UNIVERSITY OF THESSALY

SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

Thesis

“Power Generation from Waste Heat in cement plants - Application in Lafarge Volos plant”

Submitted in fulfilment of the requirements for the Postgraduate Specialization Diploma

by

Panagiota Apergi, Dipl. Electrical Engineer

Thesis Advisor: Stamatis T., Associate Professor

Volos, October 2012

Summary

This study presents Waste Heat Recovery as a way to gain energy from the exhaust gases in a cement plant.

Due to inefficient heat transfer downstream of the clinker burning process, there are huge amounts of energy which is released with the waste gases into the atmosphere. The amount of the wasted energy depends on several process parameters.

With the tendency of the energy cost to increase, the reuse of the waste energy is starting to become a very attractive issue. Power generation from waste heat is possible and its two major benefits are the reduction in the consumed electrical energy and hence the reduction of "indirect" CO2 emissions.

Waste Heat Recovery Power Generation systems exist in many cement plants around the world and their operation is based on the Rankine cycle. Three main systems exist: Water-steam system, Organic Rankine Cycle system and Kalina cycle system. Each one of them has its own advantages and disadvantages and the preferable system for each application depends on the specificities of the respective plant.

All fundamental aspects concerning the installation of a Waste Heat Recovery Power Generation facility in Volos cement production plant are examined in this study. Three possible configurations are presented and according to the results the water-steam cycle with one turbine is the preferable solution.

The main equipment of the proposed solution and the way to be incorporated into the plant layout is investigated. Moreover, the different ways in which the Waste Heat Recovery Power Generation facility may impact the normal plant operation are examined.

Safety and environmental as well as legal aspects related to the new installation are described and finally a preliminary economic evaluation of the investment is presented.

Contents

Chapter 1 Waste heat recovery

Chapter 2 Volos cement plant characteristics

Chapter 3 Design for WHR system – Theoretical approach

List of tables

List of figures

Abbreviations

AC	Alternative Current
CCR	Central Control Room
EES	Engineering Equation Solver
ESP	ElectroStatic Precipitator
ID	Induced Draft
MCC	Motor Control Center
MV	Medium Voltage
ORC	Organic Rankine Cycle
PHT	PreHeaTer
PPC	Public Power Company
RAE	Regulatory Authority for Enegry
RK1	Rotary Kiln No1
RM	Raw Mill
UPS	Uninterruptible Power Supply
WHR	Waste Heat Recovery
WHRPG	Waste Heat Recovery Power Generation

Intoduction

Increasing energy efficiency is one of the most important current entrepreneurial challenges. The cement manufacturing process is highly energy intensive. The heat consumption lies in the order of magnitude of approximately 3-3,5GJ/t clinker and the electrical energy consumed is in the range of 100kWh/t cement produced.

The process heat is generated to a considerable extent from fossil fuels and, in some countries, partly from alternative fuels. The electricity used is, to a large degree, generated in power plants which also run on fossil fuels. Consequently, the energy consumption of a cement plant creates direct and indirect CO2 emissions due to energy use. Finally, clinker burning produces additional CO2 emissions. Each tone of portland cement produced releases in total approximately 1 tone of CO2 [2]. Consequently, the cement process is one of the major industrial emitters of greenhouse gases, particularly CO2. In addition, the EU has made a commitment to increase the 20% emissions' reduction target to 30% for the post Kyoto period if there are comparable targets from other developed countries and adequate actions from developing countries.

Therefore, the discussion on climate change and energy efficiency drives the effort to increase energy efficiency in the cement industry. Cement plants will have to strengthen their efforts to increase energy efficiency and hence reduce energy consumption. The first target is to increase the reuse of thermal energy to the maximum. Many cement plants have installed additional preheater stages to dry the raw mix or have used the waste heat for drying processes for alternative fuels in order to increase the use of thermal energy. However, there are still considerable amounts of heat not used and exhaust gases are cooled down before released into the atmosphere.

Hence, after the efficiency of a cement plant has been improved by using the waste heat within the process, the remaining waste heat could be converted into electricity.

Waste Heat Recovery Power Generation (WHR PG) systems are already in operation in many cement plants with success. WHR PG systems used for cement kilns operate based on the Rankine cycle. These systems consist of heat exchangers, turbines, electric generators, condensers and a working fluid cooling system. Three primary types of WHR systems are avialable with the working fluid being the differentiating factor (Water-steam cycle, Organic Rankine Cycle or Kalina cycle).

The best economic benefit can be achieved by implementing waste heat recovery application in a greenfield cement plant. On the other hand, existing cement plants can also benefit from power co-generation. However, the subsequent retrofit is challenging with regard to building and construction issues as well as the cross linking of the thermal and electric energy flows. In any case the economic feasibility depends on the overall situation on site and might in many cases not be given.

Hence, despite the process that has been made in waste heat recovery in the cement industry it is important to keep in mind that the overall efficiency of waste heat recovery and the economic situation is very plant specific. The experiences of one plant might not be easily transferred to another and a detailed individual analysis is required in each single case.

Chapter 1 Waste heat recovery

Nowadays as it can be seen around the world the major challenge that all kinds of organizations are up to is to reduce their energy consumption, hence cost and environmental footprint. All the above can be achieved with novel initiatives and one of them concerning mostly energy production from environmental friendly sources is Waste Heat Recovery.

1.1 Waste heat

Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then "dumped" into the environment even though it could still be reused for some useful and economic purpose. The essential quality of heat is not the amount but rather its "value". The strategy of how to recover this heat depends in part on the temperature of the waste heat gases and the economics involved.

Large quantity of hot flue gases is generated from boilers, kilns, ovens and furnaces. If some of this waste heat could be recovered, a considerable amount of primary fuel used for power generation could be saved. The energy lost in waste gases cannot be fully recovered. However, much of the heat could be exploited in different ways and losses minimized.

1.2 Heat recovery

In any heat recovery application, it is essential to know the amount of heat that can be recovered and also how this energy source can be used.

The main equation for estimating the recoverable heat is:

$$Q = V \times \rho \times C_p \times \Delta T \qquad (1.1)$$

where

Q : heat content (kcal)
V : flowrate of the substance (m^3/hr)
ρ : density of the flue gas (kg/m^3)
C_p : specific heat of the substance (kcal/kg ˚C)
ΔT : temperature difference (˚C)

Waste heat can be recovered either for other processes requiring thermal energy, heating or drying purposes, or used for electric power co-generation. The subsequent use as heat for thermal processes or heating, which is usually more energy efficient than power generation, requires either a heat consumer on site or close to the facility, or a district heating network nearby. This however is usually not the case, particularly since seasonal heat supply and demand differ from each other. If there is no use for the heat as such, generating electricity from waste heat can be an option. Electricity can either partly cover the plant's energy demand or to be fed back to the public power grid.

1.3 Development of a waste heat recovery system

Understanding the process is essential for development of Waste Heat Recovery (WHR) system. This can be accomplished by reviewing the process flow sheets, layout diagrams, piping isometrics, electrical and instrumentation cable ducting etc. Factors that necessarily shall be examined are:

a. Sources and uses of waste heat
b. Upset conditions occurring in the plant due to heat recovery
c. Availability of space
d. Any other constraint, such as dew point occurring in any equipment etc

After identifying sources of waste heat and the possible use of it, the next step is to select suitable heat recovery system and equipment to recover and utilise it.

It is necessary to evaluate the selected waste heat recovery system on the basis of financial analysis such as investment, depreciation, payback period, rate of return etc. In addition the advice of experienced consultants and suppliers must be obtained for rational decision.

1.4 Waste heat recovery in cement plants

1.4.1 Need

Cement plants are huge energy consumers: their heat consumption lies in the order of magnitude of 3-3,5GJ/t clinker and the electricity consumption at roughly 100kWh/t (cement in bin). 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 CO2 emissions. This is a very important factor that has to be considered during examining the installation of a WHR system as requirements for industries to reduce greenhouse emissions increase year after year.

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 hence 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 realization of many (relatively small) measures with the great number of electricity consumers would be realized.

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” (during the process the system is thermodynamically isolated – there is no heat transfer with the surroundings, apart of the wall losses). In other words, waste heat shall be recovered to the maximum extent. This can be achieved with a small number of important measures. After the efficiency of a cement plant has been driven to the economic optimum, the remaining heat can be converted into electricity.

1.4.2 Power availability

In cement plants the waste heat can be extracted from one or two sources:

a. from the clinker cooler air
b. from the waste gas after the preheater tower

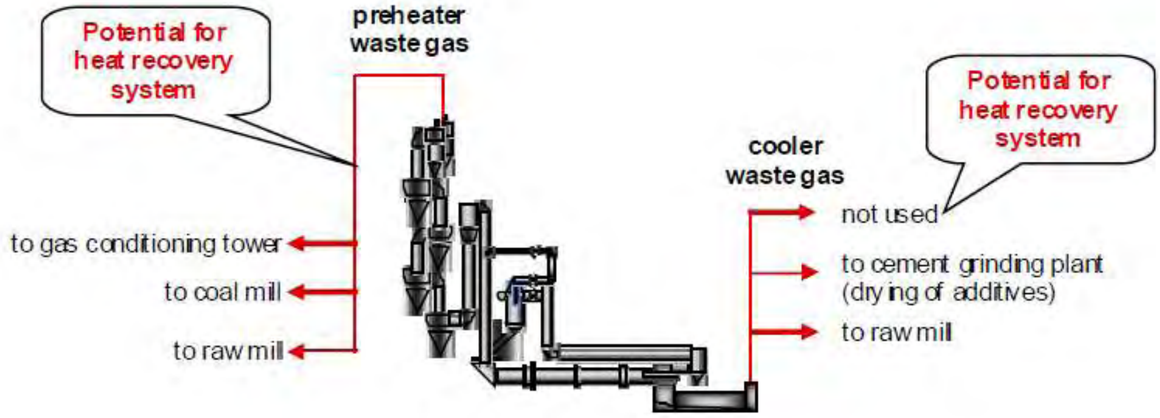


Figure 1.1: Potential heat for recovery in a cement plant

Power available for recovery though depends on several factors:

- Capacity of kiln, number of stages of cyclones of the preheater
- Process mastery: heat consumption, temperatures and flow rates of waste gas from preheater, cooler (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.)
- Drying requirement of raw material and coal, which determines the minimum temperature at preheater heat exchanger outlet
- The type of raw mill and coal mill (ball mill or vertical mill). The lower the flowrate (in ball mill case), the higher the temperature of gas at outlet of preheater heat exchanger is needed to dry material, less heat can be used for power generation
- The type of dedusting system on cooler side. If EP is used, higher gas temperature has to be maintained to keep dust conductivity compared with bag filter dedusting, hence lower power can be generated.

1.4.3 Power plant in bypass mode

The 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 making cement. 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 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.

1.4.4 History & current status

With the introduction of rotary kilns in cement clinker manufacturing at the end of 19th century, clinker was burned in wet and dry rotary kilns without preheater technologies as we know them today. The kiln exhaust gas left the furnace with temperatures between 600 and 1000°C according to the kiln type and kiln length. Lost heat was recovered for the drying of the raw materials as well as for the preheating of the combustion air. Surprisingly, for today’s point of view, even steam boilers were used for waste heat utilization in the early days of cement production.

The figure below shows the utilization of heat in flue gas by a system of heating tubes as it was done more than a hundred years ago. As lost heat in flue gas exceeded the heat demand for raw material drying and combustion air preheating, lost flue gas heat was already being recovered by steam boilers in the first decades of the last century.

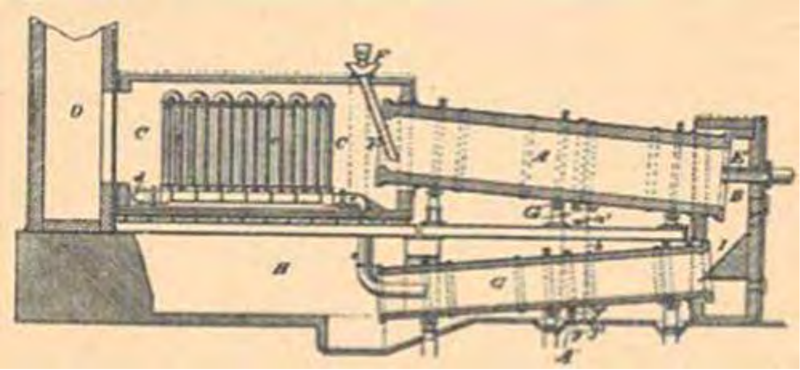


Figure 1.2: *WHR from kiln exhaust gas for preheating combustion air around 1906*

In the last couple of years, waste heat recovery systems have been experienced a renaissance. Today, in the Middle and Far East more than 100 applications in the cement industry are known, in the beginning initiated especially in cases with high energy process or with a low service security of the public electric power grid.

State-of-the-art technology for waste heat recovery systems, the development of energy prices, and the growing need to improve energy efficiency all provide new opportunities for implementing waste heat recovery systems in the already highly efficient kiln systems of the cement industry. To date, three applications are currently in operation in European cement plants while a further two are under construction.

1.4.5 Recent development

1.4.5.1 Italcementi - Morocco

Figure 1.3: *Italcementi's Ait Baha plant in Morocco*

This plant is in operation since Q3-2010. Heat recovery takes place from the kiln gas only, and the highly efficient 5000tpd, five-stage preheater dry-process kiln allows the generation of 2MW at nominal Organic Rankine Cycle (ORC) load. Waste heat from the exhaust gas is transferred to a thermal oil loop in an exchanger designed by Energia Impianti (Italy) and is then delivered to the ORC plant. Condensing heat is dissipated by means of a dry air-cooling system, leading to a "zero water consumption" plant.

1.4.5.2 Lafarge - Philippines

In the Philippines, Lafarge recently implemented a Waste heat Recovery system project at the Teresa plant of its associate Republic Cement Corporation. It has been fully operational since 2011. The facility captures and uses "lost" heat from the cement production process to generate additional electricity for the plant. It redirects most of the waste heat to run a 4,5MW capacity turbine that generates electricity. The system has the capacity to produce enough electricity to meet 25-30% of the Teresa cement plant's energy requirements.

Figure 1.4: *The Teresa plant won national recognition for its WHR project*

The installed WHR system in Teresa plant has demonstrated a significant reduction in CO2 emissions when it became less dependant on the country’s power grid, which draws its electricity from fossil fuel based power stations. The project thus allowed the plant to cut its indirect carbon emissions by 12000tpa.

1.4.5.3 Holcim – Romania

Figure 1.5: *Holcim Alesd cement plant – Romania*

Holcim Alesd operates a modern calciner kiln with a two-strong, four-stage preheater and a clinker capacity of 4300tpd. The Alesd works is the first cement plant in Eastern Europe to integrate a Waste Heat Recovery system in the clinker production process. The total investment of this project is 14M€ and, when completed in the last months of 2012, will provide the plant with a reliable supply of electrical energy at low, stable and predictable costs, without a negative impact on plant operations. The installation uses Organic Rankine Cycle technology.

Figure 1.6: *Preheater boiler*

Figure 1.7: *ORC unit including generator*

1.5 Benefits of waste heat recovery

The installation of a waste heat recovery system – “power plant” – leads to considerable energy and production improvements in the cement plant. From energy (and economic) point of view the following improvements occur:

a. The energy efficiency is increased by the conversion of waste heat into electricity. Thus the waste heat discharge through the stacks is reduced accordingly.

b. 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) plants.

c. The captive electricity production leads to a reduction in the respective amount of indirect CO2 emissions.

d. 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, by increasing the firing power of the plant. (In other words, we have reduction in equipment sizes of all flue gas handling equipments such as fans, ducts, burners etc.)

e. Reduction in auxiliary energy consumption: Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption like electricity for fans, pumps etc.

f. Less water at the raw mill entry (no water evaporation in the cooling tower) enables the operators to improve the operating parameters of the current 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).

g. 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.

h. Last but not least: water saving contributes to the sustainability of cement production by conserving the most important resource of (potential) drinking water.

Summary

Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then “dumped” into the environment even though it could still be reused for some useful and economic purpose.

Lately, there has been a significant increase in interest for waste heat recovery power generation systems in the cement industry. This interest is generated from companies’ sustainability policies, companies searching for projects with acceptable returns on investment, legislation changes and the need to produce electric power onsite.

The preheater exit gases and the clinker cooler vent air are two main sources of waste heat that are available and commonly used for waste heat recovery. The amount of waste heat available for recovery depends on the kiln system design and production and the amount of heat required for drying in the raw mill system, solid fuel system and cement mill system.

So despite the progress that has been made in waste heat recovery in the cement industry it is important to keep in mind that the overall efficiency of waste heat recovery and the economic situation is very plant specific. The experiences of one plant might not be easily transferred to another and a detailed individual analysis is required in each single case.

Chapter 2 Volos cement plant characteristics

In this chapter the main characteristics of Volos cement plant are presented. According to the “typical” plant operation, heat available for recovery is estimated and finally, a sensitivity analysis is defining the main process parameters that affect the recoverable heat.

2.1 Cement manufacturing process

Cement manufacturing process has 3 main steps, from the limestone quarry to the delivery of the end product:

- **Step 1: Extraction and preparation of raw materials**

  The raw materials needed to produce cement are extracted from the quarries (limestone, clay, schist etc), after thorough geological research and chemical analysis in specific quantities and proportions. These raw materials are crushed through a milling process and then transported to the plant.

- **Step 2: Raw grinding and burning**

  Grinding produces a fine powder, known as raw meal, which is preheated and then sent to the kiln. The kiln is the heart of the manufacturing process and in order to heat the materials, a 2000°C flame is required. Once inside the kiln, the raw meal is heated to around 1,500°C. At this temperature, chemical reactions take place to form clinker (an intermediate product). Upon exiting, the clinker is cooled and stored ready for grinding to produce cement.

Figure 2.1: Basic flow sheet of cement production

- **Step 3: Cement grinding and shipping**

  Clinker and gypsum are very finely ground, producing cement. During this phase, different mineral materials, called additives may be added alongside the gypsum. Used in various proportions, these additives give the cement specific properties. Finally, cement is stored in silos before being shipped in bulk or in bags to the sites where it will be used.

2.2 Volos plant description – Key facts – Main equipment - Priorities

Volos plant is the biggest cement plant in Europe and one of the biggest in the world. It is located 4 km away from Volos city. Volos has totally 5 rotary kilns installed, currently 3 rotary kilns in operation, and the annual plant's production reaches around 4.5 million tons of cement. Volos plant employs more than 300 people.

Its history dates back to 1924, built by a local cement company, OLYMPOS, which in 1929 merged with Heracles. Production capacity increased significantly to cover the post-war reconstruction needs, and in between 1950's to 1970's it reaches the 2 million tons per year. In 1976, a whole cement production line, ordered for a development in southern Greece which turned unsuccessful, was installed uphill of the existing plant and doubled the plant's production capacity to more than 4 million tons per year.

Heracles General Cement Company, the largest cement producer in Greece, is a member of Lafarge group since 2001.

Figure 2.2: Volos cement plant

Some key facts about Volos plant are the following:

- Plant area: 1600 acres
- 3 kilns, 3 raw mills, 6 cement mills in operation
- Annual plant’s clinker production capacity: 3.2 million tons
- Annual plant’s cement production capacity:4.5 million tons
- More than 1.5 million tons exported, cement or clinker
- 1 quality of clinker
- 7 types of cement
- Volos plant can load vessels up to 40,000 dwt
- Quality system certified according to ISO 9001/2000

The main plant equipment data is listed in the table below.

EQUIPMENT	CAPACITY	MANUFACTURER	INSTAL. DATE
Hornstone crusher	200 t/h	Hazemaq	1977
Limestone crusher	1200 t/h	Hazemaq	1992
Clay crusher	160 t/h	Bedeschi	1994
Dolomite crusher	190 t/h	Hazemaq	1996
Raw mill No1 (vertical)	390 t/h	Loesche	1976
Raw mill No4 (ball mill)	130 t/h	KHD	1966
Raw mill No5 (ball mill)	220 t/h	FLC	1971
Rotary kiln No1 (precalciner)	5200 tpd	IHI / FLS	1976
Rotary kiln No5 (precalciner RSP)	3200 tpd	FLC	1971
Rotary kiln No4 (preheater pyroclon)	1900 tpd	KHD	1966
Solid fuel mill No1	32 t/h	Polysius	1980
Solid fuel mill No2	32 t/h	Polysius	1980
Cement mill No3 (ball mill)	43 t/h		1966
Cement mill No4 (ball mill)	70 t/h		1970
Cement mill No5 (ball mill)	80 t/h		1972
Cement mill No6 (ball mill)	140 t/h		1977
Cement mill No7 (ball mill)	140 t/h		1977
Cement mill No8 (ball mill)	145 t/h		1980
Load bulk crane A1	500 t/h		1973 / 2002
Pneumatic load line A5	450 t/h		1982
Pier B - bulk loading	300 t/h		1966
Unload crane C1	177t/h		1976
Unload crane C3	179 t/h		1972
Unload crane C4	220 t/h		1982
Unload crane C5 (Iolkos)	980 t/h		1991

Table 2.1: Main Volos plant equipment data

With the cement industry as one of the world’s most energy-intensive industries, Lafarge has developed and is implementing a comprehensive strategy to reduce its environmental footprint. The group recently renewed its environmental goal and now aims to reduce CO2 emissions per ton of cement by 33% come 2020. To achieve this, the company has endeavored to focus more on increasing energy efficiency in manufacturing, using more renewable energy and increasing the use of alternative fuels and less carbon-intensive cementitious materials.

Lafarge has put forward this challenge to its global network of around 125 cement plants, encouraging each to come up with initiatives to contribute to the group’s environmental and sustainability efforts.

2.3 Plant layout

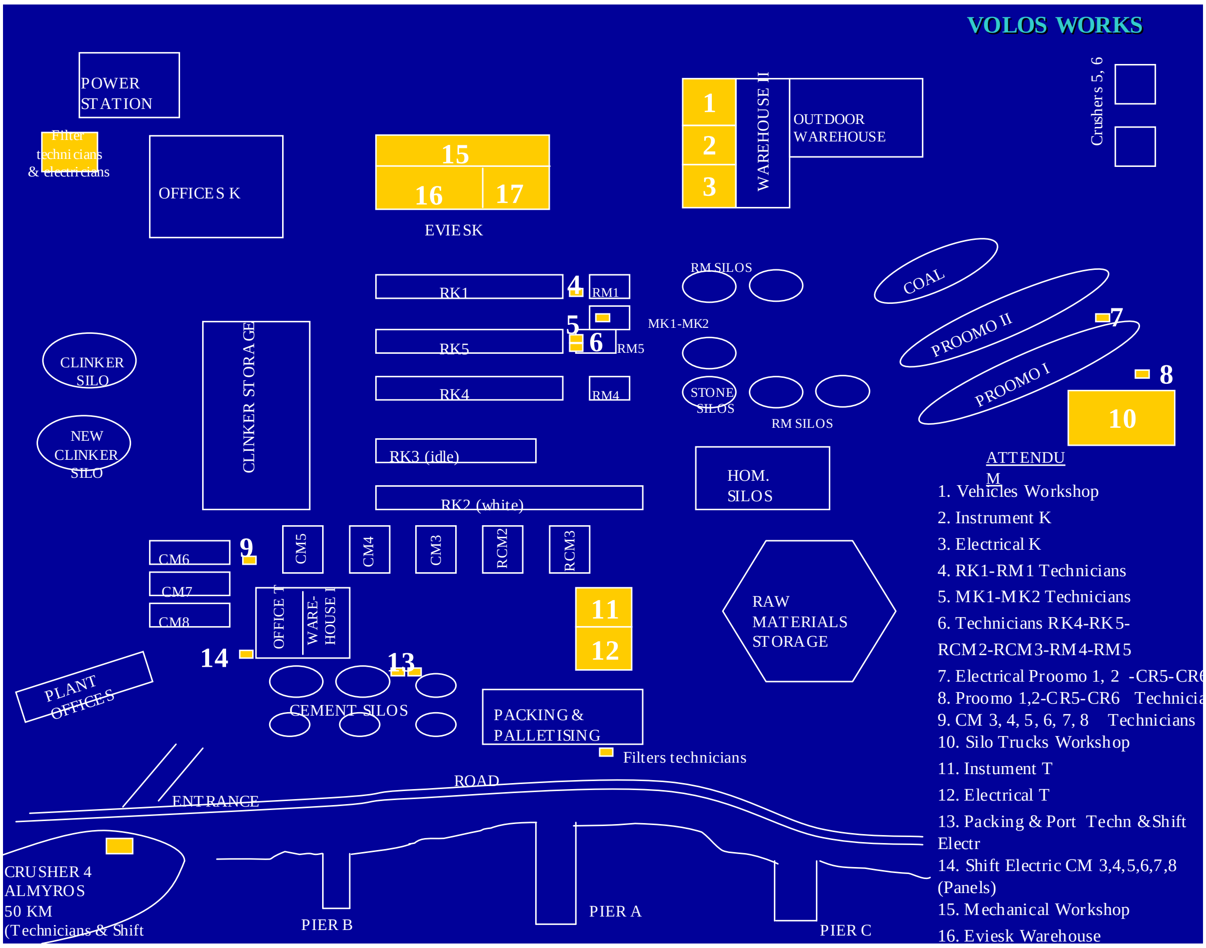


Figure 2.3: Volos plant layout

Volos plant has a very compact layout. The space is limited as it is surrounded by Goritsa hill in the west side, sea in the south side, the old quarry in the north side and a fuel company installations in the east side.

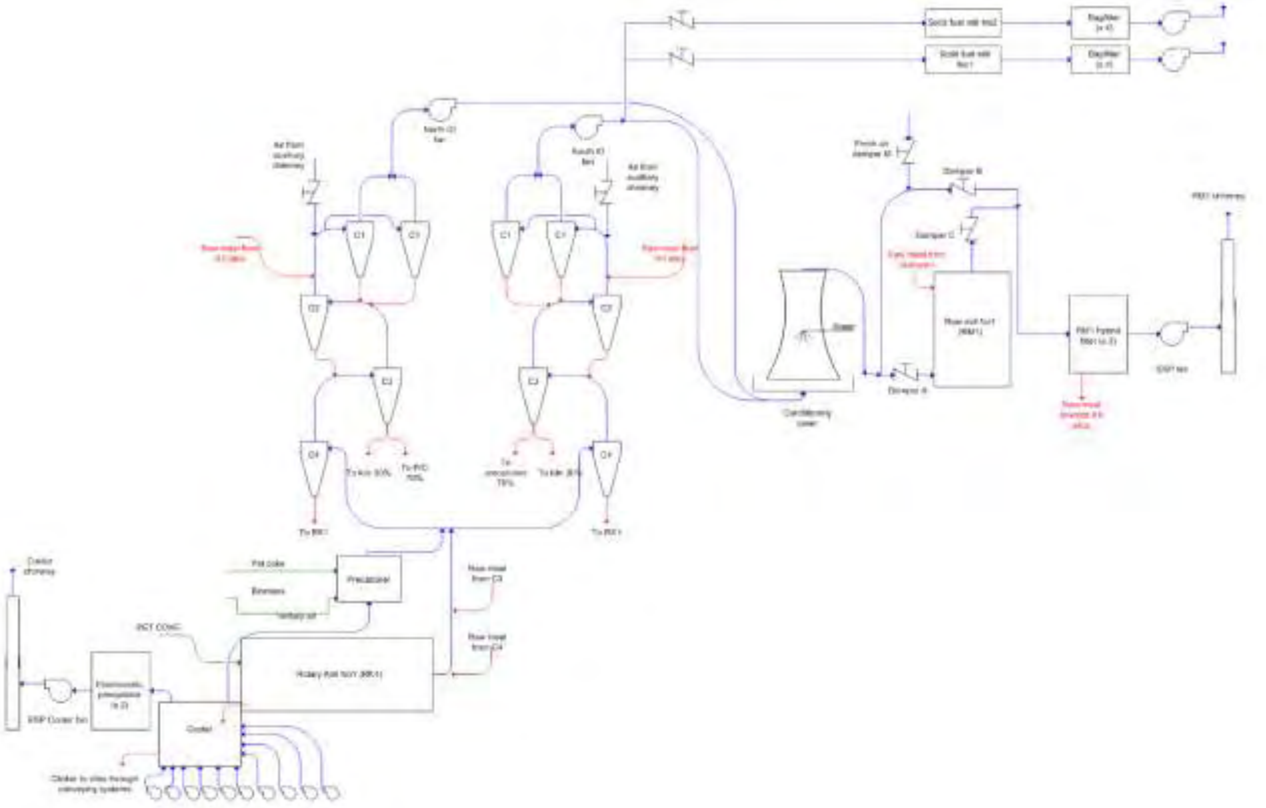
The fact that the different lines were built one after the other, as well as the fact that the plant worked for a lot of years in a sold-out market have resulted in a very compact & complex layout.

2.4 Volos - Basic flow sheet of clinker production

The basic flow sheet of clinker production for Rotary Kiln No1 is presented in figure 2.4. The kiln is a four stage preheater kiln with precalciner. There are 2 ID fans, one for each preheater circuit string, which extract the hot gases from the kiln. After the ID fans, the gases are cooled down in the cooling tower and are driven to the vertical Raw Mill to reduce moisture for the milling of raw materials. There is 1 ESP fan driven by two motors for extracting the Raw Mill gases, all of which pass through a hybrid filter before released into the atmosphere.

There are two solid fuel mills which both draw gases from the kiln system.

The cooler is of grate type with hammer crusher at the outlet. The gases from the cooler pass through an electrostatic precipitator before released into the atmosphere at the stack.



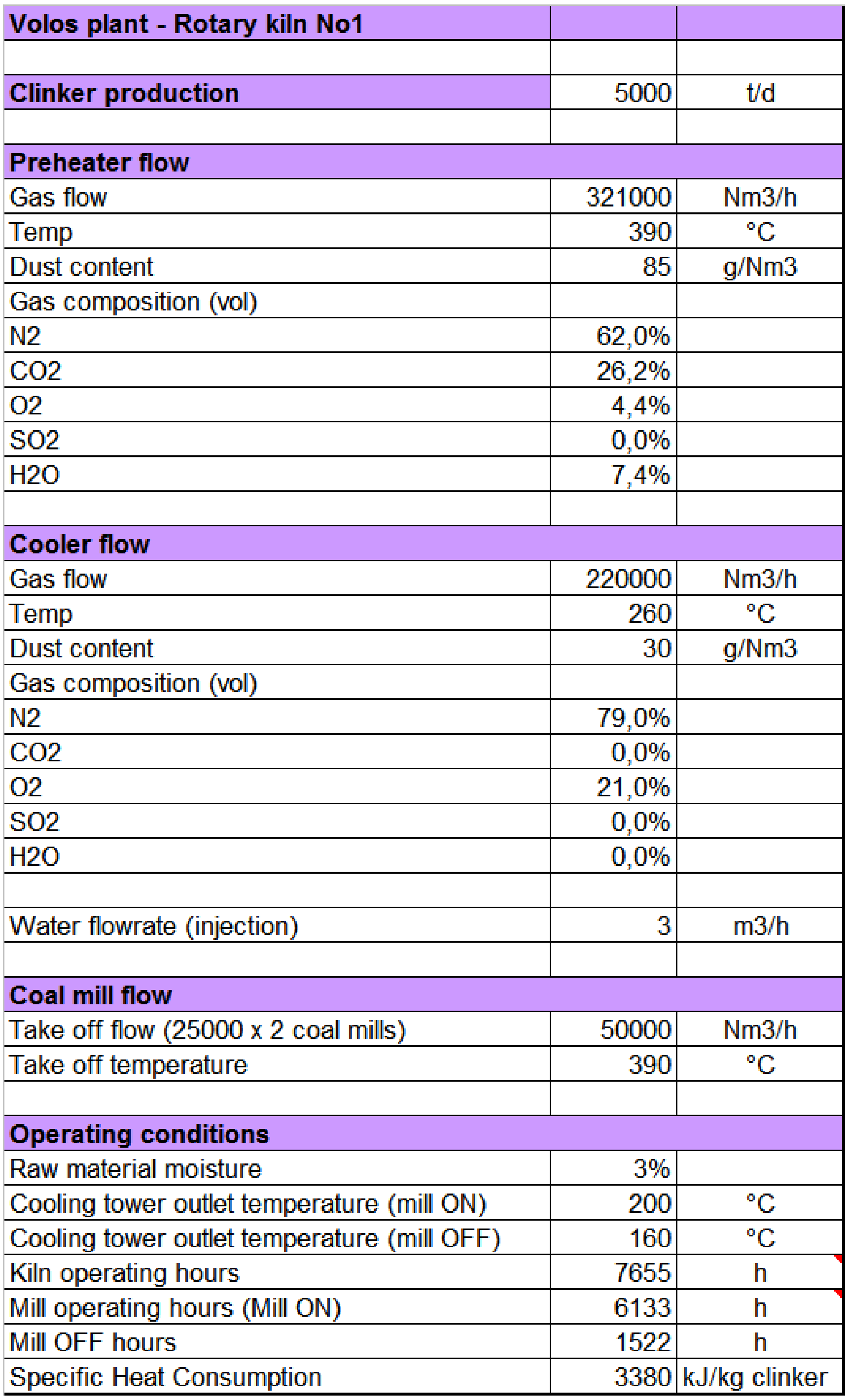
<u>Figure 2.4:</u> Volos plant – Current flow sheet of clinker production

2.5 Process data - Operation – Estimation of waste heat in different points

The main process parameters – relevant for WHR – for the two points we are interested to get gases from (after the preheater & after the cooler) are the following:

- Gas flow
- Gas temperature
- Gas composition
- Dust content

The main parameters which interest us for the estimation of the waste heat in different points are summarized in the following table:



Volos plant - Rotary kiln No1		
Clinker production	5000	t/d
Preheater flow		
Gas flow	321000	Nm3/h
Temp	390	°C
Dust content	85	g/Nm3
Gas composition (vol)		
N2	62,0%	
CO2	26,2%	
O2	4,4%	
SO2	0,0%	
H2O	7,4%	
Cooler flow		
Gas flow	220000	Nm3/h
Temp	260	°C
Dust content	30	g/Nm3
Gas composition (vol)		
N2	79,0%	
CO2	0,0%	
O2	21,0%	
SO2	0,0%	
H2O	0,0%	
Water flowrate (injection)	3	m3/h
Coal mill flow		
Take off flow (25000 x 2 coal mills)	50000	Nm3/h
Take off temperature	390	°C
Operating conditions		
Raw material moisture	3%	
Cooling tower outlet temperature (mill ON)	200	°C
Cooling tower outlet temperature (mill OFF)	160	°C
Kiln operating hours	7655	h
Mill operating hours (Mill ON)	6133	h
Mill OFF hours	1522	h
Specific Heat Consumption	3380	kJ/kg clinker

Table 2.2: Main process parameters of Volos plant

Using all the above data, it is possible to calculate the heat available for recovery in a WHR system. The efficiency of the heat exchanger recovery and power generation system is not explicitly calculated in this chapter. Instead a single efficiency estimation is taken into consideration (typically 20%) based on history of previous installations. No consideration of water supply and operational parameters of the WHR unit itself are taken into account in this part of the study. Results have been calculated for mill on operating conditions, while the raw mill is practically in operation around 80% of the kiln operating time. In case of mill off, the amount of available heat is higher.

The method used calculates heat input to the system and subtracts heating requirements. The more heat sinks, the less heat is available for recovery. The major heat source is of course the exit gas itself while the heat sinks are primarily related to raw material and fuel drying.

Heat sources

- **Preheater exit gas** – the potential energy available for recovery in the preheater system, this energy will then be reduced by the boiler / turbine efficiency.
- **Cooler exhaust gas** – the potential energy available for recovery in the cooler system, this energy will then be reduced by the boiler / turbine efficiency.
- **Water injection in cooler** – if used for temperature control, it can be discontinued if the WHR unit is in service, the water injection flow rate is therefore a heat source for the purpose of this calculation.
- Mill motor – according to the raw material grinding energy, an estimate can be made of heat input to the raw material

Heat sinks

- Drying of raw materials – according to the raw material moisture the drying energy requirement can be calculated.
- False air – additional heat is required to heat up the false air across the mill system, reducing in this way the drying efficiency of the mill.
- **Coal mill flow** – the energy required for drying the solid fuel according to the volumetric flow rate of gas from the preheater exit downcomer.
- Minimum heat outflow – there is also some heat lost to the system downstream of the raw mill exit.

The method used is simple and is based on field data for the typical cooling tower outlet temperature. This is input manually, the implication being that this already takes into account all other heat sources or sinks downstream of the preheater tower exit gas stream (heat source: mill motor, heat sink: drying of raw materials, false air, minimum heat outflow).
So according to the method used:

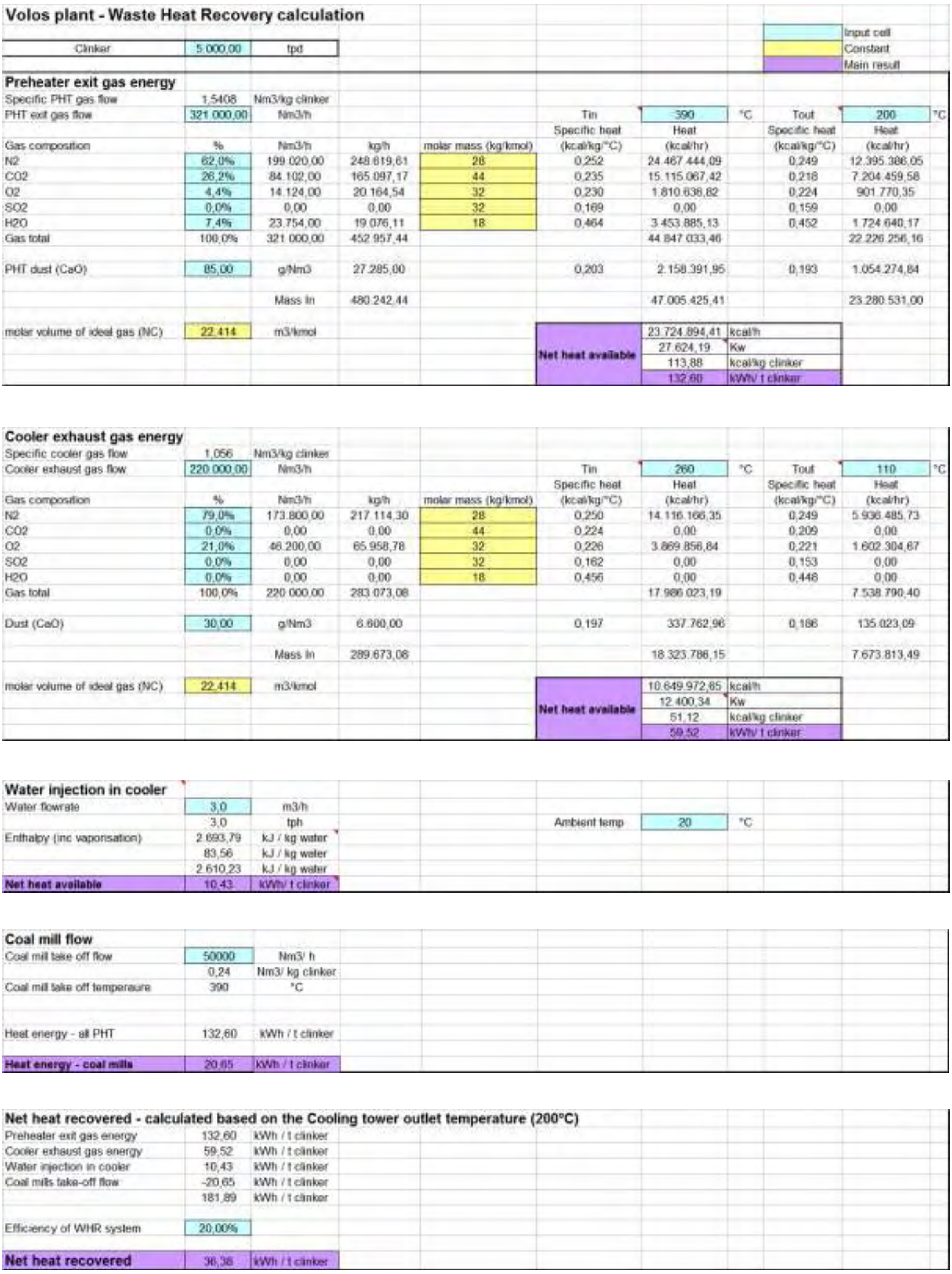
Qexh_pht= Preheater exit gas energy – coal mill flow energy

Qexh_cool= Cooler exhaust gas energy + energy from water injection

Net heat recovered = net heat available x efficiency of WHR system
Efficiency of WHR system = 20%
Net heat available = ∑(preheater exit gas energy + cooler exhaust gas energy + energy from water injection) – coal mill flow energy

For all the calculations, the most difficult case has been considered, meaning that Raw Mill and both solid fuel mills are in operation.

The results are given in table 2.3:



Volos plant - Waste Heat Recovery calculation										
								🟦	Input cell	
Clinker	5 000,00	tpd						🟨	Constant	
								🟪	Main result	

Preheater exit gas energy										
Specific PHT gas flow	1,5408	Nm3/kg clinker								
PHT exit gas flow	321 000,00	Nm3/h			Tin	390	°C	Tout	200	°C
					Specific heat	Heat		Specific heat	Heat	
Gas composition	%	Nm3/h	kg/h	molar mass (kg/kmol)	(kcal/kg/°C)	(kcal/hr)		(kcal/kg/°C)	(kcal/hr)	
N2	62,0%	199 020,00	248 819,61	28	0,252	24 467 444,09		0,249	12 395 386,05	
CO2	26,2%	84 102,00	165 097,17	44	0,235	15 115 067,42		0,218	7 204 459,58	
O2	4,4%	14 124,00	20 164,54	32	0,230	1 810 636,82		0,224	901 770,35	
SO2	0,0%	0,00	0,00	32	0,169	0,00		0,159	0,00	
H2O	7,4%	23 754,00	19 076,11	18	0,464	3 453 885,13		0,452	1 724 640,17	
Gas total	100,0%	321 000,00	452 957,44			44 847 033,46			22 226 256,16	
PHT dust (CaO)	85,00	g/Nm3	27 285,00		0,203	2 158 391,95		0,193	1 054 274,84	
		Mass In	480 242,44			47 005 425,41			23 280 531,00	
molar volume of ideal gas (NC)	22,414	m3/kmol			**Net heat available**	23 724 894,41	kcal/h			
						27 624,19	Kw			
						113,88	kcal/kg clinker			
						132,60	kWh/ t clinker			

Cooler exhaust gas energy										
Specific cooler gas flow	1,056	Nm3/kg clinker								
Cooler exhaust gas flow	220 000,00	Nm3/h			Tin	260	°C	Tout	110	°C
					Specific heat	Heat		Specific heat	Heat	
Gas composition	%	Nm3/h	kg/h	molar mass (kg/kmol)	(kcal/kg/°C)	(kcal/hr)		(kcal/kg/°C)	(kcal/hr)	
N2	79,0%	173 800,00	217 114,30	28	0,250	14 116 166,35		0,249	5 936 485,73	
CO2	0,0%	0,00	0,00	44	0,224	0,00		0,209	0,00	
O2	21,0%	46 200,00	65 958,78	32	0,226	3 869 856,84		0,221	1 602 304,67	
SO2	0,0%	0,00	0,00	32	0,162	0,00		0,153	0,00	
H2O	0,0%	0,00	0,00	18	0,456	0,00		0,448	0,00	
Gas total	100,0%	220 000,00	283 073,08			17 986 023,19			7 538 790,40	
Dust (CaO)	30,00	g/Nm3	6 600,00		0,197	337 762,96		0,186	135 023,09	
		Mass In	289 673,08			18 323 786,15			7 673 813,49	
molar volume of ideal gas (NC)	22,414	m3/kmol			**Net heat available**	10 649 972,65	kcal/h			
						12 400,34	Kw			
						51,12	kcal/kg clinker			
						59,52	kWh/ t clinker			

Water injection in cooler							
Water flowrate	3,0	m3/h					
	3,0	tph			Ambient temp	20	°C
Enthalpy (inc vaporisation)	2 693,79	kJ / kg water					
	83,56	kJ / kg water					
	2 610,23	kJ / kg water					
Net heat available	10,43	kWh/ t clinker					

Coal mill flow		
Coal mill take off flow	50000	Nm3/ h
	0,24	Nm3/ kg clinker
Coal mill take off temperaure	390	°C
Heat energy - all PHT	132,60	kWh / t clinker
Heat energy - coal mills	20,65	kWh / t clinker

Net heat recovered - calculated based on the Cooling tower outlet temperature (200°C)		
Preheater exit gas energy	132,60	kWh / t clinker
Cooler exhaust gas energy	59,52	kWh / t clinker
Water injection in cooler	10,43	kWh / t clinker
Coal mills take-off flow	-20,65	kWh / t clinker
	181,89	kWh / t clinker
Efficiency of WHR system	20,00%	
Net heat recovered	36,38	kWh / t clinker

<u>Table 2.3:</u> WHR calculations for Volos plant

Heat available out of the preheater exhaust gases is 23323kJ/s (= *(132,6-20,65) x 5000 /24)*
Qexh_pht=23323kJ/s

Heat available out of the cooler exhaust gases is 14573kJ/s (= (*59,52+10,43) x 5000 / 24)*
Qexh_cool=14573 kJ/s

Total net heat available is 36,38kWh/t clinker. Assuming that all of it is used and the WHR system will have 20% efficiency, this results in power production of 7,58MW (= 36,38 x 5000 / 24 /1000 = 7,58MW).

2.6 Sensitivity analysis to various process levers

The recovered heat, available for power generation, is sensitive to various process levers, which can be prioritized by performing a sensitivity analysis.

Each process variable is considered in turn to vary between user defined min/max value, the impact upon net heat recovered is then obtained with use of the produced excel file. The results are summarized in the table 2.4.

Process Lever	Value	Net Heat Recovered kWh/t clinker	Magnitude (kWh/t clinker) max value - min value
PHT exit gas temp (C)	370	33,96	4,85
	380	35,17	
	390	36,38	
	400	37,6	
	410	38,81	
RM inlet temp (C)	180	38,65	4,56
	190	37,52	
	200	36,38	
	210	35,24	
	220	34,09	
PHT exit gas flow (Nm3/h)	300000	34,64	3,31
	310000	35,47	
	321000	36,38	
	330000	37,12	
	340000	37,95	
Cooler exhaust gas temp (C)	240	34,77	3,22
	250	35,57	
	260	36,38	
	270	37,18	
	280	37,99	
Cooler filter inlet temp (C)	90	37,91	3,07
	100	37,15	
	110	36,38	
	120	35,61	
	130	34,84	
Cooler exhaust gas flow (Nm3/h)	200000	35,3	2,16
	210000	35,84	
	220000	36,38	
	230000	36,92	
	240000	37,46	
Coal mill flow (Nm3/h)	40000	37,21	1,66
	45000	36,79	
	50000	36,38	
	55000	35,97	
	60000	35,55	
Cooler water injection (m3/h)	2	35,68	1,39
	2,5	36,03	
	3	36,38	
	3,5	36,73	
	4	37,07	

Table 2.4: Sensitivity analysis table

From the above table, it is obvious that the two variables that mostly affect the net heat recovered are the temperature of the PHT exit gas and the temperature at the RM inlet, which we set as a prerequisite for the proper operation of the RM. This is also shown in the below graphs.

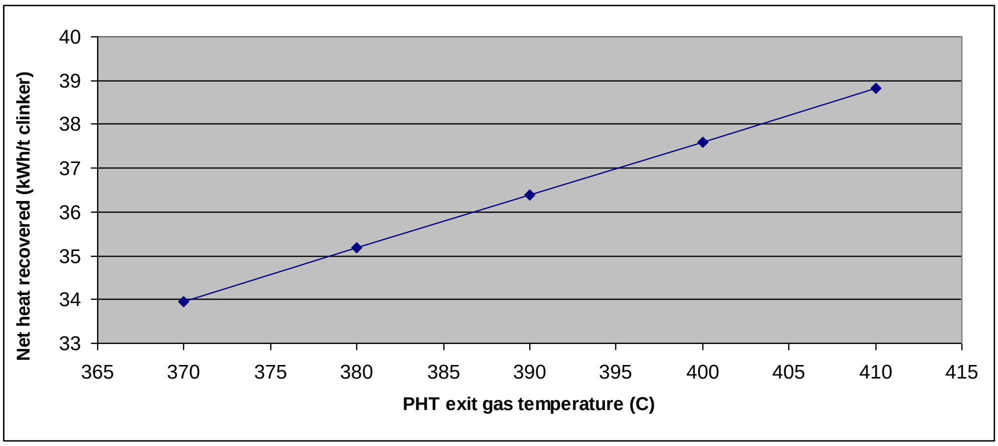


Figure 2.5: Sensitivity of net heat recovered to PHT exit gas temperature

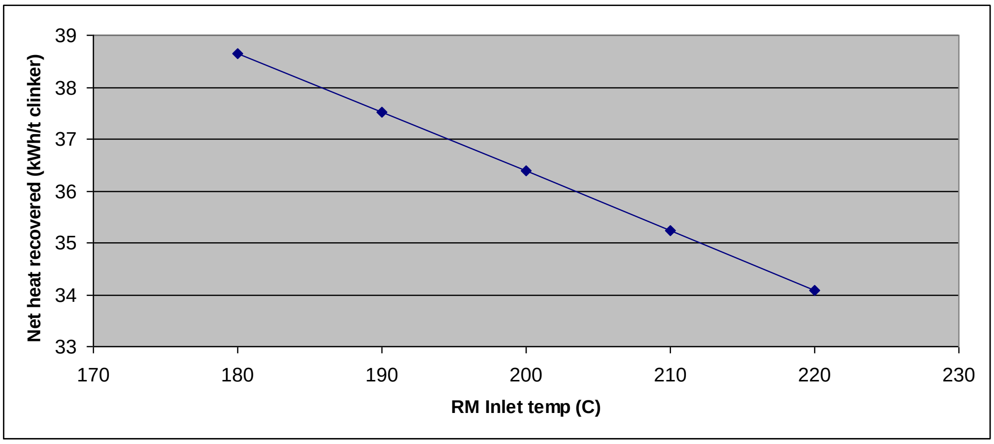


Figure 2.6: Sensitivity of net heat recovered to RM inlet temperature.

2.7 Electricity - Energy consumption

The total electrical installed power of Volos plant is around 110 MW and the total consumed power is around 35MW (for Rotary Kiln 1 only in operation). This means that if we are able to produce by a WHR system 7,58MW (as calculated in paragraph 2.5), it represents around 22% of the consumed power.

The plant is fed from PPC (Public Power Cooporation) through an overhead 150kV line. There are five medium voltage transformers installed in two outdoors substations and two main medium voltage electrical rooms plus an interconnection station. Currently, two medium voltage levels are used in the plant: 15kV and 6,6kV.

The voltage level for electrical equipment inside the plant is equal to 6,6kV for big motors and 500V for the rest of the consumers.

The cost of the energy is according to the contract a sum of two components:

- One of them depends on the real energy consumption. The unit price of the energy depends on the period of the day and is split into the three day rates – low, medium and high rate.

- The other cost component, which is impacting the energy price, is a cost of “contracted power”. This cost is constant and independent of the real power consumption. This cost is covering the electrical power availability or stand-by in the power grid.

In case of installation of WHR plant we expect decrease of the energy cost in both parts – in the energy cost as well in the part regarding power availability.

Summary

Volos plant, a member of Lafarge group, is the biggest cement plant in Europe with production capacity of more than 4 million tons cement per year. One of the key goals set by Lafarge for the coming years is to reduce its environmental footprint, by reducing the CO2 emissions by 33% per ton of cement by 2020. In this frame, every plant, including Volos, examines the possibilities and actions to take in order to achieve this target.

Based on the current operational data of Rotary Kiln No1 of the plant, it is estimated that the significant amount of 36,38kWh/t clinker could be recovered. This amount of heat driven to a WHR power generation plant with 20% efficiency could produce 7,58MW, which represents around 22% of the consumed power of the plant. Of course, this amount is sensitive to various process parameters. The two parameters that mostly affect it are the preheater exit gas temperature and the prerequisite for the raw mill inlet temperature.

Chapter 3 Design for WHR system – Theoretical approach

This chapter contains a theoretical presentation of the three main systems available for WHR PG, their main advantages and disadvantages as well as the main suppliers proposing these systems.

3.1 Possible technical solutions

Waste heat recovery power generation systems used for cement kilns systems operate based on the Rankine cycle. These systems consist of heat exchangers or heat recovery steam generators, turbines, electric generators, condensers and a working fluid cooling system.

Three primary types of WHR systems are available, with the working fluid being the differentiating factor.

- **Water-Steam circuit (or Conventional Rankine Circuit)**

The most common system used in cement plant applications, it uses water as its working fluid.

- **Organic Rankine Circuit**

The second type of system uses an organic fluid, such as N-pentane as its working fluid.

- **KALINA circuit**

The third type of system uses a mixture of ammonia and water as its working fluid.

3.1.1 Water-Steam circuit (conventional Rankine cycle system)

This technology is represented mainly by Kawasaki plant systems and Sinoma EC . Kawasaki plant systems for power generation are installed in more than 32 cement plants (mostly in Japan & China). The oldest installation by Kawasaki was in 1980 in Japan – Sumitomo Osaka cement in Gifu plant.

The principle of this method is to use as working medium overheated, saturated steam generated in preheater and cooler heat exchangers.

The expected power generation for a 5000t/day rotary kiln is 9MW and the generated power, in general, can cover around 35-40% of electric consumption in a cement plant.

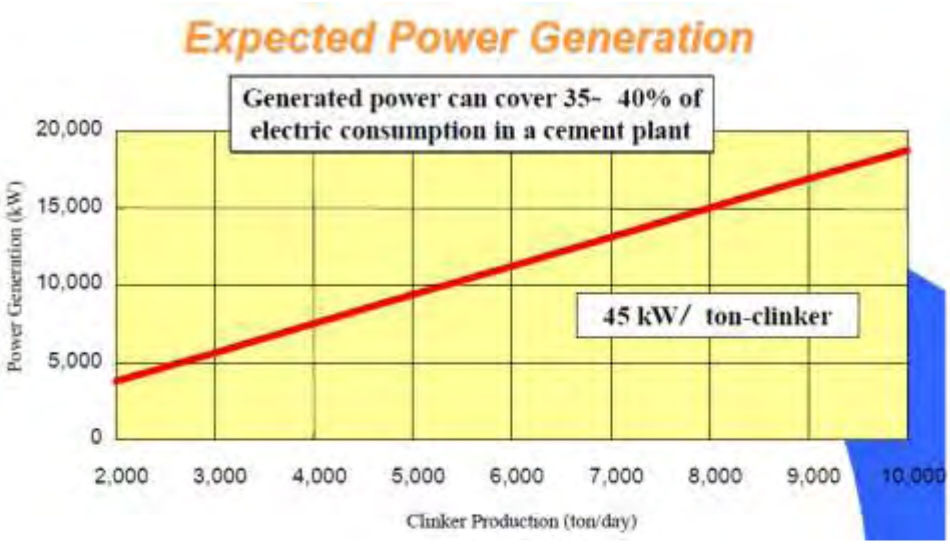


Figure 3.1: Expected power generation in a Kawasaki plant system

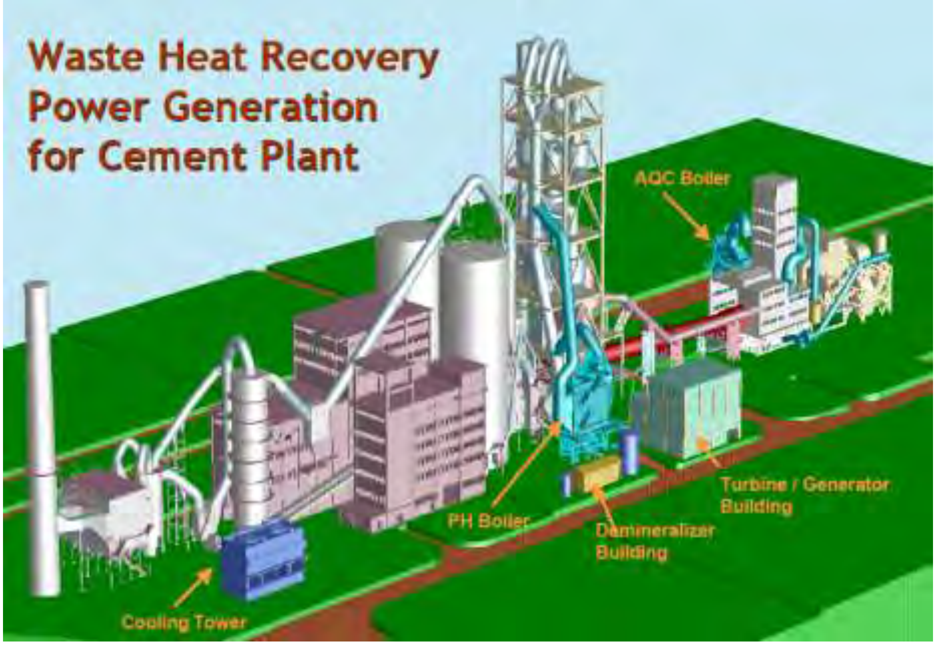
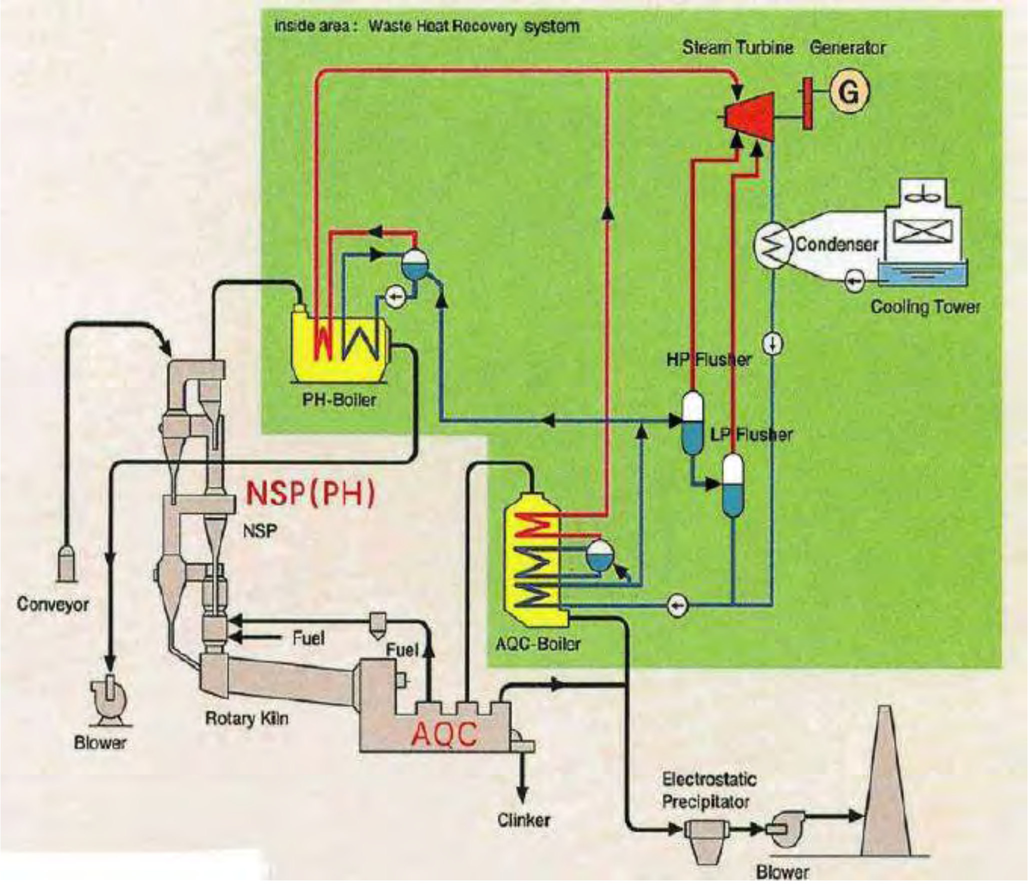


Figure 3.2: Layout diagram of WHR PG plant using the water-steam circuit

<u>Figure 3.3:</u> Preheater boiler & turbine / generator house installed by Kawasaki at Ha Tien plant in Vietnam



<u>Figure 3.4:</u> Basic flow sheet of WHR PG system using the water-steam technology

Different system configurations may be used (e.g. one-pressure level or two-pressure level systems). All conventional Rankine cycle systems though consist of the following process steps:

- The water exiting the condenser is preheated.
- The water is then converted to steam (boiled).
- The steam is superheated (heated to a temperature above its saturation temperature at the actual pressure conditions).
- The superheated steam expands in the turbine, generating power (reflecting the operating efficiency of the turbine). The expansion decreases the steam temperature and pressure.
- The steam /water exiting the turbine is condensed to liquid form in the condenser.

The conventional Rankine system has several potential drawbacks. The main potential drawback is high turbine blade erosion rate. Water droplets, impinging on the blades at high speed, cause high erosion on the turbine last stage blades. The recommended steam quality exiting the turbine is 90-95% steam to minimise erosion damage (note that the 5-10% would be in the form of water droplets). The steam quality at the turbine exit is affected by the following factors:

- turbine steam inlet conditions
- turbine efficiency
- condensing conditions at the exit of the turbine

Typically, when designing a WHR system, the objective would be to maximise the power generated. To accomplish this requires the minimisation of the condensing temperature and pressure, and maximal efficiency of the turbine selected. This decreases the steam quality, thus increasing the amount of droplets at the turbine exit. The turbine steam inlet conditions can be designed to maintain appropriate conditions. This will maintain the recommended steam quality exiting the turbine, provided the waste heat source is at a sufficiently high temperature. For reference, a turbine inlet pressure of 2,3MPa requires the steam temperature to be in the range of 300 to 385°C. At lower steam pressures, the required steam temperature range would be lower.

In cement plant applications where the preheater exit gases are near 300°C, the WHR system designer may elect to pass the steam from the preheater to a super heater located in the clinker cooler vent air to achieve the required steam temperature. However, the air temperature variation from the clinker cooler is substantially higher than from the preheater. This variation may result in steam temperatures at times lower than the required temperature to ensure the recommended steam quality. When this happens, the erosion rate increases, resulting in increased maintenance requirements or possibly the need to shut down the system.

3.1.2 ORC system

The ORC system uses an organic fluid as its working fluid. The ORC systems are designed with two heat transfer stages. The first stage transfers heat from the waste gases to a heat transfer fluid (thermal oil or water). The second stage transfers heat from the thermal oil or water to the organic fluid.

ABB proposes this system as the best for energy efficient cement power plants, where we have low waste heat temperature, so 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 fluids deliver a considerable amount of energy when it is expanded in the turbine.

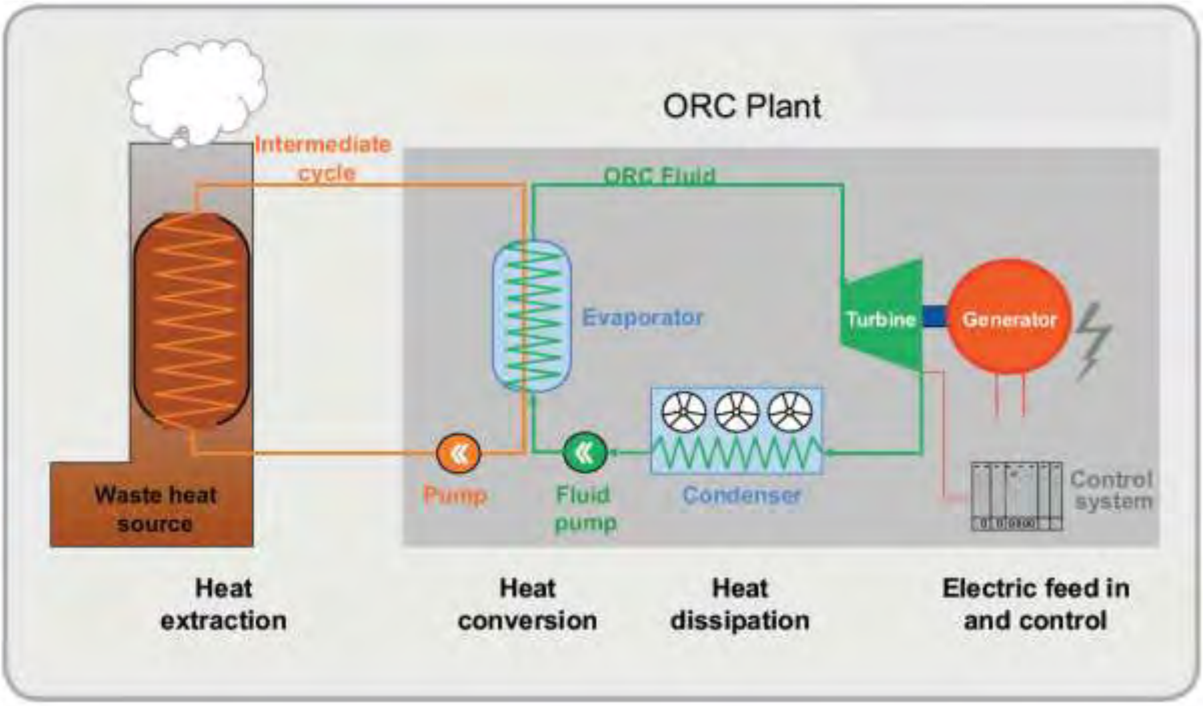


Figure 3.5: Organic Rankine Cycle power plant

The ORC power plant consists of the following main systems:

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

Heat extraction

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: the warmer the weather, the higher the back pressure and thus the lower the produced electrical power.

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 under cooled. 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 or dry air condenser

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.

Water usage and water saving are big issues in many countries. Therefore, when considering this topic with regard to sustainability, the ABB ORC power plant specifically uses high-end dry condensers designed 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.

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 ORC power plant ideally to the operating conditions of the cement plant.

The figure below 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.

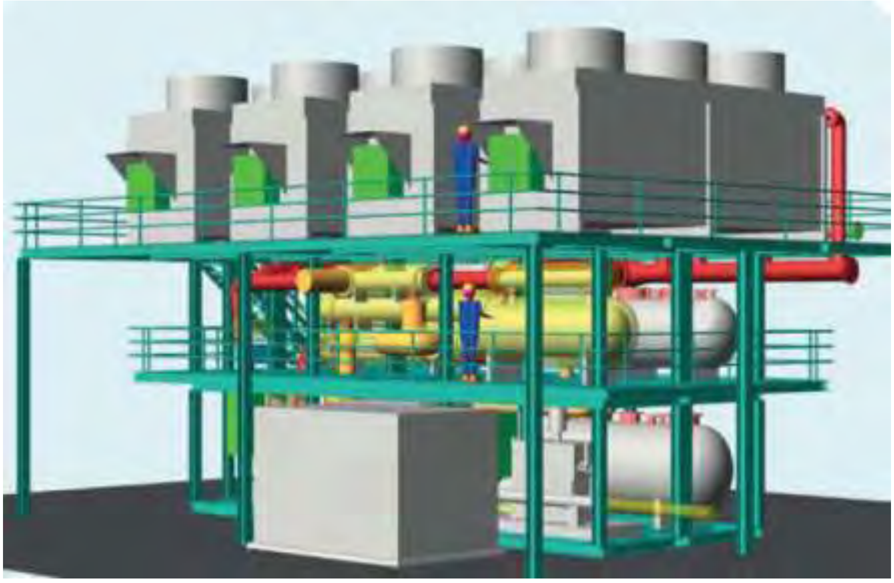


Figure 3.6: Layout of the ABB ORC power plant

The ORC has several **advantages** over the conventional Rankine system. They include the following:

- The organic fluid properties result in the working fluid remaining dry throughout the turbine, thereby avoiding any erosion problems.
- The organic fluid properties permit some of the heat in the working fluid exiting the turbine to be transferred to the working fluid exiting the pump (condenser exit), thereby increasing the overall cycle efficiency.
- If the heat is transferred to the working fluid exiting the pump, then the required amount of heat to dissipate from the condenser would be lower than the amount required otherwise. This would reduce the size of the condenser system. It would also reduce the amount of water consumed in the cooling tower, or the amount of air used in the air heat exchanger.
- The organic fluid properties permit some the WHR system to recover heat from gases that are at a lower temperature than what is possible with a conventional Rankine system.
- ORC systems are designed with the condensing pressure near but above atmospheric pressure. N-pentane, one of the organic fluids used in ORC systems, has a condensation temperature of 36°C at one atmospheric pressure. This reduces the risk of air leakage into the ORC system and eliminates the requirement for a de-aerator as in the case of the conventional Rankine cycle system.
- The organic fluid is not susceptible to freezing. Hydrocarbons freeze at temperatures below -73°C. N-pentane has a freezing temperature -129.8°C.
- The turbine would have fewer stages compared to the steam turbine.
- The piping from the heat exchangers to the turbine would be smaller in diameter than those required for a steam system.
- ORC systems can withstand larger temperature variations of the preheater and clinker cooler gases used for waste heat recovery.

- Depending on the application, the ORC system may have a lower specific cost than the conventional Rankine system.
- Typically, the ORC system has lower maintenance costs than the conventional Rankine Cycle system.

The ORC system also has its **disadvantages**, including:

- It does not generate as much power as the conventional Rankine cycle system.
- Depending on the application, the ORC system may have a higher specific cost.
- Heat transfer fluids and organic fluids normally used in these systems are combustible. If used, the system would require measures for fire protection and replacement after a certain amount of operating time. It is also an environmental concern if there are any leaks.

3.1.3 KALINA system

This technology is based on the generation of electrical power by using heat-energy in order to vaporise a mixture of ammonia and water, which is running in a close circuit.

Additional heat of the condenser either will be destroyed via cooling towers or if possible will be used further for some limited applications. The mixture of ammonia – water makes this technology exceptional. The technique is named after Dr. Alexander Kalina, who is a Russian living in USA. The Kallina technology has been developed over two decades, however the commercial marketing of the technique started only a few years ago. Behind the developed technique was the idea to use the waste heat of different industrial sources, like gas turbine or other combustion processes.

Ammonia and water, as well as other single component media vaporises and condensates at a stable / constant temperature. But the technical feature of the Kalina technology is coming from the ammonia – water mixture, which evaporates over a large temperature range. This feature gives the opportunity to utilize sensible heat sources more effectively compared to a single component media. This leads to an effectiveness increase of the electrical power generation by 20-40% compared to the well known Organic Rankine Cycle (ORC).

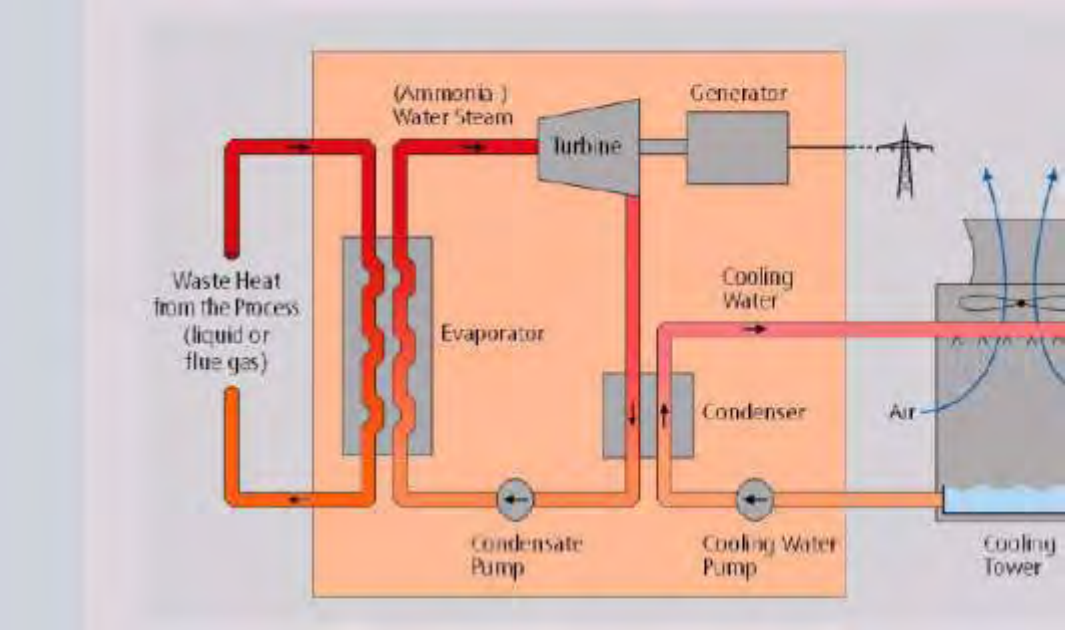


Figure 3.7: Typical working principle of Kalina power plant

Ammonia is inexpensive and is used extensively as single substance as well as in mixtures with water in industry, e.g. for absorption chiller applications. The temperature within such refrigeration cycles is quite similar compared to low temperature power cycles. Thermodynamic properties for calculating cycle components like heat exchangers, pumps and piping are well known. Even if ammonia has toxic potential there is a lot of experience in handling the substance and operating ammonia cycles. Furthermore, the environmental impact if emitted in case of failure may be neglected. Ammonia has no ozone depletion potential and no direct global greenhouse potential. Authorities' safety regulations similar to chiller applications may be expected for power plants.

Concluding, the Kalina cycle system has several advantages over the conventional Rankine system and the ORC system. They include the following:

- The system can be used in lower temperature applications than the conventional Rankine Cycle system.
- The working fluid is not flammable.
- The system requires only one heat transfer stage.

3.2 Systems' installations around the world

WHR power generation in the cement industry is dominated primarily by the conventional steam and water Rankine cycle systems. One of the system suppliers, for example (Kawasaki), has 106 installations listed between 1980 and 2011.

To date, the ORC system has had limited installations in the cement industry. Ormat, one of the ORC system suppliers, has two installations, one in India and one in Lengfurt. ABB is another supplier of the ORC system. At the moment, no ABB system is installed and operating in a cement plant. However, Holcim has recently contracted ABB to install an ORC system in a plant in Switzerland. No other suppliers currently supply ORC systems to the cement industry.

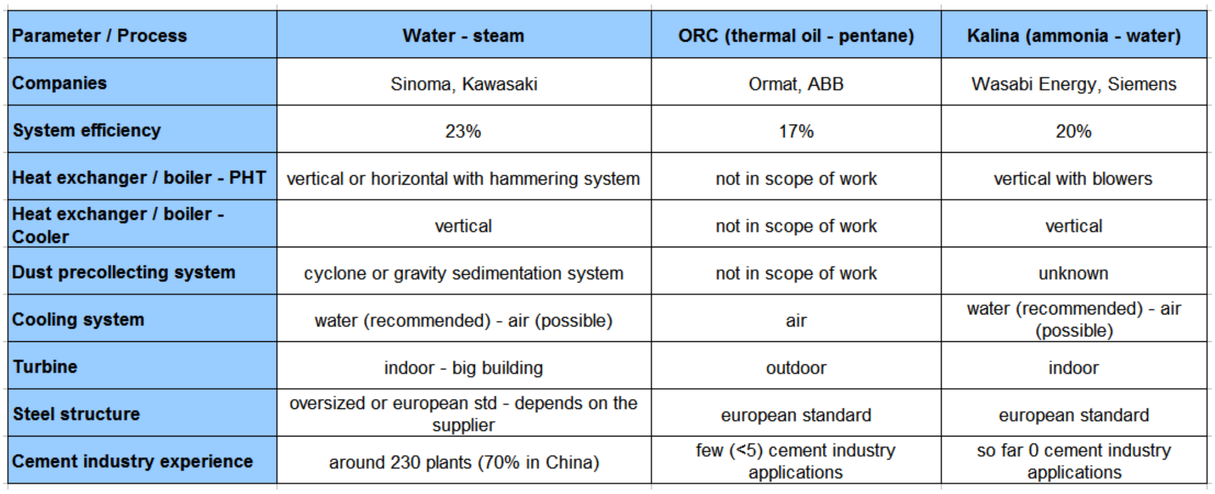
Today, there is no Kalina cycle system operating in a cement plant. Wasabi Energy and Siemens supply the Kalina cycle system. Wasabi Energy recently announced that they have secured a contract to build a kalian cycle power plant in Pakistan. The kalian cycle system has been installed in other industries, such as steel making, oil refinery and municipal incineration.

The most important variables to get evaluated for the optimum selection include:

- optimum system sizing
- optimum system configuration
- expected variation in waste heat source
- heat exchanger or HRSG design
- condenser system selection
- water treatment system

Additional items for consideration include whether to install a system to recover waste heat from more than one kiln system at a time and preferences of equipment suppliers.

The main parameters of the different systems' characteristics are presented below:



Parameter / Process	**Water - steam**	**ORC (thermal oil - pentane)**	**Kalina (ammonia - water)**
Companies	Sinoma, Kawasaki	Ormat, ABB	Wasabi Energy, Siemens
System efficiency	23%	17%	20%
Heat exchanger / boiler - PHT	vertical or horizontal with hammering system	not in scope of work	vertical with blowers
Heat exchanger / boiler - Cooler	vertical	not in scope of work	vertical
Dust precollecting system	cyclone or gravity sedimentation system	not in scope of work	unknown
Cooling system	water (recommended) - air (possible)	air	water (recommended) - air (possible)
Turbine	indoor - big building	outdoor	indoor
Steel structure	oversized or european std - depends on the supplier	european standard	european standard
Cement industry experience	around 230 plants (70% in China)	few (<5) cement industry applications	so far 0 cement industry applications

<u>Table 3.1:</u> Main systems' characteristics

Summary

WHR PG systems operate based on the Rankine cycle. Three primary types of WHR systems are available, with the working fluid being the differentiating factor:

- Water –steam circuit or conventional Rankine cycle (water-steam)
- Organic Rankine circuit (organic fluid)
- Kalina circuit (water-ammonia mixture)

Each one of the above systems has its own advantages and disadvantages and is proposed by different suppliers around the world.

Currently, water-steam cycle has the most applications for WHR PG in cement industry around the world, ORC only some applications mostly the recent years while there is no application for Kalina system in the cement industry yet.

The optimum selection though for a specific application has to be based on the specificities of the respective installation.

Chapter 4 Simulation results

This chapter aims at defining the optimum system for power generation from waste heat in Volos plant. Three different configurations are examined, using the commercial software EES. Firstly, a water-steam circuit with one turbine, then a water-steam circuit with two turbines and lastly an Organic Rankine Cycle with intermediate pressurized water circuit. At the end of the chapter, a technical comparison table is presented.

4.1 Engineering Equation Solver (EES)

The software used for the simulation of all the examined systems is EES. EES is an acronym for Engineering Equation Solver. The basic function provided by EES is the numerical solution of non-linear algebraic and differential equations. EES is an equation solver, rather than a programming language, since it does not require the user to enter instructions for iteratively solving non-linear equations. EES provides capability for unit checking of equations, parametric studies, optimization, uncertainty analyses and high quality plots. It provides array variables that can be used in finite-difference calculations. In addition, EES provides high accuracy thermodynamic and transport property functions for many fluids and solid materials that can be integrated with the equations. The combination of all of these capabilities in one program makes EES a very powerful tool for solving thermodynamic and heat transfer problems.

4.2 Basic data and equations

In this section, the basic data and equations for analyzing the system are presented. First of all, for each gas stream, the heat that can be recovered was calculated in chapter 2 as:

Qexh_ pht = 23323 kJ/s
Qexh_cool = 14573 kJ/s

Moreover, the exhaust gas temperatures were defined, and are the following:

Tin_pht = 390 (°C)
Tout_pht = 200 (°C)
Tin_cool= 260 (°C)
Tout_cool= 110 (°C)

The basic thermodynamic equations for each one of the components of the systems are presented below. The equations are given in a general form, considering in all cases that 1 is the input point of each element and 2 is the output point. The analysis of the three systems, later in this chapter, is based on these equations.

Heat exchanger

The required area for each heat exchanger is calculated using the equation:

$$A_b = K \cdot \frac{Qexh}{U_b \cdot DTL} \tag{4.1}$$

where:

A_b: heat exchange area (m^2)
K: coefficient for the contact area, for higher efficiency (-)
Q_{exh}: heat available for recovery (kJ/s)
U_b: overall heat transfer coefficient (kJ/(s*m^2*°C)
DTL: logarithmic mean temperature difference (°C), which is calculated using the relation:

$$DTL = \frac{DT1 - DT2}{\ln\left[\frac{DT1}{DT2}\right]} \tag{4.2}$$

where DT1 is the temperature difference between the two streams at end 1, and DT2 is the temperature difference between the two streams at end 2, for a counter-flow heat exchanger.

The mass of the steam produced is calculated using the equation:

$$m = a \cdot \frac{Qexh}{Dh} \tag{4.3}$$

where:

m: mass of the steam produced (kg/s)

a: efficiency of the heat exchanger (-)

Q_{exh}: heat available for recovery (kJ/s)

Dh: enthalpy difference of the working medium (kJ/kg), which is calculated using the equation:

$$Dh = h2 - h1 \tag{4.4}$$

where

h1: the enthalpy of the working medium at the input and

h2: the enthalpy of the working medium at the output of the heat exchanger, both at the operation pressure of the heat exchanger.

The heat into the system through the heat exchanger is calculated using the equation:

$$Q_{in} = h2 - h1 \tag{4.5}$$

where

Q_{in}: heat imported into the system through the heat exchanger (kJ/kg)

and h1, h2 as above.

Finally, it is important to mention that the pressure drop at the heat exchangers is considered negligible at all the systems examined.

Pump

The mechanical power provided to the system by the pump is:

$$W_{pump;in} = \frac{Ws_{pump;in}}{\eta p} \tag{4.6}$$

where:

W_{pump_in}: mechanical power provided to the system (kJ/kg),

η_P: isentropic efficiency of the compression (%)

W_{spump_in}: isentropic mechanical power provided to the system (kJ/kg), which is calculated using the equation:

$$Ws_{pump;in} = v_1 \cdot (P_2 - P_1) \tag{4.7}$$

where:

v1: volume of working medium at the pump input (m3/kg)
P1: pressure of working medium at the pump input (kPa)
P2: pressure of working medium at the pump output (kPa)

The enthalpy of the working medium at the pump output is calculated using the equation:

$$h_2 = h_1 + W_{pump;in} \tag{4.8}$$

where:

h2: enthalpy of working medium at the pump output (kJ/kg)
h1: enthalpy of working medium at the pump input (kJ/kg)
W_{pump_in}: mechanical power provided to the system (kJ/kg)

Turbine

The mechanical power produced at the turbine is:

$$W_{turb;out} = \frac{Ws_{turb;out}}{\eta t} \tag{4.9}$$

where:

W_{turb_out}: mechanical power produced by the turbine (kJ/kg),
η_t: isentropic efficiency of the expansion (%)
W_{sturb_out}: isentropic mechanical power produced by the turbine (kJ/kg), which is calculated using the equations:

$$W_{turb;out} = h_1 - h_2 \tag{4.10}$$

$$Ws_{turb;out} = h_1 - hs_2 \tag{4.11}$$

where:

h1: enthalpy of working medium at the turbine input (kJ/kg)
h2: enthalpy of working medium at the turbine output (kJ/kg)
hs2: enthalpy of working medium at the turbine output, for isentropic expansion (kJ/kg)

Condenser

For the condenser analysis, the following equation is used:

$$h_1 = Qout + h_2 \tag{4.12}$$

where:

h1: enthalpy of working medium at the condenser input (kJ/kg)
h2: enthalpy of working medium at the condenser output (kJ/kg)
Qout: heat out of the system through the condenser (kJ/kg)

In all the systems under examination, we consider that there is no pressure drop at the condenser.

4.3 Water-steam system

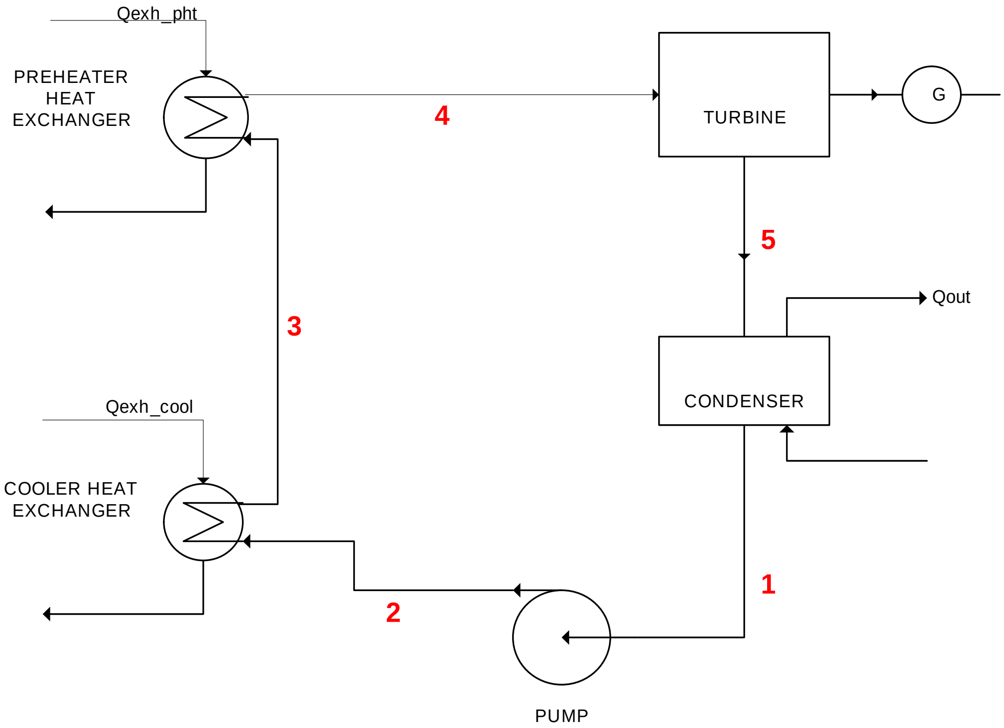


Figure 4.1: Heat recovery system with water-steam cycle

The first system examined is a water-steam cycle in order to recover the waste heat from the cement industry process. The examined system and its specification are presented in Figure 4.1.

The cycle's maximum pressure is 1700kPa at a maximum temperature of 350°C at the inlet of the turbine. The exhaust steam of the turbine, at a pressure of 6kPa, is condensed in the condenser and then pumped into the cooler heat exchanger where is preheated to 150°C.

Then, the stream passes through the preheater heat exchanger where it is evaporated and superheated to 350°C. The superheated steam enters the steam turbine and the process is repeated.

In this system, as in all systems examined in this chapter, it is considered that the preheater heat exchanger sets the mass of the steam produced. In other words, all the heat available for recovery from the preheater exhaust gas stream is used while only a part of the available for recovery heat of the cooler exhaust gas is used, actually the amount needed in order to preheat the water to the required temperature.

The main system characteristics used for the analysis of the water-steam cycle are summarized in Table 4.1.

System parameters	
Turbine isentropic efficiency (%)	85
Pump isentropic efficiency (%)	70
Efficiency of each heat exchanger (%)	90
Overall heat transfer coefficient for each heat exchanger (Kj/(s*m^2*°C))	0,075
Coefficient for the contact area of each heat exchangers, for higher efficiency (-)	1,15

Table 4.1: System characteristics

The thermodynamic diagram T-S for the described system is presented in figure 4.2, while all the thermodynamic parameters are summarized in Table 4.2.

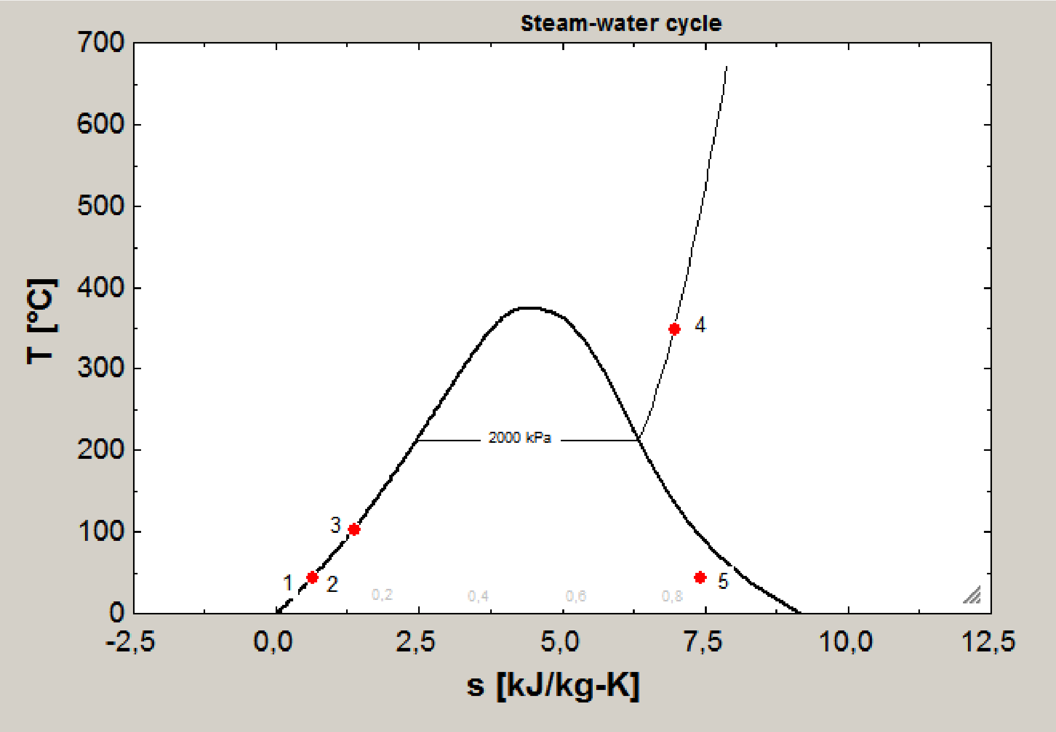
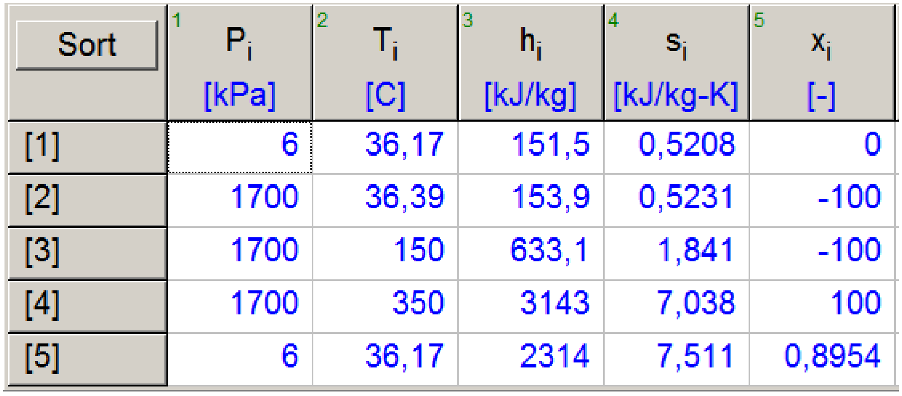


Figure 4.2: T-S process diagram for water-steam cycle

There are four processes in the Rankine cycle (these states are identified by numbers in the above T-S diagram), the following:

- **Process 1→2:** The working fluid is pumped from low to high pressure. As the fluid is a liquid at this stage the pump requires little input energy.
- **Process 2→3→4:** The high pressure liquid passes through the heat exchangers where it is preheated (2→3) and heated (3→4) at constant pressure to become overheated steam.
- **Process 4→5:** The overheated steam expands through a turbine, generating power. This decreases the temperature and pressure of the vapour, and some condensation may occur.
- **Process 5→1:** The wet vapour then enters a condenser where it is condensed at a constant temperature to become a saturated liquid.



Sort	1 P_i [kPa]	2 T_i [C]	3 h_i [kJ/kg]	4 s_i [kJ/kg-K]	5 x_i [-]
[1]	6	36,17	151,5	0,5208	0
[2]	1700	36,39	153,9	0,5231	-100
[3]	1700	150	633,1	1,841	-100
[4]	1700	350	3143	7,038	100
[5]	6	36,17	2314	7,511	0,8954

<u>Table 4.2:</u> Water-steam cycle points

The cycle statistics were calculated using the following equations:

$$\mathrm{Wnet} = \mathrm{W}_{\mathrm{turb;out}} - \mathrm{W}_{\mathrm{pump;in}} \tag{4.13}$$

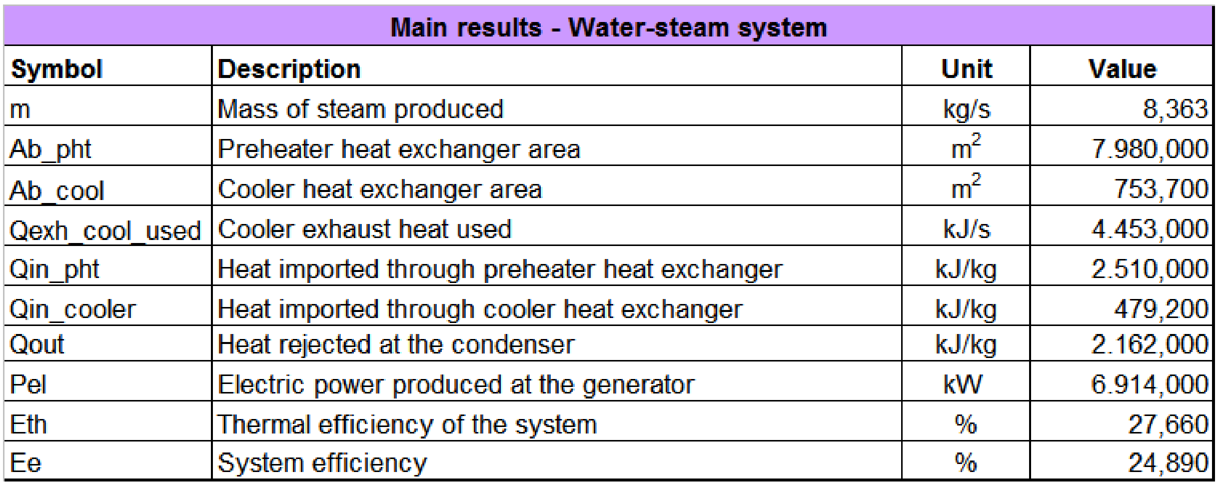
$$\mathrm{Eth} = \frac{\mathrm{Wnet}}{\mathrm{Qin}_{\mathrm{cooler}} + \mathrm{Qin}_{\mathrm{pht}}} \tag{4.14}$$

$$\mathrm{Pel} = \mathrm{m} \cdot \mathrm{Wnet} \tag{4.15}$$

$$\mathrm{Ee} = \frac{\mathrm{Pel}}{\mathrm{Qexh}_{\mathrm{pht}} + \mathrm{Qexh}_{\mathrm{cool;used}}} \tag{4.16}$$

In table 4.3, the description of the different variables of the above equations is given.

The main results are summarized in table 4.3. As a conclusion, the water-steam system has an efficiency of 24,9% producing 6,9MW electric power.



Main results - Water-steam system			
Symbol	**Description**	**Unit**	**Value**
m	Mass of steam produced	kg/s	8,363
Ab_pht	Preheater heat exchanger area	m^2	7.980,000
Ab_cool	Cooler heat exchanger area	m^2	753,700
Qexh_cool_used	Cooler exhaust heat used	kJ/s	4.453,000
Qin_pht	Heat imported through preheater heat exchanger	kJ/kg	2.510,000
Qin_cooler	Heat imported through cooler heat exchanger	kJ/kg	479,200
Qout	Heat rejected at the condenser	kJ/kg	2.162,000
Pel	Electric power produced at the generator	kW	6.914,000
Eth	Thermal efficiency of the system	%	27,660
Ee	System efficiency	%	24,890

Table 4.3: Main results of water-steam system

4.4 Water-steam system, two turbines

The second system examined is a water-steam system with two turbines with target to increase the efficiency of the system. The cycle's maximum pressure is 1700kPa at a maximum temperature of 375°C at the inlet of turbine 1 and 6kPa at the exit of turbine 2. Simultaneously, some of the steam is extracted from turbine 1 at 100kPa in order to be used at the deaerator process. The cooler heat exchanger is used in order to preheat the water to the required temperature (which in our case is set at 195°C). The main system operating parameters, concerning the machinery efficiencies remain the same as in water-steam cycle (table 4.1). The system examined is presented in figure 4.3.

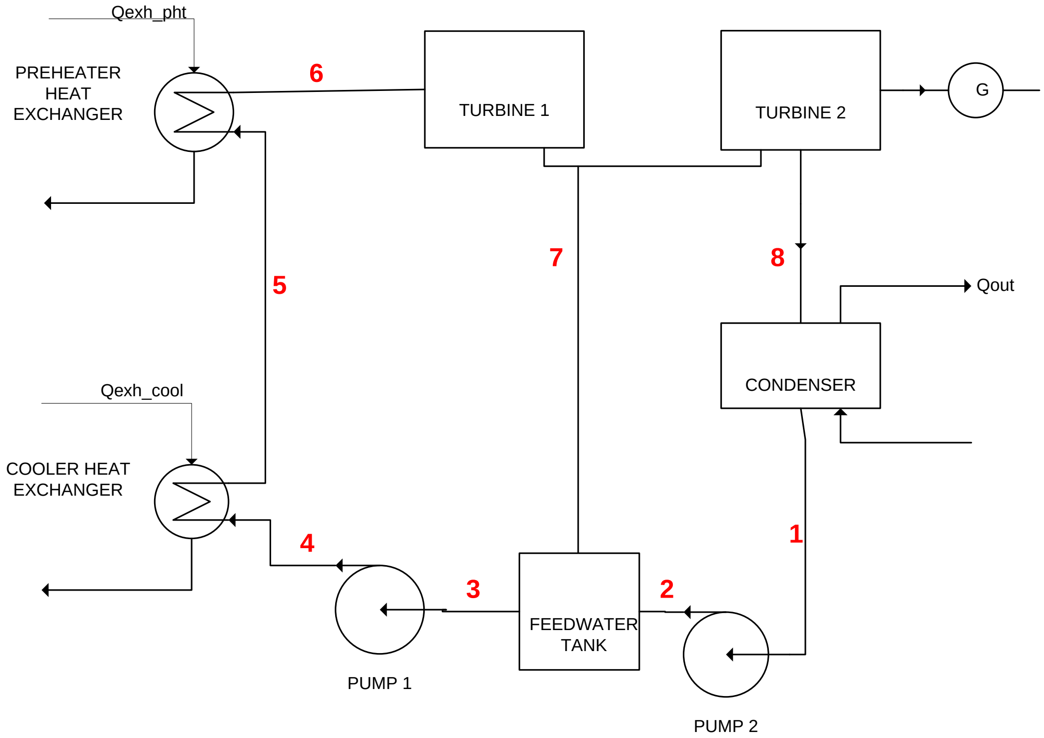


Figure 4.3: Heat recovery system with water-steam cycle - two turbines

The thermodynamic diagram T-S for the described system is presented in figure 4.4, while all the thermodynamic parameters are summarized in Table 4.4.

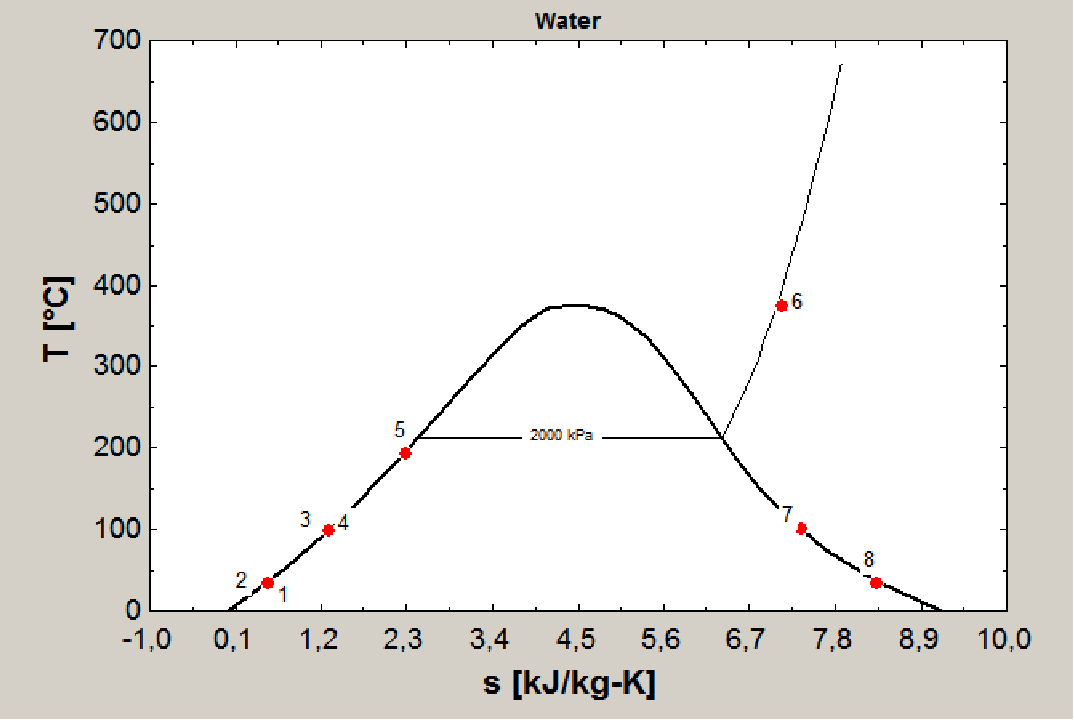
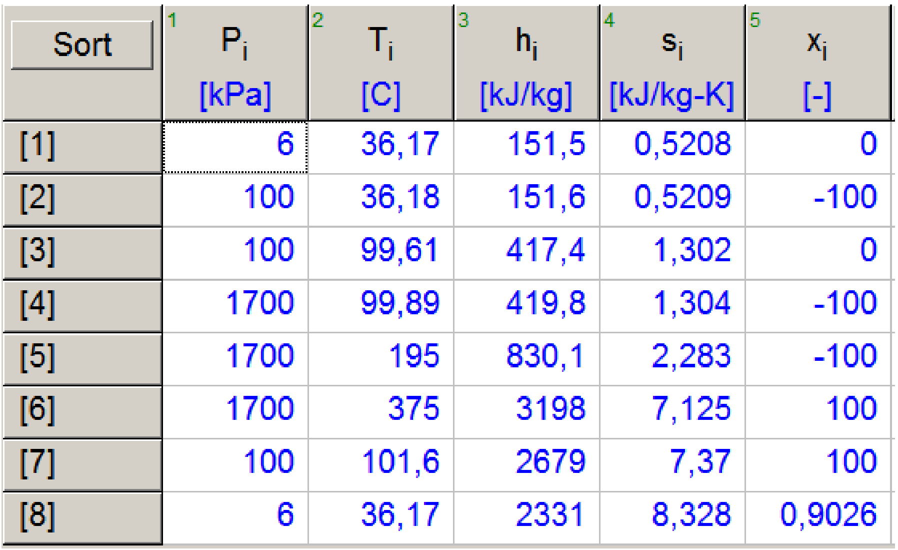


Figure 4.4: T-S process diagram for water-steam cycle – two turbines



	1 P_i [kPa]	2 T_i [C]	3 h_i [kJ/kg]	4 s_i [kJ/kg-K]	5 x_i [-]
[1]	6	36,17	151,5	0,5208	0
[2]	100	36,18	151,6	0,5209	-100
[3]	100	99,61	417,4	1,302	0
[4]	1700	99,89	419,8	1,304	-100
[5]	1700	195	830,1	2,283	-100
[6]	1700	375	3198	7,125	100
[7]	100	101,6	2679	7,37	100
[8]	6	36,17	2331	8,328	0,9026

Table 4.4: Water-steam cycle – two turbines system points

The cycle statistics were calculated using equations (4.14), (4.15), (4.16). The only difference is that in this case Wnet is calculated using the following equation:

$$W_{net} = W_{turb1;out} + (1 - y) \cdot (W_{turb2;out} - W_{pump2;in}) - W_{pump1;in} \qquad (4.17)$$

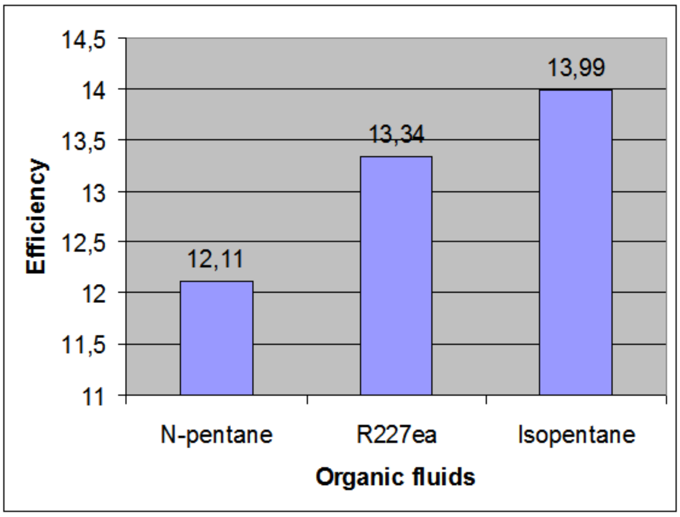
The main results are summarized in table 4.5. As a conclusion, the water-steam system with two turbines has an efficiency of 26,8% producing 7,3MW electric power.

Main results - Water-steam system - Two turbines			
Symbol	**Description**	**Unit**	**Value**
m	Mass of steam produced	kg/s	8,865
Ab_pht	Preheater heat exchanger area	m^2	49.577,000
Ab_cool	Cooler heat exchanger area	m^2	2.101,000
Qexh_cool_used	Cooler exhaust heat used	kJ/s	4.041,000
Qin_pht	Heat imported through preheater heat exchanger	kJ/kg	2.368,000
Qin_cooler	Heat imported through cooler heat exchanger	kJ/kg	410,300
Qout	Heat rejected at the condenser	kJ/kg	2.180,000
y	Percentage of steam not passing through the 2nd turbine	%	10,520
Pel	Electric power produced at the generator	kW	7.335,000
Eth	Thermal efficiency of the system	%	29,780
Ee	System efficiency	%	26,800

<u>Table 4.5:</u> Main results of water-steam system – two turbines

4.5 Organic Rankine Cycle system

Another way to recover the waste heat from a cement plant is an indirect ORC. The ORC is used in low-temperature energy sources, because of the low critical point of the organic fluids. Three different organic fluids were examined in order to choose the most appropriate working fluid regarding the thermodynamic performance for the given temperature limits. As it can be seen in figure 4.5, isopentane is the working fluid with the maximum system efficiency and thus it was selected as the working fluid for the ORC. Other parameters, such as the price of the organic fluid and the energy consumption for its production were not taken into consideration.



<u>Figure 4.5:</u> Comparison of different organic fluids

In an ORC heat recovery system there is an intermediate heat transfer fluid in order to transfer the heat from the heat sources to the working fluid through the heat exchangers. This is necessary for safety reasons, as many organic fluids are inflammable and in case of failure of the heat exchanger the hot medium of the heat source and the organic fluid would get in contact resulting in an explosion. The heat transfer fluid should remain in liquid state and thus pressurized water at 3000kPa is ideal for this use. It is important not to have steam, because steam is not able to transfer the heat to the organic fluid as effectively as water. The system examined is presented in figure 4.6.

There are two different circuits, one with pressurized water and one with the working fluid. The first one absorbs heat from the preheater and cooler exhaust gases, with the two heat exchangers, in order to transfer this heat to the working fluid. The water circuit operates between 220°C and 105°C, which is lower than the exit of the cooler exhaust gas. The energy passes from water to the working fluid through the heat exchanger. At the inlet of the turbine, the organic medium has a maximum temperature and pressure of 185°C and 3000kPa respectively. The turbine exhaust steam goes through the condenser and then the working fluid continues to the water heat exchanger and the system closes. The system operating parameters, concerning the machinery efficiencies remain the same as in water-steam cycle (table 4.1).

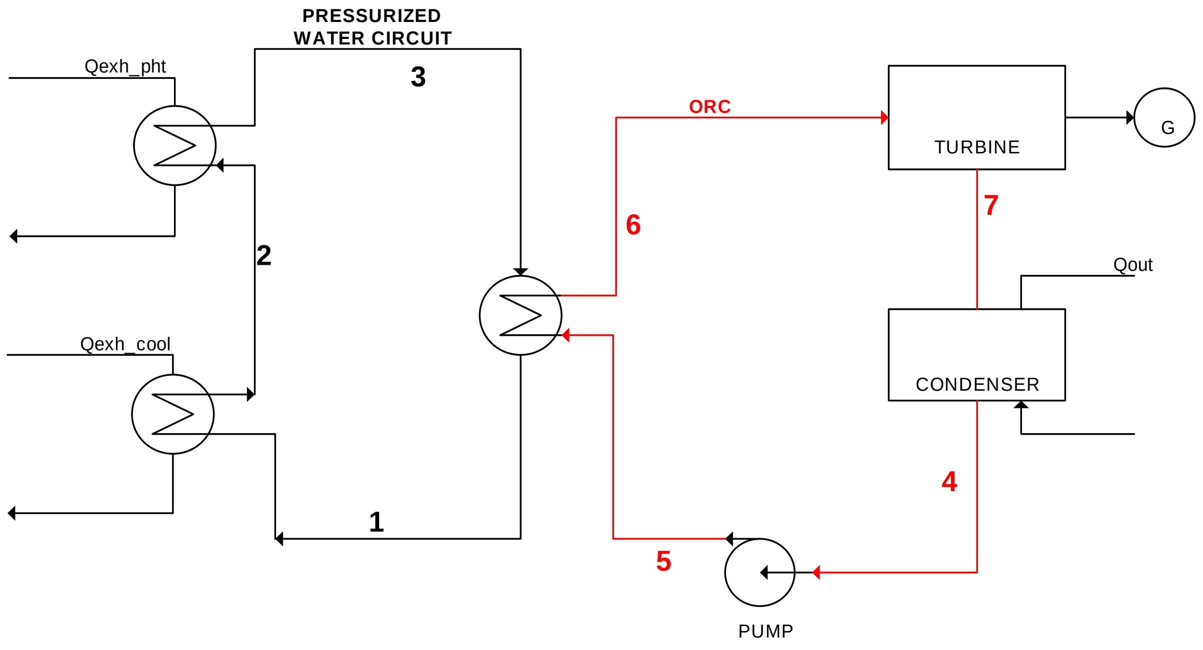


Figure 4.6: Heat recovery system with ORC

The thermodynamic diagram T-S for the described system is presented in figure 4.7, while all the thermodynamic parameters are summarized in Table 4.6.

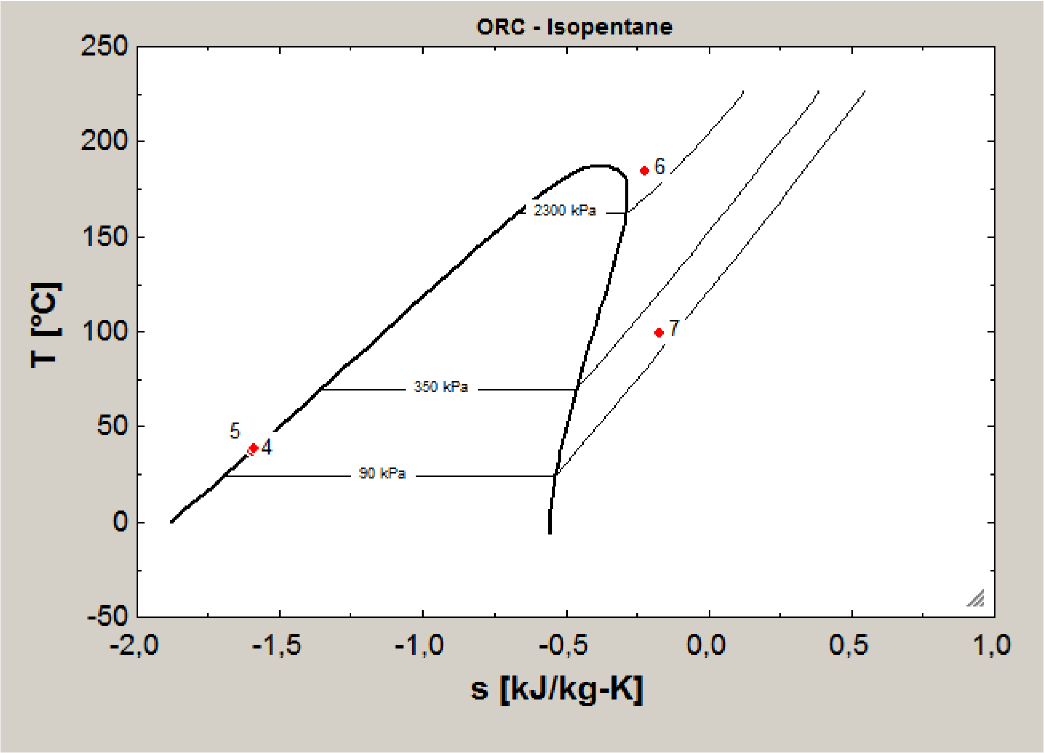
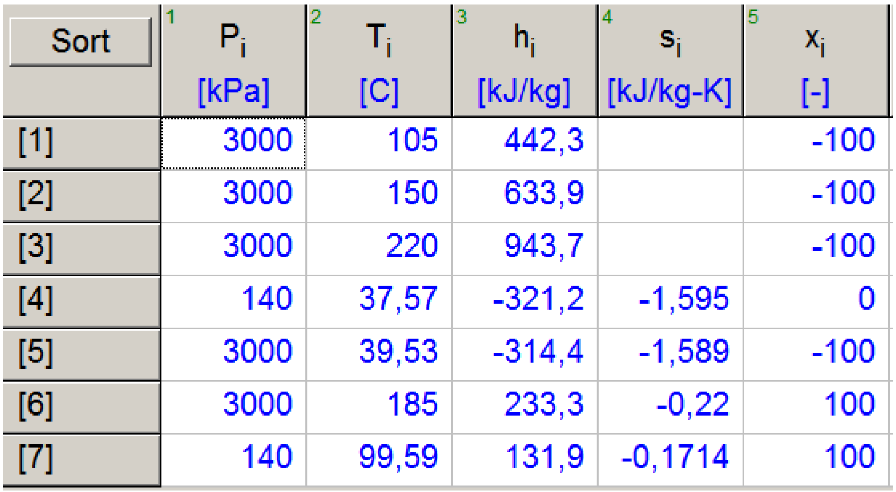


Figure 4.7: *T-S process diagram for isopentane*



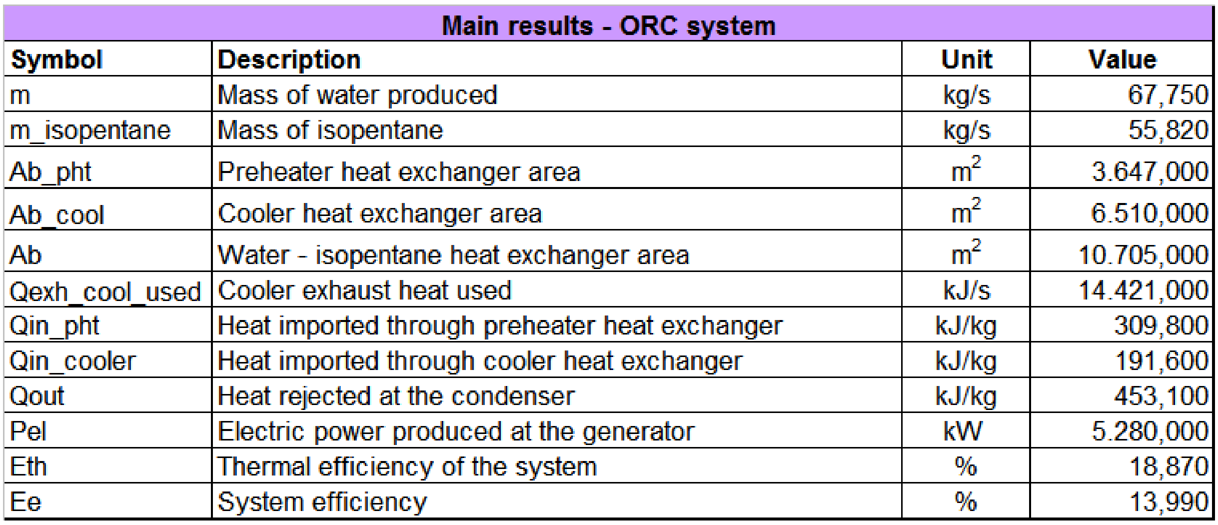
	1 P_i [kPa]	2 T_i [C]	3 h_i [kJ/kg]	4 s_i [kJ/kg-K]	5 x_i [-]
[1]	3000	105	442,3		-100
[2]	3000	150	633,9		-100
[3]	3000	220	943,7		-100
[4]	140	37,57	-321,2	-1,595	0
[5]	3000	39,53	-314,4	-1,589	-100
[6]	3000	185	233,3	-0,22	100
[7]	140	99,59	131,9	-0,1714	100

Table 4.6: *ORC points*

The cycle statistics were calculated using equations (4.13), (4.14), (4.16) and the following equation:

$$Pel = m_{isopentane} \cdot Wnet \quad (4.18)$$

The main results are summarized in table 4.7. As a conclusion, the Organic Rankine Cycle has an efficiency of 14% producing 5,28MW electric power.



Main results - ORC system			
Symbol	**Description**	**Unit**	**Value**
m	Mass of water produced	kg/s	67,750
m_isopentane	Mass of isopentane	kg/s	55,820
Ab_pht	Preheater heat exchanger area	m^2	3.647,000
Ab_cool	Cooler heat exchanger area	m^2	6.510,000
Ab	Water - isopentane heat exchanger area	m^2	10.705,000
Qexh_cool_used	Cooler exhaust heat used	kJ/s	14.421,000
Qin_pht	Heat imported through preheater heat exchanger	kJ/kg	309,800
Qin_cooler	Heat imported through cooler heat exchanger	kJ/kg	191,600
Qout	Heat rejected at the condenser	kJ/kg	453,100
Pel	Electric power produced at the generator	kW	5.280,000
Eth	Thermal efficiency of the system	%	18,870
Ee	System efficiency	%	13,990

Table 4.7: Main results of ORC system

An improvement to the above mentioned system would be to use three heat exchangers instead of one in order to transfer heat from water to the working fluid. In this case, the heat exchangers would perform as preheater, evaporator and superheater. Moreover, a regenerator could be used after the turbine, before the condenser, in order to preheat the working fluid. In this way the system would reject less energy to the environment through the condenser. Normally, the above improvements would result at increased system efficiency.

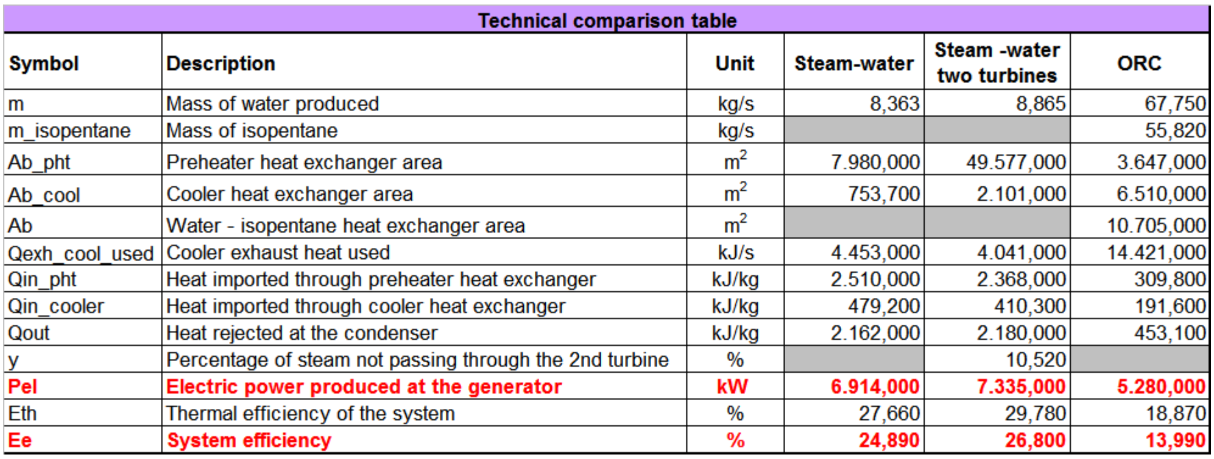
4.6 Recommended variant – Justification

Comparing the three described systems, with use of table 4.8, it is obvious that water steam cycle with two turbines is the system which shows the maximum efficiency with the maximum production of electric power. The difference though with the water-steam system with one turbine is very small. With two turbines, 7,3MW, only 0,4MW more than with one turbine (6,9MW) is produced but in order to achieve this, there is the need of the second turbine plus huge heat exchangers. So the higher cost of the investment, higher space needs & later on the maintenance needs are not justifying the slightly better results. Hence, it is concluded that for the case under examination, the desired result is achieved with just one turbine.

The efficiency of the ORC system is lower. The power generated in this case is 5,3MW. Moreover, in this case the number of required heat exchangers increases and their area in total is also high which makes the space issue really important in case this technical solution is chosen.

Another important remark is that in the case of ORC, almost all the exhaust heat from both sources (preheater and cooler) is used while in the case of water-steam technology only a percentage (around 30%) of the exhaust heat of the cooler stream is used. This means that the system may get stressed and the output will be lower in any case that the volume of the gases at the cooler outlet reduces. Moreover, the exhaust heat from the cooler that is not utilized, in the case of water steam circuit, could be used for other purposes.

On the other hand, it is noticeable the heat rejected at the condenser is significantly lower in the ORC case, which will have a direct impact on the size of the necessary cooling circuit and the quantity of the cooling medium.



Technical comparison table

Symbol	Description	Unit	Steam-water	Steam -water two turbines	ORC
m	Mass of water produced	kg/s	8,363	8,865	67,750
m_isopentane	Mass of isopentane	kg/s			55,820
Ab_pht	Preheater heat exchanger area	m^2	7.980,000	49.577,000	3.647,000
Ab_cool	Cooler heat exchanger area	m^2	753,700	2.101,000	6.510,000
Ab	Water - isopentane heat exchanger area	m^2			10.705,000
Qexh_cool_used	Cooler exhaust heat used	kJ/s	4.453,000	4.041,000	14.421,000
Qin_pht	Heat imported through preheater heat exchanger	kJ/kg	2.510,000	2.368,000	309,800
Qin_cooler	Heat imported through cooler heat exchanger	kJ/kg	479,200	410,300	191,600
Qout	Heat rejected at the condenser	kJ/kg	2.162,000	2.180,000	453,100
y	Percentage of steam not passing through the 2nd turbine	%		10,520	
Pel	**Electric power produced at the generator**	**kW**	**6.914,000**	**7.335,000**	**5.280,000**
Eth	Thermal efficiency of the system	%	27,660	29,780	18,870
Ee	**System efficiency**	**%**	**24,890**	**26,800**	**13,990**

Table 4.8: Technical comparison table

Conclusively, the most suitable cycle for Volos plant case is the water steam cycle with one turbine.

At this point, it should be noted that even though there are many existing heat recovery systems that use the ORC technology, it is concluded that the water steam cycle in this case is the more efficient solution. This is a result of the relatively high temperature level of the heat source which is over 350°C. The higher critical temperature and pressure of water provide increased efficiency compared to organic fluids. In case of lower exhaust gas temperatures, it can be shown that ORC heat recovery systems are more efficient.

The examined water – steam circuit is quite simple. There are many improvements that can be made on the proposed system in order to increase its efficiency but these may have higher capital cost. For example, for the water steam cycle it is possible to add preheating. More specifically, it is possible to drive steam after turbine 1 to the cooler heat exchanger in order to reheat it before exhausting it to turbine 2.

Finally, it is important to note that the presented analysis gives results only concerning system efficiency. A complete techno-economic analysis of each process should be implemented in order to provide the most feasible solution also from economical point of view.

Summary

Based on the amount of waste heat and the gases' temperatures at the two points of interest (after the preheater and after the cooler) for Volos plant, three different configurations for power generation are examined in terms of efficiency and electrical power generated, using Engineering Equation Solver:

- Water-steam circuit with one turbine
- Water-steam circuit with two turbines
- Organic Rankine Cycle

Analyzing the results, it comes up that the water-steam circuit with one turbine is the preferable solution for Volos plant. The proposed configuration, even if quite simple, results in power generation of 6,9MW with a total efficiency for the system around 25%, while there are possibilities to further increase both the generated power and the efficiency by slightly different configurations, for example by adding preheating to the system.

Chapter 5 Recommended variant – Technical & operational aspects

The main equipment of the Waste Heat Recovery Power Generation (WHR PG) plant as well as the incorporation into the existing plant layout is presented in this chapter. Moreover, the impact of the WHR PG unit on the normal plant operation is investigated.

5.1 Incorporation into the plant system – New flow sheet

The proposed way to incorporate WHR system into the existing layout is given in figure 5.1 (all the new equipment is coloured in red). The preheater heat exchanger is placed after the ID fans and in parallel to the existing conditioning tower. During normal operation, the conditioning tower will be bypassed and the full amount of gases will pass through the new preheater heat exchanger. In case of shut down of the WHR plant, the waste gases will be redirected to the conditioning tower, with use of the regulating damper.

The parallel installation will allow to compensate in some extent the pressure drop caused by the new preheater heat exchanger, which is expected to be around 10mbar. In order to compensate this additional pressure drop though, the speed of the ESP fan will have to increase. Currently, ESP fan operates at 930rpm with its nominal value being 990rpm so it is considered that this additional pressure drop can be faced.

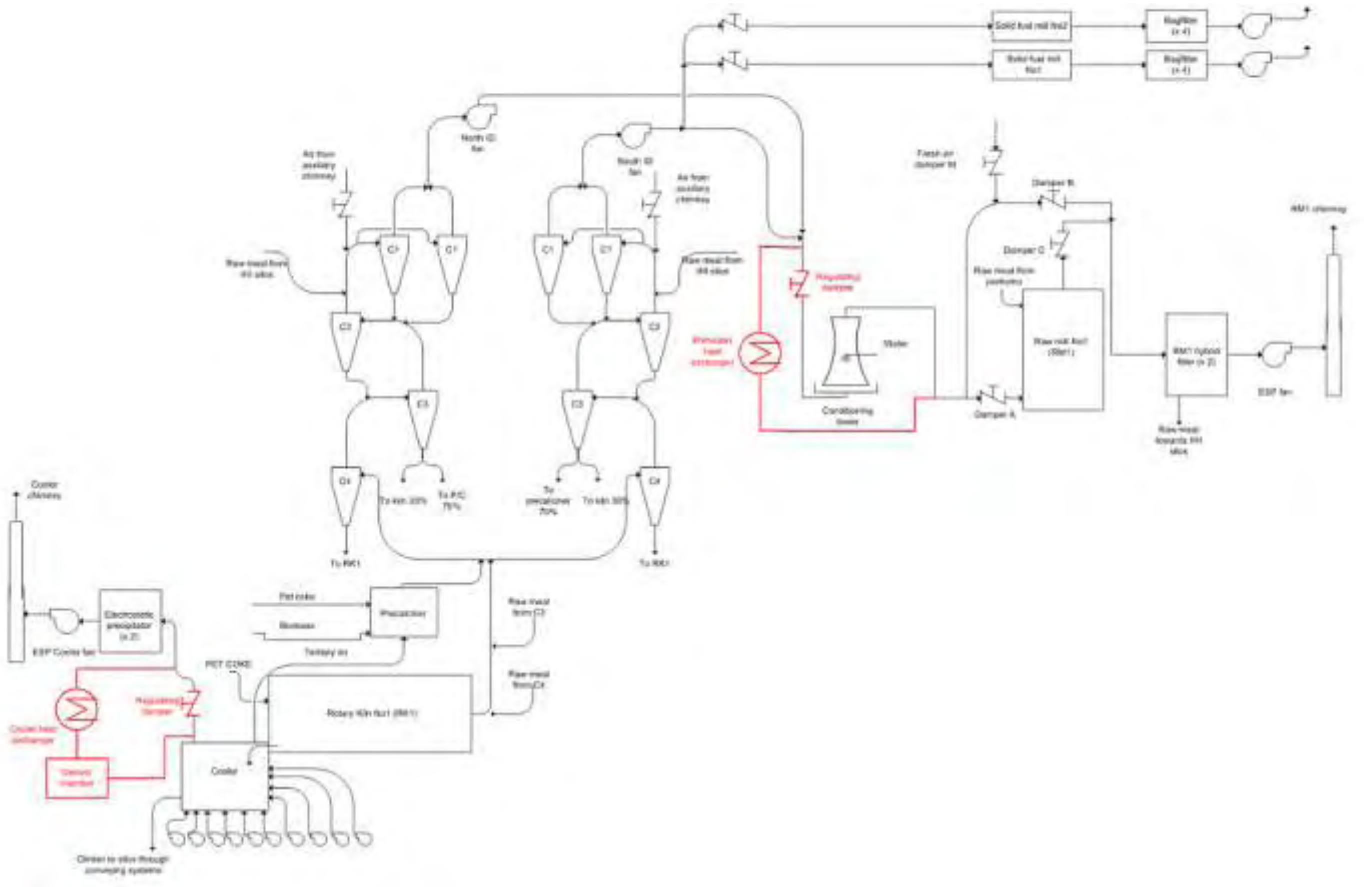


Figure 5.1: Volos plant – New flow sheet of clinker production

At the cooler side, part of the exhaust gases after the cooler will get driven to a dust pre-collecting system before they enter the cooler heat exchanger. The gases after the heat exchanger, at lower temperature, will pass through the existing ESP filter before being released into the atmosphere. The other part of the gases will follow their normal way, directly to the ESP filter. The installation of a new regulating damper is necessary in order to achieve the above.

As in the preheater side, in case of shut down of the WHR plant, the full amount of cooler waste gases will be driven directly to the ESP filter. In this way, the by-pass mode operation of the WHR power generation plant is ensured.

It is important to mention at this point that it is possible, even though according to the calculations of the previous chapter not necessary, to install a new cooler exhaust duct in the midpoint of the cooler and get all the gases for the WHR system from this point. In this way, the heat available for recovery would be higher, because of the higher temperature of the gases.

5.2 Description of basic mechanical equipment

In this paragraph, the main elements of the new installation are presented. These are the following:

- **Preheater heat exchanger**

  There are two different types of preheater heat exchangers: horizontal heat exchanger with vertical tubes and vertical heat exchanger with horizontal tubes arrangement. In horizontal heat exchanger there is less dust deposit, the cleaning of tubes is easier and the heat exchange efficiency in long term is higher / more stable. The draw back is the more difficult dust evacuation system as well as bigger space demand.

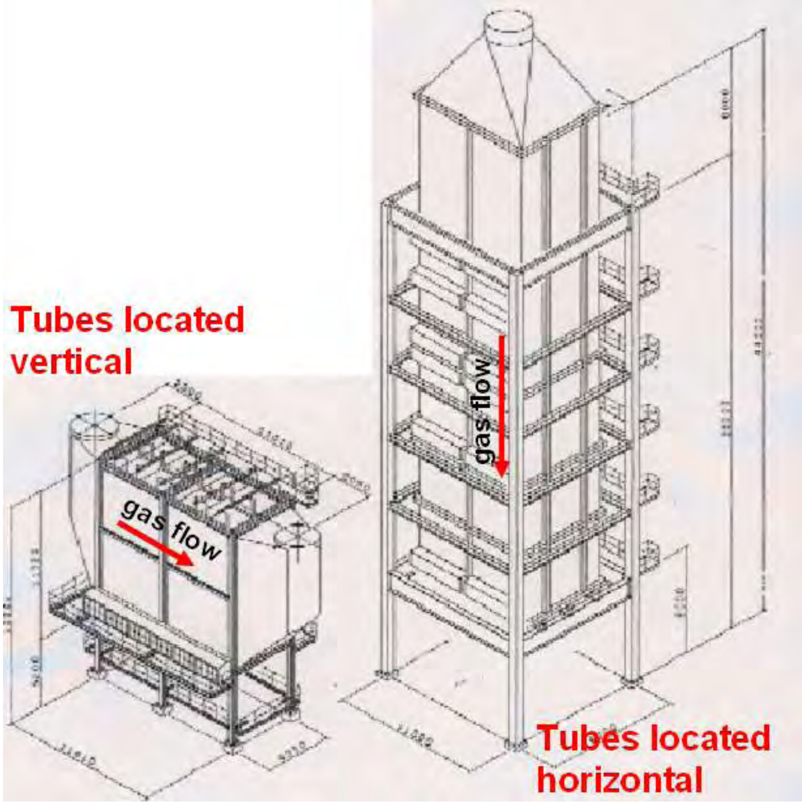


Figure 5.2: Horizontal and vertical type heat exchangers

Figure 5.3: Dust deposit in vertical heat exchanger

The waste gases from preheater contain high dust concentration (85gr/Nm3). Accordingly the waste heat exchanger should be able to withstand high dust load. Moreover, the operating conditions in cement plants require design of waste heat exchangers which should be able to withstand the problems of heavy coating formation, as the raw meal dust tends to adhere to the heat exchanging surfaces, resulting in drastic reduction of capacity and the wear of tubes due to coarse clinker particles.

Waste heat exchangers are typically huge rectangular boxes containing economiser, evaporator and superheating coils. Sometimes supplementary firing is also needed for additional steam generation (in this case they are referred to as WHR boilers). Depending on the space availability, horizontal or vertical configuration is adopted. Same constraint also determines the water/ steam circulating system used for a unit (natural or forced / assisted circulation).

The heat exchangers for exhaust gas are often exposed to heavy coating formation as the raw meal dust tends to adhere to the heat exchanging surface. The dust that settles on the heat transfer surfaces reduces the area available and reduces heat transfer coefficients and hence the rate of transfer. So, using a proper dust removal system becomes essential. To avoid this, the heat exchangers are normally designed with straight tubes which are continuously or periodically cleaned by steam or air shoot blowers, conic waves, mechanical hammering / rapping or steel shot dispersion. Of these methods the latter two have proved to be the most effective.

The required area for the preheater heat exchanger was calculated in chapter 4 at 7.980m2.

- **Dust transport system**

In the preheater heat exchanger a proportion of the dust (up to 70%) will be collected. Afterwards, this dust has to be transported away by means of the existing cooling tower bucket elevator (supposing the capacity is enough) and join the existing dust transport equipment from the hybrid filter.

- **Clinker cooler heat exchanger**

The clinker cooler heat exchanger area is 753,7m2 (calculated in chapter 4), as this exchanger is used only in order to preheat the water in the system.

The dust concentration in the waste gases is in this case much lower than the preheater case, around 30gr/Nm3. In order to collect this dust before entering the cooler heat exchanger, a dust pre-collecting system will get installed. The collected dust will be returned to the cooler.

- **Turbine / generator**

There are two types of turbines, for the single pressure system and the double pressure system or flasher system (different configurations for the water-steam system). The second type of turbine is more expensive (around 25%) but more efficient.

The turbine, generator as well as the power distribution electrical system room are in most of the cases located in one, for this reason dedicated building. Some of the suppliers propose also the control room to be located in this building, though in our case, in order to optimize the operation cost, the operation room will be integrated in the Central Control Room (CCR).

In the proposed system, the turbine, as described in chapter 4, will be fed with steam at a temperature of 350°C and pressure of 1700kPa. The quantity of the steam is around 8,36kg/s (or 30.096kg/h). The isentropic efficiency of the turbine is considered to be 85%.

The generator will be 3-phase AC synchronous type with output voltage 6,6kV, at a frequency of 50Hz, in order to be connected to the plant's Medium Voltage (MV) electrical network. The required apparent power, if we consider a power factor of cosφ=0,8, will be 8,6MVA (the generated power was calculated in chapter 4 at 6,9MW).

Figure 5.4: Modern steam-turbine generator

- **Water treatment system**

There are two technologies of water treatment systems used in such kind of applications: reverse osmosis system and ION bed water treatment. Reverse osmosis system is slightly more expensive in investment and maintenance cost (every two years the membranes have to be replaced) than the ION bed water treatment, but is more environmental friendly and it has much lower operation cost (around 30%).

- **Condenser**

It was estimated in chapter 4 that the heat rejected through the condenser is Qout=2.162kJ/kg or Qout=18.081kJ/s (as m=8,363kg/s). Wet vapour enters the condenser at 36,17°C and is condensed at constant temperature to become saturated liquid.

The condenser may be water cooler or air cooled type. The selection depends upon the availability of water nearby / in the plant. Assuming water-cooled condenser, using equations 4.1, 4.2, 4.3, it is calculate that the required area of the condenser is Ab_cond=1.174m2 (with Ub_cond=4kJ/(s*m2*°C))and the required mass of water is 389kg/s, assuming that the water enters the condenser at 25°C and exits it at 35°C.

- **Water Cooling system**

  The cooling process can be performed in two ways: in closed circuit by using internal sources of cooling water from plant wells or an open cooling circuit using sea water. Even if from economical point of view the sea water solution seems to be more tempting, this option is not considered feasible because of the permitting procedure and environmental issues. Moreover, maintenance costs in this case would be higher. It means that the standard cooling towers have to be considered.

  The water amount needed for the cooling purpose is 1,4 x 10^6 kg/h. This will enter the water cooling system at 35°C and will exit at 25°C. The characteristics of the cooling tower have to get calculated. The residual water from the cooling tower could possibly be used in several processes of the plant, serving either as cooling medium for electrical equipment such as HV water cooled transformers, water for fire distinguishing system, water to be used for reducing low pollution in the plant (spraying water on the roads) and finally for utilities (water basins, toilets etc).

Figure 5.5: Water cooling station

Other, auxiliary equipment that may be necessary for the proper operation of the installation is:

- Pumps
- Fans
- Reducers
- Lubrication units
- Tubes
- Control system

etc

5.3 Demands in space

There are three main structures that will have to be implemented into the existing plant arrangement:

- The **cooler heat exchanger including dust pre-selection cyclone**, which shall be placed next to the existing cooler and implemented between the cooler and ESP. The space needed for this kind of installation will be around 30x8m. The heat exchanger will be around 30m high.
- The **preheater heat exchanger** will be situated next to the preheater or cooling tower. The approximate size of this equipment is depending on the type of the heat exchanger selected. In case of vertical arrangement of the pipes, the requested space will be around 30x15m. If horizontal arrangement of the pipes is selected, the required space will be lower.
- The turbine **building including LV electrical distribution room, water treatment facilities and water cooling station**. This part needs the most of the space which is approximately 30x15m for the building, 15x15m for the water treatment and 30x10m for the water cooling purpose.

Space availability comes up to be one of the most challenging issues when thinking of installing a WHR power generation system in Volos plant, as the plant layout is extremely compact and available space limited. On top of this, permitting procedure for new buildings can prove a major barrier. This could mean that demolishing old buildings is a prerequisite in order to get the required permits for building new ones.

5.4 Electricity produced – Connection to the plant electrical grid

The WHR power generation plant will be connected to the existing Medium Voltage (MV) grid, and more specifically at the switchgear that feeds mainly Rotary Kiln No1 (RK1) consumers, inside MV RK1 Substation. This switchgear is fed through the south transformer (150/6,6kV, 35MVA) of outdoor substation No2.

In more detail, the respected switchgear feeds kiln 1 consumers, solid fuel mills, port & dispatch area consumers, limestone crushers and plant lighting. The total consumption is around 20MW, out of which around 12MW is fed to the kiln consumers. This switchgear may also be fed through the north transformer (150/15/6,6kV, 30-35MVA) of outdoor substation No2, as there is a second incoming circuit breaker. Currently, there are no spare circuit breakers in this switchgear so 2 new circuit breakers will have to be installed to cover WHR installation system needs.

The philosophy of the normal operation is based on the fact that the WHR PG plant operates only when kiln No1 is in operation. As calculated in chapter 4, the nominal generated power will be around 7,2MW.

New MV switchgear

The new MV switchgear will be located in the existing substation of RK1 (there is available space) and it will consist of:

- Outgoing circuit breaker (feeder), which will act as second incomer for the existing 6,6kV switchgear and will be equipped with current transformers and relevant protection system
- Measuring feeder, equipped with relevant Voltage Transformers (for protection & synchronization)
- Feeder to synchronization circuit breaker
- Bus raiser cubicle
- Measuring feeder, equipped with relevant Voltage Transformers (for protection & synchronization)
- Feeder to excitation system
- Incoming circuit breaker from generator

Existing MV switchgear

In addition to the above, two additional circuit breakers must be installed in the existing MV switchgear:

- Incoming circuit breaker, from new MV switchgear
- Outgoing circuit breaker in order to feed through a transformer the excitation system and the auxiliary equipment of the WHR PG plant.

Excitation system

The generator is of synchronous type therefore an excitation system has to be installed. For the excitation system two technical solutions are possible, depending on the supplier technology. Both technologies are considered reliable.

- **Static excitation system**: The excitation system is fed via a transformer connected to the departmental medium voltage switchgear. This excitation system is usually supplied together with the generator.
- **Excitation machine**: On the shaft of the generator an exciter machine is mounted. This exciter machine is feeding the relevant excitation source for the synchronous generator.

Low voltage distribution

In the departmental substation there is a low voltage distribution located. The standard plant voltage level for LV equipment is 500V AC. This low voltage distribution will be fed from a transformer and has to supply:

- LV motors / drives needed for WHR PG plant (500V AC)
- UPS for control system
- ACC distribution panel (via dedicated transformer)
- LV compensation unit

The voltage for system packages and other consumers using 400/230V AC are fed from the ACC distribution panel through a transformer 500/400V AC connected to the MCC.

Emergency power supply

The needed emergency consumers for the WHR PG plant have to be included in the emergency consumers of the plant, which are connected also to a backup diesel generator.

Control system

In general, the process control system for the WHR PG plant will be installed as a centralized system. The preferred manufacturer for this WHR PG plant control system is the already installed cement plant process control system based on ABB Industrial IT equipment. As the WHR PG plant could be seen as a separate system to the main cement manufacturing process there are two technical solutions available, depending on the supplier’s strategy:

- Extension to the cement plant process control system (full integration to the existing system)
- Independent control system for the WHR PG plant with interface (e.g. profibus) to cement plant process control system.

The second solution is the preferable one.

For the WHR PG plant a separate control room for local operation as well as maintenance operations will be installed. The usual and remote operation will be realized from the cement plant CCR where two independent operator stations for the WHR PG plant will be located. The maintenance and local operations will be performed from the local WHR PG plant control room.

5.5 Impact of WHR PG plant on normal plant operation

Pressure drop

The installation of the WHR plant will change the resistance of the gas circuit impacting the total pressure drop. The expected additional pressure drop caused by the WHR heat exchanger is expected to be around 8-10mbar. Previous installations in China however occasionally have experienced a pressure drop increase due to dust build-up within the heat exchanger, in worst cases the pressure drop has increased up to 16-20mbar. Control of the pressure drop is a critical fundamental element and poses significant risk of loss of production of the Raw Mill. As the preheater heat exchanger will be installed in parallel with the existing cooling tower, the net pressure drop increase is in the range of 7 to 16mbar (including additional ductwork losses). The ESP fan will have to operate with increased speed in order to compensate it.

Cooler exhaust fan

It also has to be checked whether the cooler exhaust fan has a margin to run at a higher speed in order to overcome any additional pressure drop.

Hybrid filter

Due to pre-collection of the dust in the preheater boiler, the total load of the hybrid filter will decrease significantly (up to 70%), which will have rather positive impact on the operation conditions of the filter.

Dust transport system

The load of the existing cooling tower bucket elevator is expected to increase. So it has to be checked whether its capacity is large enough in order to take this extra load or not.

Plant layout

The new buildings and machinery will take over a lot of space. So main roads of the plant are expected to narrow, while the specific areas where the connection of the new and existing part of the installation will take place (the top and bottom of the conditioning tower as well as the cooler area) will become even more crowded and narrow.

Summary

The main equipment of the WHR PG plant as well as the incorporation into the existing plant layout is being presented in this chapter. Space availability proves to be a major issue for the installation of the new equipment and a thorough approach is necessary in order the most efficient solution to be found regarding space requirements.

Finally, the impact of the WHR PG plant on the normal operation of the plant is investigated. The impact on the total pressure drop in the preheater gas circuit is the most significant; it is considered though that it can be compensated with slight increase of the ESP fan speed.

Chapter 6 Safety, environmental & legal aspects

Safety and environment are values and the first priority in all of the plant activities. So it is important to examine carefully all safety and environmental aspects related to the new installation. Moreover, permitting procedure that has to be followed in order for the WHR PG plant to operate is described in this chapter.

6.1 Safety aspects of the new system

Irrespectively of which company / world part the future equipment will come, no compromise on safety issues can be accepted. This concerns the safety issues during the implementation phase as well as safety requirements for the operation and maintenance of the new installation.

The erection phase safety issues will get considered during the preparation phase of the project, while in order to ensure achievement of the required safety level for the operation and maintenance of the new installation, the following items shall get considered:

- **CE marking / EN standards & certifications**

  All the new equipment shall fulfil the CE marking request, which is partly related to safety issues.

- **Greek safety legislation**

  All the Greek safety requirements according to the local laws have to be followed for the erection phase, equipment specifications and also for the future operation and maintenance of the installation.

- **Lafarge safety standards for design**

  On top of the above, all the specification described in the internal Lafarge Standard called “Mandatory Human Safety Requirements for Design Engineering” must be applied.

- **Operating & maintenance training**

  In order to get aware of the safety aspects, the operators as well as the maintenance staff of the new equipment have to get trained. This training can take place in running suppliers’ plant as well as on site.

6.2 Environmental aspects of the new system

The particular WHR installation elements having possible impact on the environment are described below:

- **Dust emission**

  All the waste gas is, after the heat exchangers, passing through filters (hybrid filter or ESP filter) before released into the atmosphere. The dust content in this case is below 20mg/Nm3, which means that under normal conditions the dust issue is negligible.

- **Noise emission**

  Independent of the kind of installation / used equipment, the noise emission has to fulfil the internal standard and cannot be higher than 85dB in 1m distance from a machine / noise source, which is in accordance with European norms and regulations.

- **Oil**

  Possible problem with oil would be applicable only in case of ORC technology, where thermal oil may be used in the heat exchanger circle. In this case potential problems of an oil leakage as well as fire aspects would need to take care of. Because of these aspects the ORC technology is less attractive than other, water based methods. However, if this solution would be selected, the oil issues should be strongly addressed.

- **Water**

  There will be some amount of waste water produced by the WHR plant. According to the character of the pollution of the water, which is related to the origin of the waste water, it has to be checked where this water could be used in the plant.

Other water environmental aspect is related to cooling water in case of open cooling circuit. The quantity of water needed for cooling purpose in this case is in the range of 1400 m3/h, with average temperature increase of 10°C.

- **Water chemical treatment**

  The make up water for the turbine system will be equipped with a chemical treatment system. It is important to ensure that the operation of this system will fulfil all safety and environmental aspects. Reverse osmosis system, as the most environmental friendly and applicable in Europe, is proposed in high number of similar installations.

6.3 Required permits – Legislation issues

The main permits that the plant should get, for the installation and operation of the WHR power generation plant, are the following:

- **Permit for electricity generation**

  This permit shall be applied to the Hellenic Energy Regulatory Authority and is getting issued by the Ministry of Development. The period of time needed for this step is estimated at around 5 months. However this strongly depends on the completeness of the application file.

  The main documents required for the application file are the following:

  - Application details
  - Project description
  - Energy study
  - Preliminary technical study
  - Business plan
  - Financial capability prove
  - Preliminary Environmental Impact assessment

  On top of the above, short summary of the content of the application shall be published into two daily newspapers, within a time limit of 5 workable days as of the submission of the application before RAE. Every party justifying a legal interest is entitled to submit its objections with regard to the application to RAE, within a time limit of 10 working days as of the publication.

  Finally, a copy of the application file shall be submitted also before the Ministry of Development, the Ministry responsible for finally issuing the Permit.

- **Permit for installation of power generation plant**

  The precondition to apply for this permit is an Issue of Electricity Generation Permit. The installation permit is valid for a period of two years and can be renewed for other two years.

  The main documents required for the application file are the following:

- File including the application for the approval of the power plant environmental terms and the **Environmental Impact Assessment Study**
- File including the application for the approval of the connection works environmental terms, if required
- Copy of the electricity generation permit
- Short technical description of the project

At the same time, an application form for **permit for all the civil works** (accompanied by relevant documents for civil works structure with detailed engineering and calculations) has to be submitted.

- **Permit for operation of the power generation plant**

  This permit is issued by the Renewable Sources Centre and is valid for a time limit of 20 years. The holder of the installation permit shall file an application for the issuing of the operation permit and submit the following supporting documents:

  - Copy of the certification with regard to the completion of the testing of the power generation plant connection and other installation works in accordance with the relevant regulations.
  - Copy of the **building permit**
  - **Fire Safety Certificate**
  - Formal declaration of the owner of the power generation plant confirming compliance with the environmental terms
  - Formal declaration of the owner of the power generation plant stating that the power generation plant supervision has been assigned to a supervisor engineer
  - Formal declaration of the supervisor engineer confirming compliance with the environmental terms
  - Formal declaration of the supervisor engineer confirming acceptance of the power generation plant supervision

6.4 Stakeholders’ perception

Before proceeding to the initiation of the project, it is important to describe its content and all the main aspects to the local stakeholders & residents in order to get their acceptance. This could be done in a local consultation meeting. In this meeting, all of the following aspects should be presented & discussed:

- Introduction to the project – what is the need
- Benefits of WHR power generation plant
- Basic technical info about the project (e.g main equipment, installed capacity, investment cost etc)
- Impact of the new installation on the local environment
- Impact on local water resources

Summary

All safety and environmental aspects of the WHR PG plant have to be carefully examined & respective solutions to be found, before proceeding with the investment. All the safety requirements according to the Greek legislation and Lafarge standards have to be strictly followed. The only environmental issue that seems to be important and the way to handle it has to be examined in more details, is the water needed for cooling purpose as its quantity is significant.

Another important topic is the permitting procedure that has to be followed for the installation and operation of the WHR PG unit as it seems to be time consumable. The three major permits that have to be acquired are

- Permit for electricity generation
- Permit for installation of power generation plant
- Permit for operation of power generation plant

while extra permits will be necessary to be acquired, e.g building permit, fire safety certificate and most possibly an update of the plant’s environmental permit.

Finally it is important the stakeholders and local community to be involved from the beginning of the project and make them understand its benefits in order to gain their positive approach.

Chapter 7 Preliminary economic evaluation of the investment

A preliminary economic evaluation of the investment is presented in this part of the study. Due to capital budgeting for this project, it is important to have an estimation of the payback period, the required time for the return on the investment to repay the original investment sum. The major cost saving for this investment comes from the reduced electrical energy consumption of the plant.

Cost of investment

The total **cost of investment** is estimated at table 7.1 to be around 18M€. This estimation is based on the analytical cost breakdown for a similar size investment, based on budget suppliers' offers (dated in 2008) described in [4].

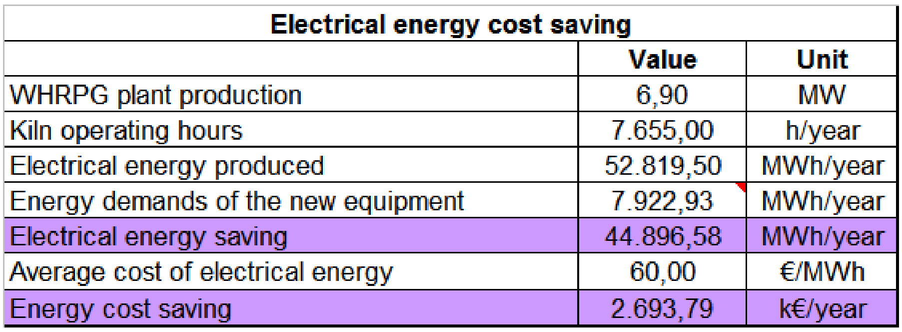
Estimation of investment cost	
Item	**Cost (k€)**
Mechanical equipment	9.190
Electrical equipment	1.530
Construction (civil works & steel structures)	1.910
Engineering / project management	3.030
Various (spare parts / contingency)	1.500
Total cost of investment	**17.160**

Table 7.1: Investment cost

More accurate calculation of the investment cost is important to take place at a later stage, by getting specific economical offers by possible suppliers according to the installation's specifics.

Electrical energy cost saving

Cost saving out of reduced electrical energy consumption is estimated at table 7.2 The net power of the WHR PG plant is 6,9MW and the installation is considered to operate the same hours with Rotary Kiln No1 (7655h/year). The electrical energy produced results 52819,5MWh/year. The energy consumed from the WHR PG plant machinery is estimated at around 15% out of its total energy production, so the electrical energy saving is 44.896 MWh/year. This results in 2.693,8€/year saving, if the average cost of electrical energy is 60€/MWh.



Electrical energy cost saving		
	Value	**Unit**
WHRPG plant production	6,90	MW
Kiln operating hours	7.655,00	h/year
Electrical energy produced	52.819,50	MWh/year
Energy demands of the new equipment	7.922,93	MWh/year
Electrical energy saving	44.896,58	MWh/year
Average cost of electrical energy	60,00	€/MWh
Energy cost saving	2.693,79	k€/year

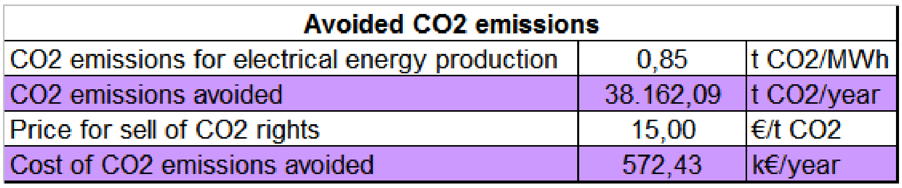
Table 7.2: Electrical energy cost saving

Concerning electrical energy cost, the following two important aspects have to be taken into consideration:

- There is a strong tendency the electric energy cost to increase within the next years.
- As described in paragraph 2.7, the energy cost is based to a specific contract with PPC. After certain time of stabilized operation of the WHR PG plant, this contract should be re-negotiated as the energy consumption will reduce. However, it has to be stated clearly that in case of unexpected shutdown of the WHR PG plant (due to any possible reason), the plant will possibly face bottlenecking concerning maximal power consumption. In this case, the plant should either temporarily shut off part of the production or pay higher unit price (above the contractual stated value) to PPC.

Avoided CO2 emissions

Based on the produced energy of the system, it is possible to make an **estimation of the avoided CO2 emissions**, table 7.3. According to the energy mix of Greece, an average of 0,85 tones of CO2 are emitted per produced MWh [2]. In addition it is assumed that all the energy produced by the heat recovery system is consumed by the plant itself. According to the above, it is estimated, in table 7.3, that the significant amount of 38162,09 t CO2 can be annually avoided. If this amount is sold in the “CO2 rights’ market”, with a price of 15€/t, the annual saving is 572,43k€.

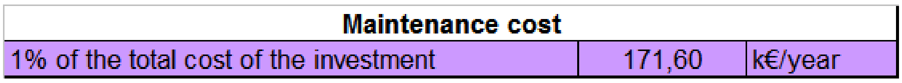


Avoided CO2 emissions		
CO2 emissions for electrical energy production	0,85	t CO2/MWh
CO2 emissions avoided	38.162,09	t CO2/year
Price for sell of CO2 rights	15,00	€/t CO2
Cost of CO2 emissions avoided	572,43	k€/year

Table 7.3: Avoided CO2 emissions & related cost

Additional maintenance cost

The average cost for maintenance of the new equipment is estimated as 1% of the total investment cost, in table 7.4, and comes up to be 171,6k€/year.



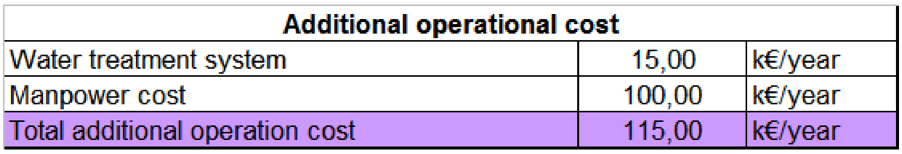
Maintenance cost		
1% of the total cost of the investment	171,60	k€/year

Table 7.4: Additional maintenance cost

Additional operational cost

The additional cost for operation of the new installation comes mainly from extra manpower cost (it is considered that 4 additional employees will be necessary for the operation of the new system, although this could be avoided) and cost necessary for the proper operation of the water treatment system, which according to bibliography […] is estimated at around 15k€/year. So the total increase at the operational cost is 115k€/year.

No cost for water supply system has been taken into account, considering that the water needed for cooling purposes will be either sea water or water coming from the existing wells of the plant, their capacity is high enough.



Additional operational cost		
Water treatment system	15,00	k€/year
Manpower cost	100,00	k€/year
Total additional operation cost	115,00	k€/year

Table 7.5: Additional operational cost

Total cost saving

Cost saving is estimated in table 7.6 as:

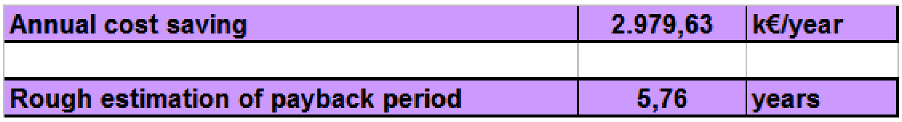
Cost saving = (electrical energy cost saving) + (cost of CO2 emissions avoided) – (maintenance cost) – (operational cost) = 2.979,63k€ /year

Payback period

A rough valuation of the payback period is also presented in table 7.6, estimated using the following equation:

Payback period = Cost of investment / Annual cost saving

The payback period comes up to be roughly 5,8years.



Annual cost saving	2.979,63	k€/year
Rough estimation of payback period	5,76	years

Table 7.6: Annual cost saving & rough estimation of payback period

Financing, subsidy

Finally, it is important to note that there are two kinds of financial benefits which could be applied alternatively for such kind of project:

- One of them is linked to financial subsidies coming from EU. Due to the category of this project, electricity production, the investment cost can be covered up to 30% by the subsidy.
- An alternative solution is to cover the investment cost by untaxed deposit. In this case the financial benefit is equal to 25% of the total investment cost.

The detailed procedures and their possibilities have to be investigated.

For all of the above, the reader must keep in mind that the calculations used and the results produced have been based on the economic conditions that apply today and are sensitive to various parameters. For example, if the efficiency of the installed system is higher and the produced electrical energy is 7,5MW (with the same investment cost) and at the same time the price of electrical energy goes up to 80€/MWh, the payback period will be 4 years.

Summary

The investment cost for the WHR PG plant is estimated at around 17M€ and the new installation produces 52,8MWh/year. The savings out of this investment come mostly from the reduced electrical energy consumption of the plant as well as from the reduced CO2 emissions. On the other hand, there will be some additional maintenance and operational cost that have to be taken into account. According to a rough estimation, and based on the economic conditions applied today, the payback period will be around 5,7years.

Of course, this estimated payback period is sensitive to various parameters so it is important an analytical cost estimation and evaluation of the payback period to be prepared.

Chapter 8 Conclusions

Increasing energy efficiency and reducing environmental footprint is a key goal for many industries around the world, including cement industry. Lafarge group has set the target to reduce CO2 emissions per tone of cement produced by 33% come 2020. In this frame, the company supports feasible and economical beneficial initiatives, from its global network of cement plants, in order to reach this target.

This study examines the feasibility of Power Generation from Waste Heat in Volos cement production plant. The preheater and cooler exhaust gases are the main heat sources. Three different configurations are investigated:

- Water-steam system with one turbine
- Water-steam system with two turbines
- Organic Rankine Cycle system

According to the results, the most suitable system for the volumes and temperatures of gases of Volos plant is the water-steam circuit with one turbine. This system consists mainly of:

- Preheater and cooler heat exchangers
- Steam turbine and electrical generator
- Condenser
- Water treatment and water cooling station

The system efficiency is close to 25%, producing 6,9MW electrical power, which represents around 20% of the total consumed energy of the plant. Moreover, the system examined is quite simple, hence there are possibilities to further improve its efficiency and increase the electrical power generated, e.g. by adding preheating.

The major drawback concerning the installation of a WHR PG unit in Volos plant comes to be space availability as there are three main new structures, of high dimensions, that will have to be incorporated into the already congested and compact plant layout. A thorough approach is necessary in order the most efficient solution to be found regarding space requirements.

The operation of the WHR PG plant seems to have some impact on the normal plant operation, affecting mostly the pressure drop in the preheater gas circuit. It seems though that this pressure drop can be compensated with slight increase of the ESP fan speed.

There are many safety and environmental issues that have to be taken care of, both during the implementation phase of the project and during its normal operation, but it seems that feasible solutions exist for all of them.

Permitting procedure for the installation and operation of the WHR PG plant is time consumable so it has to be carefully managed from the initiation of the project.

Finally, the major results of a preliminary economical evaluation of the investment are presented and are the following:

- Total cost of investment: 17 M€
- Annual cost saving: 3 M€
- Rough estimation of payback period: 5,7 years

Further economical analysis should be done though in order to confirm these results.

Bibliography

[1] Yunus A. Cengel, Michael A. Boles, *“Thermodynamics: An engineering approach”, 7th edition*

[2] S.Karellas, A-D. Leontaritis, G.Panousis, E.Bellos, E.Kakaras, Proceedings of ECOS 2012, *“Energetic and exergetic analysis of waste heat recovery systems in the cement industry*

[3] Marinos, Papacharalampous, 1986, *«Study on using available heat from exhaust gases of rotary kilns of Olympos plant for producing electrical energy”*

[4] Krynicki, W., Lafarge DEC / Regional Engineering Vienna (2008) *“Plant Milaki – Delivery and Installation of Waste Heat Recovery Power Generation Plant”*

[5] Lafarge Asia Technical Centre, DPE, August 2007, *“Waste heat recovery in cement plants – rev2: update on ATC experience”*

[6] Karounou El., July 2011, *“Volos Kiln 1 Audit”*

[7] H.P. Loh, J. Lyons, C.W. White, January 2002, **“***Process Equipment Cost Estimation Final report”*

[8] N.A.Madlool, R.Saidur, N.A.Rahim, LACSIT International Journal of Engineering and Technology, Vol.4, No5, October 2012, *“Investigation of waste heat recovery in cement industry: a case study”*

[9] Energy saving seminar in Mexico, 2007, Kawasaki plant systems, LTD, *“Waste heat recovery power generation for cement plant”*

[10] Green Cemtech 2010, Hyderabad, Sameer Bhardwaj, *“Future trend – Waste heat recovery in cement plants”*

[11] European Cement Research Academy newsletter 2/2012, pages 3-4, *“The renaissance of waste heat recovery for clinker manufacturing”*

[12] International Cement Review, November 2010, pages 75-78, *“ABB’s flexible ORC power plant”*

[13] International Cement Review, June 2012
Pages 34-35, Lafarge Philippines, *“Waste heat for energy”*
Pages 57-58, Dr. Michael Clark, UK, *“Waste heat recovery on the rise”*
Pages 59-62, Roman Menz, Alesd Cement Plant, Holcim Romania, *“From waste heat to power”*
Pages 66-71, Riccardo Vescovo, Turboden Srl, Italy, *“Making more of waste heat”*

[14] http://www.em-ea.org/Guide%20Books/book 2/2.8%20Waste%20Heat%20Recovery.pdf Bureau of energy efficiency, *“Waste heat recovery”*

[15] http://www.worldcement.com/ (May 2011), pages 113-117, *“Waste heat recovery systems”*

[16] http://www.worldcement.com/ (Mar 2012), pages 78-83, *“Recovering heat for energy”*

[17] http://www.rae.gr/old/K7/Codes/Code_RES+COGEN.pdf

[18] http://www.energymanagertraining.com/Journal/24032006 *“Cogeneration of power utilising waste heat in cement manufacture: technological perspectives”*