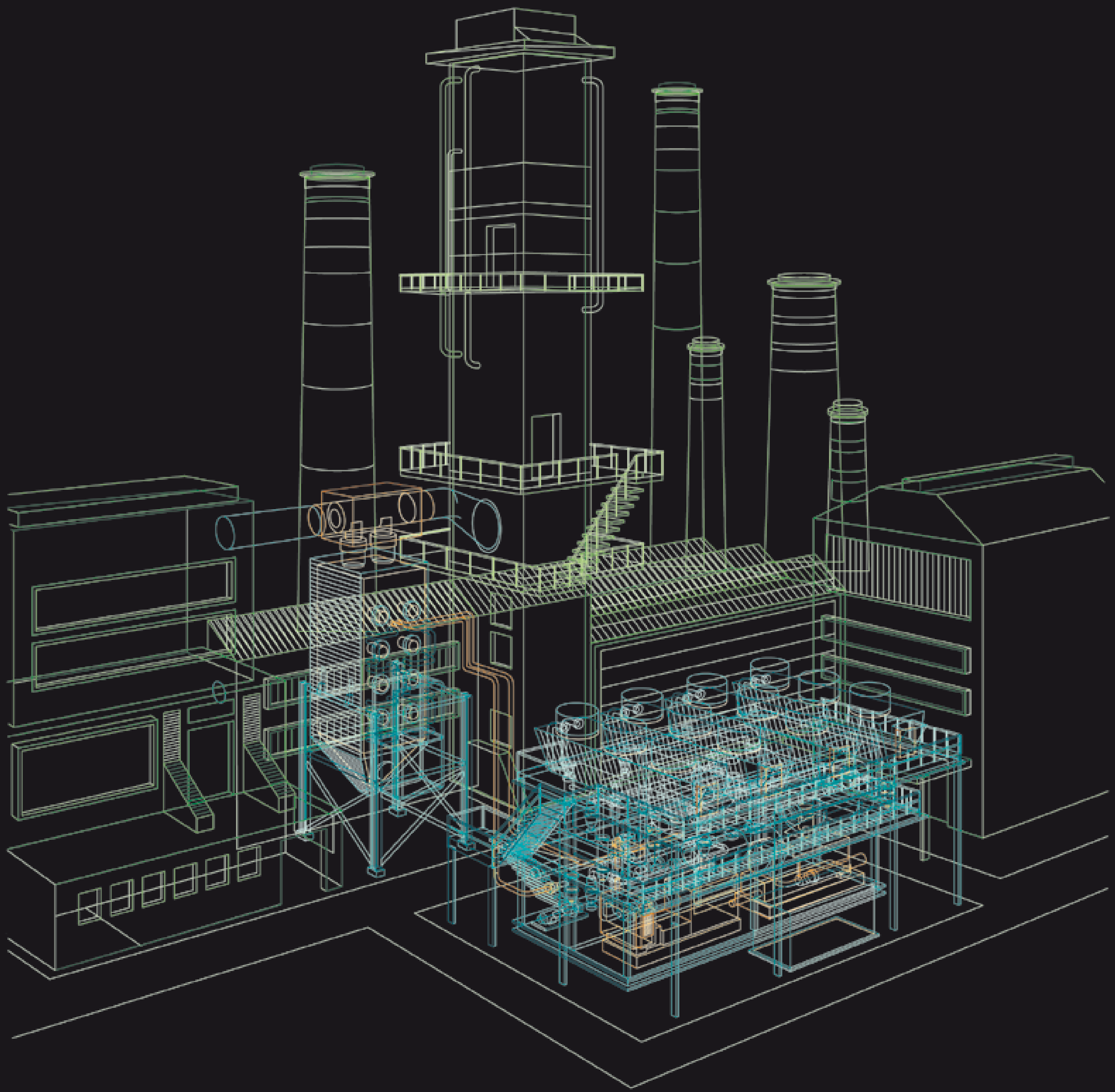
Recovering Heat *for Energy*



Dr. Thomas Bürki and Thomas Börrnert, ABB Switzerland Ltd, Local Business Unit Minerals, Heat Recovery, examine how energy efficiency can be boosted by converting low temperature waste heat to electricity.

Current situation and challenges

Cement plants are huge energy consumers: their heat consumption lies in the order of magnitude of 3 – 3.5 GJ/t clinker and the electricity consumption at roughly 100 kWh/t. The heat is generated to a considerable extent from fossil fuels and, in some countries, partly from alternative fuels, which are, in most cases, well defined waste fractions.

The electricity used is largely generated in power plants, many of which also run on fossil fuels. Therefore the energy consumption of a cement plant creates direct and indirect CO_2 emissions. Finally, clinker burning produces additional geogenic CO_2 emissions.

Although the Copenhagen conference did not result in a binding agreement to follow-up the Kyoto Protocol, it is most likely that after 2012, i.e. after the commitment period of the Kyoto Protocol ends, there will be further requirements to reduce greenhouse gas emissions, specifically by industry.

Therefore, the discussion on climate change and energy efficiency continues to heavily affect cement plants and they remain a focus of both government and public attention when it comes to mitigating climate change.

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The way forward to more efficient energy usage

Increasing energy efficiency is one of the most important current entrepreneurial imperatives – for ecological and economic reasons. Cement plants will therefore have to strengthen their efforts to increase energy efficiency and thereby reduce energy consumption.

A first action is to reduce electricity consumption. There are many possibilities in a cement plant to increase the efficiency of electricity usage. The reduction of electricity consumption is the result of a thorough analysis of the entire cement production process. As a consequence of the analysis, the realisation of a great many (relatively small) measures with the great number of electricity consumers would be realised.

The second and, from an energy and climate change perspective, more important action is to reduce the consumption of fossil fuels. The basic idea is to move plants as close as possible to "adiabatic operating conditions"; in other words: waste heat shall be recovered to the maximum extent. This can be achieved with a small number of important measures.

Figure 1. Comparison of waste heat recovery and waste heat conversion. Left: waste heat recovery in a cyclone. Right: waste heat conversion in a power plant.

The reduction of waste heat losses can be classified into two categories: i) waste heat recovery and ii) waste heat conversion.

Waste heat recovery

Waste heat recovery means to reuse waste heat as heat in the production process ("keep the heat in the process") and thus reduce the supply of heat by burning (fossil) fuels.

Modern cement plants can be thought of as huge heat exchangers. After firing the kiln (and eventually the precalciner), the heat in the stack gas and in the waste air from the clinker cooler is used, more or less, to a large extent within the plant, for example:

- Secondary air preheating.
- Tertiary air preheating.
- Preheater tower with 3 – 6 stages to preheat the raw mix.
- Coal drying.
- Drying of alternative fuels.
- Use of clinker cooler waste heat to feed district heating systems.

Waste heat recovery, as the most important measure towards low heat losses, has the highest priority. It is the most efficient way to increase energy efficiency because the efficiency of the heat recovery is high: 1 kWh of waste heat reused in the plant ends in ± 1 kWh of useful heat.

Waste heat conversion

Waste heat conversion means allowing the waste heat to leave the process, but converting it (partially) into electricity before it is discharged (at lower temperature level) to the environment.

Therefore, after the efficiency of a cement plant has been driven to the economic optimum, the remaining waste heat is converted into electricity. It must be kept in mind that with any conversion technology the thermal efficiency of the conversion (ηth) comes into the game. Therefore 1 kWh of used waste heat only produces η kWh of useful energy - but now it is electrical energy.

One thing is obvious: the more efficient the cement plant, the lower the waste heat temperatures, specifically the temperature of the waste gas after the preheater tower. Temperatures after the preheater tower in efficient cement plants can be considerably below 300 °C. Therefore waste heat conversion technology has to be configured to match this situation.

The ABB Power Plant based on Organic Rankine Cycle (ORC) technology (further referred to as "ABB ORC power plant") is designed to make use of exactly this low and medium temperature waste heat. It excellently converts low temperature waste heat from cement plants into electricity.

The ABB ORC power plant

Basic working principle

The core piece of the power plant is a steam turbine. Due to the low waste heat temperature, the temperature of the steam is low as well. Therefore, water vapour cannot be used efficiently, both in terms of energy and of costs.

Here, organic fluids are used. Organic media evaporate at relatively low temperatures and condense against ambient air at a pressure over 1 bar, thus no vacuum has to be produced in the condenser. Between the evaporation and condensation pressure/temperature levels the organic fluid delivers a considerable amount of energy when it is expanded in the turbine. The ORC power plant consists of the following main systems:

- Heat extraction.
- Heat conversion.
- Heat dissipation.
- Electric feed in and control.

Heat extraction

In cement plants, the waste heat is normally discharged from two sources: from the clinker cooler air (AQC) and after the preheater tower.

The air from the cooler can be cooled as much as possible to extract the maximum amount of heat, so a conversion system with low operating temperatures is advantageous.

The waste gas after the preheater is used in the subsequent process steps: the waste heat is used in the raw mill to dry and preheat the raw mix and in the coal mill to eventually dry the coal. Therefore, the temperature must not be reduced below typically 200 – 250 °C; this limits the extractable amount of heat. Consequently, one heat exchanger is used per waste heat source. The extracted heat is conveyed to the intermediate cycle and finally transported to the evaporator: the interface to the organic fluid cycle.

Pressurised water is used in the intermediate cycle. Because no evaporation occurs, the surfaces of the heat exchangers are comparatively small.

Heat conversion

In the conversion cycle, the waste heat is used to preheat, evaporate and superheat the organic fluid under high pressure. The superheated fluid then gets expanded in the turbine and the mechanical work is converted into electrical energy in the generator.

The back pressure after the turbine depends on the outside air temperature (OAT): the warmer the weather, the higher the back pressure and thus the lower the produced electrical power.

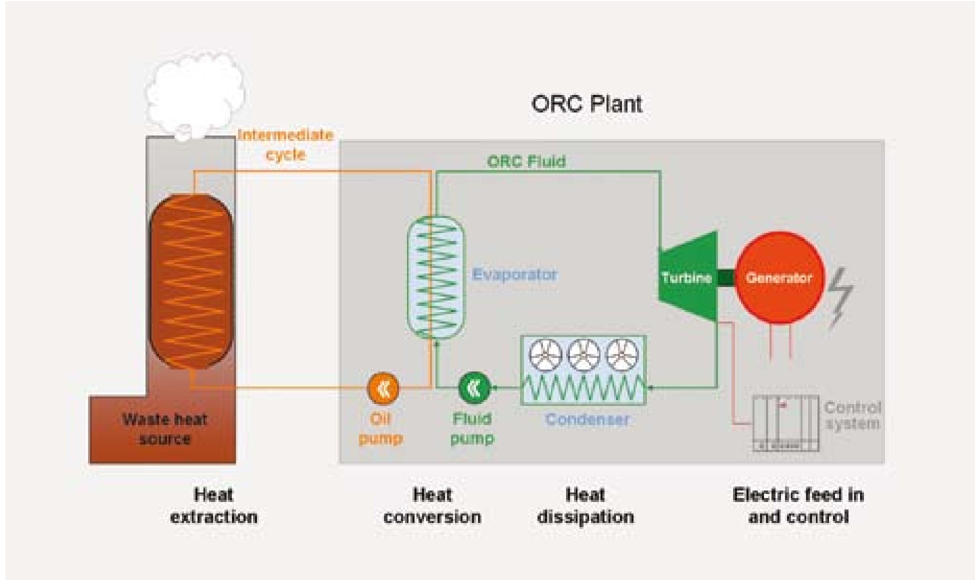

Figure 2. Functional principle ABB ORC power plant.

After the turbine, the organic vapour flows through a heat recovery heat exchanger and is cooled. Then the vapour enters the condenser, where it is liquefied and slightly undercooled. Finally, the liquid is again put under high pressure in the fluid pump and conveyed via the heat recovery heat exchanger (heat recovery from the vapour) to the evaporator and the cycle is closed.

Heat dissipation

Wet cooling tower

As with every thermal power plant, the vapour has to be liquefied. Therefore the condensing heat has to be discharged to the environment. For this last process step a condenser is necessary.

Condensers can be conventional wet cooling towers or dry air condensers.

Wet cooling towers are basically capable of reaching temperatures below ambient (theoretically wet bulb temperature) through the evaporation effect of water in the air.

Figure 4 shows that with warm and very dry air (e.g. 30 °C/20% r.h.) the undercooling effect might (theoretically) reach around 14 °C; in reality (tower efficiency), the undercooling will be roughly 10 °C. When the ambient air is warm and humid (e.g. 30 °C/80% r.h.), this additional cooling effect is reduced to approximately 2 °C. If, in addition, an intermediate cooling water cycle is installed between condenser and cooling tower, the undercooling effect on the condensing temperature is affected even more negatively.

Water for cooling towers has to be treated, which requires considerable investment and operating costs.

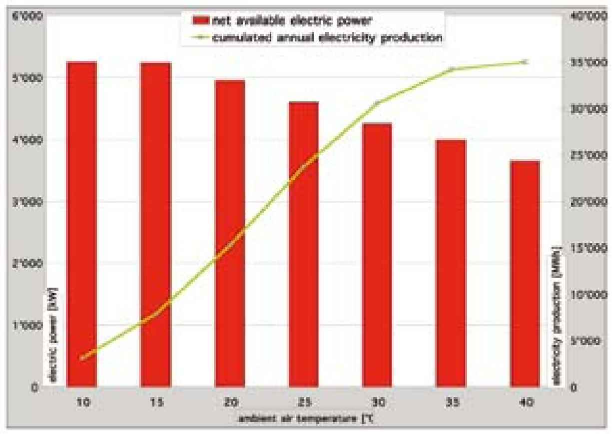

Figure 3. The net available electrical power over one year of operation.

Dry air condenser

On the other hand, dry condensers profit from humid air. The enthalpy of ambient air increases with rising humidity and consequently more heat power can be dissipated per kg of air; i.e. the same condenser is more efficient when the air is more humid.

Figure 5 shows that a dry air condenser can dissipate with dry air (30 °C/20% r.h.) roughly 10.2 kW of heat power per kg/s of cooling air. When the humidity rises to e.g. 80% r.h. the dissipated heat power rises to 10.6 kW per kg/s.

Water use and water savings are big and increasing issues in many countries. Therefore, when considering this topic and with regard to sustainability, the ABB ORC power plant uses specifically-designed, high-end dry condensers to avoid water consumption. Due to the appropriate design, the condensers can be operated with low specific electricity consumption at small temperature differences between the condensing organic vapour and the ambient air - in other words: the condensation temperature is not much higher than ambient and the difference to the wet cooling tower is small.

Electrical parts and control

The electrical power is fed into the plant's grid from the generator at an appropriate voltage level, usually medium voltage. The electrical container centralises breakers, safety equipment and the necessary control devices. Where necessary (specifically with the fluid pump) variable speed drives are installed to match the operation of the ABB ORC power plant ideally to the operating conditions of the cement plant.

Design

The main modules are designed as standard modules, which form the ABB ORC power plant. This means the power plant can easily be adapted to every waste heat source by only altering the intermediate cycle to the respective industry plant. The conversion module is designed for unchanged operating process conditions. Moreover the power plant is designed to only use a small surface area, due to a very compact construction.

Figure 6 shows the compact ABB ORC power plant: at the bottom level all the components that need observation or maintenance (electro-mechanical components as turbine, pumps, generator, valves etc.) are installed. The middle floor level contains all the static components: process heat exchangers, piping. The top of the steel frame carries the condensers.

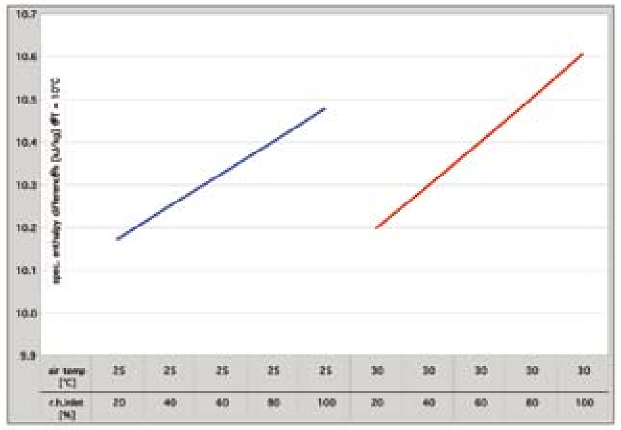

Figure 5. Influence of air humidity on heat dissipation in a dry air condenser. Blue curve: cool ambient air at various r.h.; red curve: warm air.

Figure 6. Layout of the ABB ORC power plant.

Specialities in cement plants

The highly variable conditions of the cement plant (temperatures, flow rates, drying requirements, etc.) make it necessary to accurately examine the operating conditions, ideally over one year. This is particularly easy when an expert system is installed that records the respective production data of the plant. The precise examination of the cement plant leads to an optimum design of the ABB ORC power plant and thus avoids too big an installation (unnecessarily economically expensive) or a too small power plant (loss of precious electricity from waste heat).

The waste heat sources in cement plants make a great demand on the engineering of the heat extraction part of the power plant. Specifically the high dust load of the waste gas after the preheater tower places high requirements on the design of the heat exchangers.

Waste heat sources

Preheater

The dust load of the preheater gas lies in the order of magnitude of 50 – 100 g/Nm^3. Additionally, eventual condensing components must be considered.

As the temperature of the waste gas cannot be reduced to a very low level (temperature requirements of the raw mill) the danger of condensation is, in normal cases, negligible.

The dust issue is taken into consideration by the heat exchanger design. The exchanger is a bare tube type with geometry designed accordingly. Past experience (the longest used heat exchanger of that type has been in operation since 1991 on the heavy dust side in a cement plant) has shown that this type of heat exchanger withstands the high dust load in the waste gas after the preheater tower. If circumstances should make it necessary, the heat exchangers are designed to carry dust blowers at the relevant points.

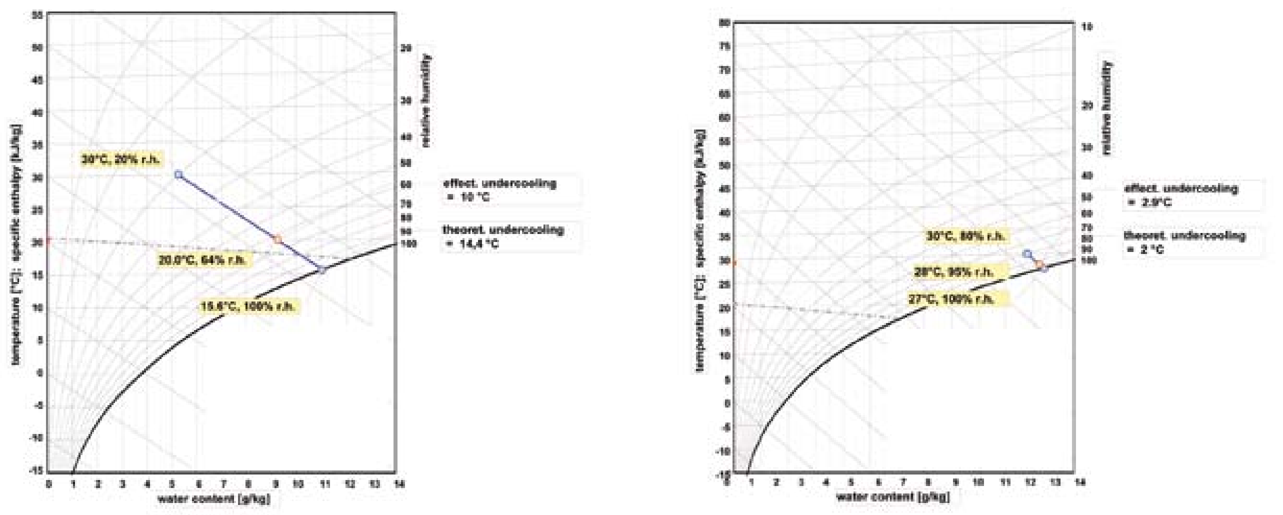

Figure 4. Water cooling in a wet cooling tower. Left: dry ambient air conditions; right: humid ambient air.

Clinker cooler (AQC)

The heat exchanger in the clinker cooler air stream is loaded with about half the dust load compared to the preheater. Contrary to the preheater waste gas stream, the air after the clinker cooler is totally dry, but the dust is hard and abrasive. Therefore, at the entry of the heat exchanger, the necessary reinforcement has to be considered.

Summary

The ABB ORC power plant is - from the point of view of the whole cement making process - an installation of secondary importance. Therefore, the installation must not interfere negatively with the core process of cement making. This need is accommodated by installing the heat exchangers in a bypass mode. Under normal operating conditions, the waste gas and the clinker cooler air flow through the heat exchangers. If for any reason the ABB ORC power plant should be out of operation while the kiln is under full operation, the waste gas bypasses the heat exchanger and takes the conventional route through the cooling tower, and the clinker cooler air flows through the air cooler before it enters the dust precipitator.

The installation of an ABB ORC power plant contributes considerably to further enhancement of energy efficiency and to a reduction of the CO_2 emissions caused by electricity consumption, even in highly efficient cement plants, where waste gas temperatures after the preheater are still typically between 250 and 300 °C. Even in such cases, a reduction of electricity consumption of up to 20% can be achieved.

The installation of an ABB ORC power plant leads to considerable energy and production improvements in the cement plant. From an energy (and economic) point of view the following improvements occur:

- The energy efficiency is increased by the conversion of waste heat into electricity. Thus the waste heat discharge through the stacks is reduced accordingly.
- The captive electricity production leads to reduced electrical power consumption from the public grid, which is a contribution to smaller transportation losses and bigger grid stability – not to mention the reduced demand for electrical power production from (mostly fossil-fired) power plants.
- The captive electricity production leads to a reduction in the respective amount of indirect CO_2 emissions.
- The saving of water for cooling purposes results in a reduced amount of steam in the waste gas, which allows for either a reduction in the power consumption of the respective ID fans or an increase in clinker production by replacing the steam in the waste gas with stack gas from the kiln, i.e. by increasing the firing power of the plant.
- Less water at the raw mill entry (no water evaporation in the cooling tower) enables the operators to improve the operating parameters of the cement plant (e.g. reduced temperatures for the raw mill, thus further reduction of waste gas temperature → more heat to be extracted and used in the power plant and further increases in energy efficiency).
- The smaller amount of steam in the waste gas reduces the possibility of agglutination of dust in the filters, particularly if textile filters are in use.
- Last but not least: water saving contributes to the sustainability of cement production by conserving the more and more important resource of (potential) drinking water.