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MINIMISATION OF ENVIRONMENTAL IMPACTS OF WASTE HEAT REMOVAL SYSTEMS IN EUROPE

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EUROVENT/ CECOMAF the European Committee of Air Handling and Refrigeration Equipment Manufacturers is made up of national associations which represent the manufacturers of air handling, air conditioning and refrigeration equipment in Europe.

EUROVENT/ CECOMAF has the aim to establish closer ties between manufacturers, promote proper use and application of equipment and contribute to the general development of the profession.

EUROVENT/ CECOMAF also represents the profession in relations with European Authorities and International Organizations and contributes to ISO and European standardization.

This document has been produced under the auspice of EUROVENT/ CECOMAF and reflects the view and experience of the associated European manufacturers of heat exchangers for waste heat removal.

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Preface

The European Directive 96/61 EC concerning Integrated Pollution Prevention and Control (IPPC) obliges the commission to organise an exchange of information on „Best Available Techniques" (BAT) for industrial installations listed in annex 1 of this directive. The resulting documents describing the Best Available Technique for different installations will be published by the commission. These are called BAT notes or BAT BREF (Best Available Technology Reference Documents). Once in place, the BREF documents need to be considered by local environmental authorities in the permitting procedure.

One of the industrial installations, for which a BREF document has to be published is cooling systems (waste heat removal systems).

The European Committee of Air Handling and Refrigeration Equipment Manufacturers (Eurovent) has asked PricewaterhouseCoopers to evaluate the existing literature on environmental impacts of cooling systems in order to provide a study about the minimisation of environmental impacts of waste heat removal systems and to define the "Best Available Technique" for waste heat removal systems in Europe.

The objective of this document is to provide information about waste heat removal systems and their environmental impacts. Therefore structure and content of this document have been geared towards adaptation the BREF-document.

Given the objective of a horizontal approach of the BREF for cooling systems, this document focuses on both direct and indirect environmental impacts of the different cooling systems. The "horizontal" approach is to describe the requirements of a typical process (waste heat removal), that is used in different applications and industries.

This document is mainly based on the existing documents according to environmental aspects of cooling systems, mainly on the documents of RIZA [16] and EURELECTRIC [6] and data provided by Eurovent and European manufacturers of cooling systems. These data have been completed by additional literature and own calculations.

PRICEWATERHOUSECOOPERS
Unternehmensberatung GmbH

Frankfurt am Main, April 1999

1 General Information

1.1 Scope and Definition

The intention of this document is to describe the "Best Available Technique" for cooling systems (waste heat removal systems) under the scope of the European Directive 96/91 EC from April 24,1996 concerning Integrated Pollution Prevention and Control (IPPC) for cooling systems. The objective of the Directive 96/61 EC is to achieve a high level of environmental protection at large industrial installations in an efficient way.

Best Available Techniques

"Best Available Techniques" means the most effective and advanced stage in the development of activities and their methods of operation. "Best" means most effective in achieving a high general level of protection on the environment as a whole, including direct and indirect environmental impacts. "Available" means techniques which are developed on a scale, that allows implementation in the relevant industrial sectors under economically and technically viable conditions. "Techniques" includes both the technology used and the way in which the installation is planned, designed, built, maintained, operated and decommissioned.

The BREF document for cooling systems has an horizontal approach, which describes the requirements of typical process - cooling systems, without a detailed specification of the different applications. Within this horizontal work, an integrated approach is followed, considering

- all environmental aspects (water/air/soil pollution, energy/water consumption, noise, waste) including an assessment of these impacts,
- direct and indirect environmental aspects, due to the influence of the cooling-system on the efficiency of the main process,
- environmental impacts during standard operation and maintenance as well as pollution arising from specific events or incidents.

Cooling System / Waste Heat Removal System

The term "cooling systems" is defined as systems which remove waste heat from any medium, using heat exchange with water and/or air to bring down the temperature towards ambient levels – in this document the term "cooling system" is used synonymous for "waste heat removal systems", which is the more exact term. This includes only part of refrigeration systems (removal of re-condensation heat), and it excludes the issue of refrigerants (ammonia, CFCs). Process-specific cooling methods, like direct contact cooling (quenching) - often used in incinerators and coke ovens - or barometric condensers - often used in the food industry - are not included in this study and could rather be addressed in the relevant vertical process BREFs. Cooling systems for nuclear technological installations, like nuclear power plants, are not covered by this document due to

these applications' very specific demands on safety and durability of used materials.
Types of cooling system covered by this study are:

- once through-flow water-cooled systems,
- cooling towers (open and closed circuit),
- evaporative condensers,
- dry air-cooled systems,
- hybrid systems

and any combination of these.

The different types are explained more detailed in chapter 2. Within these systems, the study covers the following steps:

- general process design (design, material, maintenance),
- technological and thermodynamical approaches,
- economical aspects,
- energy efficiency,
- resource use,
- emissions and other environmental impacts;.

Waste Heat

Waste heat is an inherent yet unwanted by-product of industrial and manufacturing processes, if it is not used as an energy resource for other purposes (e.g. for other heating or heat demanding processes). If the heat is not recuperative, it has to be removed to the environment as waste heat. The nearby environment, a river, a lake, a sea or the atmosphere, is used as a heat sink.

The environmental impact of local waste heat removal can range from mere nuisance to serious distortion of the ecological balance. In addition, energy is needed to remove waste heat This energy has to be generated, which in return requires additional waste heat removal.

For these reasons, it is obvious that the first target for any "best technology" is to minimise the amount of waste heat right from the beginning. However, this document's focus lies on cooling systems for the removal of waste heat rather than on systems or technologies for minimisation and use of waste heat.

In choosing the „best available" cooling system it is important to distinguish between different temperature levels of waste heat. The quantity of waste heat is as important as its quality. The quantity of waste heat is the amount, that has to be removed. The quantity of waste heat, which a cooling system is able to remove is called its capacity. The quality of waste heat relates to the temperature of the medium, that has to be cooled.

Temperature Application Range

It is useful to distinguish between three different levels of waste heat temperature:

approximately	15 - 25°C	low temperature
approximately	25 - 60°C	medium temperature
approximately	> 60°C	high temperature

These temperature scopes are specific for each process generating waste heat. This quality of waste heat influences the possibility of reuse of the heat for other purposes and the decision for the type of cooling system. The higher the temperature, the easier heat can be used for other purposes and vice versa. The quality of heat can be described by the physical term entropy. The higher the temperature, the lower the entropy of the heat.

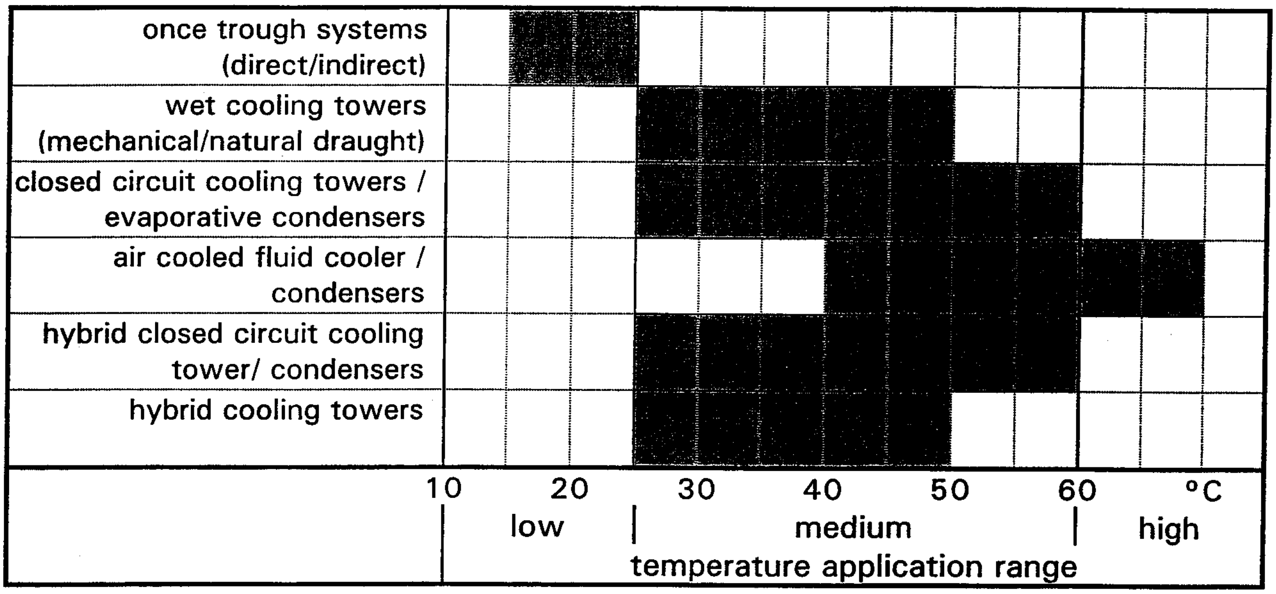

Figure 1: Typical Suitable Temperature Application Ranges for Different Cooling Systems

Figure 1 indicates typical uses for the different types of cooling systems at different temperature application ranges. Table 1 gives examples for industrial processes.

The lower the temperature, the more difficult is cooling with air cooled systems. In practice, air-cooling is often used for temperatures above about 60°C. Heat levels above 100°C are generally pre-cooled with air-coolers. Evaporative cooling is, in principle, often used to cool process flows with medium and low temperatures. For low temperature applications also once through-flow cooling systems are used.

Table 1: Suitable Cooling systems for different Temperature Application Ranges

Temperature Range	Suitable Cooling System	Typical Applications
Low Temperature (15 - 25 °C)	• once trough systems direct/indirect	• bio-chemical processes • power generation
Medium Temperature (25 - 60 °C)	• wet cooling towers (mechanical/natural draught) • closed circuit cooling towers • evaporative condensers • air cooled fluid coolers • air cooled condensers • hybrid cooling towers/condensers • hybrid closed circuit cooling tower	• refrigeration cycles • compressor • cooling of machines • autoclave cooling • cooling of rotary kilns • cement plants
High Temperature (above 60 °C)	• air cooled fluid cooler / condensers	• waste incineration plants • engine cooling • cooling of exhaust fumes • chemical processes

1.2 Sources of Waste Heat

All industrial and manufacturing processes which use energy are transforming different forms of energy (physical, chemical, electrical etc.) into heat. Depending on the process this heat is produced in an amount, that it has to be cooled. Processes with a specifically high production of waste heat and a high demand of cooling are mentioned below. In many process different sources of waste heat are existing.

Friction

By physically definition, friction is the transformation of kinetic energy into heat. Examples for cooling of waste heat caused by friction are:

- cooling of machines
- cooling of rotary kilns

Cooling systems for these processes are usually indirect systems with oil as a primary cooling circle. Due to the usage of oil as cooling medium, the cooling system is sensitive to high temperatures. Therefore, the average temperature of the waste heat is at medium level.

Combustion

Combustion is the transformation of chemical energy by oxidation into heat. Examples for combustion processes, which demand cooling systems are:

- electric power generation (cooling of exaust gases)
- waste incineration plants
- engines

Waste heat of combustion processes is at a high temperature level.

Exothermic Processes (chemical)

Many chemical processes are exothermic: chemical energy is transformed into heat without any combustion. Examples for exothermic processes, which are important in the chemical and petrochemical industry are:

- naphtha cracking
- ammonia synthesis (Haber-Bosch)
- Sulphur synthesis (Claus)
- Nitrite acid synthesis

Exothermic processes are often very sensitive to the efficiency of the removal of waste heat. The temperature level of the waste heat is medium to high, depending on the process.

Compression

Compressing a gas leads to the generation of heat. This heat usually has to be removed as waste heat. Examples for compression processes are:

- pneumatic processes,
- extraction of technical gases like Nitrogen, Oxygen, Helium etc. (Linde).

Compression generally leads to waste heat at a medium to high temperature level.

Condensation (Thermodynamic Cycles)

Many processes are working on the principles of thermodynamic cycles. A liquid medium is evaporated, taking energy and is consequently condensed, transforming energy into heat. These thermodynamic cycles are used e.g. for

- industrial refrigeration (food industry),
- cooling systems (air condition of buildings).

Thermodynamic systems are very sensitive to temperature. The temperature level of the waste heat is medium to low.

Effluent Treatment:

In most member states thresholds for the temperature of sewage exist, which is discharged into surface water. Effluent water and sewage of exothermic processes therefore has to be cooled to lower temperatures, in order to avoid the growth of bacteria or negative effects in the surface water.

Special Application: Power Generation

Power plants are the most important source of waste heat. The transformation of fossil energy into electrical energy is connected with numerous of the above mentioned waste heat generating processes.

The operation of power plants is governed by Carnot's principle: the heat source, the boiler which is heated by the burning of fossil fuel, provides the energy required for evaporating the water. This steam drives an electricity generating turbine. The cold source, the condenser, condenses the steam, that comes out of the turbine's low pressure cylinder.

Waste heat is generated during combustion, friction of the turbine, condensation of the steam and transformation of the electricity.
Table 2 shows the specific energy consumption which is needed to produce 1 kWh of electrical energy in an average power plant (simplified).

Table 2: Specific Energy Consumption of an Average Power Plant [6]

	Energy (kJ)	Energy loss (%)	Efficiency (%)
Fossil energy input (combustion)	9000		100
Steam generating loss (boiler)	1050	11,7	88,3
Condenser loss	4200	46,5	41,8
Feedwater heating	2000	(22,2)	(looping)
Turbine loss	65	0,75	41,05
Electricity transforming	25	0,2	40,85
Plant's own power demand	65	0,75	40,1
Electrical energy (1 kWh)	3600	59,9	40,1

The thermal cycle balance shows, that the main source of waste heat is the condenser. About 4200 kJ heat must be yield from the condenser for each kWh electricity generated.

Power plants also need an auxiliary cooling water system. It ensures cooling the closed loop cooling systems, such as for example:

- generator stator cooling water coolers,
- generator hydrogen coolers,
- generator seal oil coolers,
- off-gas condensers,
- turbine lubricating oil coolers,
- turbine regulating oil coolers,
- compressor lubricating oil coolers,
- compressor coolers.

These auxiliary systems represent only about 4 to 8 % of the circulating flow of the cooling system.

New power generation systems, especially combined cycles with heat and electricity generation or gas-steam turbines make it possible to obtain higher efficiencies.

Power generation is very sensitive to temperature. The efficiency of the power generation is highly correlated with the efficiency of the cooling system. The efficiency of the cooling system increases when the temperature of the cooling fluid decreases. The efficiency of power units for example increases of approximately 0,25 % when the end temperature of the cooling medium decreases of 1 K [8].

1.3 Level of Waste Heat Removal and Influence on Process Efficiency

1.3.1 Temperature Critical Applications

Many chemical and industrial processes are temperature critical applications. The efficiency of the process is sensitive to temperature and/or pressure and therefore correlated with the efficiency of the removal of waste heat.

For these processes, the horizontal approach of best available cooling technology is connected with the vertical approach of best available process technology, e.g. for the applications mentioned in chapter 1.2.

Examples for temperature critical applications are:

- power generation,
- thermodynamic cycles
- bio-chemical processes
- exothermic processes

As part of the integrated pollution prevention, it is important for the selection of best available cooling technology to include not only the environmental impacts of the different cooling systems, but also the indirect impacts due to the different processes' varying efficiencies. The increase of these indirect impacts can be considerably higher than the decrease of direct impacts of the selected cooling system.

This correlation is shown by the following example for power plants: An alternative, less effective cooling system for power plants for example could lead to a loss in efficiency of the power plant of about 3%. As a result the resource input of the power plant and its emissions will also increase about 3% (Table 3).

Table 3: Emissions of an Average Western European Power Plant due to an Efficiency Loss of 3% [20]

	emissions / energy input per kWh	additional emission due to a loss of 3% efficiency
primary energy input:	2,65 [kW/kWh]	0,08 [kW/kWh]
Emissions: CO_2	485 [g/kWh]	14,6 [g/kWh]
SO_2	2,4 [g/kWh]	72 [mg/kWh]
NO_x	1,0 [g/kWh]	309 [mg/kWh]
dust	0,2 [g/kWh]	60 [mg/kWh]

This 3% loss of efficiency could occur, for instance, if dry cooling systems were used for cooling the condenser instead of water cooling systems. The condenser vacuums that can be reached by dry systems range from 65 to 80 mbar. Compared to water cooled systems, which obtain 35 mbar, this leads to an efficiency loss of the whole power generating process of about 3%. There are numerous other potential reasons for an efficiency loss, which may lead to similar indirect environmental impacts, e.g. fouling, scaling, corrosion, sub optimal design etc.

Another temperature critical application are refrigerating systems. The example in Table 4 shows that the energy requirements of the refrigerating system is dominated by the energy consumption of the compressor. The condenser needs just 10 – 11 % of the energy of the total system. For the same refrigeration capacity the compressor energy strongly depend on the condensing temperatures, the lower the temperature, the lower the required energy.

Table 4: Ratio of Energy Consumption of the Compressor and the Condenser of an industrial Refrigeration System [7]

	air cooled system	Evaporative condenser
Climate (design temperature)		
dry bulb temperature	32 °C	
wet bulb temperature	21 °C	
Given duties		
refrigeration capacity	10 MW	
evaporating temperature	- 15 °C	
refrigerant	R 717	
approach	10 K	
Specific Data:		
condensing temperature	42 °C	31 °C
energy consumption –total	3085 kW	2385 kW
- condenser	345 kW	235 kW
- compressor	2740 kW	2150 kW

For the Netherlands calculations have been made, that an increase of the temperature of cooling water for an average of all cooling applications by 1 K (e.g. due to less effective cooling systems or ineffective maintenance) would result an increase in power consumption of 3,5 $kW_{electric}$ per $MW_{thermal}$ per K [16]. These estimations depend on the ratio of temperature critical applications on all cooling applications. However they might be representative also for other member states.

The different examples mentioned above show, that for temperature sensitive applications the focus should be on process efficiency. It is important to select a cooling system which leads to an optimal process efficiency of the whole application.

1.3.1 Non Critical Applications

Some other applications are less sensitive to temperature. The efficiency of these processes is less correlated with temperature or pressure. For these processes the focus should be on the economically and ecologically most efficient cooling system.

1.4 Other Influence Factors

The selection of a cooling system is influenced by different parameters. Besides the thermodynamic parameters which have been discussed in chapter 1.3, other parameters have important influence on the „best available" cooling system for the specific application and the specific site.

1.4.1 Space

The different types of cooling systems need different amounts of space for the same cooling performance. Depending on their concept of heat transfer, cooling systems differ in area requirements, altitude and weight.

Restrictions on space at existing site, for instance in densely built urban areas or densely built industrial sites, have important influence on the selection of cooling systems. For example a cooling tower on top of a building needs no additional ground on site, but the roof may lead to weight restrictions. Another example are historic villages or buildings, where cooling systems may have to be hidden or specially designed.

Space and altitude requirements are important criteria for air-cooled and hybrid systems. The ventilation of air can be achieved by natural draught or by ventilation with fans (mechanical draught). For the same cooling capacity natural draught cooling systems have to be far bigger than mechanical draught systems.

1.4.2 Site Specific Environmental Impacts

Cooling systems may have different impacts on the environment. Some of these impacts can be more important than others, depending on the site and its environment.

- Energy Consumption
  cooling systems require operating energy, mostly for fans and pumps;
- Water Consumption
  for many applications water-cooled systems are used;
- Use of Chemicals
  water-cooled systems may require chemicals against fouling, scaling and corrosion;
- Water Pollution
  water chemicals may be emitted into the surface water;
- Air Pollution
  chemicals or bacteria could be discharged into the atmosphere;
- Waste Generation
  in water-cooled systems, various sludge emerge from treatment of intake/cooling/blow down water;
- Plumes
  the emission of plumes by larger cooling towers may have a visual

effect on the landscape and can have influence on local climate (fog and ice forming) in the vicinity of the installation;
- Noise
  noise is mainly generated by fans, gears, motors, pumps and droplets falling onto the cooling water basin;
- Heat Discharge
  the removed heat can have negative effects on surface water or the atmosphere

The environmental impacts of different types of cooling systems are discussed in more detail in chapter 3 and 4.2. Different kinds of cooling systems cause different specific effects on the environment. Depending on the specific sites, the various environmental effects will cause different environmental impacts. The tolerated immission can vary from site to site.

The acceptable noise emission of a cooling system for a residential location, for example, will be considerably lower than the acceptable noise emission for an industrial site.

1.4.3 Availability of Operating Resources and Temperatures

The availability of the cooling medium is important for the selection of a cooling system. Especially for open once-through water cooled systems the availability of the necessary amount of water in acceptable quality and temperature and low or no water prices are important. In arid areas other systems will be selected than at a site near a big river.

It is an obvious necessity for all cooling systems, that the cooling medium has to have a lower temperature than the medium to be cooled. Although air is no limited resource, even for air cooled systems maximum ambient air temperatures can be a restriction for the selection of a cooling system. Due to different thermodynamic properties of wet and dry air, it is necessary to distinguish between wet and dry bulb temperatures.

Wet bulb temperature is the lowest temperature, to which air can be cooled down by isobar evaporation. Wet bulb temperature always lies below dry bulb temperature. The wet bulb temperature depends on the measured temperature of the atmosphere, the humidity and the air pressure. For latent heat transfer the wet bulb temperature is the relevant temperature. It is theoretically the lowest temperature water can be cooled down by evaporation. For sensible heat transfer the dry bulb (dry air) temperature is relevant.

For the selection of the type and the design of cooling systems the maximum wet bulb and dry bulb summer temperatures are important. The different climate conditions in Europe, as they are documented in Table 5, will lead to different types of cooling systems. The bigger the difference and the higher the dry bulb temperatures, the more difficult it would be to reach low end temperatures with dry air cooled systems.

Table 5: Climatic Conditions in Europe[1] [1]

Country and station		Summer climate		
		dry bulb (1%)[2]	wet bulb (1%)[2]	difference K
Greece	Athens	36 °C	22 °C	14
Spain	Madrid	34 °C	22 °C	12
France	Paris	32 °C	21 °C	11
Italy	Rome	34 °C	23 °C	11
Austria	Vienna	31 °C	22 °C	9
Germany	Berlin	29 °C	20 °C	9
Netherlands	Amsterdam	26 °C	18 °C	8
France	Nice	31 °C	23 °C	8
UK	London	28 °C	20 °C	8
Germany	Hamburg	27 °C	20 °C	7
Norway	Oslo	26 °C	19 °C	7
Belgium	Brussels	28 °C	21 °C	7
Spain	Barcelona	31 °C	24 °C	7
Finland	Helsinki	25 °C	19 °C	6
Denmark	Copenhagen	26 °C	20 °C	6
Portugal	Lisbon	32 °C	27 °C	5
UK	Glasgow	23 °C	18 °C	5
Ireland	Dublin	23 °C	18 °C	5

1) the given data in this table is just an example for the variation of the climate in Europe. Other references (e.g. Recknagel & Sprenger) may provide slightly different data. The exact data for a site can be obtained from a meteorological institute.

2) statistically only 1% of the maximum temperatures are above this data

The following example shows size, energy consumption and noise emissions of a closed circuit cooling tower (Table 6) and a hybrid dry cooling tower (Table 7) in correlation to the climate conditions of a site:

Table 6: Influence of the Climate on Size and Power Data of Closed Circled Cooling Towers

Example: closed circuit cooling tower	cold/humid climate (e.g. Amsterdam)	medium/dry climate (e.g. Brussels)	hot/dry climate (e.g. Athens)
Climate:			
dry bulb temperature	26 °C	28 °C	36 °C
wet bulb temperature	18 °C	21 °C	22 °C
Given Duties:			
capacity	5000 kW		
inlet temperature	40 °C		
outlet temperature	32 °C		
flow	150 l/s		
Specific Data:			
length	5,5 m	11 m	11 m
width	3,0 m	3,6 m	3,0 m
height	5,0 m	5,0 m	5,0 m
fan power	11 kW	45 kW	66 kW
spray pump power	4 kW	8 kW	8 kW
sound power level[1]	95 dB(A)	103 dB(A)	106 dB(A)

1) without sound attenuation

Table 7: Influence of the Climate on Size and Power Data of Hybrid Closed Circled Cooling Towers

Example: closed circuit cooling tower	cold/humid climate (e.g. Amsterdam)	medium/dry climate (e.g. Brussels)	hot/dry climate (e.g. Athens)
Climate:			
dry bulb temperature	26 °C	28 °C	36 °C
wet bulb temperature	18 °C	21 °C	22 °C
Given Duties:			
capacity	5000 kW		
inlet temperature	40 °C		
outlet temperature	32 °C		
flow	150 l/s		
Specific Data:			
length	6,8 m	7,8 m	8,3 m
width	2,4 m	2,4 m	2,4 m
height	3,7 m	3,7 m	3,7 m
fan power	20 kW	21,8 kW	24,6 kW
spray pump power	2,4 kW	2,4 kW	2,4 kW
sound power level[1]	94,5 dB(A)	93,7 dB(A)	94,3 dB(A)

1) without sound attenuation

Using the meteorological data provided in Table 5 for the selection of cooling systems, the difference in dry and wet bulb temperatures will lead to much higher differences in achievable end temperatures by choosing wet evaporative or dry cooling systems according the difference approach (Table 8). Assuming an average approach for dry systems of 12 K and and for evaporative systems of 4 K (see Table 14) the difference in the minimum achievable end temperatures of dry and evapoartive systems vary between 13,5 K (e.g. Glasgow) and 22,5 K (e.g. Athens). For the cooling of temperature sensitive processes (see chapter 1.3.1) dry systems would lead to a loss of efficiency between 3,4 % (e.g. Glasgow) and 5,6 % (e.g. Athens)[1] [8].

Table 8: Achievable End Temperatures of Evaporative and Dry Cooling Systems at Different Climates [1]

Country and station		achievable minimum end temperatures			
		evaporative systems[1]	dry systems[2]	difference	Efficency losses[3]
Greece	Athens	26 °C	48,5°C	22,5 K	5,6 %
Spain	Madrid	26 °C	46,5 °C	20,5 K	5,1 %
France	Paris	25 °C	44,5 °C	19,5 K	4,9 %
Italy	Rome	27 °C	46,5 °C	19,5 K	4,9 %
Austria	Vienna	26 °C	43,5 °C	17,5 K	4,4 %
Germany	Berlin	24 °C	41,5 °C	17,5 K	4,4 %
Netherlands	Amsterdam	22 °C	38,5°C	16,5 K	4,1 %
France	Nice	27 °C	43,5 °C	16,5 K	4,1 %
UK	London	24 °C	40,5 °C	16,5 K	4,1 %
Germany	Hamburg	24 °C	39,5 °C	15,5 K	3,9 %
Norway	Oslo	23 °C	38,5 °C	15,5 K	3,9 %
Belgium	Brussels	25 °C	40,5 °C	15,5 K	3,9 %
Spain	Barcelona	28 °C	43,5 °C	15,5 K	3,9 %
Finland	Helsinki	23 °C	37,5 °C	14,5 K	3,6 %
Denmark	Copenhagen	24 °C	38,5 °C	14,5 K	3,6 %
Portugal	Lisbon	31 °C	44,5 °C	13,5 K	3,4 %
UK	Glasgow	22 °C	35,5 °C	13,5 K	3,4 %
Ireland	Dublin	22 °C	35,5 °C	13,5 K	3,4 %

1) assumed approach of 4 K for evaporative systems
2) assumed approach of 12 K for dry systems
3) assumed average losses due to carnot circle of 0,25 % per K [24]

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[1] assumed average losses due to carnot circle of 0,25 % per K [24]

1.4.4 System Maintenance

The thermal efficiency of cooling systems is mainly influenced by the way they are maintained. The efficiency (η) of a cooling system will decrease over time. Fouling caused by sludge of micro organisms, corrosion and scaling reduces the heat exchange efficiency of the systems. An example for the loss of capacity due to scaling is shown in Figure 2.

To maintain the efficiency of the cooling system over time it is necessary to keep fouling, corrosion and scaling at a minimum level. This can be achieved by regular water treatment and cleaning, which may lead to higher water consumption or higher emissions into water. Another possibility is to use durable materials and designs which are less sensitive to fouling, scaling and corrosion, but which may increase the cost of a cooling system.

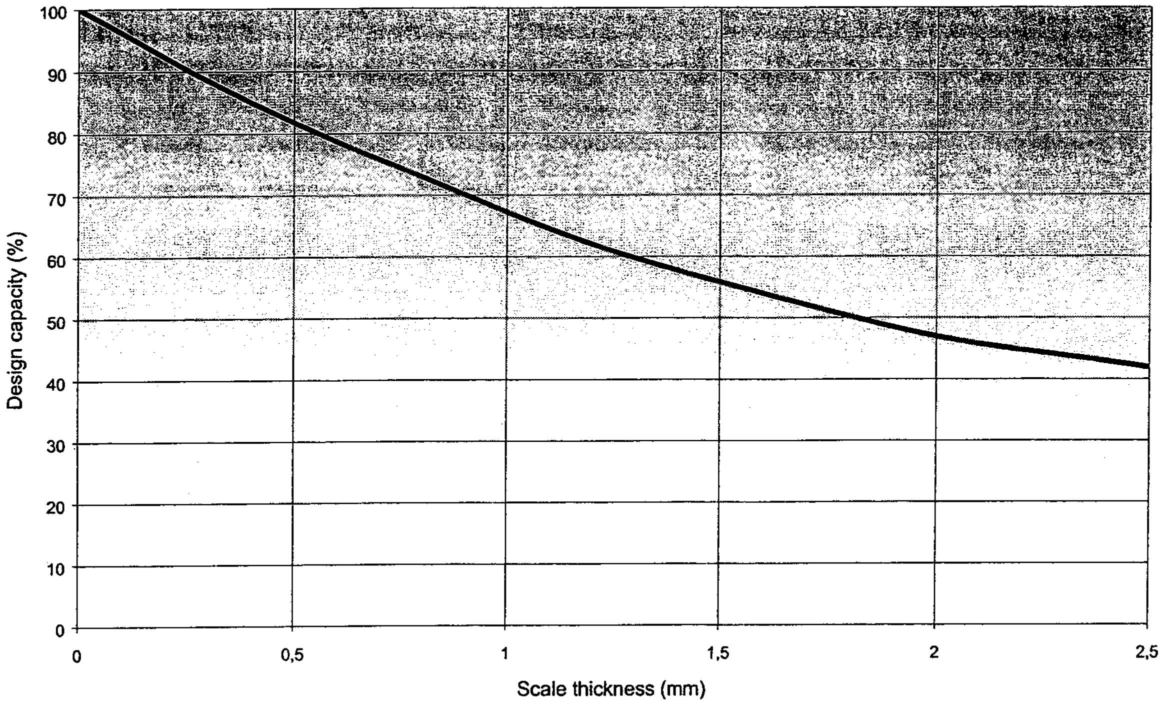

Figure 2: Loss of Capacity Due to Scaling [2]

Fouling is not a singular problem of water cooled-systems. It is also caused by air on the outside of coils and fins with similar negative effects on the efficiency of the heat transfer. In both cases costs and environmental impacts have to be assessed over time and compared to the indirect economical and ecological effects of a reduced efficiency of the cooling system. In general, regular maintenance can reduce the environmental effects by increasing the efficiency of the cooling systems. The necessity of maintenance as well as the costs are influenced by site specific factors like air pollution (dust) or water quality. Therefore, maintenance and maintenance costs are a important factors for the selection of a cooling system.

A reduced efficiency of the heat exchanger, is correlated with a reduced efficiency of the cooled process. Therefore a loss of efficiency due to insufficient maintenance will result in unnecessary resource consumption and indirect environmental impacts.

Table 9: Example for the Loss of Efficiency Due to Insufficient Maintenance [2]

Example: refrigerating system	evaporative condenser
condensing temperature	33 °C
wet bulb temperature	21 °C
refrigerant	R 717
condenser heat rejection	1.000 kW
compressor power	250 kW
annual operating hours	5.000 h
electrical requirement compressor	1.250 MWh/a
assumed loss in efficiency	20 %
resulting raise of condensing temperature	3 K
additional power requirement of the compressor	112,5 MWh/a

The example in Table 9 of a condenser shows this resulting indirect energy consumption. If the efficiency of the heat exchanger is reduced to 80 % - this could be caused for example by a scale thickness of 0,5 mm (see Figure 2) – this will result in a raise of the condensing temperature of 3 K. To compare this 3 K raise of the temperature 112,5 MWh additional annual power consumption is required for the compressor. This is about the total annual energy consumption of the condenser.

1.4.5 Legal Requirements

Depending on size and type, cooling systems are regulated by environmental legislation. Depending on the local site, legislation can have important influence on the selection of the type of cooling system. In the following, examples for German legislation are documented.

The Federal Immission Act defines heat as an emission / immission which has to be minimised according to the Best Available Technique, if it has potentially negative effects on the environment or the neighbourhood.

Cooling towers with a cooling-water demand of 10000 m³/h or more have to require a permit according to the Federal Immission Act. For other installations, which have to be permitted according to the Federal Immission Act, the cooling system is included in the permit.

There are different thresholds for noise immissions. The thresholds depend on the nature of site, for example whether it is an industrial area, a residential area or a recreation area.

The use of surface water and the water and heat emissions into surface water are regulated by the Federal Water Act. In some states, a fee has to be paid for the use of ground water. The emission of heat into surface water requires a permit.

1.4.6 Economic Considerations

The costs of a cooling system are always among the most important factors for the selection of a special type of cooling systems. Three types of costs are most important:

- investment costs,
- maintenance costs,
- operating costs related to energy and water consumption.

Depending on the systems, the absolute costs and the relation between the different costs vary. The cooling system with lowest investment cost is not necessarily also the one that requires minimal operating resources. Technical solutions to minimise resource consumption often lead to higher investment cost.

It is important that economic considerations focus not only on simple investment cost comparisons but also on operating costs of a cooling system.

Chapter 4.3 describes the economic aspects of the different cooling in more detail.

The selection of waste heat removal systems depends on application and local factors, which have to be evaluated on an individual project level. Within this horizontal approach, it is very difficult to compare different cooling systems according to their economic and environmental performance, in general.

2 Applied Processes and Techniques

2.1 Thermodynamic Approaches

Cooling systems work by transferring heat from a process flow which has to be cooled to another medium. This medium is usually either water or air. In some cases, there is an intermediate medium that absorbs the heat first and then transfers it to air or water.

Two thermodynamic principles are responsible for the heat transfer:

- transfer through conduction and convection
- transfer through evaporation of a medium

Heat transfer through conduction and convection is called *sensible heat transfer*. Sensible heat transfer to air can be calculated as follows:

$$Q = C_p \times m_a \times \Delta T$$

Q	transfered heat capacity
C_p	specific heat capacity of air (constant pressure)
ΔT	temperature range
m_a	amount of air

The amount of heat, which is transferred by sensible heat transfer is influenced by the temperature range, the air mass flow, by the surface of the heat exchanger and by the specific heat transfer coefficient.

Heat transfer through evaporation is called *latent heat transfer* and can be calculated with the following formula:

$$Q = m_a' \times \Delta h$$

Q	transfered heat capacity
Δh	amount of evaporating water x evaporation enthalpy of water
m_a'	amount of dry air

At evaporative cooling the two principles are coupled, however the main part of heat is transferred latent (about 80 % latent and 20 % sensible [6]), at dry cooling only sensible heat transfer takes place.

Comparing the amount of air, necessary for sensible and for latent heat transfer to the atmosphere, the ratio is depending on the temperature range ΔT:

$$\frac{m_a'}{m_a} = \frac{C_p \times \Delta T}{\Delta h}$$

For an increase in temperature of 10 K this ratio is about 1:4. In this example, sensible heat transfer needs four times more air than latent heat transfer.

Approach

It is important for a cooling system to always provide sufficient driving force in order to achieve the transfer of heat. A minimal temperature difference is necessary between the incoming cooling medium (e.g. cooling air) and the outgoing process medium (e.g. water to be cooled). The entry temperature of the cooling medium is called *design temperature*, the outgoing temperature of the process medium to be cooled is called *end temperature*. This difference between design and end temperature is called the *approach*.

For water-cooling, a minimal approach over the heat exchanger of 3 to 5 °C is used. Lower values can be used, but this requires a larger and therefore more expensive heat exchanging surface.

The approach of a cooling system and the design temperature, which depends on the climatic conditions of the site (see Table 5), determine the minimum end temperature, which can be achieved by the cooling system.

Capacity

The capacity (heat rejection capacity), of a heat exchanger is the amount of heat which can be removed. The required heat transfer area of a cooling system is influenced by the different heat transfer capacities of the cooling media water and air, of sensible and latent heat transfer and by the driving force. The design has also to consider drop of pressure, flow speed etc.

Due to its physical properties, water is an ideal heat carrier because of its high thermal capacity. It therefore only requires small heat exchange surfaces. The most effective heat transfer is by evaporation. The heat transfer capacity for latent heat transfer by evaporation of water is more than 500 times higher than for sensible heat transfer to water. The specific heat transfer capacities of air, water, and evaporating water are described in Table 10.

Table 10: Heat Transfer Capacities

air: (sensible heat transfer)	$Cp_{\text{(air)}}$	=	1,005	$\frac{KJ}{kg\ K}$
water: (sensible heat transfer)	$Cp_{\text{(water)}}$	=	4,187	$\frac{KJ}{kg\ K}$
steam: (sensible heat transfer)	$Cp_{\text{(steam)}}$	=	1,817	$\frac{KJ}{kg\ K}$
evaporation of water: (latent heat transfer)	$h_{v\ \text{(water at 273 K)}}$	=	2501,6	$\frac{KJ}{kg}$

A high heat transfer and driving force lead to a small required surface, resulting in a compact and cost effective heat transfer concept. Because of the lower heat transfer capacity of air, dry cooling systems require much bigger heat exchanger surfaces and driving force for the same cooling capacity. This bigger heat exchange surface results in a higher demand on space and potentially higher investment costs.

In Table 11 two cases of installed cooling systems, one for dry cooling and one for evaporative cooling are compared. The dry cooling tower with a cooling surface diameter of 20 % more, has only 47 % of the capacity of the evaporative cooling system and the approach is 20 K compared to 12,6 K [8].

Table 11: Effects of the Cooling Principle on Capacity, Approach and Cooling Surface of a Cooling System [8]

	dry air natural draught cooling tower	wet natural draught cooling tower
capacity	895 MW	1900 MW
cooling surface diameter	145 m	120 m
approach	20 K	12,6 K
temperature (dry bulb / wet bulb)	14 / 10 °C	11 / 9 °C
minimum end-temperatures	34 °C	23,6 °C

2.2 Technological Approaches

The different types of cooling systems can be classified by different criteria. The common literature uses the following criteria:

- dry and evaporative cooling - according to the dominating thermodynamic principle - latent or sensible heat transfer. At evaporative cooling the two principles are coupled, however the main part of heat is transferred latent (about 80 % latent and 20 % sensible [6]), at dry cooling only sensible heat transfer takes place.
- direct or indirect systems - whether there are at least two heat exchangers and a closed cooling circle, between the process or product to be cooled and the cooling medium. Due to the additional heat exchanger indirect systems have a higher approach (about 5 K).
- open or closed systems - whether the medium to be cooled has contact to the environment or whether the cooling medium is circled in a closed circuit system;
- air-cooled or water-cooled systems - according to the environmental medium which accepts the waste heat and transports it away from the place at which it is generated. Of course, also the water will discharge its heat to the atmosphere.

Not all of these criteria are consistent and useful for understanding the different cooling systems. Nevertheless they are used in the common literature.

Examples for the different cooling mechanisms are listed in Table 12:

Table 12: Technical and Thermodynamic Characteristics of the Different Cooling Systems

cooling system	cooling medium	main cooling principle	approach	minimum end temperature[4]	capacity
once through-flow - direct	water	conduction	3 - 5 K	18 – 20 °C	<10 kW - >100 MW
- indirect	water	conduction	6 – 10 K	21 – 25 °C	<10 kW - >100 MW
cooling tower (open) - direct	water[1] air[2]	evaporation[3]	3 – 5 K	24 – 26 °C	<100 kW - >2000 MW
- indirect	water[1] air[2]	evaporation[3]	6 – 10 K	27 – 31 °C	<100 kW - >2000 MW
closed circuit cooling	water[1] air[2]	evaporation convection	4 - 9 K	25 – 30 °C	200 kW – 10 MW
dry air cooling	air	convection	10 - 15 K	40 – 45 °C	<200 kW - 5 MW
hybrid cooling	water[1] air[2]	evaporation convection	4 - 9 K	25 – 30 °C	150 kW - 2,5 MW[5] (400 MW) 2500MW[6]

1) Water is the secondary cooling medium which is mostly re-circulated, evaporating water transfers the heat to the air.

2) Air is the cooling medium in which the heat is transferred to the environment.

3) Evaporation is the main cooling principle. Heat is also transferred by conduction/convection but in a smaller ratio.

4) End temperatures are depending on the site's climate (data is valid for average middle European climate conditions 30°/21°C dry / wet bulb temperature and 15°C max. water temperature).

5) Capacity of one unit - with a combination of several units or specially built cooling systems higher capacities, up to 400 MW, can be achieved.

6) Hybrid cooling towers (wet/dry cooling towers) can achieve high capacities up to 2500 MW

All of the mentioned cooling techniques are used in industrial applications. All techniques, however, have their own limitations and forms of implementation which chapter 2.3 discusses in more detail.

2.3 Different Cooling Systems

Once Through-flow Systems

Direct once through-flow system

The (non-renewable) once through-flow cooling (water) system is the most simple cooling system. In this system, water as cooling medium is used once, is fed through heat exchangers and then discharged in heated form. The water used is often surface water. For smaller scale uses such as pump cooling, tap water or groundwater is also used. There is no direct contact with the process flow. The heat is conducted via a partition wall usually in the form of tubes in a shell & tube or in a plate & frame heat exchanger.

Some practical examples are: power stations, large petro-chemical companies as well as production sites. Designs vary from extremely large (>1000 MW) to relatively small (<10 kW) cooling capacities.

Generally, with once through-flow systems the lowest temperature can be achieved, depending on the water temperature. The corresponding approach is 3 - 5 K. The disadvantage is the large amount of water (generally surface water) which is needed and the resulting heating of the receiving surface waters (rivers, lakes, sea). Small applications often run with tap water.

Although there is no direct contact from the process to the cooling water, there is a potential for leakages in the partition wall (heat exchanger). In this case, cooling water could flow into the process or substances from the process can enter into the surface water. Depending on the process, both scenarios may represent significant safety, environmental and financial impacts.

Indirect once through-flow system

The process/product, that is to be cooled, transfers heat to the cooling water in a closed re-circulating circuit. This secondary cooling water transfers its heat via one or more heat exchangers to surface water that flows through this heat exchanger only once, the so-called primary cooling water. Thus the water in the secondary closed circuit is not discharged. The use of this system is of specific interest if there is a risk of toxic substances from the process water leaking into the cooling water or vice versa. The additional heat exchanger leads to an increases of the approach of 3 to 5 K, depending on the efficiency of the heat exchanger [7,16].

Once through system with barometric condenser

Once through systems with barometric condensers, in which a gas flow is cooled directly by feeding water over it, are rarely used today, but can be found in the food industry. These systems are not covered by this document.

(Open) direct cooling system

Another very specific cooling system is the open direct cooling system. The process medium is directly exposed to the cooling medium. An example for this system is the cooling of hot steel in a water bath. The steel is cooled both by the conduction of heat to the water and by the evaporation of the hot water. This system is not covered by this document, either.

Wet Cooling Towers (Open Cooling Towers)

The principle of an open cooling tower is, to transport heat from a system to the ambient air. The cooling water is distributed over the cooling tower fill and discharges the heat to the surrounding air by evaporation and convection. For large power plants cooling towers are often connected with a once through-flow cooling system. The heated cooling water is cooled down in the cooling tower before it is discharged again to a river, lake or the sea.

For many purposes the water, which is cooled in the cooling tower can be re-circulated and used as cooling water again. Just a small part of the water evaporates and disappears with the cooling air. Due to the evaporation and due to the washout of pollutants out of the cooling air, the remaining water becomes concentrated with salt and dirt. This process is called *thickening*. Therefore a small fraction of the circulating cooling water has to be drained off as blow-down water. This amount of evaporated and drained water has to be supplemented with fresh water The phenomenon of thickening is described in more detail in chapter 4.2.1.1.

Numerous different types of cooling towers can be used. It is also possible to use a secondary cooling system with a heat exchanger to create an indirect cooling tower system. The additional heat exchanger leads to an increases of the approach of 3 to 5 K, depending on the efficiency of the heat exchanger [7,16].

The required air for the cooling process is driven either on natural draught or mechanical draught by fans or with a combination of both. Natural draught cooling towers are often used for big installations, e.g. power plants.

Open cooling towers can be used for a large range of cooling needs. The capacities vary from less than 100 kW to more than 2000 MW. Approaches of 4 K are technologically and economically achievable [19], at a water outlet temperature between 20°C and 30°C. Approach and minimum temperature depend on the climatic conditions of the site.

Closed Circuit Cooling Towers (Evaporative Coolers / Evaporative Condensers)

In closed circuit cooling-towers, the medium to be cooled is circled in a closed circuit without contact to the environment. The medium is led through a coil (primary circuit). The coils are wetted from the outside (secondary or spray circuit). The heat is conducted from the medium to the spray water (sensible heat transfer). The evaporation of a small part of the water leads to evaporative cooling and the heat is transferred from the water to the air. There is an additional sensible heat transfer from the coil to the air. In practice at evaporative cooling sensible and latent heat transfer is always coupled.

The heat transfer capability, however, is somewhat lower due to the lower heat transfer capacity of the coil. Typically, approaches are 8 K [19], lower approaches of 4 K are achievable [7]. The advantage is a contaminant-free closed primary cooling loop, which in some cases eliminates the need for internal heat exchangers. In terms of resources, the energy requirements for the spray water loop have to be considered. With closed circuit cooling, end temperatures between 25-30°C are achievable, depending on the climatic conditions of the site [7].

Air-cooled Fluid Coolers / Air-cooled Condensers (Dry Air Cooling)

In air-cooled fluid coolers (or dry air coolers) the process medium is circulating within a closed system. The medium is led to a coil with fine tubes, where it is cooled by draught air. The entire amount of heat is disposed into the air by sensible heat transfer. Due to the low heat conductivity and capacity of air (1.2 kJ/kg), a high air stream and a large heat-exchanging surface area is necessary. Although the air can be blown forced or unforced, usually ventilation is needed to create the draught.

The system's temperature capacity depends on the dry bulb temperature, which in the summer can be substantially higher (up to 14 K) than the wet bulb temperature (see Table 5).

Compared to evaporative (wet) cooling, the heat transfer capability of dry cooling is lower. Hence feasible approaches increase to about 10-15 K. This means that minimal outlet temperatures will range between 40 °C and 45 °C, depending on the climatic conditions of the site. The advantage of dry air cooling is, that no additional water is needed.

Air-cooled fluid coolers are also used as direct or indirect systems with a secondary cooling circuit and a heat exchanger. Approaches of indirect air cooled systems are between 13 and 20 K with achievable end temperatures between 45 and 50 °C, depending on the climatic conditions of the site.

Hybrid Condensers / Hybrid Closed Circuit Cooling Towers

Hybrid coolers are designed for the cooling of a cooling medium which is circled in a closed system, by means of ambient air and the evaporation of water from a secondary circuit. In a hybrid cooler, cooling takes place through dry air-cooling, except when outside temperatures are high. In that case, the cooling effect is increased by re-circulating water over the air-cooler. Then the heat transfer is dissipated to the sensible air convection and the latent evaporation of the wetting water. By using a hybrid or evaporative cooler, it is possible to cool down to a lower process temperature compared to using an air-cooler. Due to the evaporation of the wetting water, the air temperature approaches the wet bulb temperature. As a result, the exit temperature of the cooling medium lies below dry air temperature. The cooling limit is about 4 - 9 K above the wet bulb temperature [7]. Therefore, it is possible to attain cooling medium end temperatures between 25°-30°C, even with atmospheric temperature of 32°C and 38% relative humidity (with the corresponding wet bulb temperature of 21°C). [11]

Hybrid coolers are available in a power range of about 150 kW to 2,5 MW per cooling unit [11]. Installations with greater capacities can either be formed by using several serial cooling units or by building a specially designed installation for the specific application. Consequently, even for cooling of power stations (combined heat and power generation) hybrid systems are used.

Hybrid coolers can also be used for condensation of refrigerants (NH3, CFC). This type of cooler is not covered by this document.

The optimal area for hybrid coolers is the cooling of a process flow of 40°C to 25°C. Temperatures of over 55°C could result in calcium precipitation on the tubes. [16]

Hybrid systems combine the advantages of evaporative and sensible heat transfer. In summer hybrid systems have the temperature capability of evaporative cooling and in winter, (when temperatures are less critical) they offer the water saving capability of air-cooled systems. They can also reduce or eliminate visible plume.

In general hybrid systems require higher investment costs. Compared to a cooling tower of same cooling performance, the investment costs could be about 2.5 times higher. These higher investment cost can be compensated by lower operating costs. The annual costs for water, including water treatment and electricity can represent in some cases just about 10 % of the annual costs of a cooling tower [11]. These economic considerations depend of cause on the individual application and the prices of water and energy.

Hybrid Cooling Towers

Hybrid cooling towers, sometimes also called "wet/dry cooling towers", are similar to open cooling towers with an efficient combination of evaporative cooling sections and dry sections, to primarily reduce the visible plume of wet cooling towers. On the one hand, the advantage of this solution is to run the cooling tower with maximum performance in the summer time and on the other hand to reduce the generation of visible plume during periods with cold air temperatures.

The plume forms during heat and mass transfer within the wet cooling tower as a result of the cooling air becoming oversaturated with moisture evaporated from the cooling water. When this oversaturated air leaves the cooling tower it mixes with the atmosphere and begins to cool down. During this process some of the excess water vapour that had been absorbed is condensed again. The result is a visible plume comprising very small water droplets. The hybrid cooling tower has a dry section where warm dry air is generated in a heat exchanger, using the warm water to be cooled as a source of heat. Before being discharged to the atmosphere, the oversaturated air from the wet section mixes with this warm dry air. Due to this principle hybrid cooling towers can be designed according to most of the local meteorological conditions to avoid visible plume.

They can be built as package cooling towers, induced draught or forced draught cooling towers and - in larger scale - as cooling towers of the cellular type or circular type with the heat rejection ranging from < 1 MW up to 2500 MW. They are used even for applications with higher cooling capacities, e.g. power plants.

Hybrid cooling towers of the mechanical draught type are fitted with internal mixing systems to mix the wet and dry air flows. They can be automatically controlled according to the heat load, water flow, ambient air and plume conditions.

Natural draught cooling towers of the wet/dry design are under consideration.

3 Operating Resources and Emissions

The operation of cooling systems leads to a use of resources and impacts to the environment due to emissions of pollutants, heat and plumes. It is important for an integrated approach, to focus not only on the direct environmental effects of the cooling system, but also on the indirect effects which are related to the effects, cooling systems may have on the efficiency of the cooled process system.

Due to the long life expectancy of cooling systems (about more than 20 years), environmental effects of the construction, deconstruction and disposal of cooling systems are not included in this document.

In Table 13 the different cooling systems are qualitatively characterised by their environmental effects.

Table 13: Environmental Effects of the Different Cooling Systems

Cooling system	energy consumption (direct)	water consumption	Emissions to water		noise	air pollution	plume forming	intake of fish	risk	
			heat	additives					leakage	micro biological risk
once through-flow - direct circuit	low	+ +	+ +	+ +	--	--	--	+	+ +	--
- indirect circuit	low	+ +	+ +	+ +	--	--	--	+	+	--
open cooling tower - direct circuit	+	+	low	low	+	low	+	--	+	+
- indirect circuit	+	+	low	low	+	low	+	--	low	+
closed circuit cooling tower	+	+	low	low	+	--	+	--	low	low
dry air cooling	+ +	--	--	--	+ +	--	--	--	low	--
hybrid closed circuit cooling	+	low	low	low	+	--	low	--	low	low
hybrid cooling tower	+	+	low	low	low	low	low	-	low	low

--	none / not relevant
low	below average
+	relevant
+ +	high

3.1 Resources

3.1.1 Water

Water is an important and valuable resource. Therefore, the use of water is often seen as one of the main environmental impacts of cooling systems. Obviously, this is especially valid for once-though water cooled systems - and on the other hand not relevant for dry air cooled systems. In addition, water conservation measures are triggered by both, the need to reduce water pollution and to save energy (pumps / fans).

In Germany, annually 34,6 bill. m³ cooling water are consumed by industry and power plants (Table 14).

Table 14: Water Consumption for Cooling in Germany (1991) [17]

industry	cooling water consumption
power generation	28,3 bill. m³
mining	1,0 bill. m³
chemical industry	3,2 bill. m³
pulp and paper	0,3 bill. m³
petrochemical industry	0,2 bill. m³
steel and metal industry	0,7 bill. m³
manufacturing	0,5 bill. m³
food industry	0,2 bill. m³
other	0,2 bill. m³
total	34,6 bill. m³

99,2% of this cooling water is directly discharged into surface waters (river, sea or lake) without any sewage treatment. Main source of cooling water is surface water (99,8 % for power plants). The cooling water used in power plants is re-circulated on average two and a half times before it is exchanged. The 286 power plants are the main users of cooling water in Germany, consuming 82% of the total cooling water. The average amount of cooling water which is required for the generation of one kWh electrical energy and for the removal of one kJ waste heat is documented in Table 15. The high ratio of power generation on the consumption of cooling water will be similar in all European countries with a high ratio on thermal power generation.

Table 15: Average Cooling Water Consumption in Power Plants in Germany [17]

cooling water consumption per kWh electricity generated	cooling water consumption per kJ waste heat removed[2]
43 l/kWh	7,7 l/kJ

1) without re-circulated water

2) assuming that all energy which is not transformed into electricity is removed as waste heat (average efficiency of power generation is assumed to be 39%)

Due to the high ratio of power plants on the consumption of cooling water, saving energy is a very effective way to save water.

The assessment of environmental impacts caused by the consumption of water for cooling, depends on regional, climatic and ecological factors. The consumption of cooling water itself needs not be an environmental impact if the consumption has no relevant effect on the total amount of water of the river or lake and if the water quality does not change during the cooling process. If surface water is used, the water is usually discharged back to where it has been taken from. In this relationship it would be more exactly to speak about water use instead of water consumption.

Groundwater is used for cooling, too. Due to its lower temperature, compared to surface water, low end temperatures can be achieved. Groundwater is a valuable water resource and provides high quality water for drinking. Generally, groundwater should not be used for once through cooling systems. In some member states the use of groundwater is restricted and a special fee has to be paid for its use.

Drinking water (tap water) is often used for re-circulating systems because of its reliable and good quality. Drinking water is too valuable to be used for once through systems.

In general, water consumption should be minimised. However, it is more important to focus on the effects of emissions of heat and additives (chemicals) to surface water (see chapter 3.2.1 and 3.2.5). Another negative environmental impact is the intake of fish and other water organism at the intake of the cooling water from surface water.

The consumption of water can be minimised by the use of re-circulating systems or the use of dry cooling systems. Compared to through-flow systems, the water demand of circulated systems is 95% less.

3.1.2 Air

The use of air for air-cooled cooling systems is no real consumption. The quality of air, except temperature and wetness, is not changed. Therefore, the direct environmental impacts of the usage of air can be neglected. However, the amount of air which is used has an influence on energy consumption and noise emissions, caused by ventilation fans. Table 16 shows the air flow requirements for the various cooling systems.

Table 16: Required Air Flow for the Different Cooling Systems [24]

Cooling system	air flow (%)[1]
once through-flow	0
cooling tower (open)	25
closed circuit cooling tower	38
dry air cooling	100
hybrid closed circuit cooling	38
hybrid cooling tower	60

1) strong correlation with the ratio of sensible heat transfer

3.1.3 Energy

The removal of waste heat from a process itself requires electrical energy. The main energy consumers within cooling systems are fans and pumps. Factors which influence the energy consumption are:

- pumps:
  - determined by: difference of pressure, length of the cooling tube system, the lift the medium has to be pumped, the medium which has to be pumped, number and layout of heat exchangers;
  - indirect systems in general need more energy for pumps;
  - the amount of water which has to be pumped;

- fans for ventilation:
  - determined by: the number, size and type of fans, the amount of air which has to be draught, the lift the air has to be draught;
  - dry systems need more air for the same cooling capacity than evaporative systems;

Additionally, the indirect energy consumption due to a less efficient heat transfer and a resulting less efficient process is important. This indirect energy consumption is especially important for energy intensive processes like power plants, industrial refrigeration, chemical processes etc. In addition, inefficient heat transfer in heat exchangers can cause large amounts of energy wastage [19]. The specific energy demand of the different cooling systems is described in Chapter 4.2.

3.1.4 Additives for Water Treatment (Chemicals)

Chemicals are often added to cooling water systems in order to prevent or reduce four key problems:

- corrosion,
- scaling,
- fouling and
- biofouling.

For cooling water conditioning the following groups of chemicals are used:

- corrosion inhibitors
- hardness stabilisers
- dispersion chemicals
- biocides.

Corrosion inhibitors are separated into cathodic and anodic inhibitors. Cathodic inhibitors slow down cathodic reactions. Anodic inhibitors slow down anodic reactions. Anodic inhibitors are sodium chromate, sodium benzoate, sodium silicate and sodium-molybdate. Cathodic inhibitors are calcium and zinc salts and polyphosphates. Cathodic inhibitors are less effective against corrosion than anodic inhibitors. Also, corrosion is encouraged by an over-dose of cathodic and anodic inhibitors.

Hardness stabilisers are chemical substances, which, added to water, are able to prevent the deposit of hardness salts by hindering the recristallisation process through absorption of the nucleation of the crystals. Hardness stabilisers are polyphosphates, phosphonates, polyesters and smaller polyelectrolytes such as polyacrylates.

Dispersion chemicals are chemicals which prevent the growth and deposit of particles present in the water by increasing the electric charge resulting from absorption. Dispersion chemicals are polyacrylates, methacrylates and maleic acid copolymers.

Biocides are chemicals which slow down the microbiological growth in water and, in doing so, minimise organic pollution in the cooling system. Biocides are chlorine, ozone, quaternary ammonium and organic bromide compounds.

Chemicals are generally used to increase water quality for cooling purposes, in order to limit corrosion, calcification, sedimentation and growth of micro organisms. Tubes and pumps can be clogged by organism growth or physical sediments. Corrosion and scaling reduce the heat conduction of the system and the durability of the used materials. All problems together have a high influence on the efficiency of the cooling system and its energy consumption. Another form of additives are antifreeze agents, like glycol which are added to the water of closed circuit systems in high concentrations.

The chemicals involved are well-known, however not always their environmental profiles.

The average use of additives for cooling water treatment are described in Table 17 and Table 18. The different data results from different principles of calculation.

Table 17: Average Use of Additives for Cooling Water Treatment at Power Plants in Germany [21]

Cooling system	Use	additive (chemical)	concentration per treated cooling water[1]
once through-flow:	conditioning	Fe(II)SO_4	1 mg/l
	biocide[2]	chlorine	1-3 mg/l[3]
re-circulating systems:	flocculating agent	FeCl3	
	anti-calcification agent	$Ca(OH)_2$	
		polyphosphate	0,2-1,3 mg P/l
		polycarbonic acid	10 mg/l
	anti-corrosion agent	phosphate	7-15 mg P_2O_5/l
		silicate	
	biocide	chlorine	1-3 mg/l
		acroline	2-3 mg/l
	dispersant	polycarbonic acid	<10 mg/l
		ligninsulfonic acid	<20 mg/l

1) average concentration, if this additive is used in an installation
2) if necessary due to polluted surface water
3) depending on the hardness of the cooling water

Table 18: Average Use of Additives for Cooling Water Treatment in the Netherlands [16]

use	additives	concentration per cooling water[4]
biocides:	chlorinated lye (as chlorine)	
		0,05 mg/l
	- industry	0,47 mg/l
	other biocides	0,03 mg/l
other conditioning agents:	all other	0,13 mg/l

4) average concentration over all installations (total amount of additives used dived through the total amount of cooling water)

3.2 Emissions

3.2.1 Heat

The discharge of heat has different environmental effects, depending on whether it is discharged into air or surface water.

Discharge of heat into waters has a high potential for disturbing the aquatic ecosystem. Recent scientific findings have increased the concerns over this effect. The main effects are:

- Higher water temperatures support a growth of algae, which consume high amounts of oxygen in the water.
- The solubility of oxygen in water is negatively correlated with its temperature: higher temperatures reduce the solved oxygen in water.
- As a result, fish like salmon or trout, which have a high demand for oxygen, may die.
- On the other hand, cooling water from cooling towers is often enriched with oxygen, so that the reduction of oxygen due to the higher temperature is compensated.
- Lakes and bigger rivers have a stable temperature layer in winter and summer, which can be disturbed by the discharge of warm water.
- If water is taken from rivers and used for cooling towers or evaporation systems, the evaporation of the water may reduce the amount of water in the river or lake.
- Discharge of heat into surface water may increase the generation of fog, which may have negative effects on traffic (ships and cars) on and near the river.
- High water temperatures have negative effects on the generation of drinking water from rivers. Higher water temperatures promote the growth of pathogen micro organisms in the drinking water.

Permits in member states normally set limits to the river temperature rise or to the discharge temperature. The stringency of such requirements depends on the relative flow of a discharge. Table 19 shows these thresholds for Germany as an example:

Table 19: Thresholds for Heat Discharge in Surface Water in Germany [21]

	cold waters (summer)	warm waters (summer)
maximum temperature of surface waters	$T_{max} = 25\,°C$	$T_{max} = 28\,°C$
maximum increase of temperature	$\Delta T = 3$ K	$\Delta T = 5$ K

Heat discharge into the atmosphere can have influence on the local climate and the local exchange of fresh air around the facility [19]. In general, waste heat should be removed at the lowest possible temperature level in order to minimise environmental effects.

3.2.2 Noise

Several main noise sources were identified:

- fan assemblies (fan, gears, drive);
- pumps;
- water distribution system
- droplets falling on the cooling water basin.

The most important source of noise usually are fans. In general terms, the noise of fans of induced/forced draught cooling towers are noisier than noise of falling droplets of natural draught towers. Air-cooled systems are generally noisier than water-cooled types.

The environmental impacts of noise are correlated with the site and the neighbourhood of the site. Thresholds for noise immission (sound pressure level outside the site) will be lower for installations in residental areas or recreation areas (e.g. hospitals) than in industrial areas.

3.2.3 Plumes

Plumes are caused by re-condensation of evaporated water in the discharged air of a cooling tower. At first look, plumes just have aesthetical impacts and cause a loss of light only close to the emission point.

Plumes of large cooling towers (e.g. large power plants) can influence the local and regional climate, with effects on nearby airports, residential areas, traffic on roads, rails and rivers. The environmental effects of heat discharge into air of smaller cooling towers or other cooling systems are limited to the neighbourhood of the installation.

Plumes may effect a formation of fog, which can lead in winter to slippery ice on the ground near the cooling tower. The risk of fog formation decreases when the cooling tower is built higher. The generation of plumes can be reduced by design and by operation procedures of the cooling-system. Plume abatement devices are available as well as other techniques such as hybrid cooling towers.

3.2.4 Emissions into the Air

Emissions of air pollutants largely relate to cooling towers. Emissions can result from volatilisation of substances from the water phase and entrainment of droplets into the exit air (windage).

This emissions are very low compared with other industrial applications. With effective drift eliminators just about 0,001 % of the circulating water and also of the used chemicals for water treatment are discharged as droplets. The total concentration of chemical in cooling water is less than 100 mg/l (see chapter 3.1.4). Assuming a water flow rate of 3000 m^3/h with an average air flow of 800 m^3/s, the calculated emission of chemicals in air is about 0,1 mg/m^3 air [8].

According to the German commission of waste, heat an environmental impact due to volatilisation of substances and due to entrainment of droplets in cooling towers can be ruled out [16].

On the other hand, cooling towers are installations which can even reduce air pollution by washing several pollutants out of the air, that is draught through the tower.

More important for all types of cooling systems is indirect air pollution due to energy consumption, as well as due to inefficient heat transfer with resulting less efficient power generation in power plants.

3.2.5 Emissions into the Water (Chemicals)

A number of causes of water contamination can be identified:

- chemicals added (antifouling, antibiofouling, anti-corrosion, anti-scaling) and formed (trihalomethans from organic matter and chlorine);
- continuous leakage of process fluid into the cooling water due to corrosion of heat exchanger surfaces. These result from inadequate attention to corrosion prevention and will persist until repaired;
- accidental cross-contamination by process fluids as a result of structural failure of plants or bad operating practices (e.g. wrongly connected drain or contaminated water used as make-up);
- spillage of chemicals due to poor storage or handling;
- corrosion products or leaching from materials of combustion;
- cross media transfer of substances form air side.

Cooling water is usually discharged directly into the surface water without sewage treatment. In Germany, just 0,8% of the cooling water is discharged into the public sewage system.

For once-through systems, not only incidental leaks can be a major source of pollution, but also continuous leaks where small concentrations of a pollutant can arise in very large volumes of cooling water. From an effluent toxicity perspective, the occurrence of brocades seems most important.

3.2.6 Waste Generation

In water-cooled systems, various sludge emerge from treatment of intake water, cooling water and blow down water. The disposal options depend on composition and local circumstances. In some member states, sludge from intake water filtration can be discharged back into the surface waters of origin. In Germany this sludge has to be disposed of like sewage sludge.

Another source of waste results from the cleaning operations of the cooling system (e.g. acid waste from pickling heat exchangers). This issue is also relevant for air-cooled systems, where deposits can be a problem.

3.3 Risks of Potential Pollution

3.3.1 Leakage

A special emission into surface water are leakages of the process „products" or of the cooling medium (oil, ammonia, CFC etc.), due to defects in heat exchangers. Two factors of pollution of leakage can be distinguished:

- continuous leakage - small amounts over a long period;
- leakage due to accidents - large amounts in a short time.

The total amount of pollutants which are discharged via cooling water through leakage in the cooling system is difficult to estimate. For the Netherlands, RIZA has reported very high amounts of between 3 and 150 tons/year for each of the big industry facilities [16].

3.3.2 Emission of Bacteria

The warm water of cooling-systems promotes the growth of micro organisms and bacteria. These have negative effects on the efficiency of the cooling system by biofouling. In addition, some of these biological contaminates (bacteria) can be harmful if inhaled or ingested [5].

These bacteria can be emitted via small aerosols of dropped water of open circulated systems.

Cooling towers should be located in such a way that the introduction of discharged air into the ventilation systems of buildings be prevented. As a precaution, measure personnel who may be exposed directly to the discharged airstream and associated drift or who work at the cooling water system should wear respiratory protection equipment.

Given regular maintenance of the cooling system and several measures for reducing the growth of micro organisms (chemical biocide or various physical treatment), it is possible to exclude the risk of infections [21].

4 Candidates for Best Available Techniques

4.1 Available Techniques

Each of the different cooling systems mentioned in chapter 2 has its advantages and disadvantages. All of them can represent Best Available Technique for specific recommendations of specific applications, sites and climates.

The following chapter compares the different cooling systems with respect to their environmental and their economic performance.

Even if it is not possible to define one single cooling system as Best Available Technique, it is possible to reduce specific impacts to the environment by choosing the respective cooling system.

4.2 Environmental Performance of Candidate BAT

4.2.1 Minimisation of Resource Consumption

4.2.1.1 Water Consumption

The water consumption of the different cooling systems varies. Obviously, the water consumption of once through-flow systems is the highest. On the other hand, dry air cooling account for no water consumption at all. The water consumption of the different cooling systems is described in Table 20.

Table 20: Water Consumption of the Different Cooling Systems

Cooling system	average water consumption [m³/MW]¹	relative water consumption [%]²
once through-flow	50 – 100	100
wet cooling tower (open)	2	2,3 – 5
closed circuit cooling tower	1,5	1,7 – 5
dry air cooling	0	0
hybrid cooling	0,5	0,6 – 1,3

1) ΔT 10 K

2) assumption: cooling tower: cycles of concentration between 2 and 4
closed circuit cooling: dry operation ranging from 0 to 25 %
hybrid cooling: 75% dry operation [24]

Often, water consumption is negatively correlated to energy consumption and / or investment costs.

Among re-circulation cooling systems, the water demand is connected with the following factors:

- proportion of sensible and latent heat transfer,
- evaporative loss,
- drainage due to thickening,
- drift loss (emission of droplets)
- cleaning of the cooling system.

All the water loss of a cooling system, except evaporative loss, is defined as b*low down* (e.g. windage, drift, leaks, drainage). All the water which is add to the cooling system in order to compare the loss of water due to blow down and evaporation is called *make up.*

Water consumption due to evaporation at cooling towers is about 0,43 l/MW. The evaporation of water results in higher salt concentrations in the remaining water. This is called *thickening* (n) or *cycles of concentration*. Both terms are synonymous but can be differently defined:

$$\boxed{n = \frac{\text{evaporation + increase of salt concentration}}{\text{drainage}}}$$

or the same formula in other words:

$$\boxed{\text{cycles of concentration} = \frac{\text{concentration in blow down}}{\text{concentration in make up}}}$$

Low cycles of concentration leads to high water consumption. High thickening leads to low efficiency and scaling as well as corrosion of the system.

Two kinds of drainage are used. A continuous drainage or a drainage which is connected with a continuous measurement of the salt concentration, so that water is just drained when necessary to keep an optimal thickening. Such measurement systems are a little more expensive but can lead to a 46% reduction of water consumption (Table 21).

Table 21: Reduction of Water Consumption with Optimal Thickening [13]

water consumption	continuos blow down	automatic blow down
evaporation	100 %	100 %
drainage (n=3)	180 %	50 %
droplets	0,001 %	0,001 %
total	280 %	150 %
reduction in water consumption		46 %

Another way to reduce water consumption is the design of the heat exchanger (water - air). With a special coil design, the heat transfer surface can be increased, water consumption can be reduced and sensible heat transfer can be increased, too. In Table 22 a case study on the influence of the design of the heat exchanger on resource consumption and costs is shown.

Table 22: Influence of the Design of Heat Exchangers on Resource Consumption and Costs (relative data)[13]

Cooling system	energy consumption		water consumption	investment costs	operating costs
	total	fans			
Open cooling tower (open)	100	100	100	100	100
Closed circuit cooling tower	230	200	67	300	95
-with coils	270	200	45	450	80
-with finned discharge coils	250	200	42	500	75
Hybrid cooling tower	150	150	43	600	65

1 case study: cooling capacity: 5 MW
temperatures: 32 °/27 °/21 °C

The design of the coil is also very important for hybrid cooling systems. The more heat can be transferred sensibly by convection, the less water is needed for evaporation.

A less important cause of water consumption is the emission of water droplets into the air. These emissions can be minimised less than 0,001 % [8] of the cooling water amount with modern droplet recovery devices.

Water is also needed for the cleaning of the system once or twice a year. Water consumption for cleaning depends on the quality of the cooling water. Air cooled systems have to be cleaned as well. Air pollution leads to a fouling of the coils on their outside, which has to be cleaned in order to ensure the efficiency of heat transfer.

4.2.1.2 Energy

The difference in energy consumption between different cooling systems is mainly caused by:

- energy for pumps,
- energy for fans,
- number of heat exchangers.

Once-through cooling systems require energy just for pumps. Depending on the achievable cooling range, the energy demand due to a higher water flow is usually above the pumping energy demand of cooling towers. Mechanical draught cooling towers additionally need energy for the fans. Their energy consumption is correlated with the driving force. For dry air cooling higher driving force is necessary than for evaporative cooling. The energy consumption of pumps for closed circuit systems is usually below the consumption of open systems. Due to the higher number of heat exchangers indirect systems require more energy than direct systems.

Even within the different types of cooling systems the specific energy consumption varies depending on the climatic conditions and the required approach. The specific energy demand is described in Table 23. The variation of the energy consumption according to different approaches and design of cooling towers is also described in chapter 4.3.

Table 23: Specific Energy Demand of the Different Cooling Systems

cooling system	specific energy consumption [16]		
	total	Pumps	fans
once through-flow -direct	10 - 12 kW/MW	10 – 12 kW/MW	0 kW/MW
-indirect	16 - 18 kW/MW	16 - 18 kW/MW	0 kW/MW
wet cooling tower (open)	3 - 9 kW/MW	2 – 4 kW/MW	1 - 5 kW/MW
closed circuit cooling tower	3 – 13 kW/MW	1 – 3 kW/MW	2 – 10 kW/MW
dry air cooling	8 – 17 kW/MW	1 – 3 kW/MW	7 – 14 kW/MW
hybrid cooling	4 – 14 kW/MW	2 – 4 kW/MW	2 – 10 kW/MW

1 assumptions: 45/40/25 °C dry and 45/40/18 °C wet

Power consumption of cooling towers can be reduced by the choice of material and design of fills. Film fills require lower pumping heights compared to splash (droplet) fills and can, as a result, reduce the operating power of the circulating water pumps [15]. But materials and design of fill also have an influence on the sensitivity to fouling and scaling.

Beside the direct energy consumption the indirect energy consumption due to the efficiency of the heat transfer has to be considered. The importance of the indirect energy consumption can be proved by an example of power generation: If the efficiency of power generation due to a non optimal cooling system is reduced by 3%, the loss in energy is 30 kJ/MW, which is about twice the average energy demand of a complete cooling system (see Table 23).

4.2.2 Minimisation of Emissions

4.2.2.1 Heat

The best way to minimise heat emissions is to optimise the primary process so that less waste heat will have to be disposed of. Another possibility is to find consumers for the waste heat, in order to avoid or reduce disposal.

The cooling system itself can not minimise the heat emissions to the environment.

By choosing different cooling systems, it can be decided whether heat is discharged into the atmosphere or into surface water. The emission of heat into the environment results mainly in a problem of heat emissions into surface waters. The environmental impacts can be minimised by discharging more heat into the atmosphere and less heat into surface waters.

According to the German data of heat discharges into the environment (Table 24), 86% of the heat discharged into water is discharged by power generation. Therefore, the heating of surface water is mostly a problem for large through-flow cooling systems of power plants. Systems with open or closed circuit cooling water discharge only approximately 1,5% of the heat with the drainage (blow down water), more than 98% are released into the atmosphere.

Table 24: Generation and Discharge of Waste Heat in Germany (1980) [21]

Waste heat source	discharge in water		discharge in the atmosphere		total generation of waste heat	
Power generation	927 PJ	30,7 %	2089 PJ	69,3 %	3016 PJ	29 %
Industry	64 PJ	2,5 %	2520 PJ	97,5 %	2584 PJ	25 %
Households	66 PJ	2,0 %	3216 PJ	98,0 %	3282 PJ	31 %
Traffic	26 PJ	1,6 %	1640 PJ	98,4 %	1666 PJ	16 %
total	1083 PJ	10,0 %	9465 PJ	90,0 %	10548 PJ	100%

The total generation of waste heat is strictly correlated with the energy consumption. The total amount of energy consumption as well as the ratio of the sectors has slightly changed since 1980. Especially the ratio of traffic on energy consumption as increased about 65 %. Both data will be specific for the member states. Less specific is the ratio to which medium the waste heat is discharged. Although this data are not up-to-date, the proportions most likely have not much changed during the years and will be similar for all member states.

To reduce direct transfers of large amounts of waste heat into surface waters, a cooling tower for cooling the through-flow water before it is emitted in the surface water can be employed.

Another positive effect of a cooling tower is the increase of oxygen in the water, which overcompensates the loss of oxygen due to its higher temperature. If no cooling tower is used, the concentration of oxygen in the discharged water can be increased by ventilating the water with air.

4.2.2.2 Noise (Sound Attenuation)

Noise emissions are generally a problem of cooling towers and dry air cooled systems. For cooling towers two main sources of noise can be identified: noise generated by the mechanical equipment, mainly by the fan assembly, and noise generated by the water splashing effect. The water noise typically prevails in near-field conditions around the installation, while the noise of the fans will become progressively predominant with increasing distance from the installation. For natural draught cooling towers water is the single important source of noise. For dry air cooling only the noise of the mechanical equipment (fans, gears, etc.) is relevant. However dry systems need more fans and more air pressure drop for the same air flow. So the noise emission of dry air coolers (mechanical draught) are higher than of cooling towers, even if they have the additional noise of water. Natural draught dry systems have lower noise emissions compared with cooling towers.

The difference in noise emissions between cooling systems is mostly correlated with the amount of air which has to be ventilated by fans and the amount of water which is splashed.

Noise emissions of cooling systems are mostly depending on the design of the fans: The sound power level of centrifugal fans (90 - 110 dB(A) is lower than that of axial fans (90 - 120 dB(A)). The noise of fans can also be reduced by reducing the rotational speed. A 50% reduction of speed will result in a noise reduction of about 6-10 dB(A). This could be an effective measurement for noise reduction in the night time. With various efficient sound attenuation measures the noise emissions can be reduced to 80 dB(A) for centrifugal fans and to 85 dB(A) for axial fans. In general, natural draught cooling towers are less noisy (unattenuated) [2], but for mechanical draught cooling towers sound attenuation is more efficient, because only the mechanical draught can economically overcome the additional air-side pressure drop.

The selection of less noisy radial fans often implies higher energy consumption and resulting higher operating costs compared to axial fans.

The various sound attenuation measures allow to attain noise abatement levels of about 20 dB(A)[6] and up to 30 dB(A)[15]. For these high noise abatement levels it is necessary to combine more quiet equipment with additional sound attenuation, like acoustic baffles or noise attenuators. Such equipment for passive sound attenuation will increase the investment costs, but operating costs remain reasonable [15].

Table 25 documents data of noise emissions (sound power level) of the different cooling systems. It is difficult to compare data from different authors because of the different distances from the installation in which the noise is measured.

Table 25: Noise Emissions of the Different Cooling Systems without Noise Attenuation

cooling system		noise emission [7]
once through-flow		
cooling tower	-natural draught	90-100 dB(A)
	-mechanical draught	80-120 dB(A)
closed circuit cooling tower		80-120 dB(A)
dry air cooling		90-130 dB(A)
hybrid cooling		80-120 dB(A)

The noise emission of unattenuated counter flow cooling towers can be approximately calculated by the following formula:

Mechanical draught cooling tower: $PWL \approx 80 + 8{,}5 \log (m_w)$ $s = 2{,}4$ dB

Natural draught cooling tower: $PWL \approx 71 + 10 \log (m_w)$ $s = 3{,}2$ dB

PWL: sound power level [dB(A)]
m_W: cooling water flow in m^3/h
s: standard deviation

For natural draught cooling towers the correlation of water flow and noise emission seems to be obvious. However also for mechanical draught systems the required amount of air, and therefore also the power of the fans, is correlated with the water flow.

The following case study (Table 26) compares the design of different cooling systems - a wet cooling tower, a closed circuit cooling tower and a hybrid dry cooling tower - for a specific application with a required sound power level:

Table 26: Comparison of Different Cooling Systems with a required maximum Sound Power Level [2, 23]

	mechanical draught wet cooling tower	closed circuit cooling tower	hybrid closed circuit cooling tower
Climate:			
dry bulb temperature	26 °C		
wet bulb temperature	18 °C		
Given Duties:			
Capacity	1.200 kW		
inlet temperature	38 °C		
outlet temperature	32 °C		
flow	47,8 l/s		
maximum sound power level	90 dB(A)		
Specific Data:			
length	3,7 m	3,7 m	5,2 m
width	2,8 m	2,4 m	2,0 m
height	3,2 m	4,2 m	3,0 m
fan power	5 kW	11 kW	5 kW
spray pump power	1 kW	2,2 kW	1 kW

4.2.2.3 Plumes

The generation of plumes is a phenomenon of wet cooling towers (open circuit) and less relevant for closed circuit cooling systems. For hybrid cooling systems plumes are not relevant. The generation of plumes by cooling towers can be minimised by a special design of the ventilation and by operating measures.

Another way of minimising the generation of visible plume is to use the plume to generate demineralised water for the plant [8]

4.2.2.4 Emissions into the Air

Direct emissions of cooling systems into the air are almost negligible (see chapter 3.1.2).

For temperature critical processes indirect emissions, mainly correlated with the direct and indirect consumption of energy, due to a loss of efficiency of the main process can be important (see e.g. 1.3.1 Temperature Critical Applications). The selection of a more efficient cooling system can lead to a significant reduction of indirect emissions.

4.2.2.5 Emissions into the Water

As already mentioned in Table 17 and Table 18, the use, and as a result the emissions, of chemicals which are used as additives for cooling water, is specific for each cooling systems.

In open through-flow systems usually less additives are used than in open or closed circuit systems. Most important are measures against sludge and macrofouling. As far as circuit systems are concerned, in general less additives are used for closed circuit systems than for open circuit systems, where the cooling water has direct contact with the air.

The use of additives also depends on the water quality (concentration of micro- and macro-organism), the concentration of scaling minerals (lime, carbonate) and the sensitivity of the used materials to corrosion.

In order to minimise the use of additives, several measures are feasible [12]:

- The design of the water intake can reduce the intake of debris and organisms.
- Filters (micro- and macrofiltration) can reduce the intake of debris and organisms into the cooling water as a measure against fouling.
- Water can be treated by ion-exchangers to get demineralised water, which reduces scaling and thickening.
- An alternative to biocides are physical treatment methods, like the generation of ozone, radiation with ultra violet light. (These methods are only practicable for relatively clean and clear water.)
- Heat treatment is also a method to reduce bio fouling.
- Corrosion can be reduced by the selection of materials for building the cooling system.
- For cooling towers the design and geometry of the fill has an influence on its sensitivity to fouling and scaling [6]

There are two different ways of adding chemicals: a continuos addition of a low concentration of additives or a single addition of a high concentration of additives, in case a contamination is noticed. The single high doses of additives like biocides have higher environmental impacts and should be avoided. Instead, the necessary dose of the additives should be monitored by analysing the water in order to minimise the use of additives and to minimise fouling, scaling and corrosion.

New physical methods for water treatment are being developed, which may reduce the use of additives.

If leakages represent a risk, their occurrence can be reduced by the following measures:

- using an indirect re-circulating cooling system with additional heat exchangers between the process and the environment,
- continuous monitoring of water parameters which indicate leakage,
- using anti-corrosive materials,
- regular control of all parts of the cooling system, which are endangered for leakage, like e.g. heat exchangers,
- keeping overpressure in the cooling system compared to the process pressure,
- appropriate design and material selection of the heat exchangers [16]

Every additional heat exchanger increases the approach, and as a result the minimum end temperature which can be achieved with the cooling system. 3 to 5 K added for each additional step of heat transfer can be assumed as realistic.

Due to the risk of leakage, once through-flow cooling systems should not be used for cooling of processes, which are operating with environmentally hazardous products.

The risk of leakage is not only an environmental problem. Leakage can also reduce the efficiency of the cooling system if the primary cooling medium is discharged or if cooling water is discharged into the process.

If water from polluted rivers is used for cooling purposes, it has to be pre-treated in order to protect the cooling equipment. Some sites claim that the discharged water is of better quality than the intake.

4.2.2.6 Intake of Fish

The intake of fish is mostly a problem for once through-flow systems of power plants. To avoid the intake of fish, the intake flowrate should be less than the speed of the fish. In combination with filters or electronic systems it is possible to protect fish from being taken into the cooling water.

4.3 Economic Performance of Candidate BAT

The economic performance of the different cooling systems depends on site specific factors such as

- local climate (max. wet bulb temperature)
- costs for energy (electricity)
- costs for water and sewage
- costs for water treatment
- estimated interest rates

and on the type specific costs:

- investment costs
- water consumption
- necessity of additives
- energy consumption
- maintenance costs
- durability of the installation

The cost comparisons of different authors calculated in Table 22 and Tables 27 till 30 based on case studies and vary significantly. Costs for cooling systems depend on their the specific application, the required capacity and the different operating costs at different sites.

Table 27 provides information about the average relative investment costs of the different cooling systems. In general open once through-flow cooling systems requires the least investment costs, while hybrid cooling systems and dry air cooling system requires the highest investment costs. In between the different types of cooling systems indirect systems are always more expensive than direct systems. The investment costs of a natural draught cooling towers can be estimated as 1.5 times higher than the costs of mechanical draught systems, due to twice the surface of wetted area required for natural draught cooling towers [3, 7].

Table 27: Cost Comparison for Different Cooling Systems

cooling system	investment cost [7]
once through cooling – direct	20 %
- indirect	35 %
wet cooling tower - natural draught	150 %
- mechanical draught	100 %
closed circuit cooling tower	250 %
dry air cooling	400 %
hybrid closed circuit cooling	350 %
hybrid cooling tower	300 %

The case study in compares investment cost and operation costs of different cooling systems for a new refinery in the Netherlands:

Table 28: Alternative Cooling Systems for a Planned New Refinery - Evaluation of Feasibility and Costs [16]

cooling system¹	Investment costs (in million guilders)	Capital Costs² (in million guilders)	Operational annual costs (in million guilders)	Technical restrictions
direct through-flow	25,3 70,0 ³	2,5 7	5,4 7,0	none
indirect through-flow	45,6 90,6 ³	4,5 9,0	8,2 9,8	critical in certain uses because of T
open cooling tower	28,4 73,4 ³	2,8 7,3	14,2 15,8	none
indirect cooling tower	46,1 91,1 ³	4,6 9,1	16,1 17,7	critical because of T
dry air cooler	85,4	12,6	5,1	critical because of T,
Indirect dry air cooler	88,5	20,0	11,2	extremely limited

1) refinery complex with a required cooling capacity of 400 MW for process flows. An extra cooling equipment of about 100 MW for steam turbines/combined cycle cooling (power station) is assumed. 95 % of the other 300 MW can be covered by air-cooling. The end flow temperature is 38 °C or over.

2) 6,5% 15 years

3) bottom amount includes the shell & tube heat exchangers (approx. 60 units)

In Table 29 cost and energy consumption for different types of cooling systems at different approaches are calculated. Generally investment costs and power consumption increase with a smaller approach. The increase is higher for dry air coolers compared to cooling towers. However for each case it is possible to design a cooling tower as well as a dry air cooler with a low energy consumption, but this requires higher investment costs.

Table 29: Cost Comparison and Energy Consumption for Different Types of Mechanical Draught Cooling Towers and Dry Air Coolers [22]

case studies, capacity 5000 kW	cooling system	investment cost	power consumption
Case1: Design: 45/40/25 °C dry 45/40/18 °C wet	cooling tower A	100 %	24,4 kW
	cooling tower B	168 %	5,9 kW
	dry air cooler A	380 %	62 kW
	dry air cooler B	448 %	36 kW
Case 2: Design: 40/35/25 °C dry 40/35/18 °C wet	cooling tower C	130 %	26,9 kW
	cooling tower D	191 %	7,8 kW
	dry air cooler C	490 %	80 kW
	dry air cooler D	612 %	50 kW
Case 3: Design: 35/30/25 °C dry 35/30/18 °C wet	cooling tower E	215 %	12,3 kW
	cooling tower F	254 %	8,8 kW
	dry air cooler E	924 %	112 kW
	dry air cooler F	1098 %	70 kW

In the following example (Table 32) three solutions for a mechanical draught wet cooling tower are compared. For given duty the requested energy consumption can be influenced by specific design (height, fan power etc.). Generally for solutions with lower energy consumption, higher investment is needed. The economic performance of the different solution is depending on the specific energy cost at the site.

Table 30: Comparison of different Solutions of a mechanical draught wet Cooling Tower

Example: mechanical draught wet cooling tower	solution A	solution B	solution C
Climate:			
dry bulb temperature	32 °C		
wet bulb temperature	21 °C		
Given Duties:			
Capacity	1.000 kW		
inlet temperature	32 °C		
outlet temperature	27 °C		
Flow	47,8 l/s		
operating hours	5000 h		
Specific Data:			
Length	3,7 m	3,7 m	3,7 m
Width	3,0 m	3,0 m	3,0 m
Height	3,2 m	3,2 m	4,4 m
fan power	11 kW	9 kW	4 kW
sound power level	94 dB(A)	93 dB(A)	90 dB(A)
fans energy consumption	55 MWh/a	45 MWh/a	20 MWh/a
investment cost	100	108	125

The above calculated examples show that the economic performance of cooling systems depend on the specific applications they are calculated for. For many applications the cooling system with the lowest investment costs is not necessarily the cooling system with the best economic performance. Depending on the different operating costs (mainly costs for energy and water) a cooling system with higher investment costs but lower operating costs can have the best economic performance. It is difficult to generally rank the different cooling systems according to their economic performance.

5 Best Available Techniques

In order to determine the Best Available Technique with the chosen "horizontal" approach, this approach has to regard the indirect environmental impacts of the primary process and the direct environmental impacts of a cooling system. As already mentioned in the scope of this document, the following issues are addressed:

- all environmental aspects (water/air/soil pollution, energy/water consumption, noise, waste) including an assessment of these impacts,
- direct and indirect environmental aspects, due to the influence of the cooling-system on the efficiency of the main process,
- environmental impacts during standard operation and maintenance as well as pollution arising from specific events or incidents.

The above (in chapter 2 and 4) mentioned techniques have proved successful in their special application, determined by the amount of waste heat, required cooling temperature, temperature of the cooling environment (water, air), noise restrictions, space requirements, financial performance, maintenance requirements etc.

As shown above, it is typically not the cooling itself, but the waste heat generating process (e.g. power generation) which has the most significant influence on the environment. If efficiency of this process is increased, the reduction of environmental effects outnumbers the environmental effects of the cooling system by orders of magnitude. This is a general statement which, again, may not be correct under certain site specific conditions.

This leads to the conclusion that, from a horizontal evaluation perspective, "Best Available Technique" is not a single cooling technique. There is, however, a "Best Available *Design* Technique", which includes an overall optimisation of the waste heat generating process (primary process), site selection and the cooling process. In this optimisation multiple parameters have to be considered as described at the beginning of this chapter.

It is the design phase that grants the greatest freedom for optimisation. Design engineers state that, as a rule of thumb, during the design phase 80% of the costs and environmental effects are defined, while only 20% of the costs and hardly any environmental effects occur.

Due to its nature, this optimisation can not be an exact mathematical comparison of various solutions. The optimisation process includes a similar challenge like for all environmental balances, as it requires comparing environmental impacts of different natures and deciding which ones are the least severe. Nevertheless, the suggested Best Available Design Technique provides significant information on the implications of various solutions for the environment, on costs and risks as well as the influencing factors. Based on this information, a decision can be made which is much more justified than just concentrating on optimising one single factor (e.g. water intake, energy consumption, plume or noise emission etc.).

Due to the nature of this optimisation, the optimum solution and its cooling technique will vary from site to site and depend on the above mentioned factors. E.g. a power station in a country with cold humid summers may suffer little efficiency loss between wet and dry cooling towers, while in a country with dry hot summers it may be significantly better to use a wet cooling tower. But if on that hot site water should not be available at all, a dry cooling tower would have to be selected despite a significant loss of efficiency causing the related environmental effects - unless another site can be chosen.

5.1 Optimisation of the Primary Process

Optimising the primary process can significantly reduce the overall environmental effects.

In Germany, more than 80% of the waste heat to be disposed of by cooling systems is created by power stations. Given its low efficiency around 60% of the fuel energy is transferred into waste heat. If efficiency of the power generation is increased significantly, environmental effects can be avoided. Consequently the first and most efficient step of a Best Available Design Technique is to optimise the primary process.

The environmental impacts of reducing the efficiency of the power plant by choosing a less efficient, but at first glance environmentally „friendlier" cooling system can outweigh the impacts of the cooling system by orders of magnitude in the long run. Therefore, the Best Available Design Technology requires as a first step to exploit all possibilities of optimising the primary process.

5.2 Finding a Consumer of Waste Heat

If optimising the waste heat generating process does not lead to any further waste heat reduction, Best Available Design Technique would be to check whether any third user of waste heat can be found.

This can be done on an existing site as well as an integral part of site selection (see next chapter).

A typical example for such an optimisation can be found in combining public swimming pools with ice stadiums. The waste heat resulting from cooling the ice is used to heat the water in the swimming pool. Heat exchangers can be used in many processes to reduce cooling requirements significantly.

Finding adequate consumers is not a trivial task. Often requirements of consumers are not reconcilable with the cooling demands. In some cases, heat consumers require a higher temperature level than planned. If it is technically possible to operate the primary process on a higher temperature level, the overall energy balance has to be carefully observed. Often the loss of energy efficiency in the primary process outweighs the savings through the „waste" energy consumption.

5.3 Site Selection

Through site selection the requirements on the cooling process can be influenced significantly. The greater the amount of waste heat and the more a primary process is dependent on the cooling process, the more it is justified - and applied practice - to consider site selection under cooling aspects.

Once a site is exists, it can hardly be changed. Therefore it is important, that during the design phase all aspects are considered in the site selection process.

Issues to be considered are:

- quantity, quality and costs of cooling medium available (water as well as air),
- available size (ground, height, weight),
- effect on the quality of water and on aquatic organisms,
- effect on the quality of air,
- meteorological effects,
- discharges of chemical substances into water,
- noise emissions,
- aesthetic aspects of the building,
- capital expenditures for cooling systems, pumps, piping, water treatment,
- operating costs for pumps, fans, water treatment,
- annual costs for maintenance and repair,
- operating parameters such as minimum service life, annual operating time, average load in thermal output and water flow rate,
- operating requirements such as required approach, availability,
- environmental legislative requirements regarding heat emissions, plume emissions, acoustic emissions, overall height etc.

The German commission for waste heat has conducted some waste heat related criteria for site selection which are documented in Table 31.

Regarding site selection it should be mentioned that for a large site an environmental impact assessment will be required during the permitting procedure. This assessment has to cover all the aspects described in this paper.

Due to the high influence of site selection on the cooling performance, there are initiatives to pre-select optimum cooling sites in regional planning programmes. [21].

The site selection process requires that for the „final candidate“ site detailed considerations about the selection of the possible cooling systems are conducted in order to find the overall optimum solution.

Table 31: Waste Heat Related Criteria for Site Selection [21]

Criteria	Grade 1 (good suitability)	Grade 2 (satisfactory suitability)	Grade 3 (doubtful suitability)	Explanations
sufficient cooling water supply	$NNQ > \frac{W}{\zeta\ c\ \Delta T}$ rich cooling water supply	$NNQ \approx \frac{W}{\zeta\ c\ \Delta T}$ sufficient cooling water supply	$NNQ < \frac{W}{\zeta\ c\ \Delta T}$ insufficient cooling water supply without technical measures	NNQ: lowest know volume flow of surface water W: heatstream to be transferred into water ζ: Density of the water c: specific heat capacity of water ΔT: permitted temperature increase of surface Water
suitable water quality	water quality class II moderately polluted II/III critically polluted	water quality class III severely contaminated	water quality class	German water quality classification I non-polluted II moderately polluted II/III critically polluted III-IV very severely contaminated IV excessively contaminated
complying with permitted evaporation losses	$V < A\ a$ minor evaporation losses	$V \approx A\ a$ bearable evaporation losses	$V > A\ a$ evaporation losses not acceptable without technical measures	V: evaporation losses at selected site (volume flow) A: permitted evaporation for the site a: fraction of A which may only be used due to other waste heat sources of the site
impact on drinking water supply	cooling water discharge has no impact on drinking water supply	cooling water discharge may under certain circumstances impact drinking water supply, negative effects can be avoided	cooling water discharge impacts drinking water supply, negative effects can not be outruled without additional technical measures	This criterion has to be considered if downstream of the site drinking water is gained from the surface water (currently or planned in future)
frequency of long plumes with low altitude and waste heat transfer in direct site vicinity (radius 2 km)	very low frequency (<2% p.a. on average) long (<100 m) plumes with low altitude (<=300m) and waste heat transfer < 10 000 MW	long plumes with low altitude more frequent and waste heat transfer < 10 000 MW	waste heat transfer > 10 000 MW	
topographic situation in the vicinity of the site	no or only few elevations with an altitude above the cooling tower within about 20 km radius of the site	Several elevations with an altitude above the cooling tower within in about 2 -20 km radius of the site	Several elevations with an altitude above the cooling tower within less than 2 km radius of the site	
possibility for economic use of waste heat	Great potential for economically feasible usage of district heating	Little potential for economically feasible usage of district heating	No possibility of economic waste heat usage or in doubt-full due to missing investigation	The possibility for economic usage of waste heat increased attractiveness of a site and may overcome other disadvantages

5.4 Mathematical Modelling, Simulations on Models and Tests on Pilot Loops, First Indispensable Tools for Forecasting Thermal Changes of the Environment

In order to forecast heat exchange as well as thermal changes in both the near vicinity and in the far field, several numerical models have been developed.

In the near field, sophisticated tools serve to describe the dilution conditions of thermal discharges. They are used at the local discharge level (example: TELEMAC 3 D developed by EDF 1). These models serve to dimension the outfall structures to the best possible extent so as to ensure the optimum dispersion of the hot plume in the receiving environment as quickly as possible and thus limiting its impact to a maximum (meteorological and hydro-biological data).

In the far field, the parameters that have to be taken into account are much more complex. They do not only take into the characteristic properties of the receiving environment into account, but also discharges originating from other companies. Much more complex models have been developed to this effect (example: PEGASE developed by the University of LIEGE). They take into account biological parameters of water quality and the presence of chemical pollutants. They integrate various pollution sources and provide an assessment of the response of waterways or lakes to thermal and chemical disturbance or the excessive contribution of nutriments (eutrophisation phenomenon) [6].

There are other models used to simulate the accumulative impact of several wet cooling towers installed on the same site.

The forecast, making use of numerical models, must rely on field data and experimental knowledge. These in-situ and laboratory studies are required to define and optimise the anti-fouling treatment or system cleaning periods. Biological studies make it possible to estimate the periods of reproduction and fixation of larvae, as well as the rate of growth of the main biological species. These field and laboratory studies take their time. Indeed, in the ecological field, forecast analytical tools have not yet been wholly validated.

To determine the mode of treatment of the circuit systems, systematic tests on pilot loops are carried out. The purpose of these tests is to grasp the scaling risks on one hand, and, on the other hand, to define the optimum mode of treatment, as well as the operating instructions. Among the laboratory studies there are model simulations for the understanding and visualisation of steam and hot water plumes phenomena.

In an environmental approach for the installation of power plants with the search for a minimum impact, mathematical modelling, model simulations and on-site preliminary pilot tests appear absolutely necessary stages.

Modelling and Pilot Tests, an Indispensable Stage

The purpose of modelling is to study any physico-chemical impacts and adapt the results of this modelling to the facilities in order to reduce these impacts to the greatest possible extent. It is particularly important to study:

- water withdrawals and discharges,
- the visual aspects of the site,
- the evolution of plumes,
- the thermal and chemical impacts on the receiving environment.

The objective of the pilot loop tests is to define the optimum treatment of cooling water both with regard to scaling and to any biological developments. To do so, pilot facilities representing real commercial operating conditions are installed on the site for about one year. This makes it possible to integrate the variations of the quality of the waterway in the course of the seasons. This also serves to assess the opportunity of some choices on a representative scale (examples: choice of cooling tower fills, choice of alloy, etc.)

5.5 Retrofit

5.5.1 Retrofit – Reasons and Considerations

Considerations about "Best Available Technique" should not only be focused on the design of new installations but also include existing cooling systems. Retrofitting existing installations can be considered for different reasons:

1. replace existing technology by a different technology with lower operating demands
2. replace outdated technology equipment by modern equipment with higher efficiency
3. modify existing equipment to improve performance or to meet additional demands

Different from the selection of a new installation, where the site parameters can be more or less defined, in retrofit scenarios usually a number of parameters are fixed. In particular this are:

- space - the retrofit installation must fit into the existing space,
- the availability of operating resources – the new installation should not exceed the operating resources, which were needed of the old one, new infrastructure would result in an increase of costs,
- legislative restrictions – environmental impacts, like sound criteria, usually have to be at the same level or below the ones of the old installation.

Space is often an important reason for retrofitting itself. If a plant or building will be built new on an existing space restricted site, it could be a solution to select a new type of cooling system, which can be placed on the roof of a building or which needs less space, than the old one.

The preferred solution would be a new installation with lower operation needs, so that the retrofit is also associated with lower operating costs. Lower operating cost will be one of the main reasons for retrofitting. It is preferable however to consider a retrofit scenario, which reduces the emissions as well as operating resources. In general this will require higher investment cost. However considering the operating cost savings and any potential reduction in emissions, larger investment costs can pay off in short periods of time.

All retrofit scenarios have to consider both, the cooling technology and the process to be cooled. Both have to be seen as one system. Changes in the cooling system may have effects on the process and vice versa. The first aim of any retrofit has to be to maintain or if possible improve the efficiency of the process to be cooled. On the other hand changes in the process to be cooled will also result in different demands on the cooling system. This could be another important reason for retrofitting.

Examples for changes of the process to be cooled with resulting change in demands on the cooling system:

- Due to new technology less waste heat is generated by the process – less cooling capacity is needed (example: computer terminals, processes with friction).
- The temperature level of the waste heat has changed, both to higher or lower temperatures (example: incineration processes).
- Larger parts of the generated heat of the process are recuperated, so less waste heat has to be removed to the environment.
- The temperature sensitivity of the process is increased – more efficient cooling system is needed.

There are many possible ways to retrofit a cooling process, some typical scenarios along with their relevant considerations are listed in the following chapters.

5.5.2 Change of Heat Transfer Technology

The replacement of one heat transfer technology by another technology could have different reasons. Usually lower operation costs of the new technology or legislative restrictions will be the main reasons.

A typical example is the replacement of an once through system by a circuit system, due to save operating costs (water and sewage) or due to new legislative restrictions (Table 32).

Table 32: Example for Conversion of a Once Through System into a Circuit System

Example at compressor 500 kW	once through system	circuit system
inlet temperature	15 °C	27 °C
outlet temperature	35 °C	35 °C
flow rate	6 l/s	15 l/s
annual operating hours	1.800 h	1.800 h
evaporation loss	-	1.400 m^3/a
blow down	-	700 m^3/a
annual water consumption	38.800 m^3/a	2.100 m^3/a
extra fan and pump energy	-	15kW
investment cost	-	21.000 ECU

The economic performance of the circuit system depends on the specific costs for water, sewage and electrical energy. Assuming average water and sewage costs of 1 ECU/m^3 and electrical energy costs of 0,1 ECU/kWh, the operating costs[2] in this example are 38.800 ECU for the once through system and 4.800 ECU (2.100 ECU water and 2.700 ECU energy) for the circuit system. The annual saving is 34.000 ECU, which is higher than the investment costs of 21.000 ECU.

Considering a change of the cooling system, the effects on the system efficiency have to be considered, too. If possible the system efficiency should be increased. For temperature sensitive processes, it has to be checked, whether a cooling technology can provide lower end temperatures at the same level of safety.

The example of replacing a water cooled condenser with an open cooling tower by an evaporative condenser shows this effects on end temperature and system efficiency: Such technological replacement can potentially reduce the condensing temperature by 4 – 6 K depending on actual conditions. The efficiency gain of such retrofit can be estimated in order of magnitude of 12 – 15 % of the power requirement of the refrigerant compressor.

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[2] just the water and sewage costs of both systems and the additional energy costs of the extra energy for the fans and pumps of the circuit system

For temperature sensitive application in the medium temperature range, the introduction of hybrid systems could be favourable, if water consumption and/or water and sewage costs should be reduced. Such introduction generally does not increase electrical demand, but can reduce the annual water consumption dramatically. Depending on actual conditions, hybrid concepts may require additional space.

5.5.3 Replacement of outdated Heat Transfer Technology by modern one

Often a change of cooling technology out of different reasons is not suitable. Also a modification of the existing technology could lead to better efficiency, better performance, less emissions and lower operating costs. Development of air moving systems and heat transfer surfaces, as well as the application of more durable construction materials, are main reasons for replacement scenarios.

As there is usually no change in process temperatures (same technology) the main focus in this scenario is to reduce operating resources and environmental impacts as well as to achieve an extension of equipment's life. Equipment's life extension of more than 10 years can be realised by the use of new durable materials.

A typical example for improvement of once through cooling systems are more effective plate and frame heat exchangers. For evaporative cooling systems for example, major developments have taken place to improve the performance of fill packs and air moving systems, resulting in a more compact design with higher energy efficiency. For air cooled systems new technology to shape fins in various ways has achieved similar results. An example for this is shown in Table 35:

Table 33: Example for Conversion of an outdated Mechanical Draught Wet Cooling Tower into Modern Design

Example: mechanical draught wet cooling tower	outdated design: induced draught concept with low efficiency fill and fan system	modern design: induced draught concept with high efficiency fill and fan system
capacity	1200 kW	
inlet temperature	38 °C	
outlet temperature	28 °C	
wet bulb temperature	21 °C	
water flow	28,7 l/s	
Fan power requirement	7,5 kW	4kW
Energy consumption for fans	9 MWh/a	4,8 MWh/a
Investment cost	-	14.000 ECU

It is very likely that any equipment installed 15 or 20 years ago, can now be replaced by modern equipment with higher operating efficiency and better environmental and economic performance.

5.5.4 Upgrading existing Heat Transfer Technology

Often it is not necessary to replace the whole cooling system. The performance of existing cooling systems could also be improved by upgrading. Major components or accessories of the system are replaced or repaired, while the existing equipment remains in situ. Upgrading can increase equipment efficiency and reduce the environmental impacts.

Examples of upgrading are new more effective fill packs of cooling towers (Table 34) the use of systems, which are more easy to clean and less sensitive to scalling, fouling or corrosion. Noise emissions can be reduced by the addition of sound attenuators (Table 35) or the use of less noisy fans. Emissions into water can be minimised by phyiscal water treatment or by the use of better degredable chemicals.

Upgrading the operating strategy is another example of efficiency improvement. On and of cycling of fans can be changed into modulating control with frequency converters. This can result in significant savings of electrical energy, which depending on conditions can be 70% and more.

Depending on the type of upgrading and the age of the existing installation, investment costs for upgrading can differ greatly. Often this investment is compared by lower operating costs due to the higher efficiency. However investment cost for upgrading will generally be lower than for technology changes or replacements.

Table 34: Example for Replacement of Outdated Fill of a Mechanical Draught Wet Cooling Tower with Modern High Efficient Fill

Example: mechanical draught wet cooling tower	outdated fill	high efficient fill
Capacity	3600 kW	
Inlet temperature	38 °C	
Outlet temperature	28 °C	
Wet bulb temperature	21 °C	
water flow	86,1 l/s	
existing cell floor space	26 m²	
fan power requirement	22,5 kW	13,5 kW
energy consumption for fans	81 MWh/a	48,6 MWh/a
investment cost	-	29.000 ECU

Table 35: Example for the Improvement of Acoustical Performance by Addition of Sound Attenuation

Example: mechanical draught wet cooling tower	existing wet cooling tower	upgrading with sound attenuation
capacity	1200 kW	
inlet temperature	38 °C	
outlet temperature	28 °C	
wet bulb temperature	21 °C	
water flow	28,7 l/s	
fan power requirement	15 kW	18kW
sound power level	90 dB(A)	81 dB(A)
investment cost	-	12.000 ECU

5.6 Selecting Cooling Technique

Cooling techniques have to be chosen depending on the process and the site specific requirements. The various cooling techniques and their design specifications have been described earlier.

The following decision matrices give a qualitative overview (Table 36 and Table 37).

The decision tree for the selection of a waste heat removal system according to the "BAT" (figure 3) is a very simplified summary of the whole document.

Table 36: Decision Arguments for Cooling Systems [4]

cooling system	range of availability	advantage	disadvantage
once through-flow	• no restrictions in water consumption • acceptable water quality • no restrictions in ecological impact by water consumption	• lowest investment cost • best available temperature	• heating-up of water resources • impact on ecological balance • high water consumption
cooling tower (open)	• water available, but of poor quality • sufficient water amount for make-up water (2 to 3,5 % of circulation flow rate) • drain for blow-down water (1 to 1,5 % of circulating flow rate) available	• best economic circuit cooling solution	• evaporation losses (1,5 to 2,5 % of circulating flow rate) • electric power consumption for pumps (and fans)
dry cooling	• no water available • aggressive or toxic cooling fluid	• closed circuit, no fluid losses • no internal corrosion etc. • no plumes • lowest water consumption	• high investment costs • large installation area
hybrid cooling systems	• environmental restrictions • critical site situation (highway, airport, residential etc.) • restricted water resources	• no visible plume • reduction in evaporation losses (reduction of about 80 % compared to an open cooling tower)	• high investment costs

Table 37: Decision Arguments for Cooling Air Transportation Principles [4]

air transportation system	application	advantage	disadvantage

natural draught	• continuous operation: > 3500 h/a full load operation > 7000 h/a overall operation • power generating plants • centralised cooling water supply for industrial processes	• low operation cost • negligible maintenance cost • long service life time	• high investment cost • long erection time • great structure height (> 100 m) • progressive cooling characteristic
mechanical draught	• universal use • preferred for peak load, partial load and/or intermitting operation	• low investment cost • low structure height (5 to 20 m) • controlled operation possible • proportional cooling characteristic • lower acoustic emission with sound attenuation possible	• fan power consumption • maintenance cost • cyclic repair cost • higher acoustic emission without sound attenuation

Decision Tree

The decision tree (figure 3) based on the general order of approach for waste heat removal systems:

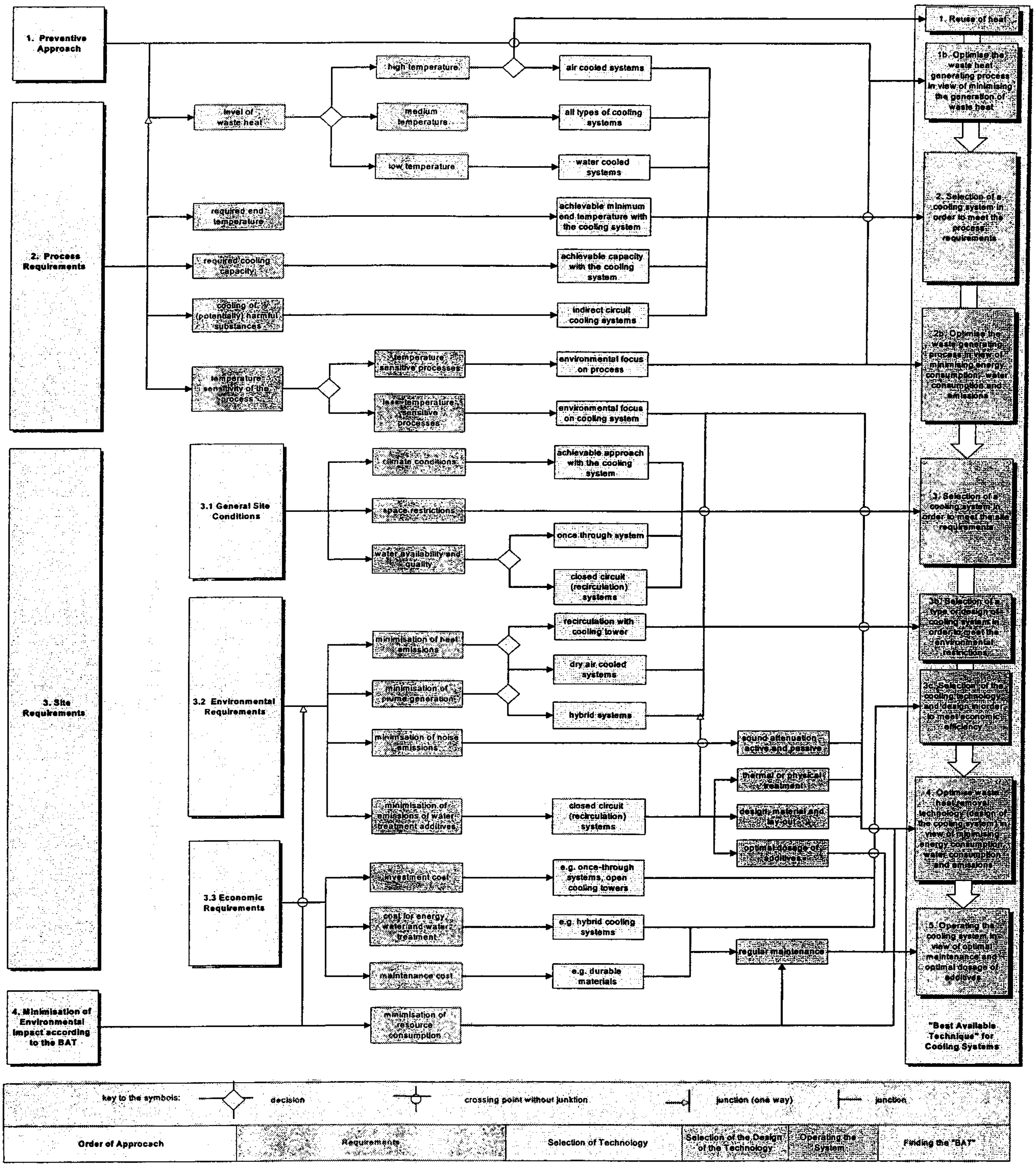
1. Preventive approach
2. Process requirements
3. Site requirements (general requirements, environmental requirements, economic requirements)
4. Minimisation of environmental impact according to the "BAT"

From the general approach it leads via the process and site specific requirements of the waste heat removal system to the selection of the cooling technology, the design of the selected cooling technology and the efficient operation of the cooling system.

The selection of the best available waste heat removal system can be described by five steps:

1. Reuse of heat
   1b. Optimise waste generating process in view of minimising the generation of waste heat
2. Selection of a cooling system in order to meet the process requirements
   2b. Optimise the waste heat generating process in view of minimising energy consumption, water consumption and emissions
3. Selection of a cooling system in order to meet the sites requirements
   3b. Selection of type and design of cooling technology in order to meet environmental restrictions
   3c. Selection of type and design of cooling technology in order to meet economic efficiency
4. Optimise waste heat removal technology (design of the cooling system) in view of minimising energy consumption, water consumption and emissions
5. Operating the cooling system in view of optimal maintenance and optimal dosage of additives.

Figure 3: Decision Tree for the Selection of Type and Design of Cooling Systems



6 Emerging Techniques

6.1 General Trends with Integrated Pollution Prevention

6.1.1 Increase in Efficiency in Power Generation

Recently significant efficiency increases from 40% up to 60% are being discussed for new power generating techniques. As power generation represents by far the greatest waste heat producer, this will reduce the need for disposal of waste heat and its correlated environmental effect significantly.

6.1.2 Reduction of Reaction Temperatures through Catalytic and Enzymatic Reactions

Chemical and pharmaceutical processes often require high pressures and temperatures to receive the desired products. In order to minimise energy consumption and design costs, companies strive to use catalytic converters and/or biological reactors which require less energy and associate less waste heat disposal.

6.1.3 Cooling Contractors

There is an overall tendency to use more and more contractors in facility management.

In some sites, chemicals management is outsourced to a contractor. The contractor is not remunerated for the amount of chemicals used as in former times. Instead remuneration depends on the reduction of chemicals. E.g. if currently chemicals for 10 Euro are used to produce a car the contractor will participate in the cost reductions if he manages to reduce the usage of chemicals down to 8 EURO per car. In order to achieve this, the contractor has the possibility to suggest changes to the primary processes in order to minimise the chemical usage. This contrasts the current situation in which the „classic" chemicals providers has an interest to sell as much of his own products as possible.

Similar tendencies are can be found for chemicals in waste water treatment.

In addition, outsourced facility management offers cooling services as well. Appropriate remuneration could represent an incentive to achieve an overall optimisation of waste heat removal.

6.2 Trends in Environmental Technology

6.2.1 Advanced Physical Methods for Water Treatment

With new physical technologies for water treatment, a reduction in water consumption and a reduction in the consumption and emissions of additives will be achievable.

Physical methods for disinfecting water and reducing scaling are already successfully used in other applications. These methods are

- radiation with UV-light, which is able to destroy micro-organisms – problem: UV-light is hardly able to radiate through highly polluted, coloured water;
- generation of ozone, which is working as a biocide. Due to its reactivity, it has almost no environmental effect on surface water – problem: ozone can lead to corrosion;
- micro-filtration with membrane filters is capable of filtering micro-organisms as well as substances, which are promoting fouling: Problem: filters are reducing the flowrate and increasing the necessary pump energy;

In many industrial applications there is a trend to almost fully closed circuit water systems. The water is often treated with physical methods and then reused for the same process. This trend will lead to a promotion of re-circulated cooling systems.

6.2.2 Advanced Methods of Sound Attenuation

The research on noise has optimised passive sound attenuation as well as an active noise reduction by the design of noise emitting equipment. With computer calculations it has become much easier to identify and reduce the noise generating parameters. Another new technology which is correlated with the development of highly sophisticated computer technology is the generation of anti-sound. The development in sound attenuation will lead to a significant reduction of noise emissions of cooling systems.

7 Conclusions and Recommendations

Summarising the existing data, it is safe to conclude that there is no single optimal solution as far as Best Available Technique of cooling systems is concerned. Each cooling system, including the different types of cooling towers, brings along its specific technical and economic advantages and disadvantages. It is only by taking into account the operating and location-related conditions and by making a straight-forward comparison of economic efficiencies that the individual optimal cooling system can be determined. Consequently, each individual application on a specific site will yield an individual "Best Available Technique".

There is, however, a Best Available Design Technique, which includes optimisation of the waste heat producing process, finding a consumer for the heat, site selection and selection of the cooling technique. Only such overall integrated optimisation will enable designers to find the solution with both optimal ecological fit and economical performance.

Therefore it is mainly up to the authorities to make sure, that such an integrated design process is followed instead of demanding a special cooling technique.

Each of the environmental impacts of cooling systems can be minimised to a very low level with available techniques. However, choosing one type of cooling system will not necessarily minimise all relevant impacts. Often enough the reduction of one single impact will lead to an increase of another impact. The decision, which impact is more important than another and which economic effects correlated with this minimisation are acceptable, has to be an individual decision for each site and application. Generally, there is no sensible way to rank different environmental impacts in order to prefer one cooling system.

Cooling systems often have high influences on the efficiency of the main processes. Therefore, it is absolutely necessary to include the indirect environmental effects of different thermodynamic efficiencies of the main process in the assessment of the environmental impacts of a cooling system.

The BREF document should supplies important information about the environmental characteristics and economic performances of the different cooling systems and how additional minimisation of impacts is achievable. With this information it is possible to select the cooling system, which offers the Best Available Technique for the special conditions at an individual site and application.

Appendix

Definitions / Glossary

Air Cooled Condenser
Air cooled condensers are working on the same principle as → *air cooled fluid coolers*. The medium to be cooled in a closed circuit is vapour (e.g. steam or refrigerant) which is cooled and condensed into liquid by draught air. Condensers are often used for cooling systems with refrigerants.

Air Cooled Fluid Cooler
In *air-cooled fluid coolers* (or *dry air coolers*) the process medium is circulating within a closed system. The medium is led to a coil with fine tubes, where it is cooled by draught air. The entire amount of heat is disposed into the air by sensible heat transfer.

Approach
Approach is the minimum temperature difference between the design temperature (entry temperature of the cooling medium) and the end temperature (outlet temperature at the heat exchanger).

Blow Down
Blow down is defined as all non evaporative water loss of a cooling system (e.g. windage, drift, leaks, drainage). In practice it is the water that has to be withdrawn from an evaporative cooling system in order to control the → circle of concentration.

Closed Circuit Cooling Tower
In *closed circuit cooling towers*, the medium to be cooled, which is circled in a closed circuit is led through a coil (primary circuit). The coil is wetted from the outside and simultaneously air is moved over the coil to achieve evaporative heat

Cooling System	→ *waste heat removal system*
Cooling Tower	→ *closed circuit cooling towers* → *mechanical draught wet cooling tower,* → *natural draught cooling tower,*

Cycles of Concentration
The evaporation of water results in higher salt concentrations in the remaining water which has to be replaced. *Cycles of concentrations* are defined as quotient of salt concentration in blow down and the salt concentration in make up.

Design Dry Bulb Temperature
Design dry bulb temperature is the temperature of the ambient air for which the heat exchanger is designed for. Usually 95 % values are used – the design temperature will not be exceeded in 95 % of time. *Dry bulb temperature* is the relevant temperature for → *sensitive heat transfer.*

Design Wet Bulb Temperature
Wet bulb temperature is the lowest temperature, to which air can be cooled down by isobar evaporation. It is the relevant temperature for → *latent heat transfer*. *Design wet bulb temperature* is the temperature of saturated air, which will be used for the design of the evaporative waste heat exchanger. Usually 95 % values are used – the design temperature will not be exceeded in 95 % of time. Wet bulb temperature is always below → *dry bulb temperature.*

Drift Loss
Drift loss describes the lost of water due to small droplets, which are emitted into the draught air. Drift losses can be minimised with droplet recovery devices.

Dry Air Coolers → *air cooled fluid cooler*

Dry Bulb Temperature → *design dry bulb temperature*

Evaporative Condensers
Evaporative condensers are working on the same principle as → *closed circuit cooling towers.* The medium to be cooled is vapour (e.g. steam or refrigerant) which is cooled and condensed into liquid by evaporating water. Condensers are often used for cooling systems with refrigerants.

Evaporative Loss
Evaporative loss of a cooling system is the cooling water, which evaporates during the operation of an evaporative cooling system.

Heat Rejection Capacity
Heat rejection capacity is the amount of waste heat, which can be rejected by a cooling system. The capacity is measured as energy.
Heat transfer through the evaporation of water into the air is called *latent heat transfer.* The heat transfer capacity of evaporating water is much higher than the heat transfer capacity of air.

Heat Transfer → *sensible heat transfer*
→ *latent heat transfer*

Hybrid Closed Circuit Cooling Tower
Hybrid closed circuit cooling towers utilises heat transfer coils, which can either operate in a wet or dry mode. Wet operation occurs during the periods with high ambient temperatures and dry operation occurs during periods with lower ambient temperatures. By using a hybrid or evaporative cooler, it is possible to cool down to a lower process temperature compared to an → *air-cooled fluid cooler.*

Hybrid Condenser
Hybrid condensers are working on the same principle as → *hybrid closed circuit cooling towers*. The medium to be cooled in a closed circuit is vapour (e.g. steam or refrigerant) which is cooled and condensed into liquid both by evaporating water or by draught air. Condensers are often used for cooling systems with refrigerants.

Hybrid Cooling Tower
Hybrid cooling towers are similar to open cooling towers with a combination of evaporative cooling sections and dry sections. The dry sections are arranged above the evaporative cooling sections with the cooling air passing in parallel through the wet and the dry sections. The advantage of this solution is to run the cooling tower with maximum performance in the summer time and on the other hand to reduce the generation of visible plume during periods with cold air temperatures.

Latent Heat Transfer
Heat transfer by the evaporation of a medium (e.g. water) without changing the temperature of the medium is called *latent heat transfer*.

Level of Waste Heat
Depending on the process, the *waste heat* is generated at a specific temperature level. *Level of waste heat* is the temperature level at which the heat has to be transferred.

Make Up
Make up is defined as all water which is added to the system to compare the loss of water due to evaporation and blow down.

Mechanical draught Wet Cooling Tower (= Open Cooling Tower)
A *mechanical draught wet cooling tower* utilises air as a cooling medium for the cooling water, which is distributed over the cooling tower fill. The air is mechanically draught by fans to the cooling tower. Fans can be arranged horizontal and vertical, both types of fans can be used for induced or forced draught. The flow can be arranged as cross or counter flow.

Natural draught Cooling Tower
The *natural draught cooling tower* is an → *open cooling tower* without fans. The air is draught by natural ventilation. This principle is often used for large cooling towers, like for Power generation.

Once Through System, Direct
For (non-renewable) *direct once through (-flow) cooling systems* water, which is used once without recirculation, is used as cooling medium. The water is fed through heat exchangers and then discharged in heated form to the environment.

Once Through System, Indirect
The *indirect once through (-flow) system* is a once through system, in which the process/product, that is to be cooled, transfers heat to the cooling water in a closed re-circulating circuit. This secondary cooling water transfers its heat via an additional heat exchanger to water, the so-called primary cooling water, that flows through this heat exchanger without recirculation. The use of this system is of specific interest if there is a risk of toxic substances from the process water leaking into the cooling water or vice versa.

Open Cooling Tower → *mechanical draught wet cooling tower,*

Plume
Plumes are the visible re-condensation of evaporated water in the discharged air of a cooling tower.
Range
Range is the difference between the inlet and the outlet temperature at a heat exchanger.

Sensible Heat Transfer
Heat transfer through conduction and convection is called *sensible heat transfer.*

Sound Power Level
The *sound power level* is the measure for the amount of sound energy which is radiated from a sound source. It is measured in dB(A). The measure is logarithmic, this means an increase in sound power level of 10 dB(A) is recognised as about twice as noisy.

Sound Pressure Level
The *sound pressure level* is the measure for the immission of sound – the

amount of sound at a defined direction and distance from the sound source. It is measured in dB(A). The measure is logarithmic, this means an increase in sound pressure level of 10 dB(A) is recognised as about twice as noisy.
transfer.

Waste Heat
Waste heat is the inherent, yet unwanted, not recuperative heat, that must be removed from industrial or manufacturing processes and has to be transferred to the environment.

Waste Heat Removal System
Waste heat removal systems remove waste heat from any medium, using heat exchange with water and/or air to bring down the temperature towards ambient levels. In literature often the term *cooling system* is used synonymous for waste heat removal systems.

Wet Bulb Temperature → *design wet bulb temperature*

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Abbreviations and Physical Units

a	year
BAT	Best Available Technique
bill.	billion (10^9)
BREF	Best Available Technique Reference Document
C_p	specific heat capacity (constant pressure)
CFC	chloroflurocarbons
CO_2	carbon dioxide
dB(A)	decibel (A) – sound power level / sound pressure level A-weighted
ECU	European currency unit
g	gram
h	hour
h_v	evaporation enthalpy of water
K	kelvin
kcal	kilocalorie
kg	kilogram
KJ	kilojoule (10^3 joule)
kW	kilowatt
kWh	kilowatt-hour
l	litre
m_a	amount of air
m_w	cooling water flow
m^3	cubic metre
mg	milligram
MJ	megajoule (10^6 joule)
mm	millimetre
n	thickening factor
NO_x	nitrogen oxide
P	phosphorus
PJ	pentajoule (10^{15} joule)
PWL	sound power level
Q	(transfered) heat capacity
s	standard deviation
SO_2	sulphur dioxide
T	temperature
°C	centigrade (Celsius)

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