Evaluation of Organic Rankine Cycle Alternatives for the Cement Industry using Analytic Hierarchy Process (AHP) Methodology and Energy-Economic-Environmental (3E) Analysis.

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Abstract.
In the cement industry, where energy efficiency and CO_2 reduction are crucial, Waste Heat Recovery (WHR) systems play a vital role. This study examines WHR systems' optimisation, evaluating three power cycle variants: simple ORC, RORC and TLC. Decision-making was guided by the Analytical Hierarchical Process (AHP), a multicriteria methodology that provides a systematic framework for evaluating multiple alternatives under different criteria. This study considered four criteria: the net present value, the investment cost, the CO_2 emissions avoided and the net work produced. The relevance of each criterion was varied according to five scenarios, and the AHP methodology allowed a flexible weighting of these criteria based on their importance. Overall, the RORC outperformed the other alternatives regarding power generation, emission reductions, and net present value. However, the results depended on the operating conditions and the selected working fluid. The optimal choice varies depending on the priorities of the plant. For example, if minimising investment cost is prioritised, simple ORC might be preferred. This study highlights the importance of multicriteria evaluation and the use of decision-making tools such as the AHP to select the best alternative based on the specific needs of each plant. In this way, it provides valuable guidance for the implementation of WHR systems, underscoring the importance of considering the specific circumstances of the plant and the operating environment when selecting a waste heat recovery technology.

Keywords: Multicriteria Decision Making (MADM), Analytical Hierarchy Process (AHP), Waste Heat Recovering, cement industry.

1. Introduction.

Carbon dioxide and global warming have forced the scientific and industrial community to develop more efficient and environmentally friendly transformation, transference, and heat-sourced energy appliances [1]. However, conventional processes, like fossil fuel combustion, generate carbon dioxide and other gaseous emissions, contributing to climate change. Therefore, one of the main requirements of any new system should be a net decrease in carbon dioxide emissions compared to existing ones to help decrease global warming [2]. Given the above, governments are proposing international policies to achieve rational and efficient energy usage. For example, the European Council is looking for a 40% reduction in greenhouse emissions (GHGs) by 2030. Also, it expects at least a 32% increase in renewable energy sources' participation in the energy market [3], [4].

Waste heat is classified as high, medium, and low based on [5]–[7]. The heat source is regularly present in gaseous emissions from engines or industrial processes [8]. Therefore, any stream leaving the system above environmental temperature or pressure could be considered a residual heat stream [9]. In order to improve primary energy resource consumption and reduce carbon dioxide emissions, one of the more studied options is to increase the thermal efficiency of intensive-energy processes by using this waste energy in a secondary process. Some options include Waste Heat Recovery (WHR) using heat pipes[10][11], heat pumps[12], heat storage [13], [14] and power cycles as an alternative to improve energy conversion. The most known used cycle is the Organic Rankine Cycle (ORC). ORC is a technology that harvests residual heat from industrial processes and produces electric power. This solution can be used when the waste heat is in the temperature range between 150°C to 300°C [15][16]. An ORC can use an organic working fluid with a lower boiling point than water, operating at temperatures between 70 to 300 ºC. This is the ideal range of temperature to recover waste heat, as previously described, to generate electric power.

The working fluid selection for an ORC is crucial because the cycle performance depends on the relationship between the heat source and the organic solvent used. This relationship mainly depends on the temperature range of the residual heat source [17]. Therefore, the working fluid should be environmentally friendly and thermally stable at high temperatures. Then, fluids like siloxanes, alkanes, and aromatics, are preferable for ORC because of their excellent thermophysical and environmental behaviour. In addition, they get better system performance in some high-temperature applications because these compounds can reach higher working temperatures than other solvents [18][19]. Several studies have been conducted to improve ORC performance using theoretical analyses [17],[20],[21],[22]. Some of them include supercritical pressures (ORC transcritical) [23], several evaporation stages [24], or a double expansion stage [25]. In addition, other ORC studies are focused on analysing the effect of intermediate recuperators [21],[26], vapour fraction extraction to preheat the working fluid (regenerative ORC) [27], two-phase expansion from the saturated liquid zone, called Trilateral Flash Cycle (TFC) [28]-[29], coupling ORC in cascade configuration [28]-[29] or zeotropic mixes used as the working fluid [30]. These alternatives are used to improve the performance of these kinds of cycles.

1.1. Organic Rankine Cycle.

ORC is a mature technology to recover waste heat between 150 - 300 °C [15]. This range of temperatures is typically found in several processes' emission streams. For example, emissions from Heavy-Duty Diesel (HDD)engines at 330–509 °C [31] or 317- 572 °C [32] have been studied before. In both cases, the gases coming from the HDD are coupled to an ORC to recover waste heat. In the research by Zhao et al., three different ORC setups are investigated: a simple ORC, a regenerative ORC and an ORC with an intermediate heat exchanger (RORC). The intermediate heat exchanger helps to improve the thermodynamic efficiency of the cycle. In addition, this component recovers part of the energy still available in the working fluid at the exit of the turbine outlet, which was going to be withdrawn in the condenser to reheat the fluid at the pump outlet. The RORC using IHE showed about 0.4 - 5 % and 2.53 – 8.78 % above net power compared to a regenerative ORC and a simple ORC, respectively [33].

Laouid et al. [34] studied the ORC architecture using two heat sources at different temperatures (573–773 K and 353–393 K) to increase the system performance. The ORC configurations were Two-Stage in-series (STORC) and Two-Stage in-parallel (PTORC). They were compared with an ORC with preheating a single stage in subcritical conditions. The STORC presented a higher thermodynamic performance in the researched range of temperatures. In addition, it showed a power increase of 8.3% compared with the preheated ORC. Also, it had a heat exchanger size reduction of 27.9%. On the other hand, the PTORC showed a negative performance compared with the preheated ORC, with a power reduction of 0.3%.

1.2. Trilateral Cycle.

The Trilateral Cycle (TLC) technology requires much development and is not widely known. However, this cycle has become attractive in the last few years because it provides a better coupling in the evaporator temperature profiles than conventional heat recovery cycles. In this cycle, the working fluid at the inlet of the expander is in the saturated liquid phase, which implies an expansion in two phases. Therefore, the TLC is as simple as an ORC because the process components are equal. The only difference is the expander, which must be a positive displacement device, like a screw expander, because of the two-phase expansion [35]. Therefore, this cycle is like a modified ORC, where the organic fluid is heated to saturated liquid. Nevertheless, instead of expanding from saturated or superheated vapour, as in a conventional expansion, the expansion begins as a saturated liquid, generating two phases [36]. Some comparative studies concluded that TLC generates 50% more power than the conventional ORC working in the same conditions with a heat source of 100 °C. Moreover, TLC can generate power using a heat source under 80 °C; at this temperature level, ORC is not economically viable [29].

This cycle presents a higher pumping demand and larger heat exchangers than traditional ORC, increasing initial capital and operational cost. However, this can be compensated by the higher net power obtained [37]. The main disadvantage of TLC is the complex expander required to manage the additional two-phase flow. This restricts the inclusion of a turbo-expander because of the damage the liquid drops generate in the rotor blades [38]. To avoid those drawbacks, a two-screw expander can be used; this type of expander consists of helicoidal rotors with a 50 μm clearance. Also, it has medium friction, leakage losses and medium noise compared to a conventional ORC expander. Also, this expander is the technology that can manage high working flows. Additionally, since it operates at high rotational speeds, it does not negatively affect its efficiency. Because of these factors, it is appropriate for use in TLC [39].

1.3. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) minimises common drawbacks of the decision-making process, like lack of focus, planning, contribution or property, which with time, are expensive interruptions that hinder the process of arriving at the right choice. AHP is one of the most used methods for multiple-parameter decision-making. This one can evaluate different alternatives. Generally, AHP is a non-linear framework for conducting deductive and inductive thinking without using syllogism. This is possible because several factors can be simultaneously considered, setting them in a hierarchy that allows dependence and making numerical compensation to arrive at a synthesis or conclusion [40] [41]. The AHP is based on the theory of relative measurement that can be used to solve complex multiple-criteria decision-making problems. AHP proposes a methodology handy for this effect because it is based on the principle that the shareholders' experience and knowledge are as necessary as the data used by the process. In other words, it provides a procedure to obtain a prioritisation and ponderation scale based on the judgement of the decision makers [42]. AHP's objective is to plan a complex problem in a hierarchical structure. Then, the decision alternatives are found at the bottom of the hierarchy, while the goal is at the top [43].

The application of this method requires four fundamental steps, as shown in Table 1. First, a complex problem must be separated into a hierarchy; each level has some controllable elements, and each element is divided into another set of features. The hierarchical structure is shown in Figure 1 for the case of this work. However, there is no single overall hierarchical structure, and flexibility is one of the main characteristics that AHP provides to decision-makers [44]. In the annexes section, the algorithms and the pseudocode used to evaluate the criteria, the creation of the analysis scenarios and the multicriteria decision have been detailed.

Table 1: Path for AHP application [43]**.**

Step	Application of AHP.
1	Construction of the hierarchical structure (define problem, objectives and criteria)
2	Comparison matrix construction
3	Synthesis of the comparison matrix and consistency check
4	Collection of individual priorities and selection of alternatives.

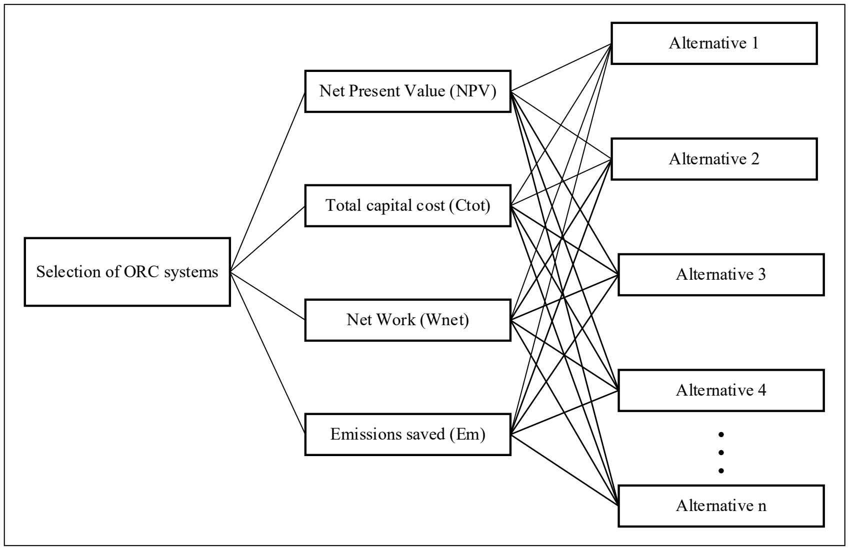

Figure 1: Hierarchical structure of AHP intake for this study.

Then, the priority of the elements within each layer of the hierarchy is established, and a measurement methodology is applied that evaluates each set of parts in the form of pairs. Therefore, the framework for data collection and AHP analysis is achieved. Finally, t pairwise comparison uses a nine-point scale called the Saaty scale [41], shown in Table 2.

Table 2: Saaty fundamental scale for comparative judgments [45].

Intensity of importance on the Saaty scale	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 5, 6, 8	Intermediate values between the two adjacent judgments
Reciprocal	If activity *i* is assigned one of the above non-zero numbers compared to activity *j,* then *j* has the reciprocal value compared to *i*

In the annexes section, the algorithms and the pseudocode used in this work to evaluate the criteria, the creation of the analysis scenarios and the multicriteria decision have been detailed. The one proposed by Alade et al. in [46] was used.

1.3.1. Analytical Hierarchy Process in the selection of Rankine Organic Cycles.

The Analytic Hierarchy Process (AHP) is a valuable tool for selecting residual heat recovery systems, as it allows for considering different criteria simultaneously and establishes a hierarchy of importance among them. One of the main benefits of AHP is that it allows for the consideration of both quantitative and qualitative criteria [47]. For example, criteria such as generated power and investment cost can be considered alongside qualitative criteria such as component availability and ease of maintenance. In [48], the authors focus their research on using multi-objective optimisation techniques to select working fluids and design subcritical ORC systems in the geothermal field that optimise energy efficiency, economic performance and environmental impact. This work includes factors such as the cost of the working fluids, the efficiency of the cycle, the environmental impact, and the availability of the fluids. They use the AHP methodology to find solutions that simultaneously satisfy these objectives. This implies finding a fluid with a high cycle performance, a low environmental impact and a reasonable cost.

In [49], the authors present an AHP methodology to evaluate and compare different ORC component options (working fluid, turbine, generator and condenser) based on various criteria such as energy efficiency, investment cost and environmental impact. The authors also use the "Technique for Order Preference by Similarity to Ideal Solution" (TOPSIS) to rank the component options based on the AHP results. The study results show that the AHP-TOPSIS approach is a valuable tool for selecting components of an Organic Rankine Cycle, as it considers multiple criteria and allows for the integration of subjective factors. The authors note that this methodology could be applied to other power generation systems and equipment selection problems.

Similarly, the authors in [50] present an approach to evaluate subcritical Organic Rankine Cycle systems that use low GWP (Global Warming Potential) fluids through an analysis that combines energy, exergetic, economic, and environmental variables. It uses the Analytic Hierarchy Process to establish a hierarchy of evaluation criteria, which includes efficiency, cost, safety and environmental impact. The authors found that R1234ze was the best working fluid regarding performance, safety, and cost. However, R1233zd has the lowest environmental impact in terms of GWP.

This work continues a preliminary study that evaluated a residual heat source of combustion gases from a rotary kiln for a cement plant with a capacity of 5000 tonnes per day [21][22]. These gases come out at an average temperature of 327 °C and are loaded with particulate material that must be eliminated before being discharged into the environment. This material is removed in a baghouse operating at 180°C to prevent thermal deterioration. Therefore, water injection is used to cool the gases in a pre-conditioning tower, where a loss of useful power in the form of heat of approximately 32 MW is observed.

In the present work, a simulation approach is used to evaluate the performance and waste heat recovery potential of three variants of power cycles: simple ORC, ORC with an intermediate heat exchanger (RORC) and trilateral cycle (TLC), using the above-mentioned flue gases from the kiln as a heat source. The exhaust gas outlet temperature varies between 150 and 180 °C in the simulations. In addition, the temperature difference at the evaporator pinch point is varied between 10 and 20 °C. Also, seven working fluids are evaluated for each technology, resulting in 168 configurations or alternatives. Finally, the multicriteria decision-making methodology called the Hierarchical Analytical Process (AHP) is used to find the option that best suits the needs of the plant according to four selection criteria: (1) net present value, (2) the total cost of capital, (3) net power output, and (4) CO_2 emissions avoided.

Five scenarios were considered: the first assumes the company has limited investment resources. Therefore, it is decided to prioritise minimising the investment cost over the other criteria. In the second scenario, the condition in which the company has sufficient availability of money to invest is studied, so the net present value is prioritised over the other criteria. The third scenario is associated with a situation in which a company has a high electrical demand, and the only way it can generate energy is through one of these alternatives. Therefore, the net power output is prioritised over the other criteria in this case. The fourth scenario includes a company forced to reduce its carbon footprint; therefore, the value in saved emissions is prioritised. Finally, a last application of the methodology was carried out in a fifth scenario, considering a hypothetical case in which economic indicators are given importance simultaneously over other factors, which eventually could be the best-case scenario for the company's interests. This study was developed with the objective that decision-makers can objectively and well-founded evaluate and select the best alternative for ORC-type waste heat recovery systems, considering relevant criteria and weighing their relative importance under any scenario.

2. Materials and Methods.

This section describes the evaluated power cycles (ORC, TLC and RORC), the thermodynamic models used for each component in terms of exergoeconomic analysis, the selection of the working fluids used for each power cycle, and the corresponding validations of the models used.

2.1. Organic Rankine cycle and trilateral cycle.

Schematically, the simple ORC and TLC cycles are identical; as shown in Figure 2 **(a)**, these cycles have four main components: pump, expander, evaporator and condenser. Conversely, the ORC with a recuperator has an additional heat exchanger located after the turbine to recover part of the heat before the working fluid reaches the condenser, as shown in Figure 2 **(b).** However, the main difference is that in the TLC, the working fluid expands from the saturated liquid state, generating two phases during the expansion process [36]. Figure 3 shows a *T-s* diagram for the TLC, simple ORC, and RORC cycles, where the working fluid follows the process in each power cycle. For all cases, the expansion and pumping processes were considered isentropic, and the pressure losses in the heat exchangers were not considered. In addition, some parameters are fixed to carry out the comparison of the cycles:

1. The entry temperature of the heat source will remain constant at 327 °C.
2. The condenser (COND) operates with cooling water, entering at ambient temperature.
3. The working fluid outlet temperature from the condenser is held at 60 °C.
4. All pressure drops in the cycle occur in the expander.
5. The expansion and pumping processes are considered isentropic.

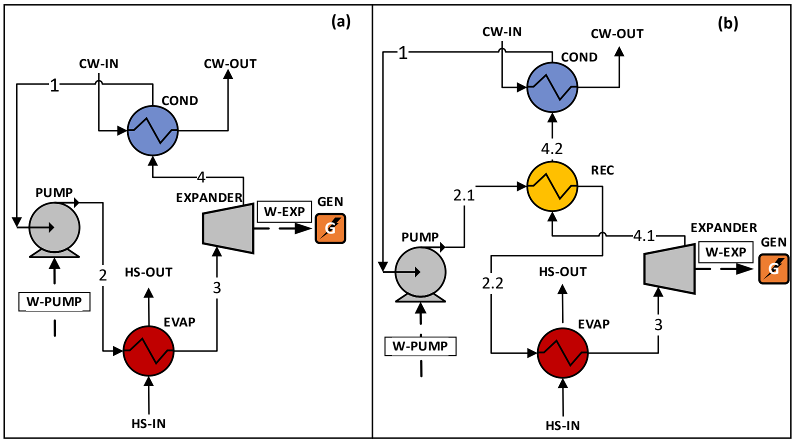

Figure 2: Simple ORC and TLC configuration (a), ORC configuration with recuperator (b) [51]**.**

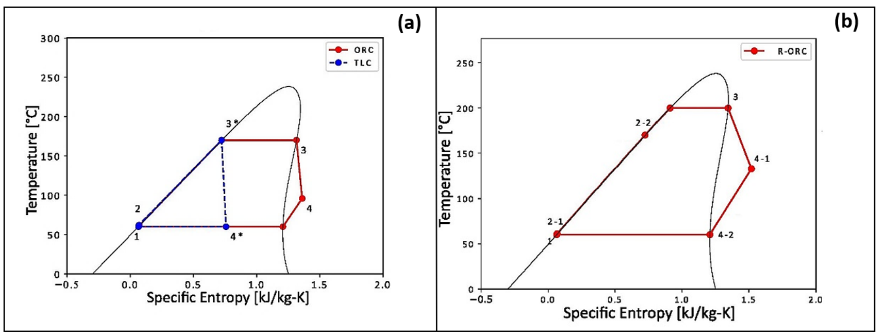

Figure 3: *T-s* diagrams for ORC and TLC (a) and ORC with intermediate recuperator (b) [51]**.**

2.2. Working fluid selection for ORC and RORC.

Selecting the working fluid must consider the impact of factors such as the possibility of wet expansion and environmental factors (e.g., ODP (Ozone Depletion Potential)) on the turbine power performance. The ODP refers to the amount of stratospheric ozone destruction caused by a substance. It is evaluated as the ratio of the impact on ozone caused by a given substance to the effect caused by a similar mass of trichlorofluoromethane (CFC-11; the CFC-11 ODP is defined as 1. Another factor to consider is Global Warming Potential (GWP). The GWP is a relative measure of how much heat can be trapped by a greenhouse gas compared to a reference gas, usually carbon dioxide. For example, the emission of one million tons of a gas with a GWP of 30 is equivalent to emitting 30 million tons of CO_2 equivalent. In addition, although the overheating of the working fluid was not considered in this study, it must be ensured that the steam fraction at the turbine outlet is more significant than 0.9 [52]. That avoids droplet formation that eventually can generate erosion in the turbine; only dry or isentropic fluids were considered to ensure this. Due to the irreversibilities associated with the process, the entropy in the expansion process increases, as seen in Figure 4. Therefore, if the fluid is dry or isentropic, after expansion, the fluid will be in the superheat region at the condenser pressure. However, if the fluid is wet, there is a risk of operating the expander with a quality of less than 1, and there is a need to superheat the working fluid so that when it expands, it is still in the superheated vapour zone. This additional superheat process will require a larger evaporator and, therefore, a higher cost [53].

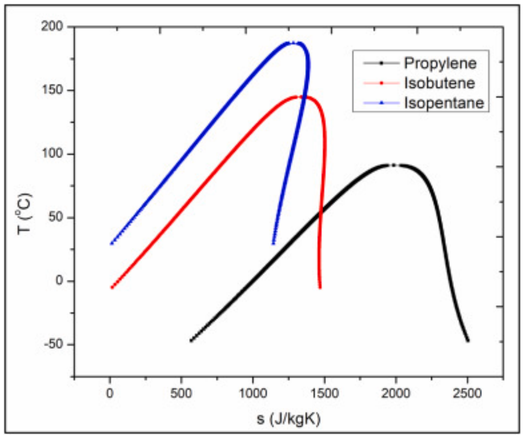

Figure 4: T-s diagram for dry fluid (blue), isentropic fluid (red), and wet fluid (black) [53]**.**

Table 3 shows the thermodynamic characteristics of the working fluids used to evaluate the ORCs' performance. These fluids present boiling points close to ambient and allow for condensation near atmospheric pressure. For the ORC, most of the selected fluids are alkanes, as these are environmentally friendly working fluids with zero ODP and relatively low GWP values [54]. In addition, alkanes have been widely used in the ORC process, showing that they can perform better than other types of fluids [55], [56].

Table 3: Working fluids for ORC and ORC with a recuperator [57]**.**

Working Fluid	T_{crit} (°C)	P_{crit} (kPa)	Type	ODP	GWP
Cyclopentane	238.54	4,515	Isentropic	0	Very low
Pentane	196.55	3,370	dry	0	Very low
R141b	204.35	4,210	Isentropic	0.11	700
R365mfc	186.85	3,270	Isentropic	0	890
Cyclohexane	280.49	4,075	Isentropic	0	Very low
Hexane	234.67	3,034	Dry	0	Very low
Heptane	266.98	2,736	Dry	0	Very low

2.3. Working fluid selection for TLC.

Regarding the working fluids for trilateral cycles, it has been shown that better performance can be achieved when the critical temperature of the working fluid is close to (but not lower than) the temperature of the working fluid after the evaporator [58] [59]. Table 4 shows the characteristics for evaluating the TLC performance of the seven working fluids selected among the 57 reported by [60], prioritising the critical temperature as a fluid selection criterion (between 170 and 200 °C).

Table 4: Working fluid for TLC [60].

Working fluid	T_{crit} (°C)	P_{crit} (kPa)	Type	ODP	GWP
R11	197.96	4,410	Isentropic	1	4,680
R141b	204.35	4,210	Isentropic	0.11	700
R21	178.33	5,180	Isentropic	0.01	210
R365mfc	186.85	3,270	Isentropic	0	890
Isopentane	187.2	3,378	Dry	0	Very low
R123	183.68	3,660	Isentropic	0.022	76
R245ca	174.42	3,930	Isentropic	0	640

2.4. Thermodynamic model

The thermodynamic modelling of the power cycles shown in Figure 2 is based on the straightforward application of mass, energy and exergy balances, as listed in Table 5. For instance, eq (1) presents the exergy evaluation for any stream in the cycle as:

$$\dot{X}_i = \dot{m}_f[(h_i - h_0) - T_0(s_i - s_0)] \quad (1)$$

In addition, the equations in the first-law column account for the heat that enters the cycle in the evaporator, eq. (2); the heat that leaves the cycle in the condenser, eq. (4); the work delivered by the expander, considering its mechanical and isentropic efficiencies, eq. (6); the work required by the pump according to its isentropic efficiency, eq. (8). Conversely, equations for the exergy destroyed by the cycle component are eq. (3) evaporator, eq. (5) condenser, eq. (7) expander, and eq. (9) pump. Finally, if considered, the intermediate heat exchanger's calculated heat transfer appears in eq. (10) and the corresponding exergy destroyed in eq. (11). Energy losses due to pressure drops in the elements were not considered.

Table 5: Energy and exergy balance equations [53].

Component	1 st-law equations		2 st-law equations	
Evaporator	$\dot{Q}_{in} = \dot{m}_{hs}(h_{hs,in} - h_{hs,out})$	(2)	$\dot{I}_{evap} = (\dot{X}_{hs,in} - \dot{X}_{hs,out}) - (\dot{X}_3 - \dot{X}_2)$	(3)
Condenser	$\dot{Q}_{out} = \dot{m}_{cw}(h_{cw,out} - h_{cw,in})$	(4)	$\dot{I}_{cond} = (\dot{X}_4 - \dot{X}_1) - (\dot{X}_{cw,out} - \dot{X}_{cw,in})$	(5)
Expander	$\dot{W}_{exp} = \dot{m}_{wf}(h_3 - h_4)n_{is,exp}n_{mech,exp}$	(6)	$\dot{I}_{exp} = (\dot{X}_1 - \dot{X}_2) + \dot{W}_{pump}$	(7)

Pump	$\dot{W}_{pump} = \frac{\dot{m}_{wf}(h_2 - h_1)n_{mech,pump}}{n_{is,pump}}$	(8)	$\dot{I}_{pump} = (\dot{X}_3 - \dot{X}_4) - \dot{W}_{exp}$	(9)
IHE	$\dot{Q}_{IHE} = \dot{m}_{wf}(h_{4.2} - h_{4.1})$	(10)	$\dot{I}_{IHE} = (\dot{X}_{4.2} - \dot{X}_{4.1}) - (\dot{X}_{2.1} - \dot{X}_{2.2})$	(11)

2.5. Performance indicators.

Performance indicators are calculated with the equations reported in Table 6 to determine each evaluated alternative's performance. This table corresponds to the models that describe the most used performance indicators.

Table 6: Performance indicators models.

Performance indicators	Equation	
Net work	$\dot{W}_{net} = W_{Exp} - W_{pumps}$	(12)
Emission saving	$EM = w_{net} * EF$	(13)
Total capital cost	$Ctot = C_{tot,elem} + COM$	(14)
Net present value	$NPV = \sum_{Z=0}^{n} \frac{R_t}{(1+i)^z}$	(15)
1st-law efficiency	$n_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$	(16)
2nd-law efficiency	$n_{exg} = \frac{\dot{W}_{net}}{\dot{X}_{hs,in} - \dot{X}_{hs,out}}$	(17)
Volumetric flow ratio	$VFR = \dot{V}_4/\dot{V}_3$	(18)
Specific investment cost	$SIC = \frac{C_{tot}}{W_{net}}$	(19)

In that order, these equations are included to consider the following aspects:

- The cycle's net power includes the work of the expander and the pumps, included in eq (12).
- The CO_2 emissions that are no longer emitted due to the self-generation of electricity are calculated with eq (13).
- The total cost corresponds to the sum of each element's costs; this considers installation, operation and maintenance costs as depicted in eq (14).
- The net present value of the cash flows (income - expenses) originating from the investment is evaluated as expressed in eq (15).
- First law efficiency depends on the plant's net power and the heat input to the cycle, see eq. (16).
- As presented in eq (17), exergy efficiency is calculated regarding the available exergy (delivered net power) and the exergy input to the cycle.
- The volumetric flow ratio, eq. (18) gives a measurement of the working fluid volume change in the expander; thus, if this exceeds the value of 50, several stages of expansion must be considered [61]. Naturally, then, the lower the VFR, the better.

- Specific investment cost (SIC) expressed in eq. (19) is a standard indicator for preliminary economic assessments of power cycles. This metric represents the system's total capital cost (TCC) per rated kW of generated power [62].

2.6. Cost model.

The total capital cost of an ORC system is primarily determined by the cost of each major component (evaporator, condenser, turbine, and pumps). The heat exchangers (evaporator and condenser) contribute the most to the total investment cost [63]. In this case, the material used for the heat exchangers is carbon steel, and their configuration is shell and tube. The heat transfer model used for sizing the heat exchangers was the logarithmic mean temperature method; the resistance due to fouling in the heat transfer process is ignored.

In the case of the evaporator, this was divided into two processes (heating and evaporation). In the case of the condenser, it was also divided into two processes (condensation and cooling) [64],[65]. It is worth mentioning that the working fluid's effect on the investment's total cost is small [66],[67]. Therefore, the cost of the working fluid is not considered in this work. Instead, the current method of the total capital cost used adopts the correlations found in [68],[69]. In this way, the capital cost of the heat exchangers, turbine, generator and pumps is determined by the equations shown in Table 7 [69]. The coefficients $\boldsymbol{K_1, K_2, K_3, B_1, B_2, C_1, C_2, C_3, F_m}$ and $\boldsymbol{F_p}$ are coefficients that adjust the cost for the different equipment used in the power cycle configuration. These have to do with the type of element used, the element's size, the material of construction, and the operating pressure [70]. These coefficients are depicted in Table 8.

Table 7: Economic model for the components of ORC cycles [69].

Name	Equation	
Heat exchanger	$Log C^0_{P,Evap,Cond} = K_1 + K_2 log_{10}(A) + K_3[log_{10}(A)]^2$	(20)
Expander/Pump	$Log C^0_{P,Exp,pump} = K_1 + K_2 log_{10}(W) + K_3[\log_{10}(W)]^2$	(21)
Generator	$C^0_{P,Gen} = 60\left(W_{gen}\right)^{0.95}$	(22)
Basic cost 2001	$C_{BM2001} = C^0_P(B_1 + B_2 F_m F_p)$	(23)
Pressure correction factor	$log F_p = C_1 + C_2 \log_{10}(p) + C_3[\log_{10}(p)]^2$	(24)
Corrected cost for 2022	$C_{BM,2022} = C_{BM,2001} CEPCI_{2022}/CEPCI_{2001}$	(25)
Total item cost	$C_{tot,elem} = C_{BM,evap} + C_{BM,cond} + C_{BM,recup} + C_{BM,turb} + C_{BM,bomb} + C_{BM,bomb\ aux} + C_{BM,\mathrm{Gen}}$	(26)
Maintenance cost	$COM = C_{tot,elem} * 1.5\%$	(27)

Table 8: Equipment cost constants [69].

Equipment	*K1*	*K2*	*K3*	*C1*	*C2*	*C3*	*B1*	*B2*	*Fm*	*Fbm*
Tube and shell	4.831	-0.851	0.319	0.039	-0.113	0.082	1.63	1.66	1.3	0
Pump	3.389	0.054	0.154	-0.394	0.396	-0.002	1.89	1.35	1.5	0
Expander	2.248	1.497	-0.162	0	0	0	0	0	0	3.3

2.7. **Parameters and boundary conditions**

Table **9** shows the parameters and boundary conditions used in this work. Due to the restriction of the bag filter (an element that does not withstand temperatures above 180 °C), the outlet temperature of the gases after passing through the cycle was evaluated between 150 and 180 °C, with 10 °C intervals for a total of four temperatures. Another parameter that was varied in this work was the pinch point of the evaporator, which was evaluated with values of 10 and 20°C. Seven working fluids were also analysed for each technology, resulting in 168 possible configurations or alternatives. This number of configurations results from multiplying the size of the variable vectors (i.e., four flue gas outlet temperatures, two evaporator pinch point temperatures, seven working fluids, and three cycle settings).

Table 9: Parameters and boundary conditions

Parameter	Nomenclature	Unit	Value
Gaseous effluent inlet temperature	T_{hs_in}	°C	327
Gaseous effluent outlet temperature	T_{hs_out}	°C	(150, 160, 170, 180)
Mass flow of gaseous effluent	$\dot{m}_{hs}$	kg/s	132.15
Cooling water inlet temperature	$T_{cw\ in}$	°C	27.8
Cooling water outlet temperature	$T_{cw\ out}$	°C	37.8
Fluid outlet temperature in the condenser	T_{cond}	°C	60
Pinch point in evaporator	T_{pp}	°C	(10, 20)
Turbine Isentropic Efficiency (ORC)	n_{turb}	%	85
Turbine Isentropic Efficiency (TLC)	n_{turb}	%	70
Isentropic pump efficiency	n_{pump}	%	70
generator efficiency	n_{gen}	%	95
operation time	t_{op}	h/año	7400
Lifecycle	Lt	años	20
Cost of electricity on the network	C_{elec}	$/kWh	0.12
Annual interest rate	i	%	5
Number of working fluids	W_f		(Wf1, Wf2, Wf3, Wf4, Wf5, Wf6, Wf7)
Settings			(ORC, TLC, RORC)

3. **Results.**

This section presents the validations of the models used to analyse the impact on the ORC and TLC configurations' first and second law performance. Then, after the validation process, this section includes a 3E evaluation (Economic, Energetic and Environmental) of each of the alternatives. The economic indicators are the investment cost and the net present value ($Ctot, NPV$), and the economic indicator is the net power ($\dot{W}_{net}$) and the environmental indicator is the emissions saved (Em). Finally, the AHP methodology is applied to the case study to account for the solutions or solutions that best fit the making-decision parameters defined for this end.

3.1. Validations.

This section presents the validations of the mathematical models used in this work to guarantee the results obtained when using the CoolProps® thermodynamic properties library. The first validation uses the Peng-Robinson model [71], which is used to model pure organic fluids. Then a second validation is performed regarding the cost model shown in Table 7. That model calculates each component's cost on all power cycles and costs associated with operation and maintenance.

3.1.1. Thermodynamic model validation.

Regarding the modelling of power cycles, the Peng Robinson model is the most used in the literature and the one that presents the best results when working with pure organic fluids [71], [72], [73]. Therefore, in this work, the Peng-Robinson model was chosen to evaluate the thermodynamic states of the cycles. The Peng-Robinson model validation was previously performed using the CoolProps® library in the Python computational tool. Table 10 shows the parameters and results of the model validation using the data reported by [74]. In the latter, the authors studied the performance of a TLC and compared it with an ORC and a Kalina cycle from a thermo-economic point of view. The authors consider a low-grade heat source with a temperature of 120 °C for all three systems. In addition, they carry out parametric studies of the systems for different working fluids in the ORC and TLC. In this case, a TLC with n-Butane and an ORC that works with R1234yf was chosen as a reference for validating the actual model. The objective parameter used for the validation was the thermal efficiency of the cycle and not the net power since the value of the mass flow of the working fluid in the said work is not reported. In this sense, in the case of the TLC, a relative error of 2.77% in thermal efficiency was obtained; in the case of ORC, the relative error was 1.12%. This indicates an excellent performance of the model when replicating results.

Table 10: Validation of the Peng Robinson model.

Operating conditions [74]		
Parameter	**TLC**	**ORC**
Working fluid	n-Butane	R1234yf
T_3 [°C]	109	84
T_1 [°C]	40	40
n_{pump}	0.75	0.85
n_{turb}	0.85	0.85
$\dot{W}_{net}$ [kW]	2,034	1,816
Validation		
$\dot{W}_{Turb}$ [kW]	2489	2,133
$\dot{W}_{Pump}$ [kW]	455.2	317.1
$\dot{W}_{net}$ [kW]	2,033.8	1,815.9
$\dot{Q}_{in}$ [kW]	29,860.9	23,583.2

η_{th} (This model)	**0.0681**	**0.077**
η_{th} (Yari [48])	**0.0701**	**0.07787**
Error [%]	2.77%	1.12%

3.1.2. Cost model validation

A model implemented in the Python computational tool estimates the cost associated with each cycle component (Evaporator, condenser, turbine, pumps, generator). Before using the model for this work to evaluate all configurations mentioned above, it was validated with the data reported by other peers. For example, in [75], the authors model an ORC using R32 as the working fluid and calculate the cost of each component using equations (20) to (27). Table 11 shows the cost adjustment coefficients associated with the type of element used, the element's size, the construction material and the operating pressure. Table 12 shows the cost model's conditions and input data; finally, Table 13 shows the validation result. It is possible to observe from the results that errors of 4.1%, 3.6%, -0.3%, and 0.3% were obtained for the evaporator, condenser, pump and turbine, respectively. This indicates a good fit of the model to calculate the cost of the elements of the cycle.

Table 11: Adjustment constants of the cost model [75]**.**

Equipment	***K1***	***K2***	***K3***	***C1***	***C2***	***C3***	***B1***	***B2***	***Fm***	***Fbm***
Evaporator	4.325	-0.303	0.163	0	0	0	1.63	1.66	1.25	-
Condenser	4.831	-0.850	0.319	0	0	0	1.63	1.66	1.3	-
Pump	3.389	0.054	0.154	0	0	0	1.89	1.35	1.5	-
Expander	2.248	1.497	-0.162	-	-	-	-	-	-	3.3

Table 12: ORC operating conditions with R32 for validation [75]**.**

Parameter	Units	Value
P evaporator	[bar]	80.52
P condenser	[bar]	1
$\dot{W}_{pump}$	[kW]	19.26
$\dot{W}_{exp}$	[kW]	105.7
A_{evap}	[m^2]	169.81
A_{cond}	[m^2]	47.06
CEPCI 2001	[-]	541.7
CEPCI 2016	[-]	397

Table 13: Cost model validation results.

Element	**Component cost [USD]**		**Error**
	Validation	[75]	
Evaporator	$ 146,326	$ 152,360	4.1%
Condenser	$ 102,888	$ 106,610	3.6%
Pump	$ 45,335	$ 45,180	-0.3%
Expander	$ 184,466	$ 185,030	0.3%

3.2. Thermodynamic analysis.

Figure 5 shows the four selection criteria analysed in this study for each of the alternatives, being a) the Net Present Value, b) the emissions saved, c) the total investment cost, and d) the net power output. For instance, it is desired to maximise the net present value, the emissions saved and the net power output, and on the other hand, to minimise the investment cost. Though, when the maximisation and minimisation criteria are applied separately, different results are obtained, as shown in Table 14. However, knowing the optimum for each criterion is not enough to decide. To make the right decision, it is necessary to integrate all the strict measures to optimise these four criteria simultaneously. Even more so, when the selection criteria do not have the same level of importance for the company, the AHP multicriteria decision-making methodology becomes essential.

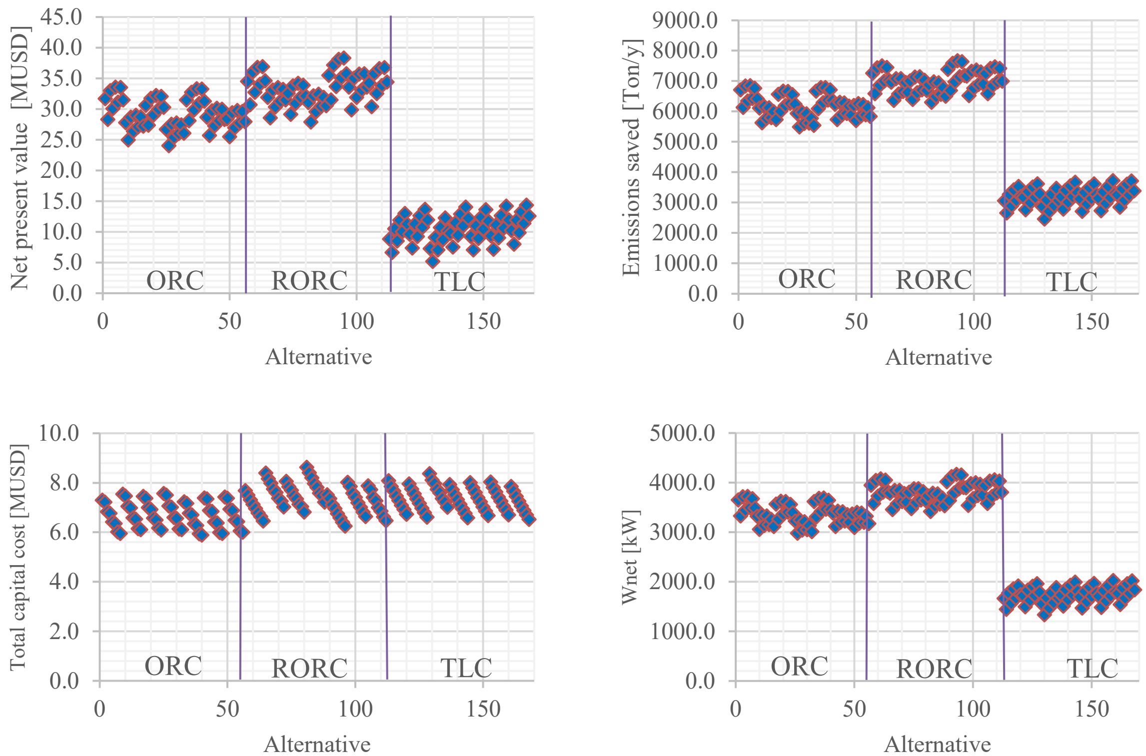

Figure 5: Selection criteria for each alternative.

The VFR parameter represents the compressibility effect through the expansion process, corresponding to a ratio between the volumetric flow at the inlet and outlet of the turbine; VFR values higher than 50 require carrying out the expansion in two stages due to the losses related to the existence of high Mach numbers. Therefore, all those alternatives with a turbine with a Volumetric Flow Ratio (VFR) greater than 50 are discarded before implementing the AHP methodology [61]. Additionally, for reaction turbines, there is a negative influence of the wide variations of the flow area across the rotor blades. Therefore, since the ORC cycles modelled in this work have a single expander, this VFR relationship is used to discard configurations that exceeded this limit before applying the AHP methodology to reduce the resulting arrays' size as much as possible. For example, Figure 6 shows the VFR graph for ORC and RORC configurations (numbers 1 -

112). It can be seen that these technologies do not exceed the VFR limit. However, in the case of the TLC (configurations 113 to 168), the R365mfc has a VFR greater than that limit, Figure 7. Therefore, arrangements with this working fluid were not considered for applying AHP.

Table 14: Best alternative for each selection criteria.

COD	Parameters				Criteria			
	Technology	Working fluid	T_4	T_{pp}	$\dot{W}_{net}$ (Max)	NPV (Max)	TCC (Min)	Em (Max)
		[-]	[°C]	[°C]	[kW]	[MUSD]	[MUSD]	[tCO2]
93	RORC	Cyclohexane	170	10	4167	38.1	6.8	7,666
95	RORC	Cyclohexane	180	10	4153	38.4	6.4	7,640
40	ORC	Cyclohexane	180	20	3459	31.3	5.9	6,362
93	RORC	Cyclohexane	170	10	4167	38.1	6.8	7,666

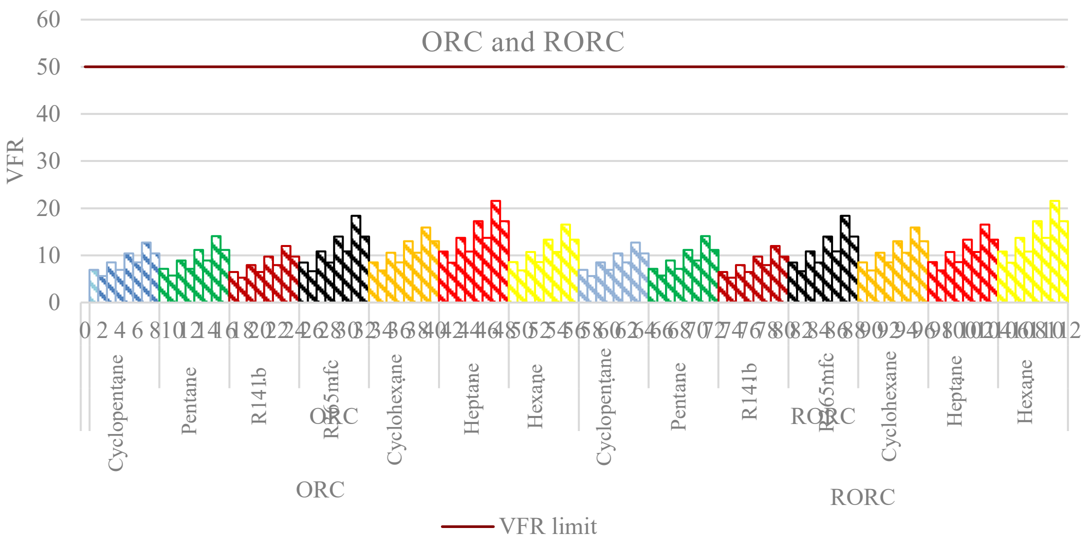

Figure 6: VFR graph by ORC and RORC.

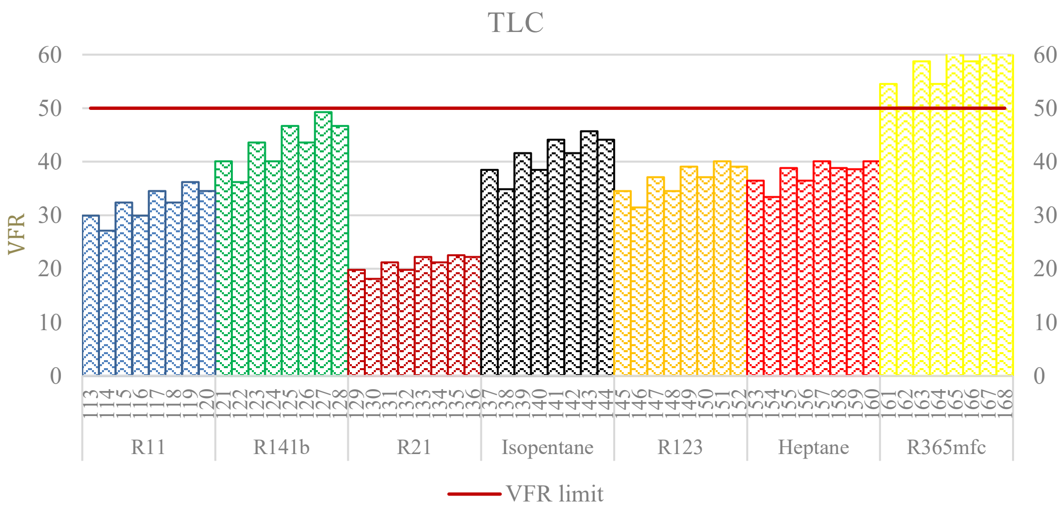

Figure 7: VFR graph by TLC

3.3. CO_2 emissions saved.

The CO_2 emissions obtained from equation (15) are reported in Figure 8 in tonnes per year that could be saved if the electricity generated with this alternative was no longer purchased from the national electricity grid. The option that presents the most significant savings in CO_2 emissions is number 93 (Figure 8 (b)). That one corresponds to a RORC cycle that works with cyclohexane and recovers waste heat from a gas outlet temperature $T_{hs\,out}$ at 170 °C. In the case of the simple ORC, the best alternative is number 5 (Figure 8(a)), which works with cyclopentane and $T_{hs\,out}$ of 170 °C. Finally, in the case of the TLC, the best alternative is number 159 (Figure 8) (c), operating with heptane and $T_{hs\,out}$ of 180 °C. In all three cases, the cycles operate with pinch point temperature T_{pp} = 10°C.

Figure 8: CO2 emissions saved

3.4. Application of the Analytical Hierarchy Process (AHP).

The analytical hierarchy method was applied considering four decision criteria (1) total investment cost, (2) net present value, (3) net energy generated and (4) CO_2 emissions avoided, including five scenarios, assuming first that the company has an economic restriction to invest. Therefore, it was decided to prioritize the minimization of the investment cost over the rest of the criteria. In the second scenario, the condition in which the company has sufficient availability of money to invest is studied, so the net present value is prioritised over the other criteria. The third scenario is associated with a situation in which a company has a high electrical demand, and the only way it can generate energy is through one of these alternatives. Therefore, the net power output is prioritised over the other criteria in this case. The fourth scenario includes a company forced to reduce its carbon footprint; therefore, the value in saved emissions is prioritised. Finally, a last application of the methodology was carried out in a fifth scenario, considering a hypothetical case in which economic indicators are given importance simultaneously over other factors, which eventually could be the best-case scenario for the company's interests.

3.4.1. Scenario 1: Prioritising the total investment cost.

Table 15 shows the matrix of judgments prioritising the total investment cost when the company has a capital restriction to invest in a waste heat recovery technology. It is observed that the investment cost presents a 55.2% importance over the other criteria to prioritise this criterion over the others.

Table 15: Matrix of judgments prioritising investment cost.

Criteria	$\dot{W}_{net}$[kW]	Emissions [Tonnes/year]	NPV [MUSD]	Total cost [MUSD]	Normalised matrix				Weighting [%]
$\dot{W}_{net}$ [kW]	1	3	1/3	1/5	0.11	0.21	0.07	0.12	12.8
Emissions [Tonnes/year]	1/3	1	1/4	1/6	0.04	0.07	0.05	0.10	6.5
NPV [MUSD]	3	4	1	1/3	0.32	0.29	0.22	0.20	25.5
Total cost [MUSD]	5	6	3	1	0.54	0.43	0.65	0.59	55.2
Sum	9.3	14.0	4.6	1.7	1.0	1.0	1.0	1.0	100

The results of applying the AHP methodology, prioritising the investment cost over the other criteria, are presented in Table 16. In total, 160 alternatives were evaluated (The complete table can be found in the annexes section). However, due to the high number of data and information to report, only the three best options for each technology are shown. The first column shows the position or prioritisation given to the alternative after applying the AHP methodology, with alternative number 1 being the one that obtained the best performance and alternative 160 the one that got the worst. The best alternative is case number 39 (i.e., ORC with cyclohexane, a gas outlet temperature of 180 °C, and a pinch point of 10 °C). This has a total investment cost of 5.9 MUSD, a net power output of 3,646 kW, a net present value of 33.3 MUSD and a specific investment cost of 1,629.9 USD/kW. As for the RORCs, their best option is number 95, occupying the second position. This option works with cyclohexane with $T_{hs\,out} = 180\,°C$ and $T_{pp} = 10\,°C$, it has a higher net power output than the simple ORC (4,153 kW), a higher net present value (38.4 MUSD), a total cost investment of 6.4 MUSD and a specific investment cost of 1,543 USD/kW. Finally, the best TLC is ranked 71st. This alternative works with isopentane with $T_{hs\,out} = 180\,°C$ and $T_{pp} = 20\,°C$. This presents an investment cost of 6.6 MUSD and a net present value much lower than the other variants (12.2 MUSD). On the other hand, it had a lower net power output, with 1,812 kW and a specific investment cost of more than double compared to the best alternatives of each variant 3,636 USD/kW.

Table 16: Best three alternatives for each technology according to prioritisation of total investment cost.

Position	Cod	Technology	Working fluid	$T_{hs\ out}$	T_{pp}	$\dot{W}_{net}$	NPV	TCC	Em	Prioritisation
[-]	[-]	[-]	[-]	[°C]	[°C]	[kW]	[MUSD]	[MUSD]	[tCO2]	[-]
1	39	ORC	Cyclohexane	180	10	3,646	33.3	5.9	6,706.7	144.9
2	95	RORC	Cyclohexane	180	10	4,153	38.4	6.4	7,640.3	139.9
3	40	ORC	Cyclohexane	180	20	3,459	31.3	5.9	6,362.4	139.6
4	7	ORC	Cyclohexane	180	10	3,678	33.6	6	6,765.8	136.6
5	96	RORC	Cyclohexane	180	20	3,906	35.8	6.3	7,184.7	134.1
9	93	RORC	Cyclohexane	170	10	4,168	38.1	6.8	7,666.5	118.2
71	144	TLC	Isopentane	180	20	1,812	12.2	6.6	3,332.7	61.6
77	128	TLC	R141b	180	20	1,791	12	6.6	3,293.8	58.5
83	152	TLC	R123	180	20	1,777	11.7	6.7	3,269.6	55.6

3.4.2. Scenario 2: Prioritising net present value.

Table 17 shows the judgment matrix prioritising the net present value in a scenario where the company has limited capital to invest in a waste heat recovery technology. It is observed that the net present value obtained 54.4% of importance over the other criteria. Table **18** shows the results of applying the AHP methodology, prioritising the net present value over the other criteria. For this case, the best alternative is number 95 (RORC with cyclohexane with a gas outlet temperature of 180 °C and a pinch point of 10 °C). This has a net present value of 38.4 MUSD, a total investment cost of 6.4 MUSD, a net power output of 4,154 kW and a specific investment cost of 15,423 USD/kW. As for the ORC, the best option is number 39, occupying the ninth place. It works with cyclohexane with $\boldsymbol{T_{hs\ out} = 180\ °C}$ and $\boldsymbol{T_{pp} = 10\ °C}$, and has a net present value of 33.3 MUSD, a total investment cost of 5.9 MUSD, a net power output of 3,646 kW, and a cost-specific investment of 1,630 USD/kW.

Table 17: Matrix of judgments prioritising net present value.

Criteria	$\dot{W}$net [kW]	Emissions [Tonnes/y]	NPV [MUSD]	Total cost [MUSD]	Normalised matrix				Weighting
$\dot{W}$net [kW]	1	3	1/5	1/4	0.10	0.21	0.12	0.06	12.2%
Emissions [Tonnes/y]	1/3	1	1/6	1/4	0.03	0.07	0.10	0.06	6.4%
NPV [MUSD]	5	6	1	3	0.49	0.43	0.59	0.66	54.4%
Total cost [MUSD]	4	4	1/3	1	0.38	0.29	0.20	0.22	27.0%
Sum	10.1	14.0	1.7	4.5	1.0	1.0	1.0	1.0	100%

Finally, the best TLC is ranked 111th. It works with isopentane with $\boldsymbol{T_{hs\ out} = 180\ °C}$ and $\boldsymbol{T_{pp} = 20\ °C}$, with a much lower net present value than the best option of the other variants (12.2 MUSD), an investment cost of 6.6 MUSD. This one also has a lower net power output, with 1,812 kW and a specific investment cost of more than double when compared to the best alternatives of each variant, 3,637 USD/kW. Previous results agree with what was found in the literature: TLC is not implemented in most cases because it still is a costly technology due to the need for much larger heat exchangers and higher pumping power [37]. For the best options for ORC and RORC, pumping powers of 64.2 and 72.9 kW, respectively, are required. However, in the case of the alternatives operating with TLC, 385 kW is required. Therefore, the TLC value is five times higher than both cases, increasing the investment cost. The positive cash flows are lower, implying a low net present value since it produces slightly less than half the net power output of the best ORC and RORC options.

Table 18: Best three alternatives for each technology according to prioritisation of net present value.

Position	**Cod**	**Technology**	**Working fluid**	**$T_{hs\ out}$**	**T_{pp}**	**$\dot{W}_{net}$**	**NPV**	**TCC**	**Em**	**Prioritisation**
[-]	[-]	[-]	[-]	[°C]	[°C]	[kW]	[MUSD]	[MUSD]	[tCO2]	[-]
1	95	RORC	Cyclohexane	180	10	4,153	38.4	6.4	7,640	152.8
2	93	RORC	Cyclohexane	170	10	4,168	38.1	6.8	7,667	140.7
3	96	RORC	Cyclohexane	180	20	3,906	35.8	6.3	7,185	133.5
9	39	ORC	Cyclohexane	180	10	3,646	33.3	5.9	6,707	120.3
10	7	ORC	Cyclohexane	180	10	3,678	33.6	6	6,766	118.2
17	37	ORC	Cyclohexane	170	10	3,691	33.3	6.3	6,789	106.6
111	144	TLC	Isopentane	180	20	1,812	12.2	6.6	3,333	39.3
112	128	TLC	R141b	180	20	1,791	12	6.6	3,294	37.5
114	143	TLC	Isopentane	180	10	1,995	14	6.8	3,670	37.0

3.4.3. Scenario 3: Prioritising net power output.

Table 19 shows the matrix of judgments prioritising net-work in a scenario where the company does not have other ways to generate energy. The only alternative is through the implementation of power cycles. It is observed that the net power output presents a 59.9% of importance over the other criteria.

Table 19: Matrix of judgments prioritising net-work.

Criteria	**$\dot{W}_{net}$ [kW]**	**Emissions [Tonnes/year]**	**NPV [MUSD]**	**Total cost [MUSD]**	**Normalised matrix**				**Weighting**
$\dot{W}_{net}$ [kW]	1	6	4	5	0.66	0.35	0.64	0.75	59.9%
Emissions [Tonnes/year]	1/8	1	1/4	1/5	0.08	0.06	0.04	0.03	5.3%
NPV [MUSD]	1/5	5	1	1/2	0.13	0.29	0.16	0.07	16.5%
Total cost [MUSD]	1/5	5	1	1	0.13	0.29	0.16	0.15	18.4%
Sum	1.5	17.0	6.3	6.7	1.0	1.0	1.0	1.0	100%

Table 20 shows the results of applying the AHP methodology, prioritising the net power output over the other criteria. In this scenario, the best alternative is number 95 (i.e., RORC with cyclohexane, a gas outlet temperature of 180 °C, and a pinch point of 10 °C). This option has a net present value of 38.4 MUSD, a total investment cost of 6.4 MUSD, a net power output of 4,153 kW and a specific investment cost of 1,543 USD/kW. Regarding the ORC, the best option is the number 39, occupying the 19th position. It works with cyclohexane with $T_{hs\ out} = 180\ °C$ and $T_{pp} = 10\ °C$, with a net power output of 3,646 kW, a net present value of 33.3 MUSD, a total investment cost of 5.9 MUSD, and a specific investment cost of 1,630 USD/kW.

Table 20: Best three alternatives for each technology according to prioritisation of net power output.

Position	Cod	Technology	Working fluid	$T_{hs\ out}$	T_{pp}	$\dot{W}_{net}$	NPV	TCC	Em	Prioritisation
[-]	[-]	[-]	[-]	[°C]	[°C]	[kW]	[MUSD]	[MUSD]	[tCO2]	[-]
1	95	RORC	Cyclohexane	180	10	4,153	38.4	6.4	7,640	154.3
2	93	RORC	Cyclohexane	170	10	4,168	38.1	6.8	7,667	149.1
3	91	RORC	Cyclohexane	160	10	4,124	37.2	7.1	7,587	136.6
19	39	ORC	Cyclohexane	180	10	3,646	33.3	5.9	6,707	105.6
20	7	ORC	Cyclopentane	180	10	3,678	33.6	6	6,766	105.2
24	5	ORC	Cyclopentane	170	10	3,722	33.6	6.4	6,847	100.9
113	144	TLC	Isopentane	180	20	1,812	12.2	6.6	3,333	31.9
114	143	TLC	Isopentane	180	10	1,995	14	6.8	3,670	31.4
115	128	TLC	R141b	180	20	1,791	12	6.6	3,294	30.4

Finally, the best TLC is ranked 113th. This cycle works with isopentane with $T_{hs\ out} = 180\ °C$ and $T_{pp} = 20\ °C$, and has a net power output of 1,812 kW, a net present value much lower than the best other TLC variants (12.2 MUSD), and an investment cost of 6.6 MUSD. It has a specific investment cost of more than double compared to the best alternatives of each variant, 3,636 USD/kW. Therefore, the net power output generated by the best TLC option is less than half of that generated by the best ORC and RORC alternatives. The pumping power is multiplied by 6 and 5.28 if compared with the best options of ORC and RORC, respectively. The previous results agree with what was reported by other authors since much higher pumping powers are required for this technology compared to conventional ORC [58].

3.4.4. Scenario 4: Prioritising saved emissions.

Table 21 shows the matrix of judgments prioritising the saved CO_2 emissions when the company is forced to reduce its carbon footprint. Again, it is observed that the target criteria, in this case, the emissions saved, has a 56.5% importance over the other criteria.

Table 22 presents the five best alternatives for each technology, showing the results after applying the AHP methodology and prioritising the emissions saved over the other criteria. For this scenario, the best alternative is the number 95 (i.e., RORC with cyclohexane with a gas outlet temperature of 180 °C and a pinch point of 10 °C). This option has a net present value of 38.4 MUSD, a total investment cost of 6.4 MUSD, a net power output of 4,153 kW and a specific investment cost of 1,543 USD/kW. As for the ORCs, the best option is number 7, occupying position number 20. The latter works with cyclopentane, $T_{hs\ out} =$

180 °C and $T_{pp} = 10$ °C, and has a net power output of 3,678, a net present value of 33.6 MUSD, a total investment cost of 6 MUSD, and a specific investment cost of 1,637 USD/kW. Finally, the best TLC ranked 113, operating with isopentane with $T_{hs\ out} = 180$ °C and $T_{pp} = 20$ °C. This option has a net power output of 1,812 kW, a net present value much lower than the best option of the other variants (12.2 MUSD), with an investment cost of 6.6 MUSD. It has a specific investment cost (3,636 USD/kW) that is more than double compared to each variant's best alternatives.

Table 21: Matrix of judgments prioritising saved emissions.

Criteria	$\dot{W}_{net}$ [kW]	Emissions [Tonnes/year]	NPV [MUSD]	Total cost [MUSD]	Normalised matrix				Weighting
$\dot{W}_{net}$ [kW]	1	1/6	1/5	1/4	0.06	0.10	0.03	0.04	5.9%
Emissions [Tonnes/year]	6	1	4	4	0.38	0.60	0.65	0.64	56.5%
NPV [MUSD]	5	1/4	1	1	0.31	0.15	0.16	0.16	19.6%
Total cost [MUSD]	4	1/4	1	1	0.25	0.15	0.16	0.16	18.0%
Sum	16.0	1.7	6.2	6.3	1.0	1.0	1.0	1.0	100%

Table 22: Best three alternatives for each technology according to prioritisation of saved emissions.

Position	Cod	Technology	Working fluid	$T_{hs\ out}$	T_{pp}	$\dot{W}_{net}$	NPV	TCC	Em	Prioritisation
[-]	[-]	[-]	[-]	[°C]	[°C]	[kW]	[MUSD]	[MUSD]	[tCO2]	[-]
1	95	RORC	Cyclohexane	180	10	4,153	38.4	6.4	7,640	155.0
2	93	RORC	Cyclohexane	170	10	4,168	38.1	6.8	7,667	150.3
3	91	RORC	Cyclohexane	160	10	4,124	37.2	7.1	7,587	138.2
20	7	ORC	Cyclopentane	180	10	3,678	33.6	6	6,766	104.4
21	39	ORC	Cyclohexane	180	10	3,646	33.3	5.9	6,707	104.4
26	5	ORC	Cyclopentane	170	10	3,722	33.6	6.4	6,847	100.8
113	144	TLC	Isopentane	180	20	1,812	12.2	6.6	3,333	30.7
114	143	TLC	Isopentane	180	10	1,995	14	6.8	3,670	30.5
115	127	TLC	R141b	180	10	1,965	13.7	6.8	3,615	29.4

3.4.5. Scenario 5: Prioritisation investment cost and net present value

Table 23 presents the judgment matrix considering both economic indicators. It is observed that the investment cost obtained a 51.4% importance, followed by the net present value with a 31.2% importance. In third place are emissions with 11.3% importance and net power with 6.1% importance. The results of applying the AHP methodology are reported in Table 24, considering only the three best cases. The complete table with the 160 alternatives can be found in the annexes section. For this case, the best alternative is number 39 (i.e., ORC with cyclohexane with a gas outlet temperature of 180 °C and a temperature difference at the pinch point of 10 °C). This has a total investment cost of 5.9 MUSD, a net power of 3,646 kW, a net present value of 33.3 MUSD and a specific investment cost of 1,630 USD/kW.

Table 23: Judgment matrix considering investment cost and net present value

Criteria	$\dot{W}_{net}$ [kW]	Emissions [Tonnes/year]	NPV [MUSD]	Total cost [MUSD]	Normalised matrix				Weighting
$\dot{W}_{net}$ [kW]	1	1/3	1/5	1/6	0.07	0.03	0.06	0.09	6.1%
Emissions [Tonnes/year]	3	1	1/4	1/6	0.20	0.09	0.07	0.09	11.3%
NPV [MUSD]	5	4	1	1/2	0.33	0.35	0.29	0.27	31.2%
Total cost [MUSD]	6	6	2	1	0.40	0.53	0.58	0.55	51.4%
Sum	15.0	11.3	3.5	1.8	1.0	1.0	1.0	1.0	100%

Table 24: Best three alternatives for each technology considering investment cost and net present value.

Position	Cod	Technology	Working fluid	$T_{hs\ out}$	T_{pp}	$\dot{W}_{net}$	NPV	TCC	Em	Prioritisation
[-]	[-]	[-]	[-]	[°C]	[°C]	[kW]	[MUSD]	[MUSD]	[tCO2]	[-]
1	39	ORC	Cyclohexane	180	10	3,646	33.3	5.9	6,707	145
2	95	RORC	Cyclohexane	180	10	4,153	38.4	6.4	7,640	140
3	40	ORC	Cyclohexane	180	20	3,459	31.3	5.9	6,362	140
4	7	ORC	Cyclopentane	180	10	3,678	33.6	6	6,766	137
5	96	RORC	Cyclohexane	180	20	3,906	35.8	6.3	7,185	134
9	93	RORC	Cyclohexane	170	10	4,168	38.1	6.8	7,667	118
71	144	TLC	Isopentane	180	20	1,812	12.2	6.6	3,333	62
77	128	TLC	R141b	180	20	1,791	12	6.6	3,294	58
83	152	TLC	R123	180	20	1,777	11.7	6.7	3,270	56

Regarding the RORCs, the best option is number 95, occupying the second position. This alternative works with cyclohexane with $T_{hs\ out} = 180\ °C$ and $T_{pp} = 10\ °C$, it has higher net power output than the RORC. The simple ORC has a net power (4,153 kW), a higher net present value (38.4 MUSD), a total investment cost of 6.4 MUSD and a specific investment cost of 1,543 USD/kW. Regarding the TLC, the best option is number 144; this one is ranked 71st, working with isopentane with $T_{hs\ out} = 180\ °C$ and $T_{pp} = 20\ °C$. That configuration presents an investment cost of 6.6 MUSD and a net present value much lower than the other variants (12.2 MUSD). It also has a lower net power with 1,812 kW and a specific investment cost of more than double compared to the best alternatives of each variant, 3,636 USD/kW. Finally, it should be noted that, although the complexity of the technology is not a selection criterion used in this work, the simple ORC has an advantage over the RORC due to the simplicity of its components, as it does not have the intermediate heat exchanger, which usually makes it more compact, less complex and therefore requiring fewer resources and maintenance time.

In this study, cyclohexane was found to be an adequate working fluid for waste heat recovery systems with a heat source that is 321°C. In similar works with nearby temperature sources (300 °C), this behaviour can be observed [76], [77]. This fluid turned out to be expected for the five scenarios considered. This indicates that this working fluid can offer good energy, environmental and economic results.

3.4.6. Criteria trend.

For scenarios 1 and 5, the AHP method favoured option 39, corresponding to an ORC that employs cyclohexane with a gas outlet temperature of 180 °C and a pinch point of 10 °C. This preference was primarily established based on its low investment cost, thus reflecting a homogeneity in the assessment of the criteria. In contrast, for scenarios 2, 3, and 4, the AHP method favoured alternative number 95, corresponding to a Regenerative Organic Rankine Cycle (RORC) with cyclohexane, the same gas outlet temperature, and pinch point. This choice is justified given that the criteria of Net Present Value (NPV) and Emissions (Em) are strongly influenced by the net power generated (Wnet). In this sense, a higher work output translates into higher cash flows from the sale of electricity, thereby increasing the NPV. Moreover, a higher energy performance leads to considerable savings in CO_2 emissions, as it reduces energy consumption from the national electricity grid. This variation is visualised in Figure 9, illustrating the evolution of the criteria for each scenario examined.

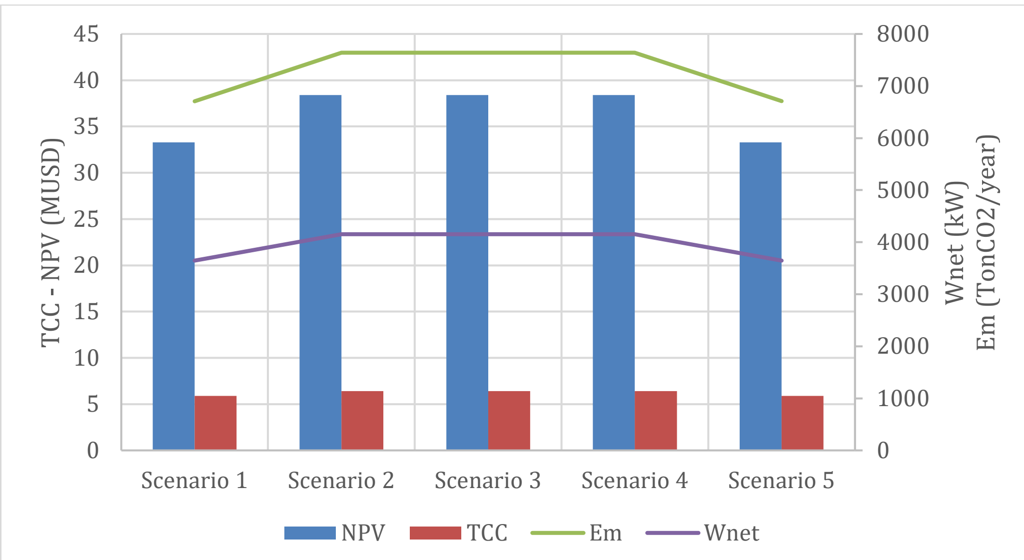

Figure 9: Evolution of Criteria Across Different Scenarios.

4. Conclusions.

The results obtained in this study after applying the AHP methodology showed that the RORC could be considered the best technology when the main objective is to maximise energy performance and emission savings since it has better values for these indicators. However, when the alternatives are analysed from an economic point of view, trying to minimise the investment cost, maximise the net present value and, in turn, maintain good net power values and saved emissions, the best technology turned out to be simple ORC. In addition, this stands out for its components' simplicity, even though technological complexity is not a selection criterion used in this work. This would imply a more compact and less complex solution requiring fewer resources and less maintenance time.

According to the five decision scenarios analysed, the AHP was applied to find the best alternatives considering technical, economic and environmental aspects. For instance, in scenarios 1 and 5 (the scenarios that could best suit the company's needs and assign more importance to economic criteria), the AHP methodology estimated that the best alternative in both cases was number 39. Alternative 39 corresponds to a simple ORC with cyclohexane with a gas outlet temperature of 180 °C and a temperature difference at the pinch point of 10 °C. This has a total investment cost of 5.9 MUSD, which is 8.47% lower than the alternative that ranked second (RORC number 95), a net power of 3,646 kW, 13.92% lower, and a net present value of 33.3 MUSD, 15.32% lower, and a potential reduction of CO_2 emissions of 6707 tonnes per year, 13.92% lower than alternative 95. However, the second-ranked alternative appeared to perform better regarding net power output, net present value, and emissions. This, in turn, had a higher investment cost. Therefore, applying the AHP method prioritised an alternative that minimised the investment cost but maintained outstanding performance in the other three indicators.

Conversely, regarding the results for scenarios 2, 3 and 4 (when net present value, net power output and saved emissions are prioritised, respectively), the first and second alternatives were RORC numbers 95 and 93, respectively. About the net present value, alternative number 95 was barely 0.65% higher; this, in turn, produced 0.35% less net power output; up to this point, it can be said that the cycles are very similar. However, Alternative 95 was 5.47% cheaper when investment cost compared to the second-placed alternative. This last indicator determined which of the two options was better. Finally, the TLC proved not significantly better than the other technologies for any criteria evaluated. Since, in the best cases (scenario 1 investment cost prioritised), the best TLC alternative appeared in the prioritisation position number 71. This technology obtained low net power output values, saved emissions, present value net and high investment costs, which makes it unattractive compared to the other two technologies evaluated in this work. However, it is expected and highly recommended in future works to include other variants of ORC, such as ORC at supercritical pressures (ORC transcritical), ORC with multiple stages of evaporation, and ORC with double stages in the expansion. ORCs with various intermediate recuperators (e.g., regenerative ORC), ORC in a cascade configuration, including Kalina cycles and their variants, thermoelectric generators and any other waste heat recovery technology can be applied and used for the case study. Additionally, cyclohexane was an adequate working fluid for cement ORC waste heat recovery systems since it was typical for the fifth scenario analysed. This indicates that cyclohexane can offer good energy, environmental and economic results.

This study significantly benefits decision-makers in the cement industry and researchers interested in optimising energy efficiency and minimising CO_2 emissions. It provides a detailed and customisable framework for evaluating and selecting the best waste heat recovery technology based on each plant's specific needs and circumstances. Using the Analytical Hierarchical Process (AHP) offers a rigorous and transparent methodology for weighing multiple decision criteria, which can facilitate strategic decision-making and long-term planning. Additionally, the findings can inform sustainability policies and emission reduction programs, benefiting broader stakeholders, including environmental regulators and society.

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