EVALUATION OF ORGANIC RANKINE CYCLE USING LOW GWP FLUIDS AS A TECHNOLOGY FOR ALGERIAN CEMENT INDUSTRIES WASTE HEAT RECOVERY

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ABSTRACT

Cement factories are among the most energy-intensive industries due to the huge consumption of the clinker manufacturing process (3.2-6.3 GJ ton^{-1}). In addition, the process is characterized by high energy losses since there are two sources of waste heat at high temperature. To improve the system overall efficiency and reduces its emission per ton of cement produced, in this work the authors evaluate the benefits of installing an organic Rankine cycle (ORC) unit adopting low GWP working fluids to recover the waste heat. To design and optimize the ORC cycle, a tool has been developed in MATLAB environment and linked with REFPROP and CoolProp databases. It permits to determine the most appropriate cycle configuration between two different options, and to select the working fluid among 12 low GWP organic media. Being the waste heat at relatively high-temperature values, multistage turbines are used, and a thermal loop is adopted between the waste heat fluxes and the organic fluid for safety reasons. The waste heat sources operating conditions are acquired during an experimental campaign conducted on an in-operation cement industry located in the North of Algeria. The two identified heat sources are recovered via an oil loop and used to feed the ORC. The thermodynamic optimization in terms of net power output is performed, while an economic analysis is carried out to verify the feasibility of the technology through the Algerian techno-economic conditions. The optimization outcomes reveal that the recuperative configuration using pentane as working fluids guarantees the best thermodynamic performance while isopentane and R1233zd(E) guarantee to achieve a net output power 2.1% and 4.6% lower than pentane. However, the economic analysis reveals that the ORC adopting R1233zd(E) ensures the best economic results. Thus, considering also the environmental and safety aspects, the choice fell on the recuperative configuration using R1233zd(E) as working medium which guarantees a net power output of 3.33 MW, a net present value of 6.39 M$, a payback time of 7 years and a higher environmental sustainability.

1 INTRODUCTION

In the recent years, waste heat recovery (WHR) is receiving a lot of attention from the industrial sector because it represents one of the most promising solutions to reduce greenhouse gases (GHGs) emissions and save energy (Huang *et al.*, 2017). Among GHGs, CO_2 is considered the most impacting substance and, based on the International Energy Agency (IEA) estimations, the industrial sector is the largest producer of CO_2 with over 21.4 Gton $year^{-1}$ (IEA, 2019). The power industry, the iron and steel production, the cement manufacturing and the chemicals and petrochemicals industries are responsible for approximately 40% of the global CO_2 emissions (Andrew, 2019). In this context, despite cement manufacturing ranks in the third place with "only" 8% of the global CO_2 emissions (Andrew, 2019), it is attracting the interest of researchers because the application of WHR technologies can contribute to reduce CO_2 emissions up to 10% without massive investments and production cycle's modifications.

Among WHR technologies, organic Rankine cycle (ORC) is considered the most feasible solution being capable of recovering from medium to low temperature heat sources with acceptable efficiency and investment costs (Wang *et al.*, 2015). Note that, at worldwide level, the ORC cumulated installed capacity is higher than 2.7 GW (Tartière and Astolfi, 2017). Despite that, there is a need of focusing on ORC unit characterised by low or even null environmental impact. To this end, the fluid screening needs to be focused on fluids with a global warming potential (GWP) less than 150, and an ozone depletion potential (ODP) equal to 0. Fluid characteristics which ensure that the WHR unit based on the ORC technology guarantees the protection of the environment (Wu *et al.*, 2021).

Considering that, at the time being, Algeria counts more than 17 cement industries in service with an annual production capacity of 40 million tons and a mean CO_2 emission of 0.5071 ton of CO_2 per ton of clinker (Algerian Ministry of Territorial Planning Environment and Tourism, 2010), the Algerian waste heat recovery potential is very high as well as the energy efficiency improvement reachable using technologies like the ORC. To this end, the present work aims to explore the ORC technology ability of recovering the waste heat of an Algerian cement plant and assessing that the technology is profitable also in a market like the Algerian one. In addition, being the environmental impact mitigation a key aspect, an evaluation of the environmental impact associated with the selected ORC working fluids is also performed. Hence, after an experimental campaign conducted on a specific cement plant, the thermodynamic optimisation of the ORC unit is performed considering the maximization of the net output power as an optimization goal. The most suitable working fluid candidate is selected among the fluids with a GWP lower than 150 and an ODP equal to zero. Then, an economic and an environmental and safety analyses are also conducted considering the Algerian price of electricity and electrical market regulations to grasp the designed ORC viability. The optimization algorithm has been developed in MATLAB environment while the thermophysical properties of the working fluids are acquired from REFPROP database (Lemmon *et al.*, 2013). The CoolProp database (Bell *et al.*, 2014) is used to acquire the thermophysical properties of the thermal oil. Being the basic and the recuperative ORC layouts the ones that guarantee the reduction of both plant complexity and investment costs (see, e.g., Pezzuolo *et al.*, 2016; Benato and Macor, 2017), the optimization code also provides the most suitable configuration between them. The need of adopting a thermal loop is also evaluated by the code based on the heat source type and organic fluid.

The rest of the paper is organised as follows. Section 2 describes the selected case study, the thermodynamic model, and the economic analysis. Section 3 presents the code settings and parameters while section 4 presents the optimization outcomes. Concluding remarks are given in Section 5.

2 METHODOLOGY

2.1 Waste heat at the level of the cement industries

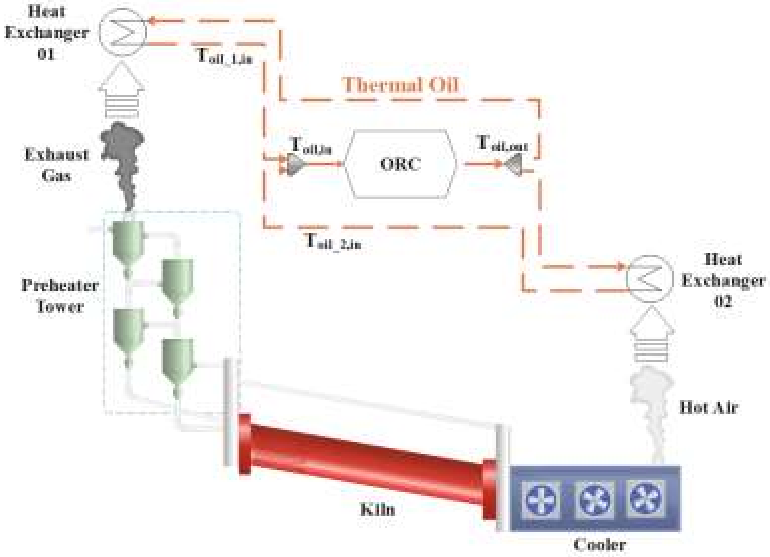


Figure 1: Cement plant waste heat sources and the thermal oil loop used to recover them

Published literature on cement industries reveals that there are two main sources of waste heat. The first one consists of the exhaust gases from the preheater tower, while the second one is the hot air at the level of the cooler. Starting from these research outcomes, the authors select, as test case, a cement industry located in the north of Algeria. Then, they investigated the production process and measured the sources of waste heat released by the selected plant. The experimental campaign conducted by the authors revealed that the exhaust gases at the level of the preheater tower present an average temperature of 382°C, a mass flow rate of 47.113 kg s^{-1}, and a composition in molar fractions as listed in Table 1. The hot air at the level of the cooler is characterised by an average temperature of 216°C and a mass flow rate of 56.321 kg s^{-1}.

Table 1: Composition of the different components exists in the exhaust gas

Components	CO_2	O_2	N_2	H_2O
Mole fraction	26%	3%	69%	2%

Starting from the collected data and in contrast to a previous study (Redjeb *et al.*, 2021), this work aims to investigate solutions in which the ORC recovers the waste heat from both air and exhaust gases. To do that, a thermal oil loop has been designed and arranged as depicted in Figure 1. In addition, the WHR unit needs to be capable of maximizing the net output power. The latter is also a requirement set by the plant owner.

2.2 Thermodynamic model

The optimization code developed to study the cement industry case is an updated version of the one originally developed by (Pezzuolo *et al.*, 2016) and (Benato and Macor, 2017). The updated tool has been modified to perform the thermodynamic optimization of the ORC unit and determine both the cycle thermodynamic points and the design parameters of the components. The expansion process is assumed to take place through an axial multistage turbine, whose efficiency is estimated employing the equation suggested by (Macchi and Astolfi, 2016). The number of stages is computed assuming that the maximum enthalpy drop per stage is equal to 65 kJ kg^{-1}, and the maximum number of stages is equal to 3. The latter constraint has been adopted in accordance to (Macchi and Astolfi, 2016). In fact, adopting more than 3 stages does not provide a significant improvement in the turbine's efficiency but increases its complexity and cost. However, it is important to note that, at industrial level, some manufacturers are developing axial turbine with 4 or 5 stages.

The candidate working fluids are listed in Table 2. These fluids have been selected by the developed code following the criterion of organic fluid environmental impact minimization. Then, only fluids with a GWP lower than 150 and an ODP approximately equal to 0 are considered (Wu *et al.*, 2021). Table 2 also lists the fluids critical temperature (T_c) and pressure (p_c) and, the safety category.

Table 2: Properties of the selected fluids (Luo *et al.*, 2015; Wu *et al.*, 2021).

Fluid	**T_c [°C]**	**p_c [bar]**	**ODP**	**GWP**	**Safety**
Pentane	196.6	33.7	0	20	A3
Isopentane	187.2	33.8	0	20	A3
R1233zd(E)	165.6	35.7	0.0003	1	A1
Butane	152.0	38.0	0	20	A3
Neopentane	160.6	32.0	0	20	A3
Isobutane	134.7	36.3	0	3	A3
R152a	113.3	45.2	0	120	A2
R161	102.1	50.1	0	12	A3
R1234ze(E)	109.4	36.3	0	<1	A2L
Propylene	91.1	45.6	0	20	A3
Propane	96.7	42.5	0	3	A3
R1234yf	94.7	33.8	0	6	A2L

2.3 Economic analysis

The economic analysis is conducted adopting the method of the cost modelling, a technique that requires the determination of the purchasing costs of the devices which build up the cycle including their direct and indirect costs. So, adopting this method, the bare module cost, C_{BM}, of each device is computed as a function of the equipment purchase cost, C_P^0, and the bare module correction factor, F_{BM}, as given in:

$$C_{BM} = C_P^0 F_{BM} \tag{01}$$

The equations proposed by (Turton, 2013) are used to determine the purchase and the bare module costs of the pump which is a centrifugal machine.

$$Log_{10}\, C_P^0 = 3.3892 + 0.0536 Log_{10}(P_p) + 0.1538\left[Log_{10}(P_p)\right]^2 \tag{02}$$

$$F_{BM} = (1.89 + 1.35 \cdot 1.575 \cdot 10^{(-0.3935+0.3957 Log_{10}(p_{ev}) - 0.00226[Log_{10}(p_{ev})]^2})) \tag{03}$$

where P_p and p_{ev} are the power consumed by the pump and the maximum pressure of the cycle (which corresponds to the evaporation one). Similarly, for the pump electric motor, the purchase and the bare module costs are computed as:

$$Log_{10}\, C_P^0 = 2.4604 + 1.4191 Log_{10}(P_p) - 0.1798\left[Log_{10}(P_p)\right]^2 \tag{04}$$

$$F_{BM} = 1.5 \tag{05}$$

For the heat exchangers, the shell and tube type has been selected being considered the most suitable choice for the expected power range of the ORC (Zhu *et al.*, 2018). In this case, the equations suggested by (Smith, 2016) are adopted for estimating the purchase and the bare module costs:

$$C_P^0 = 32800\left(\frac{A}{80}\right)^{0.68} \tag{06}$$

$$F_{BM} = F_M \cdot F_P \cdot F_T = 1 \cdot 1.5 \cdot 1.6 \tag{07}$$

The multistage turbine costs are estimated using the equation proposed by (Astolfi *et al.*, 2014)

$$C_{Expander} = 1230 \cdot 1.19 \cdot \left(\frac{n}{2}\right)^{0.5}\left(\frac{SP_{LS}}{0.18}\right)^{1.1} \tag{08}$$

where n and SP_{LS} are the number of stages and the last stage parameter, respectively. Whilst, the electric generator purchasing cost is computed with the equations proposed by (Toffolo *et al.*, 2014).

$$C_{BM} = 1850000\left(\frac{A}{1180080}\right)^{0.94} \tag{09}$$

$$F_{BM} = 1.5 \tag{10}$$

To compute the heat exchanger costs, there is a need of estimating the heat transfer area. To this end, the overall heat transfer coefficients are set in accordance to (Dimian and Bildea, 2008) and assumed constant for all the fluids. This assumption is reasonable since the main goal of this analysis is not the exact design of the devices, but the evaluation of the feasibility of the proposed solutions. The adopted values are as follows:

$U_{condenser,A}$= 300 W m^{-2} k^{-1}, $U_{condenser,B}$= 700 W m^{-2} k^{-1}, $U_{recuperator}$= 300 W m^{-2} k^{-1}
$U_{economiser}$= 400 W m^{-2} k^{-1}, $U_{evaporator}$= 700 W m^{-2} k^{-1}, $U_{superheater}$= 300 W m^{-2} k^{-1}, $U_{TL,HE}$=200 W m^{-2} k^{-1}

Finally, the total cost of the ORC unit, C_{ORC}, is computed as:

$$C_{ORC} = \sum_{1}^{n} C_{BM,i} \tag{11}$$

where $C_{BM,i}$ is the investment cost of the *i-esim* component. Then, the total cost of the site is assumed equal to the one of the ORC increased by 10% as suggested by the cement industry manager.

$$C_{site} = 1.1\ C_{ORC} \tag{12}$$

while the operation and maintenance costs are assumed equal to 2% of the site cost as suggested by (Pezzuolo *et al.*, 2016).

$$C_{O\&M} = 0.02\ C_{site} \tag{13}$$

According to the government executive decree (General Secretariat of Government, 2002), in Algeria, a tax exemption must be considered. Therefore, the cash flow from electricity generation is given as:

$$CF = (S_{annual} - C_{O\&M}) \tag{14}$$

where S_{annual} is the annual incomes computed as:

$$S_{annual} = E_{annual} \cdot s_E \tag{15}$$

$$E_{annual} = H_{op,annual} \cdot P_{el} \tag{16}$$

$$H_{op,annual} = f_a \cdot 365 \cdot 24 \tag{17}$$

where f_a is the operational factor, $H_{op,annual}$ is the annual operating hours, s_E is the price of electricity, and E_{annual} is the annual electricity production. Note that, the electricity price is estimated using the data provided by the Algerian Ministry of Energy (Electricity and gas regulation commission, 2015) and considering that the produced electricity covers the consumption during the rush hours. This need arises from the fact that the price of electricity during the rush hours is around 5 times more expensive than normal hours.

$$s_E = [(P_{el,day} - P_{AvC})\ s_{E,N} + P_{AvC}\ s_{E,RH}]/P_{el,day} \tag{18}$$

where $P_{el,day}$, P_{AvC}, $s_{E,N}$ and $s_{E,RH}$ are the daily production, the average consumption during the rush hours, the price of electricity during the normal hours, and the price of electricity during the rush hours. The net present value, NPV, is computed as suggested by (Bejan *et al.*, 1995)

$$NPV = CF \cdot RF - C_{site} \tag{19}$$

where RF is the capital recovery factor computed as:

$$RF = \sum_{1}^{n} \frac{1}{(1+i)^n} \tag{20}$$

where i denotes the annual interest rate while n is the number of years considered as ORC lifespan. The profitability index, IP, is calculated as:

$$IP = \frac{NPV}{C_{site}} \tag{21}$$

while the levelized cost of energy, $LCOE$, and the simple payback, SPB, are given as:

$$LCOE = \frac{C_{site} + C_{O\&M} \cdot RF}{E_{annual} \cdot RF} \tag{22}$$

$$SPB = \frac{C_{site}}{CF} \tag{23}$$

3 OPTIMIZER SETTINGS

As previously said, the tool has been developed in MATLAB environment and linked with REFPROP (Version 9.1) and CoolProp (Version 6.4.1) databases. The code employs the MATLAB genetic algorithm toolbox for the optimization while, for the selected case, the optimization goal is the maximization of the net output power of the ORC, which permits the evaluation of the industry waste heat recovery potential. To perform the optimization, the population and the generations are set equal to 350 and 250, respectively. These values are derived from a sensitivity analysis and constitute the best compromise between accuracy and computation time. Being a single objective optimization, the tool evaluates the cycle's thermodynamic points. Then, for the optimized ORC arrangements in terms of both layout and working fluid, the code performs the economic analysis and provide environmental and safety information. Note that, for both safety and technical reasons, to recover both the heat sources of the cement plant, an oil thermal loop is employed. In this way, the oil recovers the thermal power from the heat sources and transfer it to the ORC working fluid. Considering its high stability, no-toxicity and an auto-ignition temperature extremely far from the heat sources ones, Therminol VP1 (Eastman, 2020) is used in the thermal loop. For the sake of clarity, the implemented ORC architectures are depicted in Figure 2.

The authors, using data taken from the literature (see, e.g., Pezzuolo *et al.*, 2016; Benato and Macor, 2017) and provided by the cement industry operators and ORC manufacturers, fixed some of the ORC unit parameters (see Table 3), while the upper and lower bounds (UB and LB) of the variables that need to be optimized have been summarized in Table 4.. Note that, both pressure drops, and heat losses are neglected during the optimization process.

With the aim of ensuring reasonable pumping conditions and a subcritical structure of the cycle as suggested by (Marcuccilli and Zouaghi, 2007), the maximum pressure, p_{max}, is assumed equal to:

$$p_{max} = p_{critic} \quad if \quad p_{critic} < 50\ bar \tag{24}$$

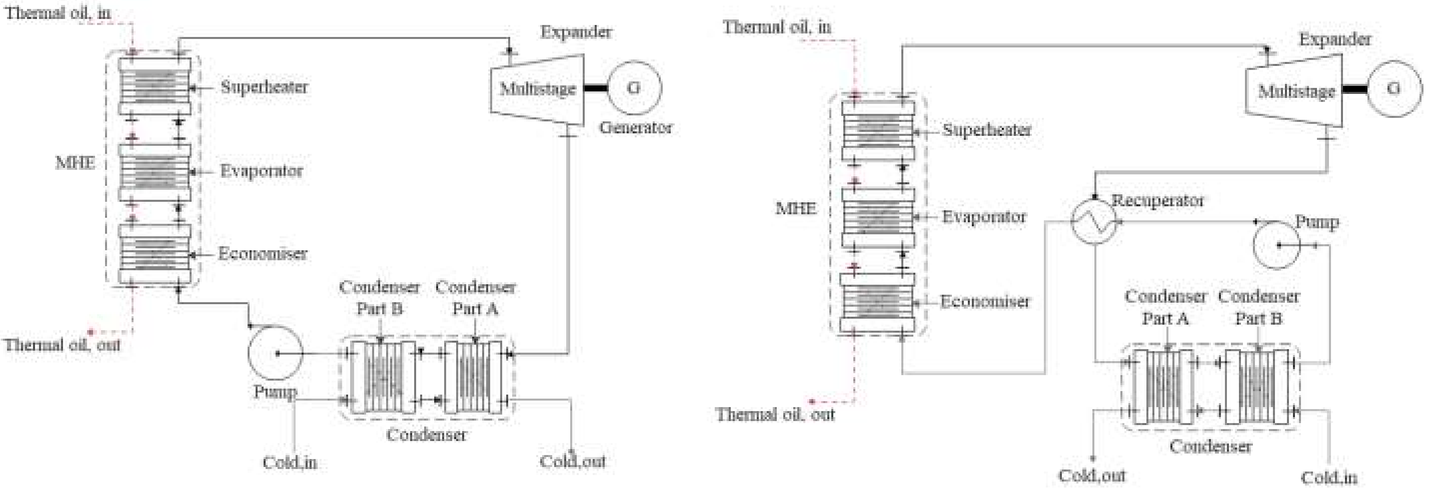
$$p_{max} = 50\ bar \quad if \quad p_{critic} > 50\ bar \tag{25}$$

Similarly, to guarantee the stability and durability of the thermal oil, its maximum temperature, $T_{oil,max}$, is assumed equal to the minimum between $T_{max,bulk}$, which represents the maximum operating temperature of the thermal oil without the risk of thermal degradation (for the considered oil $T_{Bulk,THVP1}$=400°C), and T_{hot}, which refers to the highest temperature of the heat source.

$$T_{oil,max,1} = T_{hot} \tag{26}$$

$$T_{oil,max,2} = T_{max,bulk} - 40°\text{C} \tag{27}$$

$$T_{oil,max} = \min\,(T_{oil,max,1}, T_{oil,max,2}) \tag{28}$$



(a) (b)

Figure 2: (a) Basic and (b) recuperative ORC configuration with the thermal oil loop

Table 3: Assumed parameters for the different devices of the ORC unit

Parameter	Value
Thermodynamic	
Pump isentropic efficiency (-)	0.80
Pump mechanical efficiency (-)	0.92
Pump electric motor efficiency (-)	0.90
Turbine mechanical efficiency (-)	0.90
Electric generator efficiency (-)	0.92
Economic	
Interest rate (%)	2.5
System lifetime (year)	15
Electricity average price during rush hours $S_{E,RH}$ (\$ kWh^{-1})	0.061
Electricity average price during normal hours $S_{E,N}$ (\$ kWh^{-1})	0.013

Table 4: UB and LB used in the optimisation of the ORC

Parameter	LB	UB
Thermal oil inlet temperature, $T_{oil\_1,in/oil\_2,in}$ (°C)	180	$T_{oil,max}$
Thermal oil, hot gas, and hot air outlet temperature, $T_{oil,out/hot,gas,out/hot,air,out}$ (°C)	70	$T_{oil,in/hot,gas/hot,air}$
Evaporation pressure of the organic medium, p_{ev} (bar)	p_{cond}	p_{max}
Turbine Inlet Temperature, TIT (°C)	TIT_{min}	TIT_{max}
Recuperator efficiency, E (-)	0	0.8
Condensation temperature, T_{cond} (°C)	45	70
Minimum temperature difference in the MHE, TLHE, $\Delta T_{pp\_MHE/TLHE}$ (°C)	10	20
Minimum temperature difference in the condenser, $\Delta T_{pp,cond}$ (°C)	10	20

4 RESULTS AND DISCUSSION

After the tool validation process, the simulations are performed, and their outcomes are listed in Table 5 and Table 6.

Pentane is the most promising working fluid among the tested ones because it guarantees a net power output of 3.49 MW: a value 2.1% and 4.6% higher than adopting Isopentane and R1233zd(E), respectively. In addition, the optimization reveals that the recuperative ORC configuration guarantees the higher net power output and efficiency. Thus, from a thermodynamic point of view, the recuperative configuration using Pentane as a working fluid seems the best option for the Algerian cement industry.

Table 5: Most promising fluids in term of net power output

Fluid	P_{el} (MW)	$T_{oil,in}$ (°C)	$T_{oil,out}$ (°C)	TIT (°C)	p_{ev} (bar)	p_{cond} (bar)	E (%)	η_{cycle} (%)	$\eta_{is,t}$ (-)	stages (-)
Pentane	3.49	271.7	97.9	199.9	29.44	1.40	78	17.57	0.897	3
Isopentane	3.42	255.7	89.9	191.9	31.95	1.82	73	16.52	0.899	3
R1233zd(E)	3.33	266.8	90.9	201.9	34.75	2.59	76	16.23	0.894	2

Table 6: Most promising fluids' optimum values for optimized variables

Fluid	$T_{hot,gas,out}$ (°C)	$T_{hot,air,out}$ (°C)	$\Delta T_{pp,TLHE,1}$ (°C)	$\Delta T_{pp,TLHE,2}$ (°C)	$\Delta T_{pp,MHE}$ (°C)	$\Delta T_{pp,cond}$ (°C)	$\Delta T_{pp,rec}$ (°C)
Pentane	110.9	109.9	11.0	10.5	11.6	11.7	14.2
Isopentane	103.9	102.9	10.2	11.0	10.2	11.9	15.3
R1233zd(E)	103.9	101.9	12.3	11.0	10.1	11.7	14.3

However, Algeria guarantees a very cheap price for electricity because its price does not exceed 0.04 \$ kWh^{-1} due to government subsidies (Penaka *et al.*, 2020). Therefore, an economic analysis is required to confirm that the adoption of the ORC technology at the level of the cement plant is profitable and acceptable also from an economic point of view.

The results of the economic analysis for the three most promising working fluids are listed in Table 7.

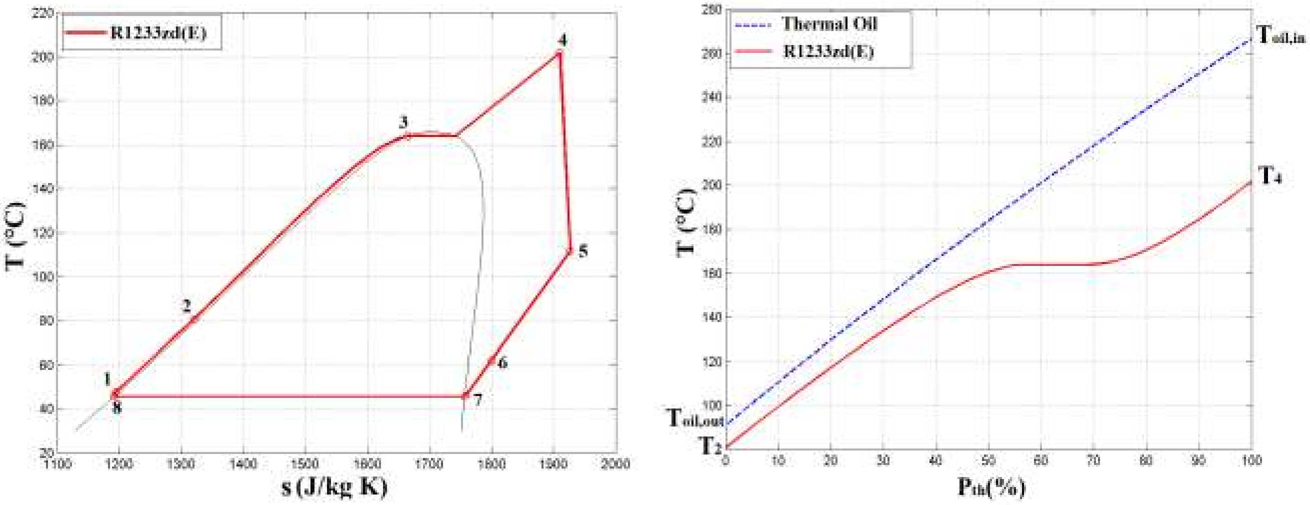
Table 7: Economic analysis results for the most promising fluids

Fluid	C_{site} (M\$)	SPB (year)	Price of installed capacity (k\$ kW^{-1})	NPV (M\$)	IP (-)	LCOE (\$ kWh^{-1})
R1233zd(E)	8.24	7.0	2.25	6.39	0.78	0.031
Isopentane	8.93	7.6	2.37	5.64	0.63	0.033
Pentane	9.23	7.8	2.41	5.35	0.58	0.033

In contrast to the thermodynamic optimization, the economic analysis reveals that adopting R1233zd(E) as working fluid guarantees the best economic results in terms of both net present value (6.39 M\$) and payback time (7 years). Isopentane, as previously, ranks second with a payback time 8% higher than the R1233zd(E) one, while Pentane placed third with a SPB 11% higher than the best option. Comparing again Isopentane and Pentane with R1233zd(E), it is possible to note that the NPV results 11.7% and 16.3% lower, respectively.

In addition, the results of this analysis reveal that the investment cost of the expander for the ORC unit represents the major cost, the latter depends directly on the last stage size parameter and the number of stages. Among the fluids, R1233zd(E) shows the smallest value of the last stage size parameter (0.2066 m) and then, it leads to a cheaper price of the expander, followed by the Isopentane and Pentane. The value of the last stage parameter for the Isopentane and the Pentane is higher compared with R1233zd(E). This leads to a higher ORC purchasing cost and SPB; then a lower NPV. Despite that, the analysis of the price per kW of installed capacity underlines a maximum difference of 7% between the fluid ranking first and the one ranking third, while the LCOE reveals a substantial equality among them.

Therefore, the thermodynamic optimization shows that the best option is a recuperative ORC using Pentane as working fluid while the economic indexes reveal that a recuperative ORC working with R1233zd(E) is better from the economic point of view. Then, the performed analyses provide opposite results and, to solve this issue and select the best option, the authors performed the environmental analysis. In fact, the R1233zd(E) is characterised by a GWP 20 times lower than Pentane, a higher safety and a non-toxicity (it belongs to category A1 while Pentane to A3) despite its ODP is 0.0003 and not 0 as for Pentane. Based on these environmental considerations and the better economic performance, R1233zd(E) is preferred to Pentane as working fluid despite the net output power results 4.6% lower than the one reachable with Pentane. Therefore, the best waste heat recovery unit option for the analysed cement industry operating in the Algerian market is a recuperative ORC adopting R1233zd(E) as working medium. The heat sources waste heat is exchanged to the ORC using a thermal loop employing Therminol VP1. The T-s diagram of the designed ORC cycle and the T-Q diagram of the Main Heat Exchanger are depicted in Figures 3(a) and 3(b), respectively.



(a) (b)

Figure 3: (a) T-s diagram of the cycle and (b) T-Q diagram of the evaporator using R1233zd(E)

Finally, it is important to remark that the proposed solution requires further investigation because, in literature, some study indicate that R1233zd(E) is not stable at temperature higher than 180°C (Rached *et al.*, 2018). In particular, due to geometric isomerization, there is a limitation in the fluid performance and stability. Thus, before implementing this solution in the cement plant, there is a need of performing experimental tests aimed to improve the knowledge on R1233zd(E) thermochemical stability.

5 CONCLUSIONS

Algeria is classified among the largest cement producing countries in the Northern Africa. But cement industries are characterised by large energy losses and CO_2 emissions. So, there is a need to study solutions able to improve the environmental sustainability of these industries. In this context, organic Rankine cycles (ORCs) are a good option especially if they employ low GWP fluids.

To this purpose, the authors selected a cement manufacturing plant located in Algeria and measured the available source of heat. Then, they built an optimization tool able to guide the selection of both ORC plant configuration and working fluid. To complete the picture and better lead the ORC unit selection, the authors conducted also an economic and an environmental analysis.

The thermodynamic optimization reveals that the best ORC configuration is the recuperative one while the working fluid needs to be Pentane. Contrary, the best economic performance is guaranteed by R1233zd(E), a fluid that ranks in the third place if the thermodynamic analysis guides the fluids comparisons. Despite adopting R1233zd(E) as working fluid gives a net output power 4.6% lower than Pentane, this solution is preferred due to its higher environmental sustainability. In fact, R1233zd(E) is characterised by a GWP 20 times lower than Pentane, a higher safety, and a non-toxicity despite its ODP is 0.0003 instead of 0 as in the case of Pentane.

NOMENCLATURE

CF	cash flow	(k$)
C_P^0	basic purchase cost	(k$)
LCOE	levelized cost of energy	($ kWh^{-1})
NPV	net present value	(k$)
P_{avC}	power average consumption	(kW)
P	power	(kW)
SPB	simple payback period	(year)
S_{annual}	annual incomes	(k$)
s_E	Electricity price	($)
Subscripts		
cond	condensation	
ev	evaporation	
MHE	main heat exchanger	
TL,HE	Thermal loop heat exchanger	
Greek symbols		
η	efficiency	(%)

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