

# Waste heat recovery in a cement plant using an organic Rankine cycle

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## Abstract

In this project, a waste heat recovery solution using an organic Rankine cycle (ORC) has been studied, where the energy source comes from the exhaust gases of a clinker kiln. This The electricity produced will be self-consumed by the factory, reducing costs due to lowered grid demand and cutting down scope two emissions of the cement production. The ORC will be modeled by its behaviour equations. A preliminary design of its components will be done, calculating the main dimensions of each one and the footprint of the installation. The energy supply will be analysed besides the scope two emission reduction associated to the project. An economic study will be done, calculating the LCOE and the main indicators (NPV, IRR, PB).

The best configuration for the cement plant generates 1.6 MWe, covering 25% of the annual electricity consumption of the factory with a 63 €/MWh LCOE. The project NPV is 11 M€ and saves of 2255  $CO_2$  tons per year. There are other configurations possible for the ORC that generate up to 6.1 MWe with roughly the same LCOE and able to supply up to 95% of the demand. Despite those better results, certain drawbacks make these configurations not as interesting for the cement plant as the one selected.

**Keywords:** ORC, cement plant, heat source, gases, electricity, fuel, energy supply, emissions.

## 1. Introduction

Cement is the most consumed material after water, being the annual production 4100 million tons. The reason behind this high consumption is concrete: a mix composed of sand, gravel and cement; and the most common used construction material. Cement production causes more than 7% of global greenhouse gas emissions [1, 2, 3]. Currently in Spain, 729 kg of  $CO_2$  are emitted for every ton of cement produced [4], and the cement sector faces several challenges to achieve decarbonization. The cement production process releases big amounts of  $CO_2$  captured in rocks, and a high energy consumption is needed to obtain it. Furthermore, cement consumption is increasing and many clients are demanding low carbon products [4, 5, 6], so efforts must be done to produce green cement.

Urgent decarbonization actions are needed to tackle the current situation of the industry, and several solutions are being developed such as the use of alternative fuels,  $CO_2$  capture, improvements in the energy efficiency of factories, boosting circular economy by using recycled raw materials or creating new low clinker cements [1, 2, 4, 5, 7, 8].

This project studies an energy efficiency solution in a cement plant located in Spain, where a bottoming cycle consumes part of the waste heat coming from the clinker

kiln exhaust gases. An ORC will be used in this combined heat and power application due to its good adaptation to low temperature heat sources [9]. The electricity generated is a cheap, carbon-free and reliable energy source, so it will be self-consumed by the factory and grid demand will be lowered. Thanks to this energy source, the factory will reduce its scope 2 emissions, its electricity bill and will be more resilient to grid blackouts.

The project scope is to model and optimize the ORC to achieve maximum power generation, make a preliminary design of its components, calculate demand coverage, evaluate the economic feasibility of the plant (normalised costs, revenues and profitability) and analyze the carbon footprint.

## 2. State of art

The cement production process begins in a quarry, where limestone, sand, clay and other raw materials are extracted. These materials are transported to the factory where they are ground with some additives in the correct proportions to obtain a fine gravel called crude. Then, crude is transported to the upper part of the preheater tower, a building where exhaust gases from the kiln raise up the gravel temperature while it falls to its lower part.

The precalcinator is located in the lowermost part of the tower; a small boiler where crude reaches 900°C and begins calcination. This solid-state chemical reaction involves the separation of carbon from the limestone composition, having as a result carbon dioxide and calcium oxide [10, 11]. Limestone calcination causes up to 60% of cement production  $CO_2$  emissions [4, 12], also called process emissions since they are intrinsic to the production process.

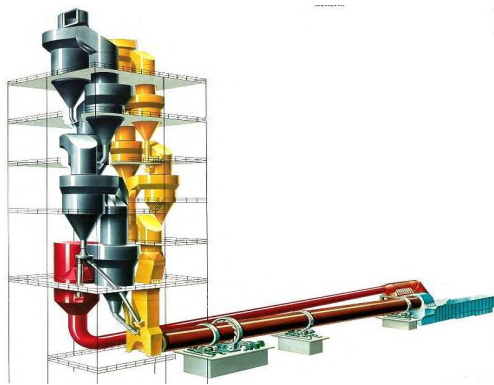
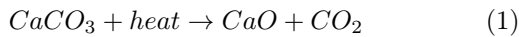


Figure 1: Clinker kiln and preheater tower. Source: Deyna Pinho 2003

Then, calcinated crude goes into the rotary kiln, where it reaches 1500°C thanks to a 2000°C flame. At this temperature, clinkerization occurs; a series of chemical reactions where silicon, iron and aluminum present in the crude combine with the calcium oxide to form clinker [10, 11, 13]. To maintain those high temperatures, the kiln is constantly consuming fuels. The combustion gases formed in the flame follow the opposite path to crude. At the beginning of the kiln their temperature is around 2000°C, and they transfer their heat to the raw materials as they flow through the installation. 330°C are reached in the exit of the preheater tower, and this residual heat is used partially to dry the crude in the grinders. When the exhaust gases leave the chimney, their temperature is around 190°C [10, 11, 14]. The  $CO_2$  emission caused by combustion add up the 40% remaining of the factory carbon footprint [4].

Traditionally, cement factories have used coal to fire their kilns. Then, they moved to petcoke, fuel-oil and natural gas. When  $CO_2$  emissions began to be an issue, cement plants started using alternative fuels. These combustibles are residue-based, helping waste management in cities and reducing combustion-caused  $CO_2$  emissions. Some of these residues contain a fraction of biomass, so they help to reduce net emissions. The main alternative fuels consumed in Spain are refuse derived fuels (RDF),

animal meal, used oils, used tyres, WWTP sludge... [4, 11, 12, 15, 16, 17]. Thanks to alternative fuels, cement factories are reducing their cost because now they play a role as waste managers. Usually, the price paid for these combustibles is lower than the one for fossil fuels, and in some cases they are able to receive these residues free [18].

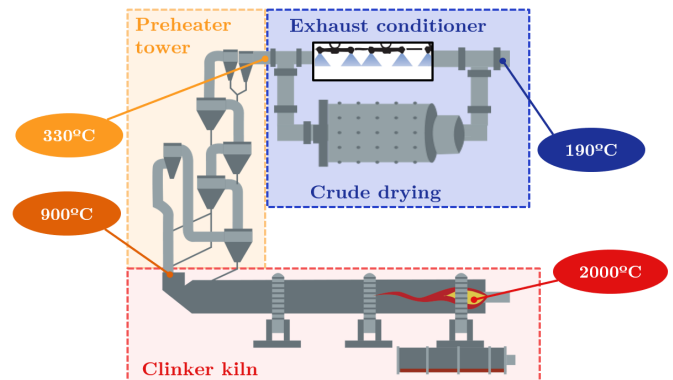


Figure 2: Exhaust gases temperature profile along the kiln. Adapted from Oficemen, 2020.

The last part in the cement production process is cement grinding. Here, clinker is ground with additives such as gypsum, limestone, pozzolana or ferrous sulphate. The amount of each one is selected depending on the cement quality desired, being clinker up to 85% of this mix [4, 12]. Calcination and combustion emissions are associated to clinker, so the lesser amount is used to produce cement, the lower carbon footprint it will have. However, clinker has the properties that grant concrete its resistance and its easy setting, so reducing its fraction in cement jeopardizes cement quality.

Hot exhaust gases stream allows the installation of a bottoming cycle that generates electricity from the waste heat of the clinker production process [9]. Due to the temperature level of the system, around 190-330°C, an ORC is a suitable solution since its good performance with heat sources between 100 to 350°C [11, 9]. These power cycles are Rankine cycles which use an organic fluid instead of water. These organic fluids can be hydrocarbons (propane, butane, pentane...), halogenated hydrocarbons (R134a, R245fa, R141b...) or silicone oils (D4, D5, MDM...) [9, 19]. The properties of these fluids fit well with heat sources below 350°C, in addition to lower pressure operation compared to water Rankine cycles and simpler installations since several complex and expensive components can be removed [9, 11, 19].

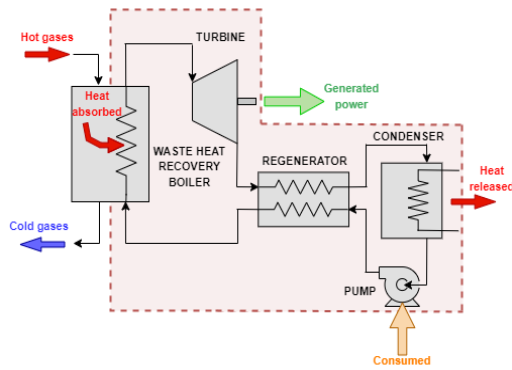


Figure 3: ORC diagram and components. Source: Own elaboration.

The elements that make up an ORC are the turbomachinery (turbine and pump), the waste heat recovery boiler, the condenser, the regenerator and the ducts. Basically, the waste heat recovery boiler transfers the thermal energy from the exhaust gases to the organic fluid, which is expanded in a turbine to convert its energy into useful work. The condenser gives away the excess heat to the cold focus. The pump raises the fluid pressure and the regenerator preheats the fluid to improve the efficiency of the cycle [9].

Currently in Europe there are only 10 ORC's installed in cement plants, with capacities between 2 and 7 MWe [20]; none of them located in Spain. The study case of Chinese cement plants demonstrates that energy efficiency in factories make possible a significant emission reduction in the cement production process [21, 22].

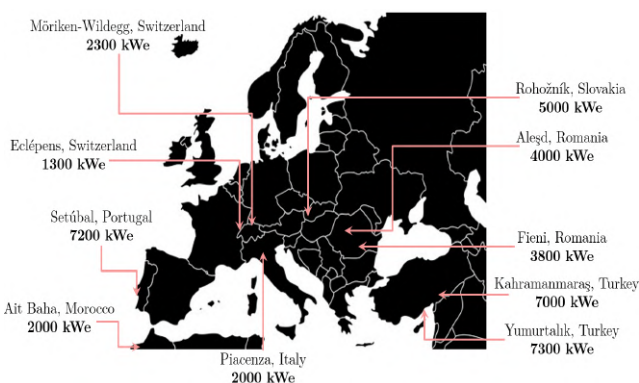


Figure 4: ORC penetration in the European cement sector. Source: Own elaboration.

### 3. Objectives

The aim of the project is to evaluate the results obtained by electricity generation from the exhaust gases waste heat

recovery using an ORC. To do so, the following objectives are established:

1. ORC numerical modeling: a numerical model of the ORC will be done in its nominal operation point, and its results will be analyzed for several scenarios. The model will be optimized to generate as much power as possible within the boundary conditions.
2. Preliminary design of the ORC components: all the components of the ORC will be modelled and designed, calculating their main dimensions and characteristics. The components modelled are the three heat exchangers (waste heat recovery boiler, condenser and regenerator), the turbomachinery (turbine and pump) and the pipes.
3. Production analysis: Annual energy production will be calculated to evaluate the demand fraction covered by the ORC.
4. Economic analysis: Costs and revenues will be calculated to determine the electricity normalized cost and the project profitability.
5. Carbon footprint analysis: The scope 2 emission reduction will be calculated thanks to the electricity substituted from the grid.
6. ORC CAD design: Once the ORC components are dimensioned, a CAD model will be done to have a deeper insight on its configuration and the space needed for its installation.

### 4. Methodology

The exhaust gas mass flow rate is 110 kg/s, and its energy can be recovered at 190°C or at 330°C if more fuel is burned in the precalcinator to supply the extra heat for crude drying. For both scenarios, the results of the ORC will be evaluated according to the outlet gas temperature from the waste heat recovery boiler, which will never drop below 100°C. Specifically, the scenarios analyzed are those of 6. All those scenarios below 120°C are theoretical ones, since acidic products condensation could not be avoided and there would be chimney corrosion risk.

The ORC diagram is shown in Figure 7, whose behaviour equations will be defined solved and the cycle parameters will be optimized to maximize the power generated. Also an exergy analysis will be done to study the cycle performance. The ORC boundary conditions are defined by the cement plant and the cold focus where excess heat is released. The exhaust gases flow is modelled as an ideal gas. Condensation temperature of the fluid organic is set at 35°C to ensure the ORC can be either air-refrigerated

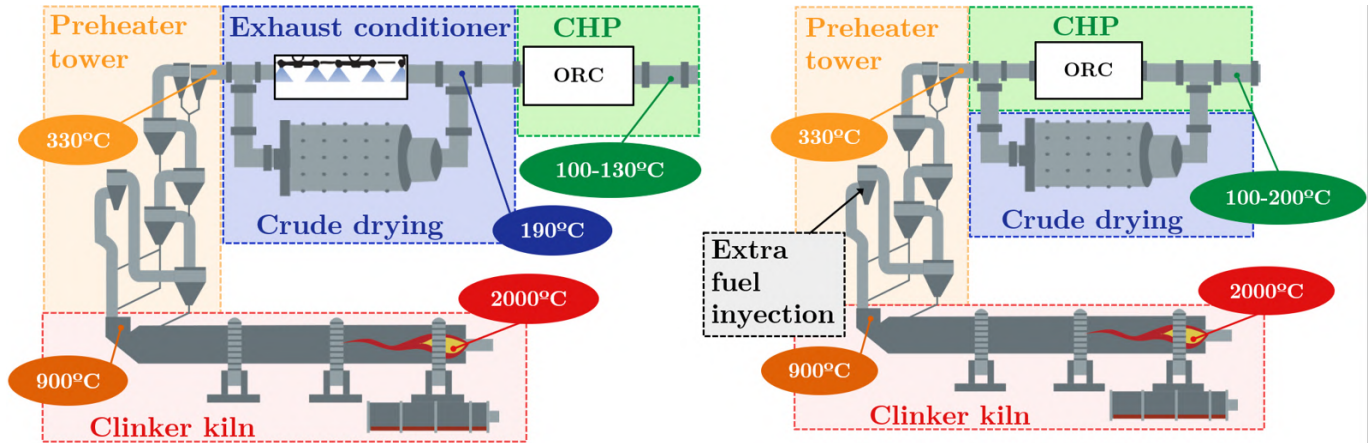


Figure 5: ORC coupling to the kiln system for each heat source temperature. Source: Own elaboration.

or water-refrigerated. If this temperature involves a condensation pressure below 2 bar, this pressure will be set instead, and the condensation temperature will be the one associated to it. Pressure drop in pipes and heat exchangers is not considered in the model, but it is taken into account in the preliminary design of ORC components. The last boundary condition is the temperature of refrigerating water in the condenser. 25°C is set in the inlet and 30°C in the outlet:

ORC electric generation	SCENARIO 1 190°C heat source	OUTLET GAS TEMPERATURE			
		100°C	110°C	120°C	130°C
SCENARIO 2 330°C heat source	OUTLET GAS TEMPERATURE				
	100°C	110°C	120°C	130°C	
	140°C	150°C	160°C	170°C	
	180°C	190°C	200°C		

Figure 6: Considered scenarios where the model will be evaluated. Source: Own elaboration.

Those parameters not depending on boundary conditions will be the ones modified to optimize the ORC output. The choice of organic fluid affects to all the thermodynamic properties, so its election is the most important parameter to maximize the ORC power. The model will be evaluated with the following substances, where the one with better results is chosen: acetone, cyclohexane, ethanol, propane, isobutane, isopentane, isohexane, N-butane, R134a and R245fa. For each fluid, two operation pressures of the the waste heat recovery boiler will be decided: one below the critical point (subcritical cycle) and other above it (transcritical cycle). Then, for each combination of fluid and pressure, the model will be solved

with and without regenerator, so it can be decided if the regenerative cycle is a cost-effective solution. Lastly, the temperature approach between hot gases and the organic fluid at both of its ends will be selected to fix the outlet gas temperature and maximize power production.

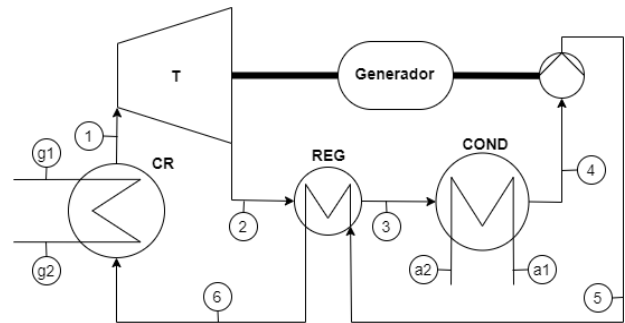


Figure 7: ORC diagram for the numerical model. Source: Own elaboration.

Once the model is optimized, a preliminary sizing of the cycle components is done. The waste heat recovery boiler will be a cross-flow compact heat exchanger, where the organic fluid flows through finned pipes embedded by the exhaust gases (Figure 8). The pipes have been chosen from a library where their diameter, type of fins and separation are set. Specifically, the biggest separation possible has been selected to avoid dust accumulation. A thermal conductivity of 400 W/m-K and a 1.5 μm roughness are assumed for the tubes. The heat exchanger dimensions, pressure drops, number and type of tubes will be calculated using the LMTD method. The heat transfer area can be obtained since the heat transferred, the logarithmic difference of temperatures, the thermal resistances and the correction factor are known. This area and pipes separation makes possible the calculation of the three main dimensions. After the dimensions of the heat exchanger

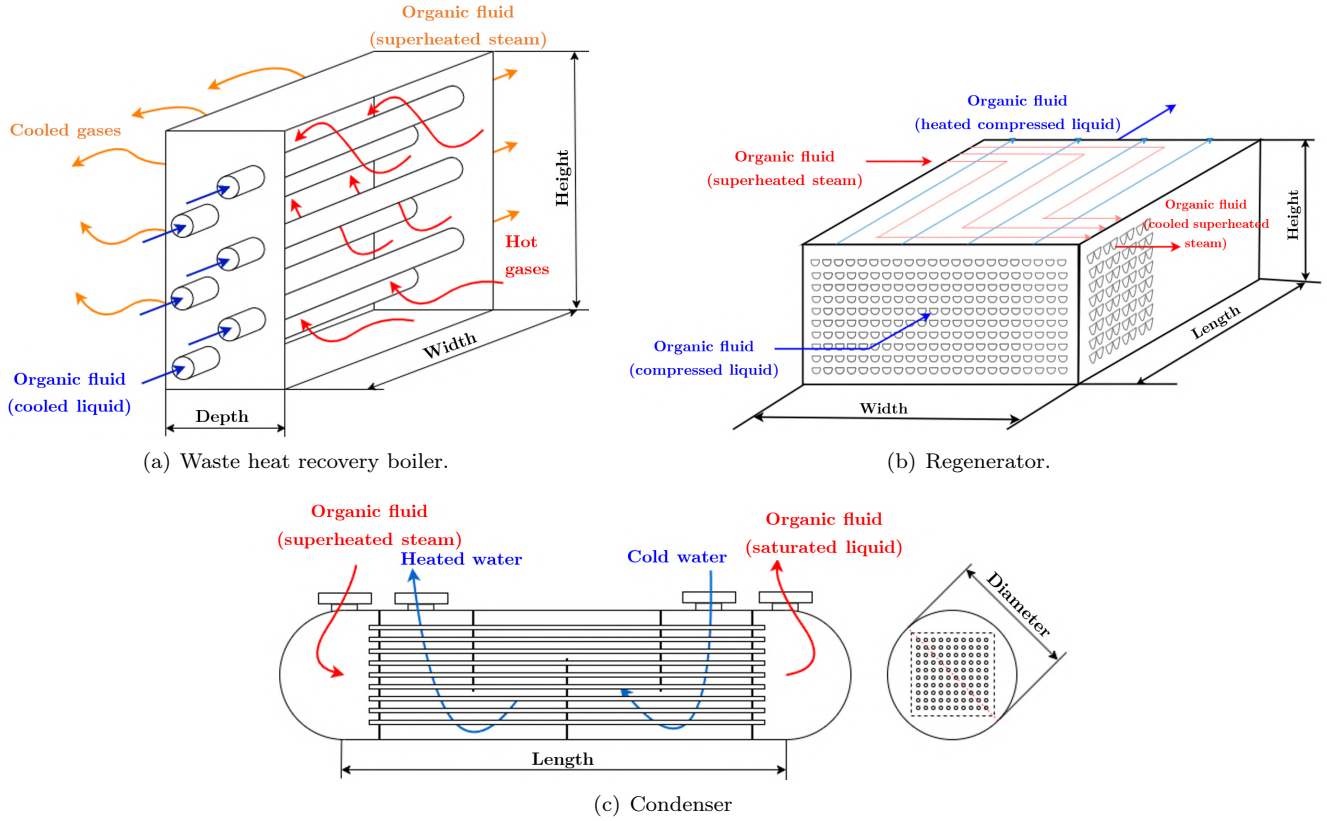


Figure 8: Heat exchangers diagrams. Source: Own elaboration.

are determined, the pressure drop will be evaluated, where it must be under 2.49 kPa.

$$\dot{Q}_{CR} = \bar{U}A \cdot \Delta T_{lm} \cdot F \quad (2)$$

$$\Delta T_{lm} = \frac{\Delta T_h - \Delta T_c}{\ln\left(\frac{\Delta T_h}{\Delta T_c}\right)} \quad (3)$$

$$\frac{1}{\bar{U}_{ARB}} = \frac{1}{h_i \cdot \pi \cdot d_i \cdot L} + \frac{\ln\left(\frac{D_e}{d_i}\right)}{2 \cdot \pi \cdot k \cdot L} + \frac{1}{h_e \cdot A_e \cdot \eta_e} \quad (4)$$

$$L_{CR} = \frac{S_T \cdot S_L \cdot L_{tubo} \cdot n_{tubos}}{A_{trans}} \quad (5)$$

The condenser is a shell and tube heat exchanger and will also be solved using the LMTD method. For this component, its length, diameter, number of tubes and pressure drops will be calculated. Once again, the heat transfer area is obtained as the rest of the parameters can be calculated. A 400 W/m-K thermal conductivity and a 1.5  $\mu$ m roughness have been assumed for the tubes. The diameter of the condenser only depends on the number of tubes, their separation and their diameter. Specifically, the diameter of the tubes is set in 10 mm and the separation among them is 2 cm in every direction. The tube bundle is square and the condenser diameter is a 10% bigger than

the diagonal length of that square. The flow through the tubes has to fulfill the pressure drop threshold established in 5 kPa.

$$\frac{1}{\bar{U}_{A_{cond}}} = \frac{1}{h_i \cdot \pi \cdot d_i \cdot L} + \frac{\ln\left(\frac{D_e}{d_i}\right)}{2 \cdot \pi \cdot k \cdot L} + \frac{1}{h_e \cdot \pi \cdot D_e \cdot L} \quad (6)$$

$$D_{cond} = 1,1 \cdot \sqrt{2 \cdot n_{tubos}} \cdot SEP_{tubos} \quad (7)$$

The regenerator is a printed circuit heat exchanger (PCHE), which will be solved with its specific methodology [23, 24], obtaining its dimensions, number of ducts and pressure drops. This methodology solves the heat transfer between two ducts and extends it to all the ducts that compose the PCHE, taking into account the maximum pressure drops established. For the hot side of the regenerator, 10 kPa drop has been set, and 50 kPa for the cold side. Furthermore, this kind of heat exchanger is modular, stacking blocks 60 cm wide and 60 cm long. This means that the total width of the PCHE is 60 cm and the total length will be a multiple of 60 cm.

Pump and turbine will be sized with Baljè's curves [25, 26], which give information on the size of the impeller, its speed and machine performance. To do so, the specific speed of the machines will be calculated with Equation 8

considering the number of stages of each one, their speed, the volumetric flow and the reversible work exchanged between fluid and impeller. Both turbine and pump are coupled to the same shaft, so they will spin at the same speed and it will be chosen as a multiple of 3000 rpm to match the alternator speed. Thanks to the specific diameter obtained from Balje's diagrams, and Equation 9, the impeller diameter of the machines is calculated. Lastly, the blade tip speed will be checked to be under 450 m/s to ensure material resistance due to centrifugal forces.

$$\omega_s = \omega \cdot \frac{V^{1/2}}{W^{3/4}} \quad (8)$$

$$D_s = D \cdot \frac{W^{1/4}}{V^{1/2}} = \frac{\Psi^{1/4}}{\Phi^{1/2}} \quad (9)$$

Ducts will be designed following Norsok Standard P-001, ASME B31.1-2007 and ANSI B36.10M [27, 28, 29]. These standards give guidelines for calculating the size of the ducts following the maximum velocity criterion and the pressure drop criterion. For each pipe, a diameter is chosen and both the speed and the pressure drop are calculated using the flow and its properties obtained from the numerical model. The values obtained must be under the limits established by the standards.

Once the numerical model is solved and the ORC power is known, the demand coverage is calculated. To do so, the power cycle is assumed to work the entire year (8760 hours) since clinker kilns are rarely stopped for maintenance issues. Last year, the cement plant consumed 56,622 MWhe, so the energy percentage supplied by the ORC will be calculated regarding this value.

LCOE will be calculated (LCOECD with the heat source at 330°C since crude drying is also included<sup>1</sup>). In addition to LCOE, other economic indicators will be studied such as the NPV, the IRR and the payback period of the project. CAPEX has been estimated from several similar projects [30]. The maintenance costs are usually around 2.3% of the CAPEX, and the wage of the operators has to be added, which is 16000€ per year [31]. Different scenarios will be evaluated for the electricity price (between 50 and 150 €/MWhe) and fuel cost (between 5 and 30 €/MWhth), to have a broader idea of the project profits. The lifespan of the project will be established in 20 years [31, 32, 33], considering a wacc of 7.5%, a nominal rate for maintenance and fuel cost of 2.5% and a nominal rate for electricity cost of 5%. LCOE and LCOECD will be calculated with Equation 10 and 11. NPV will be calculated with Equation 12. IRR and PB do not have an explicit formula, and they will be calculated in the exact

way using an equation solver.

$$LCOE = \frac{INV \cdot f_a + OM \cdot f_a \cdot f_{\Sigma}^{OM}}{E_{gen}} \quad (10)$$

$$LCOECD = \frac{INV \cdot f_a + OM \cdot f_a \cdot f_{\Sigma}^{OM} + F \cdot f_a \cdot f_{\Sigma}^F}{E_{gen}} \quad (11)$$

$$NPV = ES \cdot f_{\Sigma}^{elec} - OM \cdot f_{\Sigma}^{OM} - F \cdot f_a \cdot f_{\Sigma}^F - INV \quad (12)$$

The energy produced will replace the one consumed from the grid. It will be carbon-free, so it is possible to calculate the emission reduction. To do so, the emission factor of the Spanish electricity mix will be considered, which is 161.4 kg CO<sub>2</sub>/MWhe [34]. The value obtained may change if the cement plant buys electricity with guarantee of origin. In that case, the emission reduction will be lower than the one calculated. When the 330°C heat source is used, extra fuel is burnt and new emissions must be taken into account. Different fuels have been considered to analyze the impact of each one to the carbon footprint.

Table 1: Considered fuels and their characterization for the carbon footprint analysis. Source: Own elaboration.

Fuel	LCV [GJ/t]	Emission factor [t CO <sub>2</sub> /t]	%Biogenic
Petcoke	32,5	3,16	0
Used oil	30,6	2,25	0
Used tyres	31,6	2,50	28,90
RDF	20,5	1,60	50,85
Animal meal	18,9	-	100,00

CAD model of the ORC will be done for the optimal configuration. To build the plant, pipelines length will be minimized, always ensuring enough space for operators to work in operation and maintenance tasks. The footprint of the ORC will be obtained to determine its size and the space needed in the factory to install it. The design of this project is a preliminary one, being possible to obtain a more compact solution in more detailed studies where the available space is known and a more detailed model is done.

<sup>1</sup>In addition to electricity cost (LCOE), this index includes the required extra fuel for crude drying (CD).

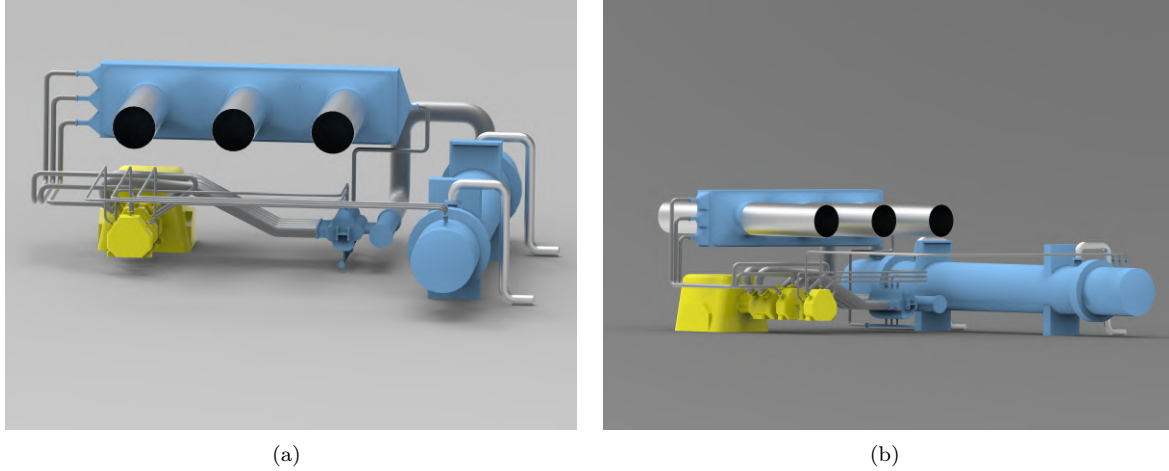


Figure 9: ORC CAD model for the 190-120 scenario. Source: Own elaboration.

Table 2: Pipe dimensions for the 190-120 scenario. Source: Own elaboration.

Pipes							
Name of pipe	Number of pipes	Nominal diameter	Thickness [mm]	Name of pipe	Number of pipes	Nominal diameter	Thickness [mm]
Gases				N-Butane			
G1	3	DN1150	9.53	1	3	DN125	6.55
G2	3	DN1150	9.53	2	4	DN300	12.7
Water				3	1	DN550	9.53
				4	3	DN65	5.16
A1	1	DN250	6.35	5	3	DN65	5.16
A2	1	DN250	6.35	6	1	DN100	6.02

## 5. Results

The optimal configuration for both heat sources is to use N-Butane as organic fluid in a transcritical regenerative cycle. Once the fluid is decided, condensation pressure is set in 3,3 bar and the waste heat recovery boiler works at 50 bar. For every scenario the optimal geometries are an axial turbine and a centrifugal pump, both single-staged. Lastly, in every case the materials selected for piping are stainless austenitic steel ASTM A-213 TP304 for N-Butane ducts, carbon steel ASTM A-106B for water ducts and stainless steel ASTM A-213 TP316L for gas ducts.

Using the 190°C heat source the optimal scenario is that whose outlet temperature is 120°C. This ORC generates 1595 kWe, covers 24.68% of the demand and avoids 2,255 tons of CO<sub>2</sub> per year. The LCOE is 62.85 €/MWh, re-

sulting a NPV of 10.9 M€, a return of 21.18% and a payback period of 6.7 years. The best case scenario, given by high electricity prices, yields a NPV of up to 40 M€, and in the worst case scenario, when electricity prices are the lowest considered, the NPV would drop to 3 M€.

For this scenario, the waste heat recovery boiler is 8 meters wide, 2 meters high, and 0.75 deep. The condenser is 10.72 meters long and its diameter is 1.7 meters. The regenerator is 0.47 meters high, 0.6 wide and 1.8 long. The optimal turbine is single-staged, with an axial impeller of 26.7 cm in diameter and a rotation speed of 30,000 rpm. The pump optimal configuration is centrifugal and single-stage, rotating at the same speed as the turbine and with an impeller of 6.8 cm in diameter. The dimensions of the pipes are shown in Table 2. According to this preliminary design of the ORC, it would fit in a room 15 meters long,

## WHR in a cement plant using an ORC

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17 meters wide and 6 meters high.

The cooler the gases are expelled, the higher the ORC power is. Comparing the four outlet gas temperatures, between 1923 and 1390 kWe can be produced. The demand coverage varies between 29.75 and 21.50% of the cement plant annual grid demand, leading to an emission reduction between 2538 and 1965 annual  $CO_2$  tons. Those scenarios with higher production lead to lower LCOE, being between 60 and 65 €/MWh, and higher benefits.

In every scenario with this heat source, the waste heat recovery boiler has the same size (8x2x0.75). The condenser has approximately the same length (10.7 m), but as the power cycle decreases its diameter is smaller. The biggest diameter is 1.94 meters for 100°C outlet temperature, and the smallest is 1.58 for 130°C. Three modules are needed for the regenerator in every scenario except for the 130°C one, which needs two. The height of the regenerator is around 0.47 meters in every case. The more powerful the ORC is, the bigger the turbine is and the slower it spins; passing from 28.7 cm and 27,000 rpm in the 100°C scenario, to 24.9 cm and 33,000 rpm in the 130°C case. The pump also grows in diameter when the power increases, passing from 7.9 to 6.8 cm. Gas pipes have the same dimensions in every case. Water and N-Butane pipes grow slightly with ORC power, but the overall size is mainly the same for all scenarios.

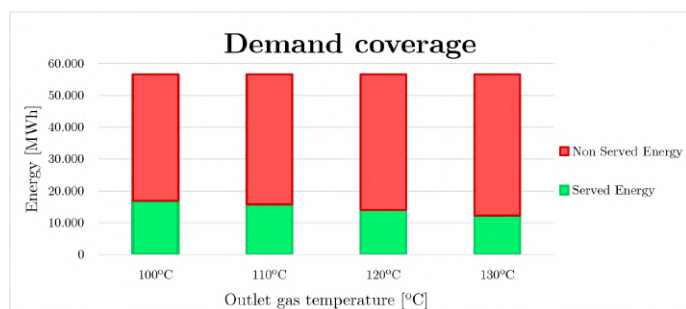


Figure 10: Demand coverage for every scenario with the 190°C heat source. Source: Own elaboration.

The most relevant scenario among all the studied with the 330°C heat source is that who generates more power (120°C outlet temperature). This ORC produces 6159 kWe and covering 95.29% of the cement plant demand. The electricity generated has an LCOECD of 62.44 €/MWh, being the NPV of the project of 42.2 M €. The IRR is 24.81% and the payback period is 5.6 years. The best case scenario yields profits up to 93 M €, but the worst case scenario, where fuel becomes very expensive while electricity prices remain very low, could mean losses of 35 M €. A sensitivity analysis has been done considering the biomass and the electricity costs, obtaining the map shown in Figure 11. For this scenario, the

waste heat recovery boiler is 8 meters wide, 3.75 high and 2.01 deep. The condenser is 10.75 meters long and its diameter is 2.87 meters. The regenerator is 1.02 meters high, 0.6 wide and 6 long. The optimal turbine is single-staged, with an axial impeller of 53.4 cm in diameter and a rotation speed of 15,000 rpm. The pump optimal configuration is centrifugal and single-stage, rotating at the same speed as the turbine and with a 14.2 cm diameter impeller. The dimensions of the pipes are shown in Table 3, being a little larger in this case. The CAD model of the ORC has not been made, but the cycle could be located in a room with dimensions similar to the previous case, requiring a little more height.

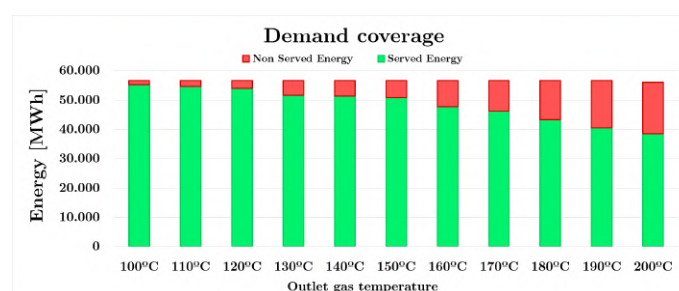


Figure 12: Demand coverage for every scenario with the 330°C heat source. Source: Own elaboration.

Comparing all the scenarios considered with the 330°C heat source the ORC power of the cycle is between 6300 and 4400 kWe depending on the outlet gas temperature. The demand coverage is between 97.51 and 68.01% of the annual demand of the factory. To achieve emission savings, it is necessary to burn a 100% biomass-based fuel. Otherwise the project would cause additional emissions to those already generated. In case of using biomass-based fuels, the savings are between 6000 and 9000 annual tons of  $CO_2$ ; otherwise, in the worst case scenario where pet-coke is burnt, 40,000 extra  $CO_2$  tons would be emitted each year. The lower energy production, the higher risk of economical losses for the factory. Again, for high fuel costs and low electricity prices, the NPV of the project is negative; where the border between gains and losses is closer to cheaper fuel costs when the ORC power is lower. The LCOECD varies with fuel cost, being competitive with the 190°C heat source LCOE when the fuel is the cheapest (5 €/MWh). At this cost, the LCOECD varies between 60 and 70 €/MWh.

The waste heat recovery boiler gets bigger for lower power scenarios, being slightly higher in each case (from 3.75m in the 120°C case, to 4.38m in the 190°C scenario). The heat exchanger width remains constant in 8 meters, and the depth grows a little, passing from 2 to 2.3 meters. The condenser has almost the same length in every scenario (10.7 meters) and decreases its diameter with the ORC



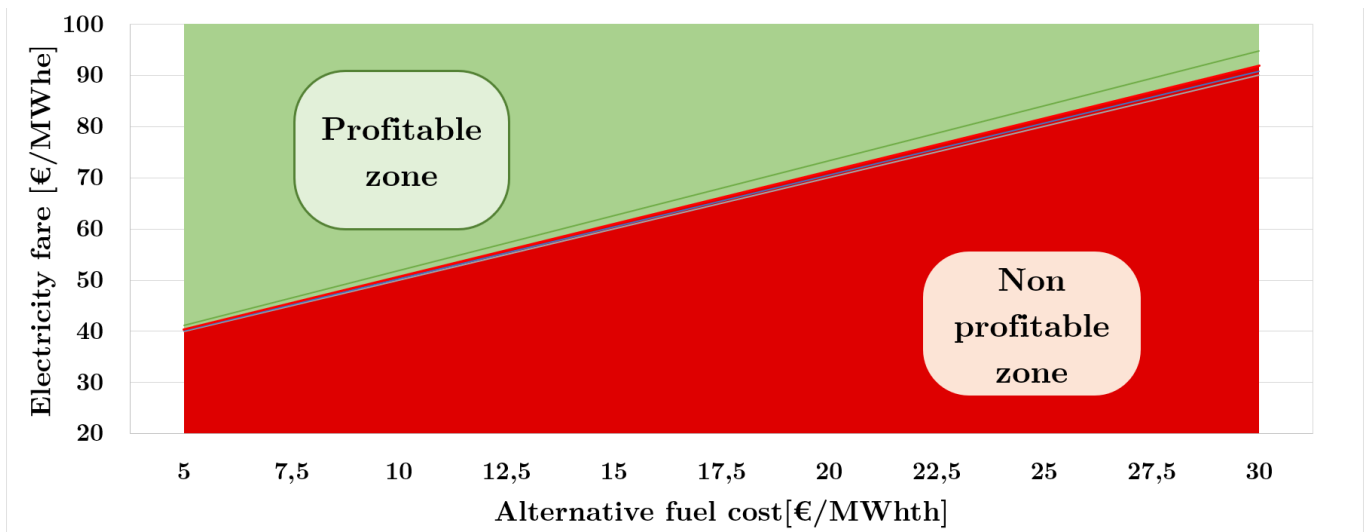


Figure 11: Profit map based on fuel and electricity costs with the 330°C heat source. Source: Own elaboration.

Table 3: Pipe dimensions for the 330-120 scenario. Source: Own elaboration.

Pipes							
Name of pipe	Number of pipes	Nominal diameter	Thickness [mm]	Name of pipe	Number of pipes	Nominal diameter	Thickness [mm]
Gases				N-Butane			
G1	3	DN1150	9.53	1	1	DN125	9.53
G2	3	DN1150	9.53	2	5	DN450	7.92
Water				3	1	DN800	12.7
				4	1	DN150	7.11
A1	1	DN400	7.92	5	1	DN150	7.11
A2	1	DN400	7.92	6	1	DN150	7.11

power. The biggest diameter is 2.87 meters and the smallest 2.31. The lesser the ORC power, the lesser modules are needed for the regenerator, passing from six in the 120°C scenario, to four in the 190°C one. The height of the heat exchanger is similar in every case, being around 1.15 meters. The diameter of the turbine impeller grows with power while the rotation speed decreases. The biggest turbine is 53.4 cm in diameter and spins at 15,000 rpm while the smallest one has 47 cm in diameter and spins at 18,000 rpm. The pump diameter also increases with diameter, passing from 14.2 to 11.9 cm. As it happened with the 190°C heat source, the overall pipe size remains mainly the same among scenarios, varying slightly the diameter of some ducts.

## 6. Discussion

In this project, the waste heat recovery from the exhaust gases of the clinker kiln of a cement factory in Spain has been analyzed. An organic Rankine cycle has been selected as the power cycle to generate power due to its good coupling with low temperature heat sources. The ORC generates electrical energy that can be used on site and thus reduce grid consumption, which implies less expenses for the purchase of electricity and a reduction in scope 2 emissions, since the energy produced is carbon-free. In this project, different scenarios have been analyzed depending on the waste heat temperature used (190°C or 330°C) and depending on the exhaust gases temperature after being cooled in the waste heat recovery boiler (from 100 to 130°C, or from 100 to 200°C). Different prices of



electricity and fuel have also been considered in the economic evaluation of the project to do a sensitivity analysis of these variables.

Beginning with the heat source at 190°C, it only makes sense to install the ORC that cools the gases down to 120°C. The electricity production is 1595 kW<sub>e</sub>, which allows to cover a maximum of 24.68% of the annual electricity demand from the factory (note that this coverage assumes uninterrupted operation of the kiln throughout the year). The power cycle is quite compact, fitting in a room 15 meters long, 17 meters wide and 6 meters high. In addition, the footprint could be further reduced in more detailed designs adapted to the factory.

The energy is produced with a LCOE of 62.85 €/MWh<sub>e</sub>, a competitive value compared to current electricity costs. The project generates a NPV of almost 11 M€, and could give benefits of up to 30 and 40 M€ if the price of electricity continues to rise as it has in recent years. Thanks to the ORC, a saving of 2255 tons of CO<sub>2</sub> is achieved each year; less than 1% of the factory's annual emissions.

With the 330 °C heat source, the ORC power increases, being between 6.3 and 4.4 MWe. Thanks to a higher quality energy source, electricity production can be multiplied by almost four, although it comes with the inconvenience of having to modify the factory layout and burn more fuel in the precalcinator. This increased power production allows better coverages, where even the worst case of all makes possible to supply almost 70% of the annual electricity demand of the factory. The most interesting scenario is the one that cools the gases down to 120°C, although if the cement company plans to use some of the heat for other purposes, the convenience of the ORC that cools the gases down to 150°C or 190°C could be evaluated. The 330-120 power cycle generates 6159 kW<sub>e</sub> with a better performance compared to its equivalent with the 190°C heat source. The ORC elements are larger in this case, although the installation would fit in a room about the same size as the above case since the lengths of the largest components barely change. More than 95% of the factory's demand can be met. The normalized cost of energy is highly dependent on the cost of the extra fuel burnt, which is currently purchased by the factory at 5 €/MWh<sub>t</sub>. This price implies a LCOE of 62.44 €/MWh<sub>e</sub>, but if fuel becomes more expensive, it could reach costs even higher than 100 €/MWh<sub>e</sub>. The NPV in this case is more than 42 M€, and this value could be doubled in the case that electricity becomes more expensive while the fuel price remains the same. There is a risk if the fuel cost rises at the same time that the electricity price falls, since the project could generate economic losses. In addition, emissions savings are only achieved in the case of burning 100% biomass fuels. In that case, it would be possible

to reduce almost 9,000 tons of CO<sub>2</sub> per year, which is still very little compared to the emissions from the factory. For the rest of the alternative fuels considered, the ORC would suppose an increased carbon footprint for the factory.

## 7. Conclusions

Despite better electricity production and higher economic gains, the ORC with the 330°C heat source has two weaknesses: logistics and fuel.

The transition to alternative fuels has caused an increase in factories logistics complexity. For each new type of fuel, it is necessary to install an entire injection system to introduce it to the kiln. At any time, the mixture burnt must be controlled to keep the flame conditions stable and optimal for a good clinkerization. The transport and storage of many different fuels must be coordinated and needs extra space in the factory. Furthermore, efforts are needed to find residue suppliers in nearby areas. These tasks are done to reduce combustion emissions, and they are currently allowing a 15% reduction of the total clinker emission factor. Firstly, there is the difficulty and the time spent with the kiln stopped caused by the modification of the layout of the gas outlet to be able to install the recovery boiler. In addition to that, a degree of complexity would be added to the control of the precalcinator since now it would not only affect the operation of the kiln, but also to that of the ORC.

On the other hand is the fuel. If any alternative fuel is burned in the kiln, it will achieve a reduction in CO<sub>2</sub> emissions to a greater or lesser extent. However, the ORC is "forced" to burn biomass, which in the case of burning it directly in the kiln, it would allow a much greater reduction in the carbon footprint than that provided by the ORC. Thus, the project is forcing the burning of a highly valuable fuel for the cement company in an application that is secondary to it (the factory's job is to produce cement, not electricity). As mentioned, currently many factories receive alternative fuels at very low or even zero prices. However, in the cement industry and in any industry that requires fuel burning, biomass is becoming increasingly valuable and its price is rising sharply. This would lead to lower gains due to higher fuel prices and the ORC results would be less interesting.

The power cycle with the 190°C heat source is a humbler solution, since it generates less energy, and does not bring as many benefits. However it is much easier to install and does not affect the operability of the factory. In addition, the benefit obtained is less uncertain since it only depends on the price of electricity and as long as the energy crisis continues, it is expected to remain high. Furthermore, it allows biomass and alternative fuels to be



reserved for the kiln, where they have a truly beneficial effect on emission reduction; and it is added to the one caused by the ORC. For these reasons, it is considered that the best option for the factory is to take advantage of the gases at 190°C, and cooling them to 120°C in the waste heat recovery boiler.

As mentioned at the beginning of the project, one of the motivations is the reduction of greenhouse gas emissions from the cement company. It has been seen that in no case it is possible to achieve considerable savings, but the project does have a positive impact in terms of decarbonization for two reasons. The first is that the cement industry is very carbon intensive, and although reducing emissions by 1% seems little, behind that 1% there are several thousand tons of  $CO_2$  each year. Increasing that percentage implies very large decarbonization projects and some of them with technologies that are still under development. The second reason is that the project generates a direct benefit for the factory, as well as a competitive advantage since it can strengthen its sale of low-carbon cements. This injection of money into the company will allow investments in more ambitious decarbonization projects such as carbon capture or the use of green hydrogen to replace fuels.

As an improvement to this project, it is proposed to install the ORC studied with an extra heat source coming from the stream of cooled clinker. When this material leaves the kiln, it is cooled by fans and the heated air forms the secondary air used in the kiln. After cooling it, the clinker is propelled with a current of air through ducts to the silos where it is stored. At this point, the flow is around 300°C, so it would be possible to install another waste heat recovery boiler in that area. Given the distance between both heat recuperators and the fact that heat is being obtained from two different sources at two different temperatures, it would be convenient to use a heat transfer fluid that transports the thermal energy to a heat exchanger where the N-Butane of the ORC is heated. With this system, a cycle similar to that of 190°C would be obtained, but with a much higher production since more waste heat is being absorbed from the cement factory.

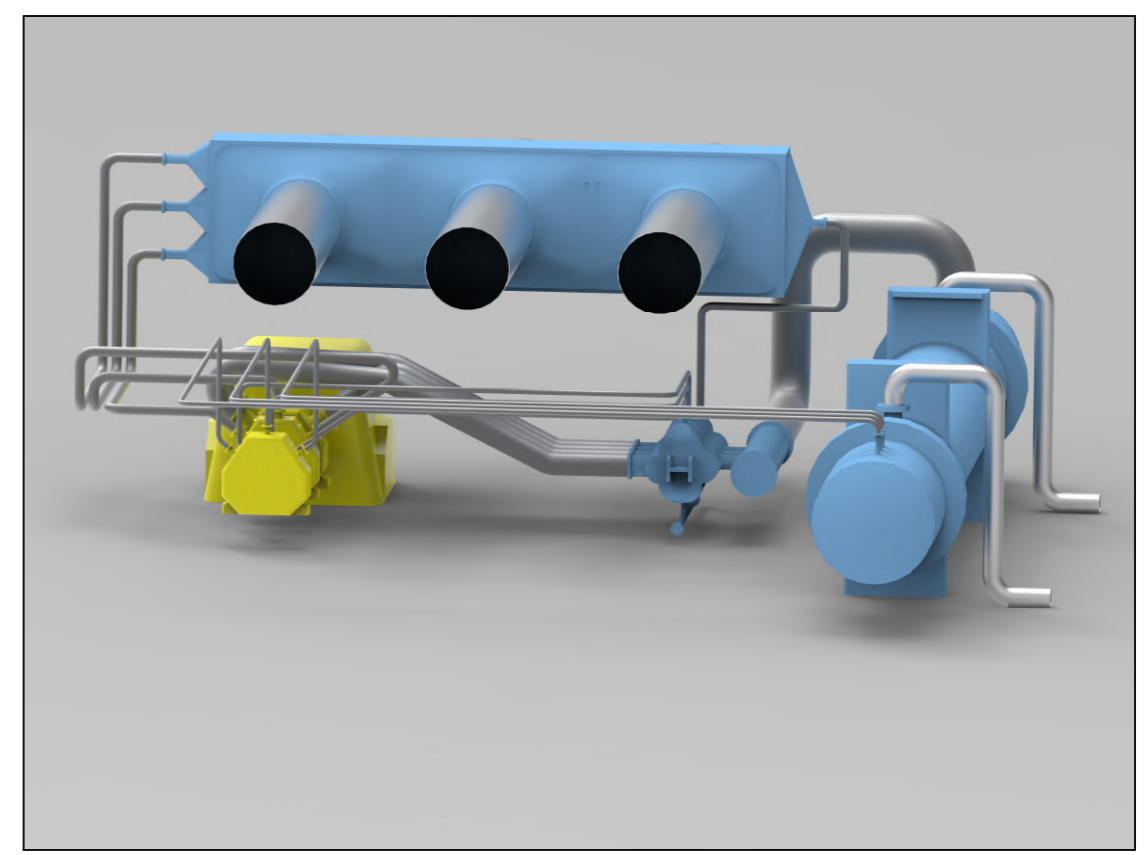
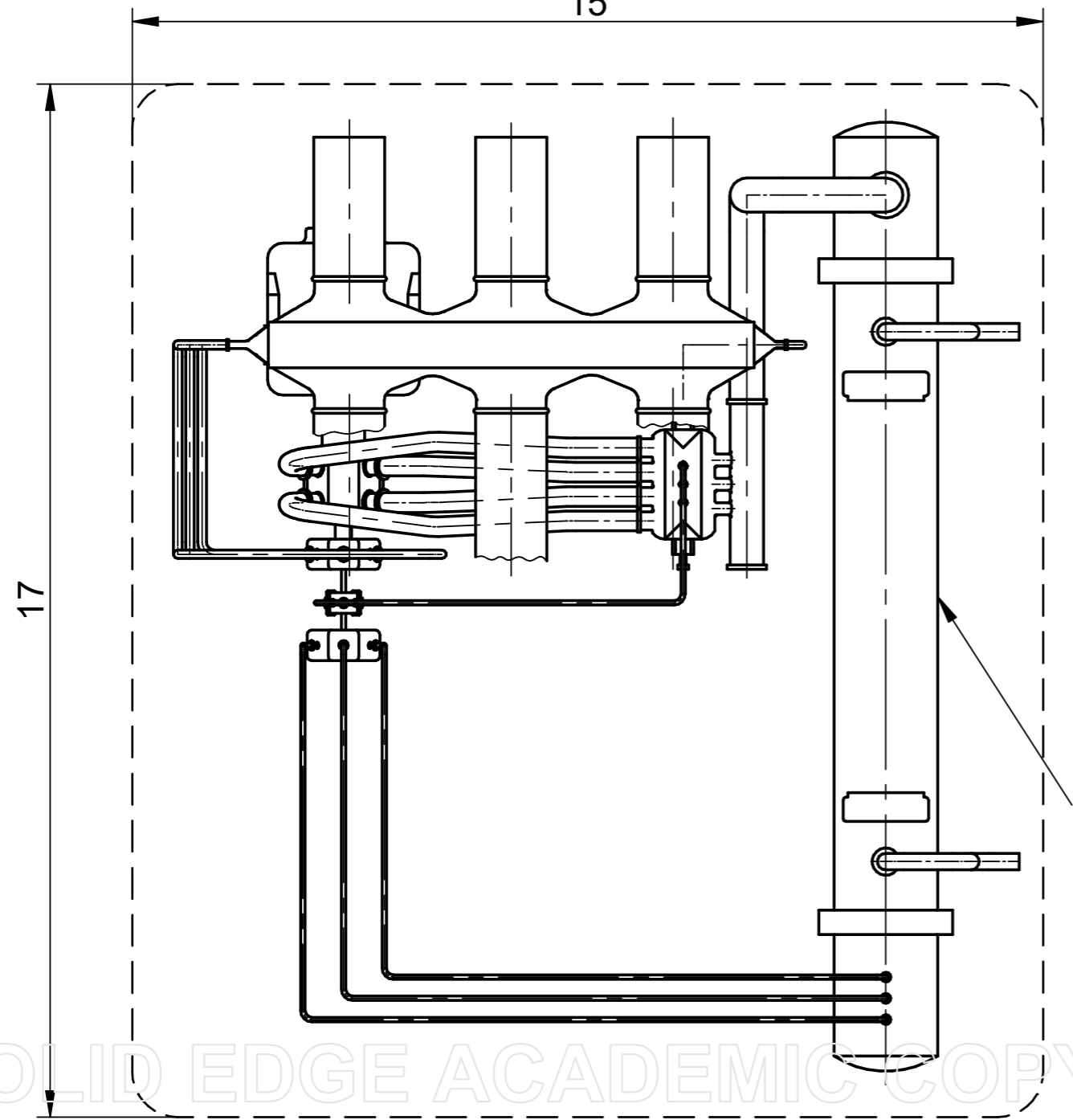
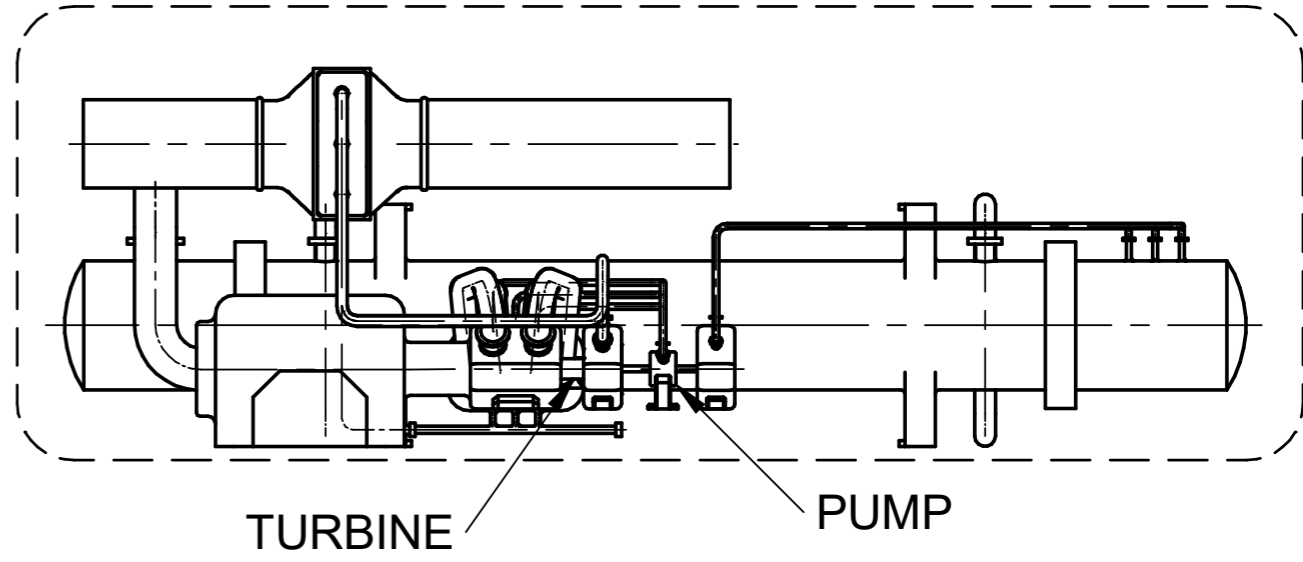
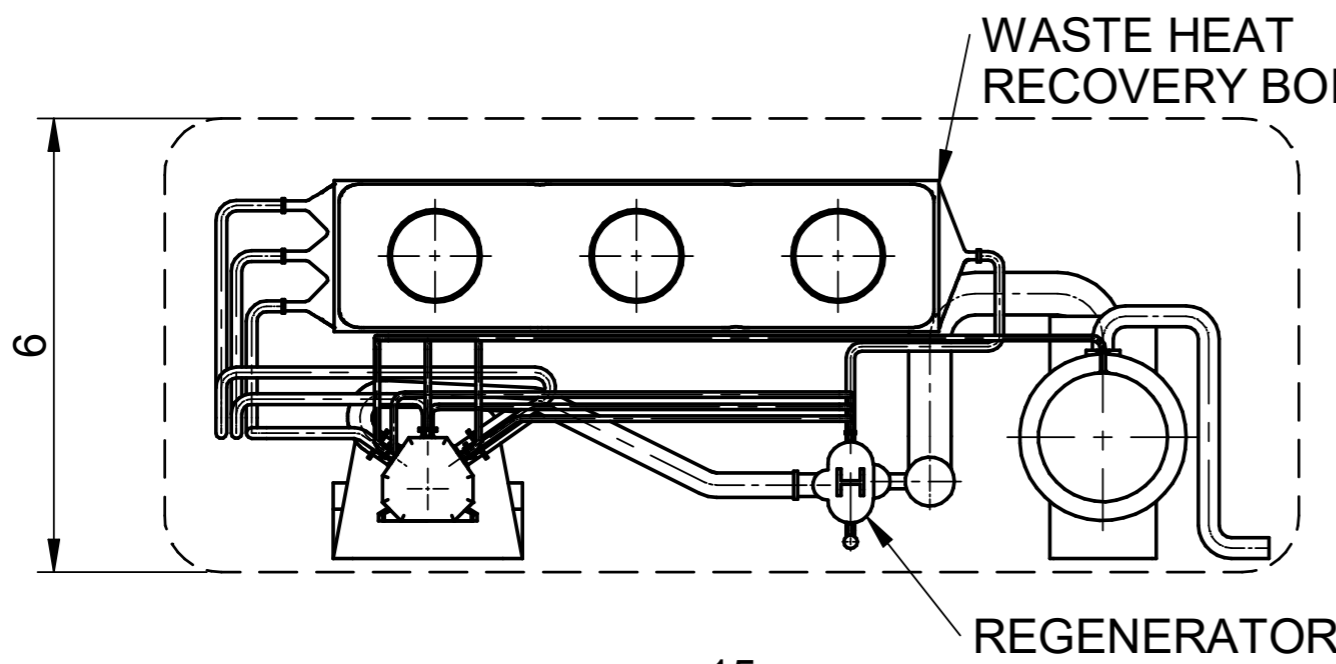
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1 2 3 4 5 6 7 8

A  
B  
C  
D  
E  
F



\*Dimensions in meters

MATERIAL	-	FORMAT	A3	SUPPLEMENTARY TITLE	Power cycle plant
TOLERANCE	-			TITLE	ORC Cement factory
DRAWN	Lorenzo Serrat Albano	DATE	23/06/23		
CHECKED	José Porras Galán	DATE	23/06/23		
SCALE:	1:100	SIGN		CODE	1.1

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