energy storage (ATES) is based on an open-loop geothermal technology (Figure 5.8). The system stores energy by charging cold groundwater in winter and warm groundwater in summer. The groundwater has to be situated within an aquifer. Therefore, the feasibility for using a warm-cold aquifer/buffer in the earth depends in the soil, which has to be suitable for this type of energy storage. Depending on the feasibility of this, it may be possible to implement one or several aquifer systems.

Figure 5.8 Aquifer TES (DEERNS).

Good practice (requirement) of using an ATES system is a balance of storing warm and cold groundwater within the timespan of one year. During the cold season (winter), the groundwater is distributed from the "warm well" to the "cold well" of the aquifer. The "warm" groundwater can be cooled by using free cooling before being fed into the cold well (cold storage). This energy transfer is done using a heat exchanger.

From the cold well, the cold groundwater is used during summer months. After the water has been used for cooling, the warm water is injected into the warm storage of the aquifer. The cycle is repeated seasonally.

ATES consists of (at least) two thermal wells (one cold and one warm well). Other required installation components are the following:

- Pump and filter system
- Heat exchanger in between the ATES system and the cooling and heating installation
- Pipework and valves
- Control systems
- Heat pumps and/or free cooling components (i.e. cooling towers)

The advantage of using an ATES system is the availability of chilled water during the warm season (summer).

Using an ATES system combined with cooling towers gives an advantage in the summer period. Using cooling towers for generating chilled water for the

Data Centre is an energy-efficient way of cooling. However, during summer period, it might not be possible to reach the required chilled water temperature by using (only) cooling towers. In this period, chillers and the ATES system have to "take over" and deliver the required cooling.

Because the ATES system is much more energy efficient, this is used first. As a result, the use of chillers is reduced, because they only are in operation for "peak" cooling in the summer.

Free cooling from, e.g., cooling towers to the ATES is possible during winter period, by minimising the approach of the cooling water in respective to the outside (wet bulb) temperature. Therefore, the cooling towers of a Data Centre can be used for regeneration of the cooling capacity of the aquifer. The design of the cooling towers has to be adjusted to the required injection temperature to the cold well of the aquifer.

The temperature of the cooling water supplied from the cooling towers to the ATES has to be 2–4 K lower than the minimum water temperature in the cold well.

This temperature transition is due to using two heat exchangers:

- Heat exchanger for the cooling towers, to separate water of the cooling tower from the cooling tower for the building installations (i.e. CRAH units)
- Heat exchanger for the ATES system, to separate groundwater from the cooling water system of the Data Centre

Another condition is the cooling capacity of the cooling towers: it has to be equal to the capacity of the ATES.

An essential condition is that the required cooling capacity in summer period may not exceed the regeneration capacity in winter. Otherwise, extra cooling capacity by means of chillers is required in the summer period.

Hydraulic Scheme

The hydraulic scheme of the ATES system (Figure 5.9) consists of the wells, pumps, piping and heat exchangers.

Control

The most important control issue for ATES are the stringent local government rules of the energy balance in the underground wells. During wintertime, the system is charged with cold water from cooling towers or heat pumps (when there is a heat demand, e.g. district heating network). With variable frequency

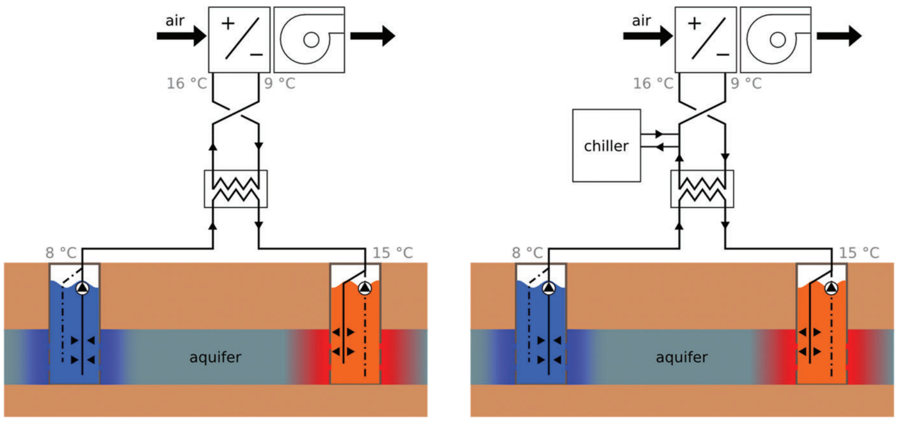

Figure 5.9 Principle of ATES system without or with chiller/heat pump (DEERNS).

drive controlled pumps, the inlet temperature of the cold well is controlled at a minimum of 6°C. Based on the outside temperature, the cooling can be directly delivered by the cooling towers. During summertime with higher outside temperatures, the chilled water for the Data Centre is cooled via a heat exchanger with groundwater from the cold well. Based on the desired chilled water temperature and measured temperature, the well pumps are controlled with variable frequency drives. The chilled water can directly be used for white space cooling by CRAH units.

Limits of Application

Using a warm/cold aquifer in the ground depends on the soil, which has to be suitable for this type of energy storage. Therefore, the local site geology is crucial. If it is possible to use an ATES system, local permits are needed. In addition, the Data Centre has to have a chilled water cooling installation, where the ATES cooling can be incorporated during the summer period.

The required cooling in the summer has to be "regenerated" or "reloaded" in the winter. It is required to have a balance of storing warm and cold groundwater within the timespan of one year.

Economic Aspects

The cost for ATES systems can be divided into two types of ATES: mono-well ATES for smaller capacities ranging from <10 to 50 m^3/h (Table 5.2) and doublet-well ATES for larger capacities ranging from 40 to 200 m^3/h (Table 5.3). The investment costs for the two types are compared in Figure 5.10.

Table 5.2 Investment cost of a mono-well ATES (costs 2008) [3]

Capacity	Investment Cost	Cost/Flow Rate
10 m^3/h	75,000 €	7,500 €/(m^3/h)
20 m^3/h	125,000 €	6,250 €/(m^3/h)
30 m^3/h	145,000 €	4,833 €/(m^3/h)
40 m^3/h	160,000 €	4,000 €/(m^3/h)
50 m^3/h	170,000 €	3,400 €/(m^3/h)

Table 5.3 Investment cost of a doublet-well ATES (cost 2008), based on information from [3]

Capacity	Investment Cost	Cost/Flow Rate
40 m^3/h	175,000 €	4,375 €/(m^3/h)
80 m^3/h	210,000 €	2,625 €/(m^3/h)
120 m^3/h	255,000 €	2,125 €/(m^3/h)
160 m^3/h	280,000 €	1,750 €/(m^3/h)
200 m^3/h	290,000 €	1,450 €/(m^3/h)

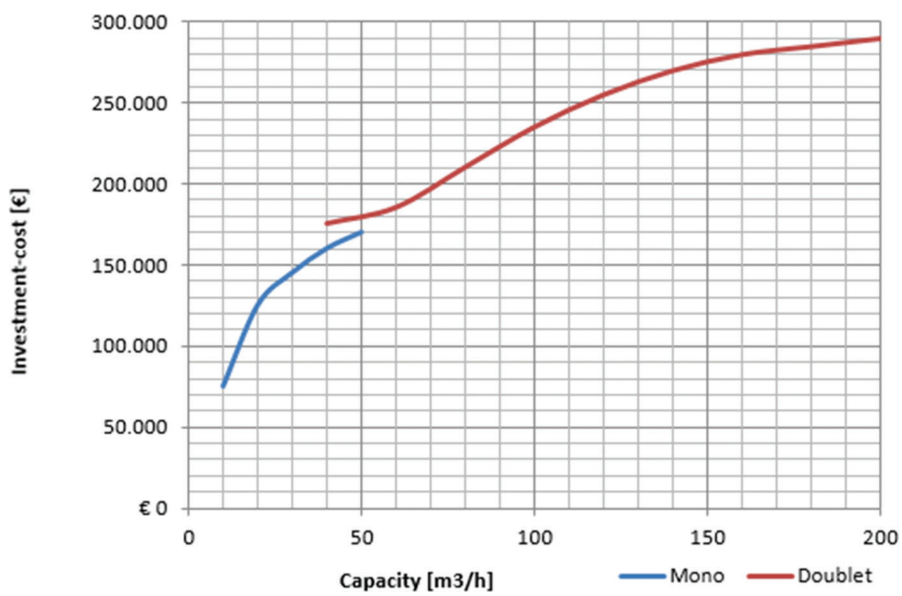

Figure 5.10 Investment costs of a mono- and doublet-well ATES m^3/h flow (costs 2008) [3].

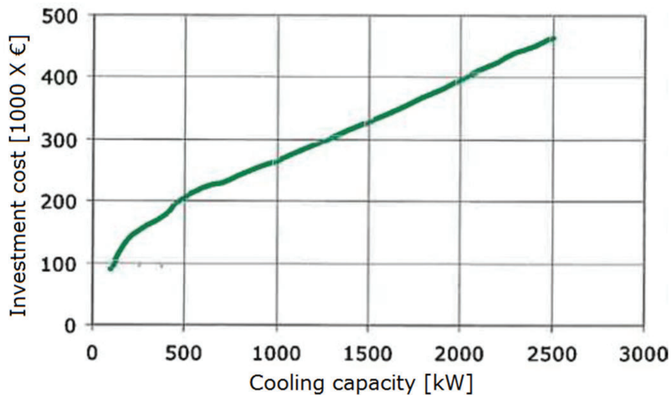

Figure 5.11 Investment costs of an ATES system (2008) per kW cooling capacity with an ATES temperature difference of approximately 6 K [3].

The cooling capacity of the ATES system depends on the temperature difference between warm and cold well. Normally, this is between 6 and 8 K. The maximum cooling capacity of the ATES can be determined by using the ATES design flow and the temperature difference. Based on this, the costs per kW cooling can be calculated (Figure 5.11).

5.3 Increasing Allowable IT Temperatures

Increasing the allowable IT temperatures directly influences the allowable white space temperature. An increased white space temperature leads to improved energy efficiency for any type of cooling concept if proper measures are taken. The degree of effect on the energy efficiency depends on the type of cooling installation which can be air or water cooling.

5.3.1 Increased White Space Temperature with Airside Cooling

Increasing the IT room supply temperature has been suggested as the easiest and most direct way to save energy in Data Centres. However, just implementing a higher inlet air temperature while still relying solely on mechanical cooling[1] may not improve the efficiency of the cooling system. Alternatively, when using air free cooling, raising the maximum allowable white space temperature allows for more annual hours and therefore less hours of additional

[1]The term “mechanical cooling” refers to cooling with chiller operation.

cooling by the chiller units. This results in a reduction in the energy demand. In some cases, this may even result in not needing to install chiller units. By raising the maximum allowable white space temperature, evaporative cooling may be sufficient to deliver the required cooling for those "peak" summer conditions. On the other hand, at cold regions, raising the allowable white space temperature may even lead to not needing to apply evaporative cooling anymore.

Moreover, not needing a chiller installation will also affect *PUE* values:

- Lower annual *PUE* results from using more free cooling
- Lower peak *PUE* because no chillers are operating

The lower peak *PUE* also affects the required capacity of the UPS system, which can be reduced. Therefore, the annual energy losses of the UPS system are reduced, leading to an additional increase in energy efficiency.

The impact of raising the maximum allowable white space temperature in reference to the number of annual hours of available free cooling is illustrated in Figure 5.12. The share of free-cooling hours in the total annular number of hours is shown for different locations (Barcelona, Chemnitz, Luleå) and types of airside free cooling (direct, indirect and indirect with evaporative cooling).

The capital expenses costs (*CAPEX*) depend on the location and the increase in allowable white space temperature. Significant cost reduction might be reached when chillers become expendable. Otherwise, implementing free cooling will not cause significant investment cost reduction. Regarding the operational costs (*OPEX*), aspects on the *EER* of the air-cooling units are

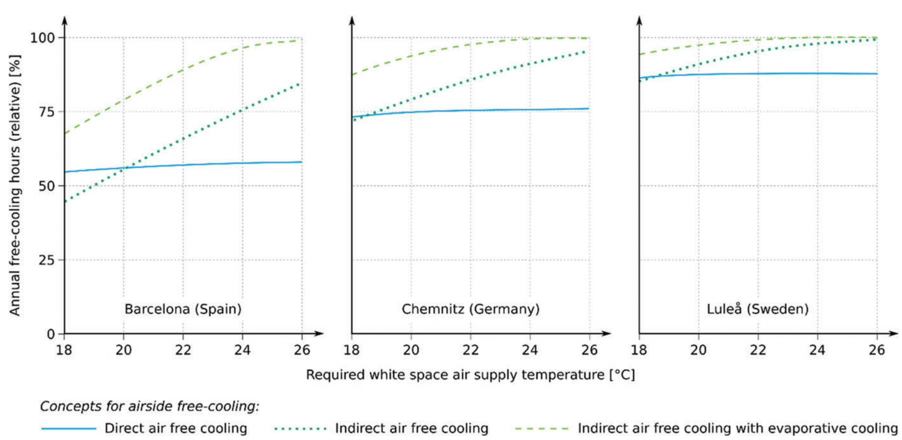

Figure 5.12 Hours of free cooling for different locations and concepts of airside free cooling.

given in Subsections 5.2.1 and 5.2.2. However, a complete analysis of *PUE* and operational costs has to consider, e.g., climate/geographical location and Data Centre allowable temperatures.

5.3.2 Increased White Space Temperature with Chilled Water Cooling

When raising the allowable white space temperature, the energy usage with chilled water cooling systems will significantly decrease due to the following reasons:

- More waterside free cooling can be applied annually.
- The chillers operate more energy efficient.

The increased number of annual hours of waterside free cooling is directly related to raising the allowable white space temperature. The main reason is that the set point of chilled water supply temperature can be raised. This results in an increase in free cooling for all waterside concepts.

Notice that raising the chilled water supply temperature also leads to a decrease in annual energy usage of the chillers. The chillers operate in a more energy efficient way with higher chilled water temperatures (see Figure 5.13).

A point which has to be respected is the maximum allowable chilled water temperature, which depends on the type of chiller. Following ASHRAE and chiller manufacturer recommendations, the maximum chilled water temperature is approximately 16°C. However, the chilled water supply temperature

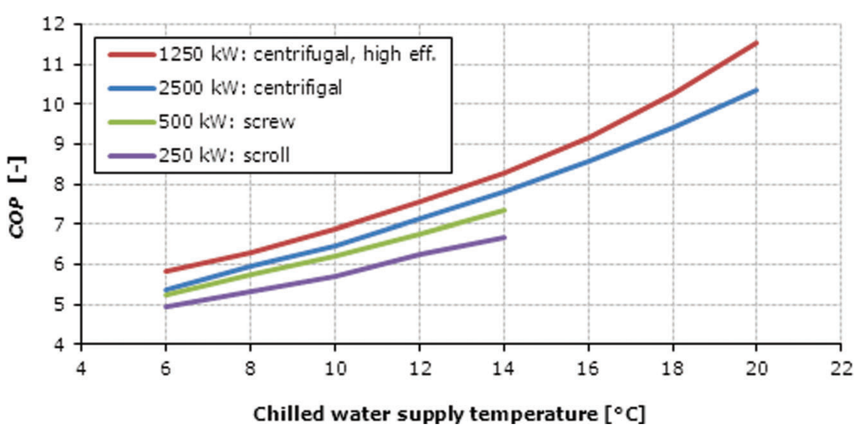

Figure 5.13 Coefficients-of-performance of chillers with condenser water temperature of 30–36°C and variable chilled water temperatures [6].

for the Data Centre can be higher than the allowable chilled water temperature of the chiller. This can be achieved by letting the chilled water partly bypass the chiller. The warm return chilled water is mixed with the cold chilled water from the chillers in order to achieve the required higher chilled water supply temperature.

In conclusion, raising the allowable white space temperature significantly reduces the energy usage for cooling due to more hours of free cooling and more efficient chiller usage.

However, the CRAH units or other type of local cooling equipment do not experience any reduction in energy usage due to the higher allowable Data Centre temperature. Since the required cooling capacity and the temperature difference between air inlet and outlet remain the same, the airflow of the CRAH units and thus their energy demand are constant.

5.3.3 Increasing the Delta *T* Through the IT Equipment

Increasing the Delta *T* (air temperature difference between inlet and outlet) through the IT equipment directly reduces the required airflow rate through the white space. As an example, Figure 5.14 shows the required air volume flow for a 120 kW Data Centre in function of the allowed Delta *T* through the IT equipment. Notice that increasing the Delta *T* by 5 K results in an airflow reduction of more than 30% with the associated energy reduction in the fans.

Moreover, this strategy allows raising the chilled water return temperature. Assuming that the chilled water supply temperature remains the same, the water outlet temperature from the cooling coil (water-air heat exchanger) increases due to a higher air-side Delta *T*. This results in a reduction in the

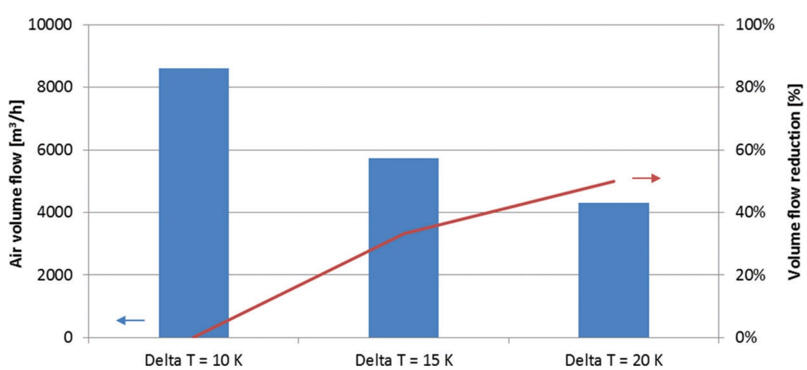

Figure 5.14 Air volume flow required for a standard Data Centre of 120 kW IT power.

required chilled water flow. The benefit of a reduced chilled water flow is that smaller size chilled water pipework can be used. Another option is not to resize the pipework, but use a lower chilled water velocity and lower pressure drop in the chilled water distribution system, which has a positive effect on the required pump energy.

Generally, energy savings depend on the allowable increase in IT temperature. Assuming that the air supply temperature can be increased from 18°C to 24°C, the PUE may decrease by approximately 0.2. This will result in 25% electrical savings for the mechanical installations, which implies a saving of 10% in the total energy demand of the Data Centre. The payback period of this concept will be less than one year, since no extra investments but only modifications in control systems and a different selection of components are required.

5.4 Hot or Cold Aisle Containment

The objective of alternating aisles containments (Figure 5.15) is to separate the source of cooling air from hot air discharge, preventing the cold supply air and hot return air from mixing [9]. Therefore, this strategy can improve predictability and efficiency of traditional cooling systems.

Cold aisles are defined as having perforated floor tiles that allow cooling air to come up from the plenum under the raised floor. The cooling air is distributed to and through the IT racks/equipment and is exhausted from the back of the equipment rack to the adjacent hot aisles. On the other hand, hot aisles do not have perforated tiles. These would mix hot and cold air and thereby lower the temperature of the air returning to the cooling units, which reduces their usable capacity [9]. While hot aisle containment is the preferred solution in all new installations and many retrofit raised floor installations, it may be difficult or expensive to implement due to low headroom or no accessible

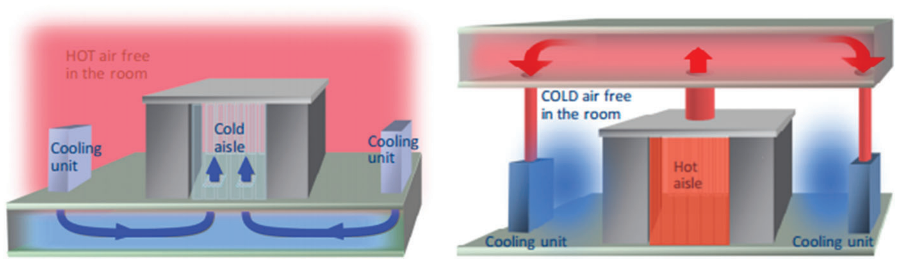

Figure 5.15 Cold and hot aisle containment configuration [7].

dropped ceiling plenum. Cold aisle containment, although not optimal, may be the best feasible option in these cases [7]. In any case, it is essential to separate completely the cold supply air and the warm return air. This way, no temperature mixture takes place and the cooling can be supplied directly to the heat sources (namely the IT racks).

However, it is a common phenomenon with cold and hot aisle containments that the cold air is short-circuiting back to the cooling units (called bypass airflow). This results in only partial usage of the available supplied cooling air. Bypass airflow occurs through unsealed cable cut-out openings and miss-located perforated tiles [10]. Thus, important points related to aisle containments are as follows:

- Blanking panels should be put in unused rack unit positions in equipment cabinets in order to avoid mixing of hot and cold air.
- Unused cabinet/rack positions in equipment rows should be filled with a cabinet/rack or otherwise sealed in order to prevent mixing of air in hot and cold aisles.
- All cable, duct and other penetrations should be airtight.
- Equipment should match the airflow design for the enclosures and white space in which they are placed.

Both hot aisle and cold aisle containment provide significant energy savings compared to traditional uncontained configurations. Niemann et al. (2013) analysed and quantified the energy consumption of both containment methods and concluded that hot aisle containment can provide 43% cooling system energy savings over coldaisle containment mainly due to increased free-cooling hours. They also highlighted that new Data Centre's designs should always use or provision for hot aisle containment.

Generally, aisle containment is estimated to save between 10 and 20% of the cooling system energy, which implies a total saving of 5–10% of the Data Centres total energy demand. Payback period is approximately 5 years for the perforated floor and aisle containments.

5.5 Variable Airflow

The common practice in air-cooled Data Centres is to supply a constant air volume, based on the maximum design-cooling load. This is a robust system without complex control systems. The disadvantage of a constant air volume system is the energy usage: throughout the year, all fans are 100% in operation and require the energy for maximum air recirculation. When the actual heat load is much lower than designed, it may be possible to put a number of units out of operation, but that has to be done "manually" via the building management system (BMS) or on the data floor.

However, the maximum cooling load on which the design is based will never be reached due to the following reasons:

- The data hall/white space may only be partially filled with racks.
- The designed IT power/cooling load is considered as a maximum – in reality, the "maximum" IT rack power will always be lower than designed.
- The IT power might fluctuate during time (depending on the usage of the IT equipment in the racks).

Therefore, the best practice is using variable airflow cooling units. A variable airflow system is based on the actually required cooling, not on the maximum required cooling. Thus, the airflow can be adjusted to the required cooling load. Reducing the airflow implies reduced pressure drop inside the ventilation units. Consequently, running in partial operation gives a significant reduction in the energy usage.

There are different approaches to run a variable airflow strategy: pressure difference, actual IT load and return air temperature.

5.5.1 Strategy A: Pressure Difference

The best and most efficient way for achieving variable airflowis creating a pressure difference between the aisle containment and the data hall where the server racks are situated [5]. In order to achieve this pressure difference (about 10 Pa), the aisle containment has to be airtight. If not, no pressure difference will occur and it will be impossible to control the variable volume system.

In this system, each server controls its required amount of airflow. Each server has one or more integrated fans, which adjust the airflow to the actual power usage of the server. If the power usage of a server decreases, the integrated fans consequently operate on lower speed. This results in a slightly altered pressure difference of the aisle containment and the data hall, leading to reduction in the cooling supply air from the air cooling system (and vice versa).

The advantage of controlling the variable airflow system with pressure difference is that it is performed independently of the temperature difference over the IT racks. This way, each rack can have its own specific air temperature difference, "customised" for that type of server. Therefore, the pressure difference between the aisle containment and the data hall always represents the actual cooling demand.

5.5.2 Strategy B: Actual IT load

The second way to control the variable airflow is by using the actual IT load. This has to be measured per aisle containment. The variable flow is then based on the aisle containment with the highest power density. This system is somewhat less optimal, but also less demanding in regard to the airtightness of the server racks and patch panels. With this method, each aisle receives the airflow that is supplied to the aisle with the highest IT load.

The main disadvantage of controlling the variable flow based on the measured IT load is that this system does not control on the actual required amount of cooling air, but on the average loads and temperatures. Consequently, the supplied cooling air should always be more than the actual required cooling air and there might be a higher risk of hotspots.

5.5.3 Strategy C: Return Air Temperature

A more straightforward, but less efficient way of controlling a variable airflow system is based on the return air temperature to each air-cooling unit. With this control system, the return temperature consists of a mixture of the return temperatures of all different IT racks. However, the maximum allowable return air temperature varies per IT rack. Therefore, the IT rack with the lowest allowable return air temperature determines the maximum allowable return air temperature to the air cooling units. As a result, the supplied cooling air will always be much more than the actually required cooling air and there may be a higher risk of hotspots.

As mentioned before, a variable airflow system is based on the actually required cooling, not on the maximum required cooling. Thus, the airflow can be adjusted to the required cooling load leading to reduce pressure drops in the ventilation units. Additionally, a higher air Delta T is reached which implicates the possibility for higher chilled water Delta T and thus reduced water volume flow rates as well. Consequently, running in partial operation gives a significant reduction in energy usage. However, an important point with variable flow air cooling units is that the partial load is limited since CRAH units have a minimum partial load of approximately 40%. Lower airflows will result in insufficient pressure and cooling capacity.

The energy usage of fans and pumps[2] decreases significantly when their speed is reduced. For the case of a fan, the required power depends on the airflow, the pressure drop and the fan efficiency. It can be calculated as follows:

$$P_{\mathrm{fan}} = \frac{\dot{V} \cdot \Delta p}{\eta_{\mathrm{fan}}} \tag{5.3}$$

where

P_{fan} = fan power consumption [W]
$\dot{V}$ = airflow [m^3/s]
Δp = pressure drop [Pa]
η_{fan} = fan efficiency [-]

A reduction in the required airflow results in a reduction in the required fan power as both $\dot{V}$ and Δp are reduced in the equation. Since the airflow has a linear relation to the air speed and the pressure drop has a 2nd power relation to the air speed, theoretically, the energy demand of the fan decreases by the 3rd power. This relation is shown by the following equation:

$$\frac{P_{\mathrm{fan},1}}{P_{\mathrm{fan},2}} \sim \frac{\Delta p_1^2}{\Delta p_2^2} \sim \frac{\dot{V}_1^3}{\dot{V}_2^3} \tag{5.4}$$

However, the efficiency is not constant but varies in function of the fan load. It has a maximum value at the ideal working point and decreases in any other situation. Thus, a dynamic study for each case has to be done, taking into account the working parameters of the specific fan. Therefore, at high-level design with variable flows from 50 to 100%, the reduction in the required fan power is approximately to the power of 2.5 instead of the 3rd power.

Figure 5.16 shows an example of fan power consumption in function of its volume flow ratio. For example, when the velocity of the fan is reduced by 25%, fan power consumption decreases to about 50%. Please notice that these numbers are just given to understand the phenomenon and should be recalculated for specific fans.

As far as pumps are concerned, it has to be noticed that the reduction in the pressure drop depends on the hydraulic system of the pump. This may result inless energy reduction, as control valves may require a constant pressure drop. In that case, this has to be corrected in regard to the energy reduction.

[2]The flow through evaporator and condenser of a chiller may not be reduced too much in order to prevent the heat transfer from dropping. Reduced water flow is especially interesting for the chilled water distribution circuit.

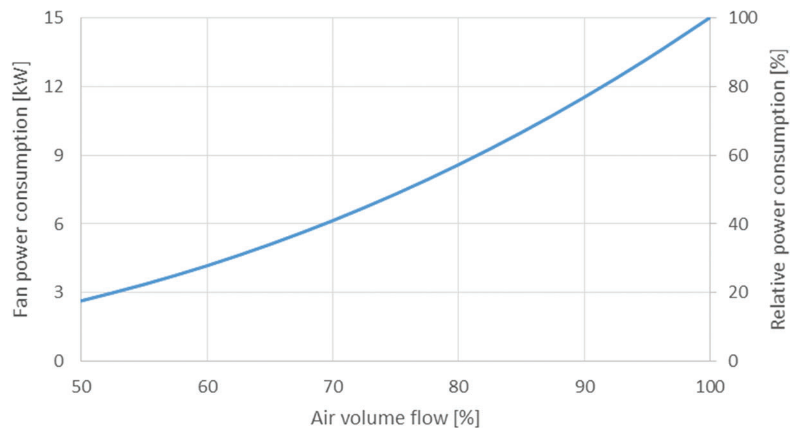

Figure 5.16 Power consumption of a 15 kW fan in function of the airflow ratio.

Assuming the average IT load of a Data Centre to be 50–75% of the design load, applying variable flow will result in approximately 15–20% electrical savings for total mechanical installations, which implies a saving of 8–10% of the total energy demand. The payback period is estimated to be approximately 5–7 years for control systems and airtight containments.

5.6 Partial Load – Redundant or Oversized Components

When using components in partial load, the energy usage will decrease. This applies to all components such as fans, pumps and chillers. Moreover, an increase in energy efficiency can also be achieved. However, this depends completely on the specifications of the different components and on the percentage of partial load (approximately 70%). Especially with chillers, partial load has positive effects on the efficiency. In this section, first it is described how to achieve partial load operation and why it might be beneficial to use redundant and/or oversized components. Then, the effect of partial loads for different mechanical components is discussed.

5.6.1 Redundant Components and Oversizing Components

The components of the cooling installation in a Data Centre can operate in partial load due to the following reasons:

- The actual IT power is usually (much) less than the contracted/designed IT power.

- Using redundant components: Most Data Centre installations consist of redundant components (for service/maintenance and fail-safe purposes). When all components are used – including the redundant components – the installation runs in partial load (e.g. with an $N + 1$ configuration, when N = 4, all components can operate at 80% of their full load).
- Oversizing components for more efficiency: Oversizing the capacity of components makes it possible to run on partial load, even when no redundant units are available (Data Centre with N-configuration).

The effect of the partial load on the energy efficiency depends on the installation component. Therefore, the effect of partial load on common used components for cooling installations of Data Centres is discussed first for chillers and then for fans and pumps.

5.6.2 Partial Load with Chillers

It is well known that most chillers operate more efficiently in partial load using variable speed compressors and pumps, resulting in a reduced (variable) water and refrigerant flow. This is illustrated with four types of chillers: high-efficiency centrifugal compressors (Figure 5.17), centrifugal compressors (Figure 5.18), screw compressors (Figure 5.19) and scroll compressors (Figure 5.20). For each type of chiller, a full load and 50% partial load curve is shown. For each chiller, the 50% load operation is more efficient than the operation at 100% load[3].

Notice that the characteristics of partial load differ per type and design of the chillers, so these are just examples to illustrate the benefit of partial load on the energy efficiency. In addition, the performance of the chillers with partial load is limited. Minimal partial loads are, e.g., approximately 15–25% depending on the type of chiller. Concerning the energy efficiency, an optimum exists at a certain partial load. Below this, the energy efficiency starts to decrease again.

5.6.3 Variable Flow with Fans and Pumps

As mentioned before, the energy usage of fans and pumps decreases significantly when operating in partial load. For variable flows between 50 and

[3]Cooling water temperature was 30–36°C for 100% and 30–33°C for 50% (Johnson Control 2014). However the auxiliary energy has to be taken into account. For wet cooling towers 27°C is assumed.

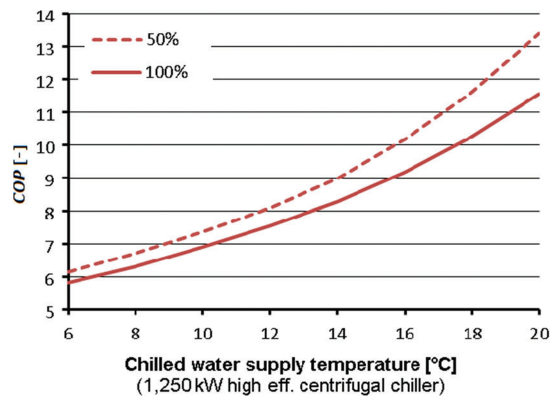

Figure 5.17 *COP* of a high-efficiency centrifugal chiller at 50% and 100% cooling load [6].

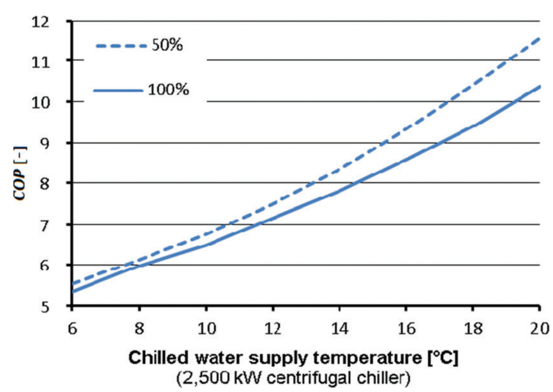

Figure 5.18 *COP* of a centrifugal chiller with at 50% and 100% cooling load [6].

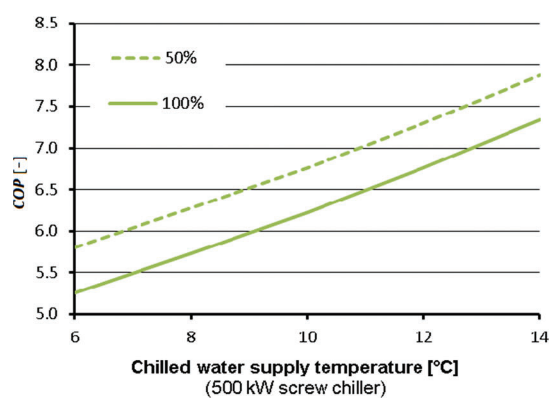

Figure 5.19 *COP* of a screw compressor chiller at 50% and 100% cooling load [6].

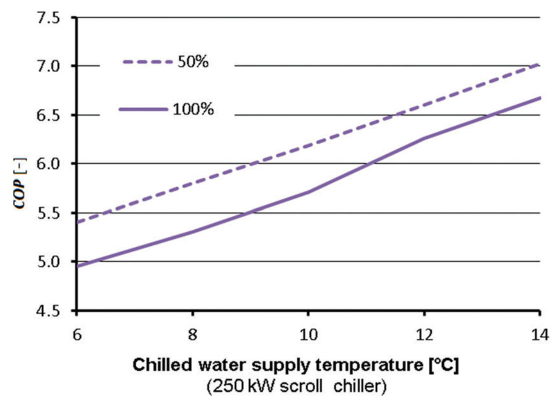

Figure 5.20 *COP* of a scroll compressor chiller at 50% and 100% cooling load [6].

100%, the power demand of fans and pumps approximately decreases by the power of 2.5 with reduced flow. However, splitting a constant water or airflow between several pumps or fans (redundant components) only reduces the total energy demand if the efficiency of each component is higher for the reduced flow than for design flow.

5.6.4 Oversizing Dry Coolers and Cooling Towers

Dry coolers or wet cooling towers are commonly used for rejection of waste heat from water-cooled chillers. An oversized dry cooler or cooling tower is able to generate free cooling at higher outside air temperatures. This is because the approach between the outside temperature and the cooling water supply temperature from the cooler decreases with an oversized cooler. Thus, the annual amount of free cooling increases when using oversized coolers.

5.6.5 Energy Savings and Payback Periods

Generally, energy demand reductions of 20–40% will be achievable for most components when operating in partial load. This results in a total electrical saving of 10–20% for the mechanical installations, which implies a saving of 6–12% related to the Data Centre's total energy demand. Payback period is less than one year when redundant components are used since that does not require extra investments. Oversizing components leads to extra investments; in this case, the typical payback period will be 7–10 years.

5.7 High Energy Efficiency Components

5.7.1 Fans and Pumps

Energy efficiency can be increased by selecting components that are specifically designed for the cooling specifications of the white space. Examples of these are distribution components such as follows:

- High-efficiency, direct-driven and variable speed fans for the CRAH units
- High-efficiency, variable speed pumps

Therefore, the energy efficiency of these components should not only be assessed at 100% load, but also on partial loads (i.e. 25%, 50% and 75% load). The improvement of the energy efficiency may lead to energy reductions for fans and pumps varying from 10 to 30%.

5.7.2 Air-Cooled Chillers

A free cooling option can be incorporated in an air-cooled chiller, although this is very limited. Only at very low outside temperatures, it is possible to generate the required chilled water without using compression cooling. This can be optimised by using advanced high-tech free-cooling chillers. These types of chillers have an optimised free-cooling module using bypass piping, a dedicated pump for free cooling and a high-efficient heat exchanger. In addition, high-efficient compressors (with magnetic bearings, using variable speed permanent magnet) are used. This results in an improvement of the energy efficiency of the chiller:

- Significantly more annual hours of free cooling are available. Normally, the temperature difference between the outside temperature and the chilled water temperature is 8–10 K, while with the high-efficiency chiller, this can be reduced to 2–3 K according to quotations and technical specifications from APAC air conditioning.
- At free-cooling mode, the *EER* will be approximately twice as high (50% reduction in energy usage) compared at the same outside temperatures.
- At "standard" compression cooling operation, the efficiency is also higher (approximately 25% higher *EER*).

However, the cost of these high-tech free-cooling chillers is significantly higher than the "standard" air-cooled chillers. As an example, chillers with a cooling capacity of 250 kW and a chilled water supply temperature of 16°C are compared[4]:

[4]Based on quotations from Carrier and Apac Air-conditioning.

- Standard free cooling air-cooled chiller ∼150 €/kW
- High-efficiency free-cooling air-cooled chiller ∼250 €/kW

Therefore, the economic feasibility has to be studied before implementing such systems in the infrastructure.

5.7.3 Water-Cooled Chillers

Water-cooled chillers are available as high-efficiency performance chillers as well. This is also achieved by using magnetic bearing technology with variable speed drives. An example of this is a comparison of a standard and a highly efficient chiller, as is shown in Figure 5.21. The improvement of the efficiency of the high-efficiency chiller depends on various items, such as the following:

- Condenser water inlet temperature
- Chilled water inlet temperature
- Partial load

This results in an *EER* being 5–50% higher than with the standard centrifugal chiller. However, the costs of the high-tech centrifugal chillers are also significantly higher than the standard chillers. The estimated costs[5] of different water-cooled chillers are as follows:

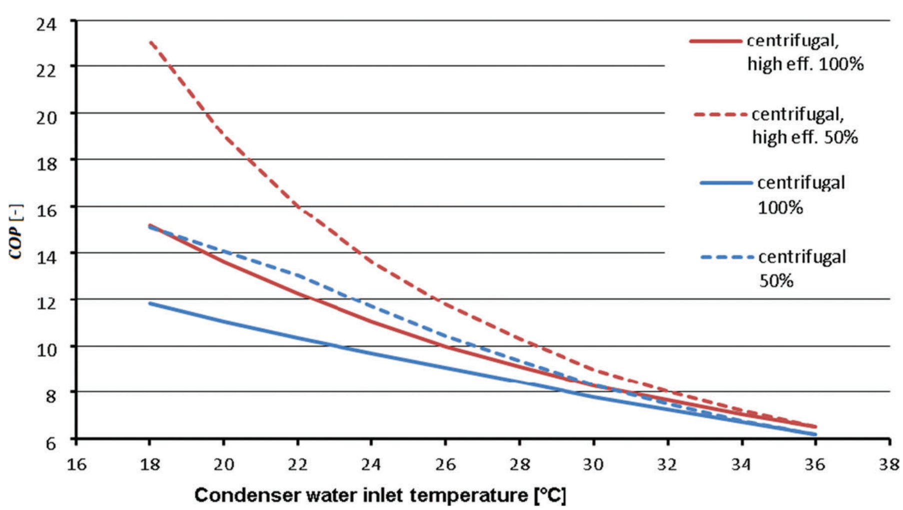

Figure 5.21 Comparison of a “standard” and a high-efficiency centrifugal chiller with variable condenser water inlet temperatures [6].

[5] Based on quotations from different suppliers, mainly from York (Johnson Control).

- Scrollcompressor, cooling approximately 250 kW ∼125 €/kW
- Screwcompressor, cooling approximately 500 kW ∼120 €/kW
- Centrifugalcompressor, cooling approximately 2500 kW ∼100 €/kW
- High-efficiency centrifugal compressor, cooling approximately 1250 kW ∼125 €/kW

Therefore, as in the previous subchapter, the economic feasibility has to be studied before the implementation of such systems in the infrastructure.

Generally, the impact of using highly efficient components depends on the type of component. Normally, an energy saving of 15–25% can be achieved for a number of components. This has a total impact on the electrical savings for the mechanical installations of approximately 10% leading to savings in the total energy demand of about 5%. High-energy-efficiency components will lead to extra investments with payback periods being 10 years or less.

5.8 Conclusions

Data Centres not only need electrical energy to run the IT equipment but also need a lot of energy for cooling, i.e. for removing the heat generated by the IT hardware. Six advanced technical concepts are proposed in this chapter which lead to a reduction in the electric energy required for cooling. Free cooling and increased allowable IT temperature additionally reduce the load of mechanical cooling. With free cooling, heat is transferred actively to the environment without using a mechanical chiller, while increased IT temperatures lead to better operational requirements of the equipment (chiller) and also enhance the hours of free cooling.

Further concepts, hot/cold aisle containment and variable airflowcover the optimisation of air and chilled water flows by preventing mixing of hot and cold air and adapting the volume flow to the load. This leads to increasing return temperatures and temperature differences, which are favourable both for electricity demand and for potential heat reuse. Concepts, i.e. at partial load with redundant or oversized components and highly efficient components, deal with increasing the efficiency of components as chillers, fans and pumps by running them under part-load conditions and by implementing highly efficient products.

The next step after load minimisation by means of efficiency measures is to supply the electrical and cooling load efficiently and with a high share of renewable energy resources. This subject will be discussed in the next Chapter 6.

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