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Potential of recovery and conversion of waste heat from rejected exhaust gases in Moroccan industry: Application to the cement manufacturing sector

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Abstract

Morocco can take advantage of the thermal releases of its industry by recovering and converting the waste heat into electricity by means of facilities dedicated to this purpose. Cogeneration plants have the advantage of being flexible and working in different conditions. In the cement sector, for example, the minimum potential for generating electricity from the exhaust gases is estimated to11.83 kWh per ton of clinker through the ORC technology and 31.55 kWh with a conventional steam cycle. Thus, between 172 and 453 GWh of electricity can be generated and atmospheric emissions can be reduced by over 140,000 tons of CO2 per year. The investment cost is of the order of 31.35 MDH/MW installed for the ORC cycle and MDH 29.25/MW for conventional cycle. This project can be adapted to all industrial sectors generating adequate heat rejection. It is also possible to require heat recovery for any new industrial plant during the design phase to ensure optimization of consumption and thus contribute to a real energy transition in the country. Such investments should be supported as part of a public-private partnership.

1. Introduction

Morocco is heavily dependent of energy importation. In 2011, 96.6% of energy needs are covered by imports. The energy bill has represented 10.6% of gross domestic product (GDP). The intensity of primary energy, defined as the ratio of gross inland consumption in Tep on GDP in MDH, recorded an increase. It stood at 26.2%. Given such dependence, Morocco launched several projects of energy efficiency in order to improve its consumption levels and reduce energy bills. The energy strategy has brought among others the assurance of a diversified energy mix and optimized around reliable and competitive technology choices, the mobilization of national resources by the rise of renewable energy and improving overall energy efficiency of the country. The reform and strengthening of the regulatory framework is also a priority to allow the feasibility and coherence of the various national energy programs. These axes of the national strategy concern, in particular, the industrial sector where the energy intensity has evolved to 6.47% compared to 2005 and stood at 19.99 Tep/MDH (the energy intensity of the industrial sector being defined by the ratio of primary energy consumption in Tep and added value MDH). For Morocco, a strong causality between the power consumption level and the country's economic growth was demonstrated [1].

Taking into account the above, the improvement of energy efficiency in industry, in its thermal and electrical forms, is of great importance considering its cost by having a sustained growth trend and its heavy weight on economic balance. Indeed, the energy bill is increasingly affected by higher prices and growth in consumption. Among the energy-intensive industries, cement industry with high energy consumption and for which the world's energy needs are estimated to be around 6.1 GJ of heat and 200 TWh of electricity. The energy part is about 40% of the cost price of cement excluding amortization of facilities.

Multiple uses are made of the energy in the cement sector. The major items correspond to the clinker burning and grinding operations. Considering the above, it is necessary to find ways to reduce energy consumption and to take advantage of thermal discharges for loss reduction. This paper presents the state of the art in the field of electricity generation in the cement sector, a projection on the cement sector in Morocco and the estimated potential for energy recovery.

2. Cement manufacturing process

Cement is the most used building material in the world. The cement is a binder material which is mixed with an aggregate such as sand or gravel, and water to form concrete. More than three tons of concrete is produced per person each year for the entire global population, making it the most widely used manufactured product in the world. Twice the concrete is used worldwide as the total of all other combined building materials, including wood, steel, plastic and aluminum, and for most applications, none of these other materials can replace concrete in terms of efficiency, price and performance.

The preference for concrete as a building material is due to the low manufacturing cost, and the fact that it can be produced locally from widely available raw materials; it is flexible and has a high compressive strength. Cement ensures the cohesion and strength to the concrete mix and low permeability and high durability.

Clinker is an intermediate product in the manufacture of cement. It is produced by a burning process of a finely ground raw meal generally from a first material mixture such as limestone, clay or shale. These raw materials, which can also be supplemented with additives such as bauxite, iron ore and sand, are mixed in proportions that give the right combination of major oxides: CaO, SiO_2, Al_2O_3 and Fe_2O_3. These minerals enter into chemical reactions when melting in the kiln during the burning process and thus provide new mineralogical forms under the effect of high temperatures (Passage from 900 to 1400 °C) [2].

Calcium oxide (CaO) is the primary oxide in clinker; it mainly comes from the limestone being the most abundant raw material for the cement manufacture.

Thereafter, the clinker is ground to a very fine powder mixed with metered amounts of limestone and gypsum (and with other possible materials such as pozzolana or ash) to form Portland cement. The percentage of clinker in the mixture generally varies between 60 and 95% and depends on the quality of cement manufactured and regulatory guidelines and finished product testing.

The cement industry has a significant environmental footprint due to amounts of energy and raw materials used in the process. Cement manufacturing is an energy-intensive industry; the production of one ton of clinker requires up to 3600 MJ and the production of cement ton about 105 kWh. These values may vary with factories functions, process and used raw materials and fuels.

Furthermore, cement manufacturing generates a lot of carbon dioxide CO_2. CO_2 emissions from fuel used for burning and calcining the raw material (limestone) according to equation:

$$CaCO_3 + \text{Heat} \Rightarrow CaO + CO_2.$$

In principle, 40% of the emissions come from the combustion while 60% are due to decarbonation. Several types of fuel are used but coal and petroleum coke are the most consumed.

The strategies of the cement industry for CO_2 emission reduction are focused on reducing emissions in production by improving facilities (efficient kilns), the introduction of low emission fuels (Substitution of conventional fuels), substitution conventional raw materials (use of fly ash for example) and the establishment of units of electrical energy production (parks connected to plant networks). Optimizations are also made on the process and energy management.

3. Moroccan cement market

3.1. Cement manufacturers based in Morocco

Morocco currently has five cement manufacturers (Lafarge, Ciments du Maroc, Holcim, Ciments de l'Atlas and Asment Temara) and a new entrant Atlantic Ciment (projects in progress). The five operational cement companies are members of the APC (Professional association of cement manufacturers) and agree on sustainable development strategies, reducing the impact on the environment and reducing energy consumption. Indeed, cement manufacturers adhere to national policies and it has been shown that between 1997 and 2009, the cement sector's contribution to gross domestic product GDP has increased by a third while its share of environment damage was divided by seven.

3.2. Cement plants

During the last decade, several investments have been made and this has enabled a doubling of the production capacity. In 2013, production capacity reached 20.5 million tons. Table 1 shows nominal production capacities of cement companies in Morocco.

New plants and extensions are planned; the total production capacity will be increased in the few next years.

Table 1: Cement companies operating in Morocco.

Cement company	Plants	Production capacity (Mt/y)
Lafarge Maroc	3 cement plants + 1 grinding plant	6.9
Ciments du Maroc	3 cement plants + 1 grinding plant	5
Holcim Maroc	3 cement plants + 1 grinding plant	4.2
Ciments de l'Atlas	2 cement plants	3.2
Asment Temara	1 cement plant	1.2

3.3. Cement demand

Cement demand and focus on sales are reported in following Table 2 and Table 3.

Table 2: Cement sales trend.

Period	Evolution rate
1980 – 1989	2.4%
1990 – 1999	4.7%
2000 – 2002	5.5%
2003 – 2012	6.5%
2013 – 2015	-4.12%

Table 3: Cement sales between 2010 and 2015.

Year	Cement sales t
2010	14570708
2011	16129623
2012	15871055
2013	14864340
2014	14059897
2015	14251456

Between 2010 and 2015 the average inland cement consumption was about of 14,957,846 tons/year. The average ratio of cement consumption in relation to the population is 456 kg/year.

4. Potential of waste heat recovery

4.1. Exhaust gases

In rotary kiln process (Figure 1), the raw material mixture is introduced from the top of the cyclone preheater tower. The material is preheated up to 850 °C and is then introduced into the inclined rotary kiln at a controlled rate. The material advances under the slope effect and the cylinder rotating speed. The fuel (coal, petroleum coke, gas or other alternative fuel) is injected into kiln burner and precalciner located upstream of the oven (Dry process) with a flow rate and pressure controlled in order to have flame up to 1800 °C. As the kiln is driven at a low speed (2-4 rpm), the material advance towards the burner placed at the end of the cylinder to an expect temperature of 1450 °C. The material is then melted and passes through various chemical reactions before being discharged then quenched and cooled in the cooler to form clinker.

Rotary kilns are either dry or wet, depending on how the raw materials are prepared. In the wet process kilns, the raw materials are introduced into the kiln in the form of sludge with a moisture content of 30 to 40%; this explains the high heat consumption of this process for water evaporation. In the case of a dry process kiln, the material is preheated and precalcined in the cyclone preheating tower by heat exchange with the gases from the kiln. The exchange is in all stages of the tower and the process is relatively energy efficient.

The hot gases are produced in the kiln and cooler. They come from the cooling of clinker, the air supplied for combustion and also generated by the combustion itself. In the case of a dry process kiln, the combustion also occurs in the preheating tower if it's equipped with a precalciner. The gas flow is divided into two parts: the first part passes through the kiln and preheats raw material and a second left the enclosure out of the cooler [3]. The exhaust gases exiting the kiln are used for preheating and calcining the material before it enters the kiln. The gas temperature at the outlet is between 320 and 360 °C. Gases are typically conveyed through fans to dry the material in the mills (raw, coal and cement), then they are evacuated via the chimney after filtration. These gases carry a large part of the waste heat produced by the process.

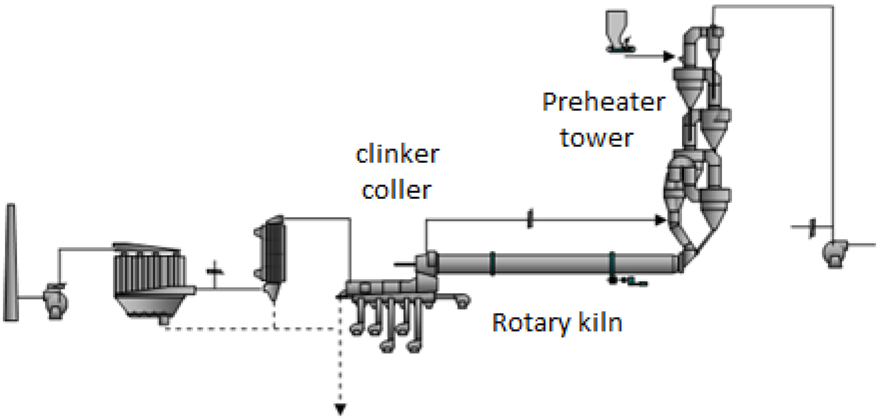


Figure 1: 5 stage and precalciner burning line (Preheater, kiln, cooler and components)

4.2. Heat recovery and conversion techniques

Dry kiln exhaust gases, leaving the tower and the clinker cooler, have considerable thermal energy which can be converted into useful form. In fact, these gases can reach higher temperatures of about 360 to 380 °C depending on burning line design. Before their use for drying the material in grinding phase and for conveying the fine material, these gases are cooled by water spray until their temperature is acceptable for fans, mills and filters. The gases are subsequently discharged after filtration at an elevated temperature. Stopping the raw mill for example induces an abundance of energy that is simply vented to the atmosphere. For energy performance of the installation, it should exploit the surplus of the thermal energy of gas. The heat can be recovered and suitably used for the purposes of heating or for electricity generation as shown in Figure 2 for example.

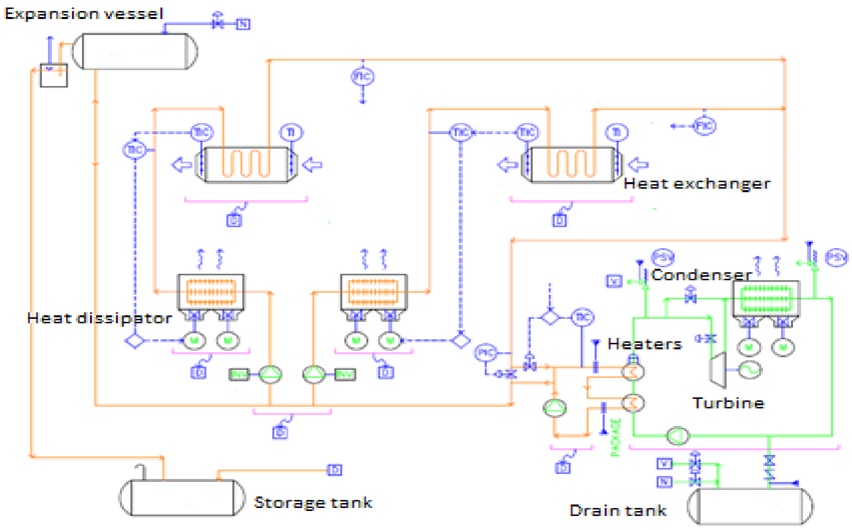


Figure 2: Block diagram of an ORC based heat recovery system

The potential for recovery depends on the production rate, mills running, moisture content of the raw material and used fuel. In principle, the self-production of electricity can cover 5-30% of the overall power consumption but it also depends on the number of recovery points and the used technology.

4.3. Heat recovery systems

Heat recovery systems used for cement kilns are based on the Rankine cycle. The principle is used in most conventional thermal power stations. Boiler source transforms the working fluid into vapor that expand afterwards through a turbine coupled to an electric generator. The steam is then condensed and the cycle repeated. The heat source is the kiln or the clinker cooler exhaust gases. Several variants of this cycle are used for this purpose:

- Steam Rankine cycle [4-6]: This is the most used cycle. Steam at high pressure is produced by the boiler. It is most suitable when the temperature exceeds 300 °C. The specific cost per kWh is relatively lower. It can be expensive in terms of maintenance but it remains the best-known and accessible process for the energy industry.
- Organic Rankine cycle [4-7]: using an organic fluid which has advantages of high efficiency at medium low temperatures. Organic fluids have a large molecular mass and a relatively low evaporating pressure. These two properties ensure higher yields compared to conventional Rankine cycles in the case of smaller power production and medium low temperature heat sources ranking from 150 to 600 °C [8].
  In such configurations the working fluid is generally circulating in a secondary loop and receives heat from a primary coolant which recovers heat from the main source (i.e. thermal oil, saturated steam or superheated water). The ORC technology is beginning to be very common in the industry; particularly in the field of geothermal energy, biomass or to recover heat from cement kilns, steel and glass production plants and industrial compressors.
  This technology offers several advantages:
    - Matches with medium-low temperature heat sources,
    - Can be operated very quickly and automatically at partial loads (6-8% of thermal power), following the cement plant production program without interruption of the electric production and thus increasing the power plant reliability,
    - Provides the ability to make better use of heat regeneration,
    - Allows a condensation at a relatively higher pressure than conventional systems and reduces the air intake risk,
    - Given the low temperatures and pressure, the system can operate in fully automatic mode without risk,
    - No partial condensation occurs at the level of the turbine. The blades are not exposed to wear or corrosion due to the properties of the working fluid, and this a key factor in the long term operational and maintenance costs,
    - The condenser may, in certain circumstances, use ambient air,
    - Does not consume water and there is no need of water treatment,
    - The turbine rotating at an average speed allows a coupling to the alternator without intermediate reduction stages,
    - The ORC systems are relatively compact due to the low surface required in the heat exchangers and the reduced number of turbine stages,
    - There is no requirement of supervision personnel, thus reducing operational cost.

  However ORC cycles exhibit some disadvantages [9]:
    - The ORC technology is more adapt to be used for low-medium temperature and for sizes smaller than 10-12 MWe,
    - The system integrating an intermediate heat transfer fluid, some heat loss may occur and affect the overall effectiveness,
    - The specific cost per kWh is relatively high because more components are needed due to the intermediate circuit and higher level of automation,
    - Some environmental risks are inherent to this type of facility in case of fluid leaks but this problem is addressed and periodic checks of protective measures are taken.

  The ORC technology is best suited for the recovery of gas high-performance cement kilns and in the case of relatively wet raw materials.

- Kalina cycle: Cycle using a mixture of water and ammonia as working fluid which allows a more efficient recovery at very low temperature. This cycle makes it possible to recover heat from low-temperature sources from 90 °C. Theoretically, it is 15 to 20% more efficient than the ORC for the same temperature. The Kalina cycle technology is beginning to break into the market and still lacks experience. It is nevertheless already exploited in areas such as refining and geothermal.

This last technology offers some advantages:

- o Works at very low temperatures,
- o Rapid response to changes in operation,
- o The mixture of water and ammonia can be managed for optimal recovery of waste heat,
- o The working fluid is not flammable but aggressive with materials.

This technology is still little known and must be proven [6]. A careful management of working fluid shall be considered due to dangerous fluid.

4.4. Heat recovery systems in cement plants

The first heat recovery system was established in Japan in 1980 by Kawasaki Heavy Industry KHI at Sumitomo Osaka Cement. Then after, a key project with 15 MW capacity has been released in Kumagaya plant (Taiheiyo Cement) [10]. China installed its first system in 1998 in partnership with a Japanese manufacturer. Thanks to incentives for the development, China now counts more than 700 heat recovery units using gaseous discharges [11]. Today, several enhancements have been made and some new generation of heat recovery installations in cement kilns producing up to 45 kWh per ton of clinker are installed worldwide.

In the case of a heat recovery system of a cement kiln based on the Rankine cycle, a boiler is placed at the outlet of the tower and a second at the outlet of the cooler (Figure 3) to produce water steam at medium pressure. The steam is then conveyed to a turbine to produce electrical energy. After condensation, water rejoined the boiler to repeat the cycle. Other auxiliaries are installed such as the water treatment and pumping systems.

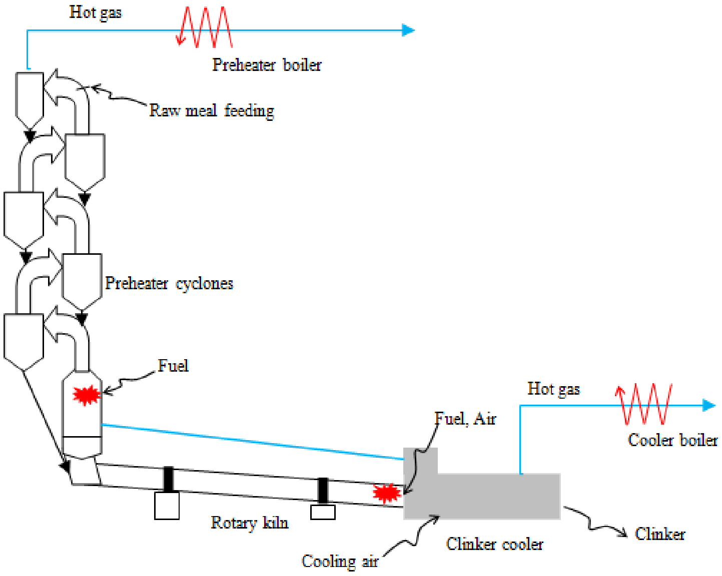


Figure 3: **Typical positioning of heat exchangers.**

Depending on preheater stages number, the gas temperature at the outlet of the tower varies between 250 and 400 °C and that at the outlet of the cooler varies between 250 and 350 °C.

For based ORC cycle systems, one or two heat exchangers can be used to recover heat from gas at the tower outlet and from the cooler exhaust. The first replaces the conventional cooling tower operating in the water spray and the second replaces the air heat exchanger serving to cool the gas. In both exchangers circulate in opposite directions gases and coolant.

In Morocco, the water shortage is the main motivation to exploit the ORC technology. This technique makes it possible to considerably reduce water consumption of the conventional process while producing electricity.

5. Heat recovery potential

5.1. Exhaust gas at preheater and clinker cooler exit

In 2013, about 70% of world clinker production comes from kilns with cyclones preheater and calciner, 12% from dry kilns without preclaciner and almost 10% from long dry kilns. In Morocco, kilns are with dry process, and over 75% of clinker production is from kilns with precalciner. Thereafter we will only focus on dry process kilns. Tables 4 and 5 summarize available heat at preaheater tower and cooler exits.

Table 4: Exhaust gases at preheater tower exit

Parameter	Unit	Without precalciner	With precalciner		
Cyclones		4	4	5	6
Kiln capacity	t/d	1000-2500	2000-8000		
Exit temperature	°C	390	360	316	282
Available heat at exit	GJ/t	0.904	0.754	0.649	0.586
Available heat at exit	kcal/kg	216	180	155	140
Available heat at exit	GJ/h	113	94.3	81.1	73.3
Available heat at exit	Mcal/h	27	22.5	19.4	17.5
Specific heat consumption	GJ/t	3.55	3.14	3.01	2.93
Specific heat consumption	kcal/kg	850	750	720	700

Table 5: Exhaust gases at clinker cooler exit

Parameter	Unit	1st generation	2nd generation	3rd generation
Aeration mode		Vertical	Horizontal	Horizontal
Quenched air	Nm3/kg clinker	2 - 2.5	1.8 - 2	1.4 - 1.5
Exhaust gas flow	Nm3/kg clinker	1 - 1.5	0.9 - 1.2	0.7 - 0.9
Available heat at exit	kcal/kg	0.419 - 0.502	0.335 - 0.419	0.293 - 0.335
Available heat at exit	GJ/h	100 - 120	80 - 100	70 - 80
Available heat at exit	Mcal/h	52.3 - 62.8	41.9 - 52.3	36.6 - 41.9
Available heat at exit	GJ/t	12.5 - 15	10 - 12.5	8.8 - 10
Cooler efficiency	%	<65	<70	>73

5.2. Case study

In this section we consider a cement kiln with dry five-stage preheating tower and a precalciner and a nominal production of 5,000 tons of clinker per day.

5.2.1. Heat reconvery exchangers capacity

Table 6 and Table 7 give operating parameters for tubular heat exchanger operating with thermal oil to recover heat of exhaust gases at preheating tower and cooler exits:

Table 6: Rated heat exchange at preheater tower exit:

Parameter	Unit	Value
Inlet gas flow	Nm3/h	350 000
Specific gas flow	Nm3/kg clk	1.68
Inlet temperature	°C	360
Outlet temperature	°C	230
Concentration N_2	% vol	59.6
Concentration O_2	% vol	3.7
Concentration H_2O	% vol	7.2
Concentration CO_2	% vol	29.5
Gas density	kg/Nm3	1.44
Dust content	t/h	38.0
Heat exchanged	Gcal/h	17.2

Table 7: Rated heat exchange at clinker cooler exit

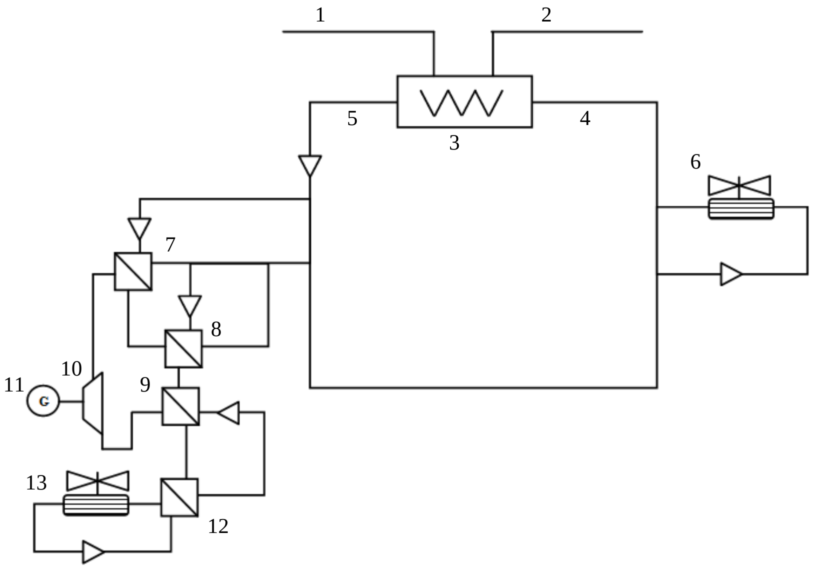
Parameter	Unit	Value
Inlet gas flow	Nm3/h	310 300
Gas specific flow	Nm3/kg clk	1.5
Inlet temperature	°C	370
Outlet temperature	°C	220
Concentration N_2	% vol	71.5
Concentration O_2	% vol	19.0
Concentration H_2O	% vol	9.5
Concentration CO_2	% vol	0.0
Gas density	kg/Nm3	1.28
Dust content	t/h	9.5
Heat exchanged	Gcal/h	15.7

Potential of heat recovery from preheating tower is 10% higher than from clinker cooler.

5.2.2. Study of a real case installation [12]

- Simplified schema

Figure 4 below gives a simplified schema of an existing ORC based heat recovery plant in Morocco installed in 2010. In this case, the heat is recovered on the preheater side only. Clinker cooler air was not used. In case clinker cooler heat is used in the ORC based heat recovery plant, about double electric power can be produced.



1- Preheater exhaust hot gas inlet
2- Gas outlet
3- Main heat exchanger
4- Heat fluid inlet
5- Heat fluid outlet
6- Heat dissipator
7- Heating module
8- Split
9- Economizer
10- Turbine
11- Generator
12- Condenser
13- Air cooler

Figure 4: Simplified schema of an ORC based HRS

- Heat recovery

Table 8 below summarizes operating parameters of main heat exchanger.

Table 8: Gases released heat (point 1-2 in figure 4)

	Unit	Nominal	80% Nominal
Inlet gas temperature	°C	360	333.8
Outlet gas temperature	°C	230	228
Gas flow	Nm3/h	350000	255294
Average gas heat capacity C_p	kJ/kg.K	1.10	1.05
Average gas density	kg/Nm3	1.44	1.43
Gas circulation fan rate	%		70%
Available heat	kWth	20090.00	11308.60

Table 9 below gives heat exchanged.

Table 9: Heat recovered by heat transfer fluid (point 5-4 in figure 4)

	Unit	Nominal (kiln rate)	80% Nominal
Inlet heat transfer fluid temperature	°C	120	105
Outlet heat fluid temperature	°C	260	231
Heat transfer fluid flow	m3/h	265.82	165.1
Average heat transfer fluid heat capacity C_p	kJ/kg.K	2.45	2.41
Heat fluid density	kg/m3	766	773
Circulation pump rate	%	78	38
Recovered thermal power	kWth	19400.08	10764.94

Table 10 summarizes heat exchanger performance.

Table 10: Exchanger performance (Point 3 in figure 4)

	Unit	Nominal (kiln rate)	80% Nominal
Exchanged heat	kWth	19400.08	10764.94
Heat transfer rate	%	97%	95%
Gas cooling rate	%	36%	32%
Fluid heating rate	%	117%	120%
Waste heat (dust. losses…)	kWth	689.92	543.66
Loss rate	%	3%	5%

- Heat dissipation

Heat dissipated is given in Table 11.

Table 11: Dissipated heat (point 6 in figure 4)

	Unit	Nominal (kiln rate)	80% Nominal
Inlet fluid temperature	°C	181	136
Outlet fluid temperature	°C	120	76
Heat fluid flow	m3/h	260.05	71.4
Average heat fluid heat capacity C_p	kJ/kg.K	2.37	2.19
Average heat fluid density	kg/m3	783	818
Circulation pump rate	%	76	21
Dissipated thermal power	kWth	8176.88	2131.79

Table 12 shows the heat dissipater global performances.

Table 12: Dissipator performance

	Unit	Nominal (kiln rate)	80% Nominal
Echanged thermal power	kWth	8176.88	2131.79
Heat fluid cooling rate	%	34%	44%

- Auxiliaries

Table 13 presents main heat recovery and dissipation auxiliaries consumptions.

Table 13: Heat recovery auxiliaries consumption

Consumers	Rated power kW	Power demand kW
Dust conveyors	2.2	5.87
Dust recovery	0.55	0.15
Rapping hammers	0.55	0.18
Ciculation pump	90	34.20
Heating module pump	55	29.07
Split pump	11	6.20
Dissipater pump	75	15.75
Filling pump	15	0.01
Dissipater fans	11	3.15
Total power demand (full time, 10% high) kW	104	

- Cogeneration

Operating parameters of each cogeneration plant component are reported in Table 14.

Table 14: Cogeneration unit

Heating module (point 8-9 figure 4)	Unit	Nominal (kiln rate)	80% Nominal
Inlet heat transfer fluid temperature	°C	260	226.8
Outlet heat transfer fluid temperature	°C	160	152.3
Heat transfer fluid flow	m^3/h	154.5	167.8
Average heat transfer fluid thermal capacity	kJ/kg.K	2.61	2.5
Average heat transfer fluid density	kg/m^3	734	755
Circulation pump rate	%		60
Thermal power into heating module	kWth	8221.72	6554.40

Preheating module (point 7 in figure 4)	Unit	Nominal (kiln rate)	80% Nominal
Inlet heat transfer fluid temperature	°C	160	151.2
Outlet heat transfer fluid tempertaure	°C	110	118.3
Heat transfer fluid flow	m^3/h	65	69
Average transfer fluid heat capacity C_p	kJ/kg.K	2.99	2.31
Average heat transfer fluid density	kg/m^3	794	794
Circulation pump rate	%		64
Thermal power into split	kWth	1609.00	1156.58

Condensing module (point 12-13 in figure 4)	Unit	Nominal (kiln rate)	80% Nominal
Water inlet temperature	°C	30	35.6
Water outlet temperature	°C	47	49.2
Water flow	m^3/h	381.96	366
Dissipated thermal power	kWth	7539.47	5765.72

Overall unit balance	Unit	Nominal (kiln rate)	80% Nominal
Inlet thermal power	kWth	9830.72	7325.43

Generated power (Pg)	kWe	1856	1033

Consumed power (Pc)	kWe	259	126
Ratio Pc/Pg		13.95%	12.20%
Net generated power	kWe	1597	907

Net efficiency of the plant	%	16.24%	12.38%

Generator power factor Facteur		-0.9	-0.86
Generator reactive power	kVAr	898.90	612.95
Generator power	kVA	2062.22	1201.16

- Cycle efficiency

From the foregoing, we note that a cogeneration unit placed at the outlet of the preheating tower can be operated with a thermal energy conversion into electrical energy of between 15 and 20% according to the kiln operating conditions and the unit itself. Under good work conditions, about 1.85 MW can be generated from a heat of 9.8 MWt at the inlet.

If we compare the generated power to the primary power recovered by the heat exchanger, it is observed that the final conversion into electrical energy is about 9.2% in normal conditions and 9.1% to 80% of rated operation. Under normal conditions a specific production of 8.9 kWh/t.clk at the kiln rated operation and 6.19 kWh/t.clk at a reduced rate. We have seen that from 12.2 to 13.95% of the power generated is consumed by the auxiliary of the cogeneration station. This means that the net power transited into internal electrical grid of the factory (Kiln electrical room for example) may vary between 7.65 kWh/t.clk at the rated operation of the kiln and 5.43 kWh/t.clk at a reduced rate. The various auxiliaries of recovery and dissipation system, not part of the cogeneration unit itself, cannot be considered. Indeed, the system recovery and dissipation, constituted by the exchanger, the heat dissipator and the thermal oil circuit is required for kiln operating and merely replace the conditioning tower having the same consumption and even more. The thermal power that can be recovered to the cooler level represents approximately 91.2% of the one available at the output of the preheating tower.

Considering latest improvement on ORC technology and an optimization of the heat recovery plant, the power producible per ton of clinker is higher than the existing plant in Morocco. The power producible is also influenced by external factors such as humidity of raw material, number of cyclones in the preheater tower, etc.

The potential for recovery and power generation can be estimated as seen in Table 15:

Table 15: Potential of electricity generation per clinker ton

Heat recovery point	Gross specific electrical energy kWh/tclk		Net specific electrical energy kWh/tclk	
	Nominal rate	Reduced rate	Nominal rate	Reduced rate
Preheater tower (1)	8.9	6.19	7.65	5.43
Clinker cooler (2)	8.11	5.64	6.97	4.95
Global (2)	17	11.83	14.62	10.38

5.3. Potential of energy recovery in Morocco

5.3.1. Cement Sector

5.3.1.1. Total convertible energy

In 2015, cement production reached 14,251,456 tons. It is known that the average rate of clinker in the cement is about 72% (varying according to the quality of produced clinker and cement). According to CSI, the rate is between 71 and 78%. The Moroccan standard requires minimum rate of clinker in the cement 65, 65 and 95 respectively for CPJ35, CPJ45 and CPA55 qualities (Except gypsum). A correlation with cement productions gives about 72%. We can estimate the amount of clinker used to manufacture cement in 2015 to 10,261,048 t.

Clinker production also includes the quantity exported to foreign sites. In average, 15% of clinker production is dedicated to export and this gives an annual production of approximately 11,800,205 t in 2015.

Based on the production of 2015, the electricity generation potential from process waste gases of cement kilns will be (table 16):

Table 16: Annual potential of electricity generation

Heat recovery point	Preheater tower	Clinker cooler	Global
Gross electrical energy GWh/year	105	95.7	200.6
Net electrical energy GWh/year	90.3	82.2	172.5

5.3.1.2. Coverage of electricity needs

In 2013, the average electricity consumption per ton of cement produced is 91 kWh. Whereas this is a specific ratio for the production of 14,251,456 tons of cement, the overall electricity needs for the period 2015 will be 1,297 GWh (table 17).

Table 17: Coverage rate of electricity demand

Heat recovery point	Preheater tower	Clinker cooler	Global
Gross electrical energy GWh/year	8.10%	7.38%	15.47%
Net electrical energy GWh/year	6.96%	6.34%	13.30%

5.3.1.3. Conclusion

Morocco has a potential of recovery of 172.5 GWh per year as net electrical energy saved from heat cement plants gases. This corresponds to 13.30% of the energy demand of all cement plants currently implemented.

This amount of energy is equivalent to the production of a 50 MW power station operating 10 to 11 hours per day and 330 days/year. Considering the specific consumption for producing a ton of cement, this energy amount covers the overall power consumption for producing 1,895,600 tons of cement.

Considering the latest development on ORC technology and heat recovery system, producible energy could be up to 50% higher than mentioned above.

5.3.2. Other industries

Several other industries can benefit from the recovery of energy from gaseous discharges. In principle, any industry evacuating a volume sufficiently abundant and hot gas may use a recovery system to self-produce a portion of its power consumption or optionally for drying and heating needs. A study conducted in France has evaluated the heat lost through waste heat to 51 TWh per year with temperatures above 100 °C. Gas temperatures in the industry vary from 45 to 1600 °C [13], sectors such as steel, glass and chemicals can be concerned by the heat recovery given their temperature variation margins respectively of 190-600 °C, 140-200 °C and 45-230 °C [14]. Overall, the temperature of the gas released into the mineral process industry, steel and chemicals exceed 400 °C in more than 50% and 100 °C in 75% of cases. The fact remains that these areas have the greatest potential for energy recovery than other industry sectors [9].

Table 18: Heat loss rate by industry type

Industry	Waste heat rate %
Chemical & plastics	20
Non steel materials (cement/glass)	19
Food	17
Steel & similar	17
Paper & packaging	12
Refining	7
Others	8

In Europe, industrial activities are behind 62% of total energy consumption [4]. Sectors of chemicals and plastics, non-metallic materials, food and steel are behind more than 70% of industrial waste heat. Table 19 presents power genration potential for some key industry sectors [15].

Table 19: Example of energy recovery potential:

Industry	Cement	Steel	Glass
Capacity t/d	2500	6000	500
Rejected thermal power MW	12	13	5
Net electrical power MW	1.6	2.4	1
Net electrical energy MWh/year	12800	9200	8000

For example, power generation from exhaust gases heat in England is estimated to 12% for cement sector and 28% for the glass sector [16].

6. Investments

Economic calculation is based on the choice of technology (thermodynamic cycle of cogeneration) to set up and the number of recovery points. The power that can be generated by each type of installation can be a relevant base of decision but there are other points to consider such as investment and operating budget, the actual number of discharge points thermal and their remoteness. Today, industrials are motivated and begin to participate to country energy plan aware of the challenge that this represents an opportunity offered coupled with appropriate incentives and funding opportunities presented by various financing organizations such as banks and institutions for energy development. An operator wishing to pre-evaluate the project can benefit from the support of experts and technology providers to discuss more fully the potential recovery and energy conversion rejected by its production units. We consider the above minimum values for determining the energy savings generated by the recovery facility:

6.1. Economic calculation for medium productions (ORC based)

6.1.1. Medium efficiency current plants

Table 20 summarizes a simplified economic calculation for a project to install a heat recovery system and cogeneration for the three different industrial sectors. The calculation is based on average values and is subject to the above conditions. The values are closely related to the nominal capacity.

Table 20: Economic data per type of industry

Industry	Cement	Steel	Glass
Capacity t/d	2500	6000	500
Rejected thermal power MW	12	13	5
Net electrical power MW	1.6	2.4	1
Net electrical energy MWh/y (8000h/y)	12800	9200	8000
Cogeneration unit investissement MDH	20.52	27.36	14.82
Heat recovery system investment MDH	29.64	18.24	12.54
Global investment (10% inforeseen) MDH	50.16	45.6	27.36
Annual operating costs MDH	0.4	0.4	0.4
Average electricity price DH/kWh	0.76	0.79	0.82
Electricity cash flow MDH/year	9.73	7.27	6.56
Net cash flow DH/year	9.33	6.87	6.16
Pay back time (years)	6	7	5

We deduce the average cost of energy as reported in Table 21.

6.1.2 High efficiency plant: Actual state of art

Last development on ORC technology (Turboden srl as reference), allows reaching 27-28% efficiency in case of higher temperature sources. Biggest ORC with a single turbine is now 16-18 MWe. ORC plants in cement field typically use both heat sources (preheater and cooler) and more than 6 MWe can be produced in a 5000 t/d cement plant.

Table 21: Average cost of energy

Industry	Cement	Steel	Glass
Installation cost MDH/MW	31.35	19	27.36
Profitability year	7	8	6
Average electricity cost before depreciation cDH/kWh	68.43	75.15	73.40
Average electricity cost after depreciation cDH/kWh	3.12	4.34	5.00
Net cash flow DH/t	11.19	3.43	36.96

Table 22: Potential of electricity generation per clinker ton with latest ORC technology

Heat recovery point	Gross specific electrical energy kWh/tclk	Net specific electrical energy kWh/tclk
Preheater tower (1)	14	12
Clinker cooler (2)	13.4	11.5
Global (2)	27.4	23.5

6.2. Economic calculation for high productions (Steam turbine)

Using the convential steam cycle, power is clearly important and it is such as to justify substantial but also profitable investments. Installation type diagram is shown in Figure 5 [17].

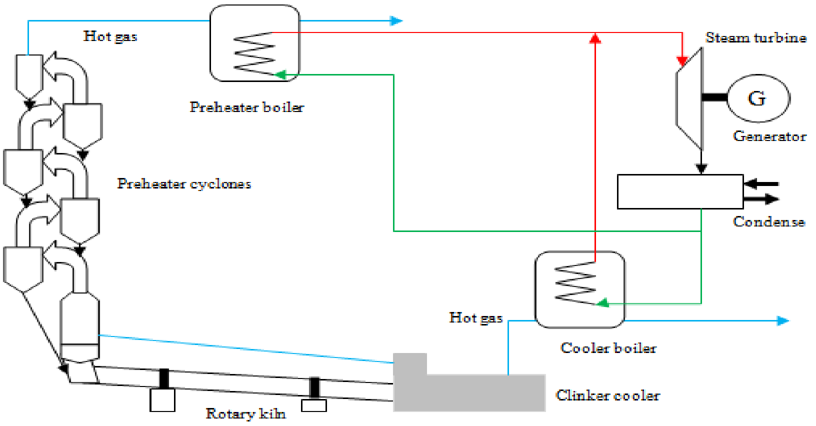


Figure 5: Block diagram of a steam tubine based heat recovery system

The following data reported in Tables 23 to 25 is set to a preheating tower and clinker cooler recovery system depending on kiln rated production.

6.2.1. Capacity of 2,500 to 3,500 tons of clinker per day

Table 23: Electrical specific production - Capacity of 2,500 to 3,500 tons of clinker per day

Clinker capacity t/d	Preheater stages	WHRS		
		Installed capacity kW	Gross power generation kW	Specific power kWh/t clk
4000	4	7500	6220	37.32
3300	5	4500	3870	28.15
2500	5	6000	4367	41.92
2800	5	6000	4850	41.57
3500	5	6000	6100	41.83
3200	5	6000	5102	38.27

An average of 38.17 kWh/t clinker for the class of 2500 to 3500 tons of clinker per day.

6.2.2. *Capacity of 4000 to 5000 tons of clinker per day*

Table 23: Electrical specific production – Capacity of 4000 to 5000 tons of clinker per day

Clinker capacity t/d	Preheater stages	WHRS		
		Installed capacity kW	Gross power generation kW	Specific power kWh/t clk
5000	4	9000	8463	40.62
5000	5	9000	8638	41.46
4600	5	9000	8485	44.27

An average of 40.62 kWh/t clinker for the class of 4000 to 5000 tons of clinker per day.

6.2.3. *Capacity of 1000 tons of clinker per day*

Table 25: Electrical specific production – Capacity *of 1000 tons of clinker per day*

Clinker capacity t/d	Preheater stages	WHRS		
		Installed capacity kW	Gross power generation kW	Specific power kWh/t clk
10000	5	16000	13145	31.55
10000	5	16000	15330	36.79

An average of 34.17 kWh/t clinker for the class of 10000 tons of clinker per day.

6.2.4. *Economic calculation for a 5000 t/d kiln with convential steam cycle*

Tables 26 and 27 give estimated investment amounts and economics calculations for a 5000 t/d cement plant [15,18].

Table 26: Investment for 5000 t/d kiln

Capacity t/d	5000
Gross electrical power brute MW	8.52
Net electrical power MW	7.92
Net energy MWh/year (8000h/y)	63388.8
Cogeneration unit investment MDH	180
Heat recovery system investment MDH	59.28
Global investment MDH	239.28
Annual operating costs MDH	3
Average electricity cost DH/kWh	0.96
Electricity cash flow MDH/year	48.17
Net cash flow DH/year	45.17
Pay back time (years)	2

Table 27: Typical 5000 t/d kiln payback

Installation cost MDH/MW	29.25
Profitability year	3
Average electrical energy cost before depreciation cDH/kWh	193.47
Average electrical energy cost after depreciation cDH/kWh	4.73
Net cash flow DH/t	27.11

6.3. Overall power generation and CO_2 saving potential

Comparing the two technologies for a typical line of 5000 t/d clinker:

Table 28: ORC and steam cycle comparison

Parameter	ORC	Steam
Installation cost MDH/MW	31.35	29.25
Profitability year	7	3
Average electrical energy cost before depreciation cDH/kWh	68.43	193.47
Average electrical energy cost after depreciation cDH/kWh	3.12	4.73
Net cash flow DH/t	11.19	27.11

Note that the average cost of energy in the early years is not significant in this calculation because the repayment can be spread over several years based on established financial arrangements. In this case, the financial costs of investment will be integrated. The ORC technology is limited in terms of power and it affects the cost of installation as well as the cash flow generated per ton of clinker produced. Water consumption should be taken into consideration, especially in a country like Morocco. The average water consumption for a 9 MW facility for 5000 t/d kiln is about 98 t/h while the system based on Rankine technology does not require water consumption. The only use of water is specific to condensation but closed circuit and air cooling system are used without any losses. In all cases, it must be considered a significant water savings due to the elimination of the gases conditioning tower using water spray.

From the above, we can divide the recovery potential on cement plants, operating until now, as follows:

Table 29: Overall electricity generation potential

Cement company	Plants	Production capacity (Mt)	Potential with steam GWh/year	Potential with ORC GWh/year
Lafarge Maroc	3 cement plants + 1 grinding plant	6.9	263	100
Ciments du Maroc	3 cement plants + 1 grinding plant	5	194	73
Holcim Maroc	3 cement plants + 1 grinding plant	4.2	160	61
Ciments de l'Atlas	2 cement plants	3.2	122	47
Asment Temara	1 cement plant	1.2	45	17
Global Maroc		20.5	784	298

As reported above, the recovery potential is only 172.5 GWh, but this value was estimated based on the amount of clinker consumed for the production of cement in 2015. With the current conditions, it represents about 57% of overall potential calculated at nominal conditions of production and which is 298 GWh in case of the ORC cycle. To confirm this percentage of 57%, we check by the ratio of clinker production capacity: in 2015 the clinker consumed was estimated to 10 261 048 t while nominal capacity was 20.5 Mt. The ratio is closed to 50%. The difference between 50 and 57% can be justified by clinker export activity.

In summary, the facilities have a total rated capacity of 298 GWh with ORC cycles and 784 GWh with conventional cycle but the actual production, which depends on kilns rate to nominal capacity, is only about 57% for both technologies.

As per power generation, waste heat recovery systems in Moroccan will guarantee a significant CO_2 emission saving. CO_2 amount calculation is based on average of CO_2 emissions factor between 2002 and 2012 which is about 802.8 gCO_2/kWh. Main results are shown in table 30.

Table 30: Power generation and CO_2 saving potential

Cycle	Potentiel at nominal production GWh/year	Potential at actual production GWh/year	Nominal Saved CO_2 CO_2 eq/year	Actual saved CO_2 t CO_2 eq/year
ORC	298	172.5	242214	140208
Conventional	784	453.8	637235	637235

In 2008, England has set a target of reducing its CO_2 emissions by 80% in 2050 compared to 1990 levels by drastic measures on energy conservation [14].

Conclusion

The aim of this paper is to assess the potential of heat recovery and conversion to electricity in cement industry sector. We have demonstrated that at least 172.5 GWh can be generated by recycling exhaust gases coming from clinker burning process. Waste heat recovery systems can allow a minimum saving of 13.30% of electricity consumption with an important erasing of instantaneous power demand. Alike energy saving guarantees a substantial reduction of CO_2 emissions estimated at least to 140,208 t/year. Heat recovery systems apply on any industry and are foreseen to significantly contribute in energy efficiency and environmental performance by reducing the carbon footprint and then to improve the competitive positioning of Moroccan industry.

Heat recovery and cogeneration plants can be implemented in cement plants and considered in a specific agreement context between governments, cement industrials and funding agencies. Several incentive scenarios can be studied to make easier the establishment of facilities and thus achieve real energy transition.

This proposal obviously concerns all industrial sectors with potential for recovery and energy recovery of waste gases. It is also recommended, under Moroccan law 47/09 on energy efficiency, to require the establishment of such facilities for all new eligible industrial units.

It is manifest that the similar project contribution is not limited to energy intake and energy costs but can also be developed in the context of environmental protection (saved CO_2, water saving) and as part of the promotion of the country's energy subsidiary. The impact will be seen on the absorption of skills in energy fields, industry-related facilities and maintenance services with a great enrichment of knowledge both in industry and in research and training institutions.

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