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PU Public
PP Restricted to other programme participants (including the Commission Services)
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CO Confidential, only for members of the consortium (including the Commission Services)

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1. Executive summary

The project's main objective is to develop new solutions to recover waste heat produced in energetic intensive (EII) processes of industrial sectors such as cement, glass, steelmaking and petrochemical and transform it into useful energy.
One of the solutions to generate electricity recovering waste heat is by the Organic Rankine Cycle (ORC).
The project addresses the design and the development of a new generation of ORC for heat recovery adoptable in different EII processes in order to transfer heat directly from the flue gases to the organic fluid of the ORC system thanks to a Direct Heat Exchange solution.
The whole Waste Heat Recovery System will be installed and validated in the Cementi Rossi industrial facility located in Italy.

The object of this deliverable is to show a collection of pictures regarding the several manufactured components of ORC.

1.1 Cement Manufacturing Process

Cement production is a resource-intensive practice involving large amounts of raw materials, energy, labour and capital. Cement is produced from raw materials such as limestone, chalk, shale, clay, and sand. These raw materials are quarried, crushed, finely ground, and blended to the correct chemical composition. Small quantities of iron ore, alumina, and other minerals may be added to adjust the raw material composition. Typically, the fine raw material is fed into a large rotary kiln1 (cylindrical furnace) where it is heated to about 1450 °C (2640 °F). The high temperature makes raw materials to react and form a hard nodular material called "clinker." Clinker is cooled and ground with gypsum and other minor additives to produce cement.

The heart of the state-of-the-art clinker production is the rotary kiln. In the rotary kiln process, raw material mixture is fed into the upper end of large cylindrical, refractory-lined steel kiln that range from 60 to 300 meters long and from over 3.0to 8.0 meters in diameter. The blended mixture is fed into the tilted kiln at a rate controlled by the slope and rotational speed of the kiln. Coal, pet coke, natural gas and more increasingly, alternative fuels such as plastic, solvents, waste oil or meat and bone meal are fed into the lower end of the kiln and burned to feed the flame, which can reach as high as 1800 to 2000°C. As the kiln slowly rotates (1 to 5 revolutions per minute), the raw material tumbles through progressively hotter zones toward the flame at the lower end of the kiln. Inside the kiln's burning zone, raw materials reach temperatures of 1430°C to 1650°C (2600°F to 3000°F). At 1480°C (2695°F) a series of chemical reactions causes the materials to break down, become partially molten, and fuse into nodules called "clinker" – grayish-black pellets, often the size of marbles (LBNL 2008, DOE 2003). Hot exhaust gases exiting through the kiln are used to preheat and calcine the raw material feed before it enters the kiln's burning zone. Clinker is discharged red-hot from the lower end of the kiln into air coolers to lower it to handling temperatures. Cooled clinker is combined with gypsum and other additives and ground into a fine grey powder called cement. Many cement plants include the final cement grinding and mixing operation on site. Others ship some or all of their clinker production to standalone cement-grinding plants situated close to markets.

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1 Clinker can be produced in many different kiln types. There are two basic kiln configurations—vertical (or shaft) kilns and rotary kilns—many variations of each type are in use around the world. Generally, shaft kilns are an older, smaller, less-efficient technology. Modern cement plants use variations on the dry rotary kiln technology, incorporating various stages of preheating and pre-calcining.

Rotary kilns are either dry-process or wet-process, depending on how the raw materials are prepared. In wet-process kilns, raw materials are fed into the kiln as slurry with a moisture content of 30 to 40 percent. Wet process has much higher energy requirements due to the amount of water that must be evapourated before calcination can take place. To evapourate, the water contained in the slurry, a wet-process kiln requires additional length and nearly 100 percent more kiln thermal energy compared to an efficient dry kiln. Three major variations of dry-process kilns are in operation: long dry kilns without preheaters (LD), suspension preheater (SP) kilns, and preheater/precalciner or new suspension preheater (NSP) kilns. In SP and NSP kilns, the early stages of pyro-processing occur in the preheater sections before materials enter the rotary kiln. A preheater is a series of vertical cyclones. As the raw material is passed down through these cyclones it comes into contact with hot kiln exhaust gases moving in the opposite direction and as a result, heat is transferred from the gas to material. This preheats and partially calcines the material before it enters the kiln so that the necessary chemical reactions occur more quickly and efficiently. Depending on the moisture content of the raw material, a kiln may have three to six stages of cyclones with increasing heat recovery with each extra stage. As a result, SP and NSP kilns tend to have higher production capacities and greater fuel efficiency compared to other types of cement kilns. Figure 1 shows typical thermal energy consumption by wet and dry rotary kiln types.

During pyro-processing, three important processes occur with the raw material mixture. First, all moisture is driven off; second, the calcium carbonate in limestone dissociates into carbon dioxide and calcium oxide (free lime) in a process called calcination; third, the lime and other minerals in the raw materials react to form calcium silicates and calcium aluminates, which are the main components of clinker in a process known as clinkering or sintering. After the clinker is formed in the rotary kiln, it is cooled rapidly to minimize glass phase formation and ensure maximum yield of alite (tricalcium silicate) formation, an important component for cement hardening properties. The main cooling technologies are a grate cooler or a tube, or planetary cooler. In the grate cooler, the clinker is transported over a reciprocating grate through which air flows perpendicular to the clinker flow. In the planetary cooler (a series of tubes surrounding the discharge end of the rotary kiln), the clinker is cooled in a counter-current air stream. The cooling air is partially used as secondary combustion air for the kiln. After cooling, clinker can be stored in domes, silos or bins. The material-handling equipment used to transport clinker from the coolers to storage and then to the finish mill is similar to equipment used to transport raw materials (e.g., belt conveyors, deep bucket conveyors, and bucket elevators). To produce powdered cement, clinker nodules are ground to the consistency of powder. Clinker grinding, together with additions of approximately 5.0 percent gypsum to control cement setting properties can be done in ball mills combined with roller presses, vertical roller mills, or roller presses. Coarse material is separated in a classifier, recirculated and returned to the mill for additional grinding to ensure the final product has uniform surface area (LBNL 2008).

Kiln Type	Heat Input, MJ/tonne of clinker	Heat Input, MMBtu/tonne of clinker
Wet	5,860 – 6,280	5.55 – 5.95
Long Dry (LD)	4,600	4.36
1 Stage Cyclone Preheater (SP)	4,180	3.96
2 Stage Cyclone Preheater (SP)	3,770	3.57
4 Stage Cyclone Preheater (SP)	3,550	3.36
4 Stage Cyclone Preheater plus Calciner (NSP)	3,140	2.97
5 Stage Cyclone Preheater plus Calciner (NSP) plus high efficiency cooler	3,010	2.85
6 Stage Cyclone Preheater plus Calciner (NSP) plus high efficiency cooler	<2,930	2.78

Figure 1 Specific thermal energy consumption by rotary kiln type *(Source: Based on Madlool 2011)*

1.2 Waste Heat Recovery in the Cement Process

State-of-the-art new suspension process (NSP) kilns include multi-stage preheaters and pre-calciners to pre-process raw materials before they enter the kiln, and an air-quench system to cool the clinker product. Kiln exhaust streams, from the clinker cooler and the kiln preheater system, contain useful thermal energy that can be converted into power. Typically, the clinker coolers release large amounts of heated air at 250 to 340 °C (480 to 645 °F) directly into the atmosphere (that part which is not used as secondary combustion air for the kiln). At the kiln charging side, the 300 to 400 °C (570 to 750 °F) kiln gas coming off the preheaters is typically used to dry material in the raw mill and/or the coal mill and then sent to electrostatic precipitators or bag filter houses to remove dust, before finally being vented to the atmosphere. If the raw mill was down, the exhaust gas would be cooled with a water spray or cold air before it entered the dust collectors. Maximizing overall kiln process efficiency is paramount for efficient plant operation. Yet, the remaining waste heat from the preheater exhausts and clinker coolers can be recovered and used to provide low temperature heating needs in the plant, or used to generate power to offset a portion of power purchased from the grid, or captive power generated by fuel consumption at the site. Typically, cement plants do not have significant low-temperature heating requirements, so most of waste heat recovery projects have been for power generation. The amount of waste heat available for recovery depends on kiln system design and production, the moisture content of the raw materials and the amount of heat required for drying in the raw mill system, solid fuel system and cement mill. Waste heat recovery can provide up to 30 percent of a cement plant's overall electricity needs and offers the following advantages (LBNL 2008, EPA 2010):

- Reduces purchased power consumption (or reduces reliance on captive power plants), which in turn reduces operating costs
- Mitigates the impact of future electric price increases
- Enhances plant power reliability
- Improves plant competitive position in the market
- Lowers plant specific energy consumption, reducing greenhouse gas emissions (based on credit for reduced central station power generation or reduced fossil-fired captive power generation at the cement plant).

1.3 Waste Heat Recovery with Power Generation Systems

Waste heat recovery power systems used for cement kilns operate on the Rankine Cycle[2]. This thermodynamic cycle is the basis for conventional thermal power generating stations and consists of a heat source (boiler) that converts a liquid working fluid to high-pressure vapour (steam, in a power station) that is then expanded through a turbogenerator producing power. Low-pressure vapour exhausted from the turbogenerator is condensed back to a liquid state, with condensate from the condenser returned to the boiler feedwater pump to continue the cycle. Waste heat recovery systems consist of heat exchangers or heat recovery steam generators (HRSGs) that transfer heat from the exhaust gases to the working fluid inside, turbines, electric generators, condensers and a working fluid cooling system.

The ORCs (Organic Rankine Cycles) typically use a high molecular mass organic working fluid such as butane or pentane that have a lower boiling point, higher vapour pressure, higher molecular mass and higher mass flow compared to water. Together, these features enable higher turbine efficiencies

2 The Rankine cycle is a thermodynamic cycle that converts heat into work. Central station power plants that generate electricity through a high-pressure steam turbine are based on the Rankine cycle.

than those offered by a steam system. The ORC systems can be utilized for waste heat sources as low as 150 °C (300 °F), whereas steam systems are limited to heat sources greater than 260 °C (500 °F). The ORC systems are typically designed with two heat transfer stages. The first stage transfers heat from the waste gases to an intermediate heat transfer fluid (e.g., thermal transfer oil). The second stage transfers heat from the intermediate heat transfer fluid to the organic working fluid. The ORCs have commonly been used to generate power in geothermal power plants, and more recently, in pipeline compressor heat recovery applications in the United States. The ORC systems have been widely used to generate power from biomass systems in Europe. A few ORC systems have been installed on cement kilns. The ORC's specific features include the following:

- Can recover heat from gases at lower temperatures compared to conventional steam systems, enabling ORCs using all recoverable heat from the air cooler;
- Operate with condensing systems above atmospheric pressure, reducing risk of air leakage into the system and eliminating the need for a de-aerator;
- Not susceptible to freezing;
- As ORCs operate at relatively low pressure, they can operate unattended and fully automated in many locations depending on local regulations;
- The organic fluid properties result in the working fluid remaining dry (no partial condensation) throughout the turbine, avoiding blade erosion;
- Lower-speed (rpm) ORC turbine allows generator direct drive without the need for and inefficiency of a reduction gear;
- ORC equipment (turbines, piping, condensers, heat exchanger surface) is typically smaller than those required for steam systems, and the turbine generally consists of fewer stages;
- Although ORCs can provide generation efficiencies comparable to a steam Rankine system, ORCs are typically applied to lower temperature exhaust streams, limited in sizing and scalability and generally are smaller in capacity that steam systems;
- Depending on the application, ORC systems often have a higher specific cost (€/kW) than steam systems;
- The two-stage heat transfer process creates some system inefficiencies;
- The heat transfer fluids and organic fluids normally used in ORCs are combustible, requiring fire protection measures and periodic replacement over time. Moreover, there may be environmental concerns over potential system leaks;
- In general, ORC systems are well-matched with small- to medium-size, high-efficiency kilns or kilns with elevate draw material moisture content.

2. *WHRS in Cementi Rossi plant*

Cementi Rossi cement plant, located in Piacenza, Italy, (figures 2 and 3) has a different configuration compared to the standard one. In this facility, exhaust gas streams from clinker cooler and pre-heater are unified in a unique stream.
The unified stream is sent to a conditioning tower to lower the temperature before the bag house and then sent to the chimney.
Direct heat exchanger is positioned in by pass to the conditioning tower and downstream a manifold collecting different gas streams. As flue gas is a mix from exhaust gas of the clinker cooler and from the preheater, the dust quality will be a mix of these two points. Dust from clinker cooler is abrasive. Dust from preheater is not abrasive, but is sticky. In Cementi Rossi plant, there is a cyclone on clinker cooler exhaust, before the mixing point direct heat exchanger.

In Cementi Rossi, the installation of WHRS, besides all previously described advantages, will allow also a lower water consumption, with cost savings for the company and reducing its impact on environment. Water is used in the conditioning tower to lower temperature; because WHRS takes heat out of gases, less water will be used.

Figure 2 Cementi Rossi facility

Figure 3 Cementi Rossi facility

2.1 Direct Exchange scheme

Direct heat exchange between exhaust gas and organic fluid is the next step in the development of the heat recovery solution for cement plants. In this scheme, no heat transfer loop is needed: the liquid organic fluid is pre-heated and evapourated in a heat exchanger where the hot gas passes through. The organic vapour is then sent to the turbine where it expands, generating mechanical power that drives the electric generator. After the turbine, the expanded fluid first releases its sensible heat in the regenerator and then condenses, returning to liquid form and closing the loop.
It is the first time a direct heat exchanger is installed in a cement factory. Traditional scheme includes a thermal oil loop between gas and organic fluid: there is a Waste Heat Recovery System, that is a heat exchanger fed by thermal oil without any phase change. Downstream, thermal oil feeds one or more heat exchangers in order to preheat, evapourate and potentially superheat organic fluid. All these heat exchangers are replaced with only one WHRS, where organic fluid is directly preheated and evapourated. The design of this innovative WHRS is conditioned by several factors which are not present in the traditional designs:

- Thermo-chemical cracking of organic fluid is easier to occur than in case of thermal oil, because organic fluid maximum acceptable temperatures are lower and organic fluid flows inside WHRS also in vapourous state: vapour has worse thermal exchange coefficients compared to liquid, so wall temperature increases easier.
- Phase change (different thermal behavior, speed, valves…)
- Management of start-up and emergency stops

Moreover, organic fluid choose had to take care of several requirements:

- Not flammable fluid (most of organic fluids used in ORC are flammable)
- Efficiency of thermo-dynamic cycle
- Low global warming potential

In Cementi Rossi, the chosen organic fluid is a particular refrigerant, which is probably the first time worldwide it is used for a real scale ORC. It is not flammable and its GWP is less than 1. So, the study of its properties has been fundamental for the design of all heat exchangers and turbine.

2.2 Innovative aspects of the equipment

The new ORC developed during the project shows a lot of innovative aspects if compared to a standard configuration with thermal oil:

- Use of a refrigerant, nor toxic, nor flammable and with low GWP as working fluid in an ORC for heat recovery. Refrigerants (like R-245fa and R-134a, with relative high GWP) are often used as working fluid in geothermal ORC, that is low temperature applications. Thanks to Turboden thermal engineers, it has been possible to use the new fluid also for high temperature applications, maintaining good performances.
- The use of this innovative alternative fluid permits to reduce the Global Warming Potential of the working fluid used in the Organic Rankine Cycle. It also contribute to the Fluorinated Gases Regulation
- Based on the existing literature it is the first time worldwide this specific low GWP refrigerant is used as working fluid for a real scale ORC. Design of heat exchangers and turbine blades have been changed according to thermodynamic properties of the new fluid
- WHRS design able to efficiently recover heat from gases and maintain organic fluid temperature below decomposition limits
- WHRS design able to remove dust from exchange surfaces
- Higher recovered thermal power
- WHRS materials able to resist high temperatures and dust, but also cheap enough to be economically feasible
- No use of thermal oil, hence exclusion of all related possible environmental impact
- This solution (ORC with Direct Heat Exchange) represents the first worldwide application in the cement sector

3. ORC components

Main ORC components are shown in following figure and listed here:

- Pump
- Regenerator
- Turbine
- Lube unit
- Electrical generator
- Storage tank
- ACC (Air cooled condenser)
- Direct WHRS

Pump, turbine, generator and lube unit will be installed in a soundproofed cabinet (orange in figure 4 and 5).
3D figures have been taken using Autodesk Navisworks.

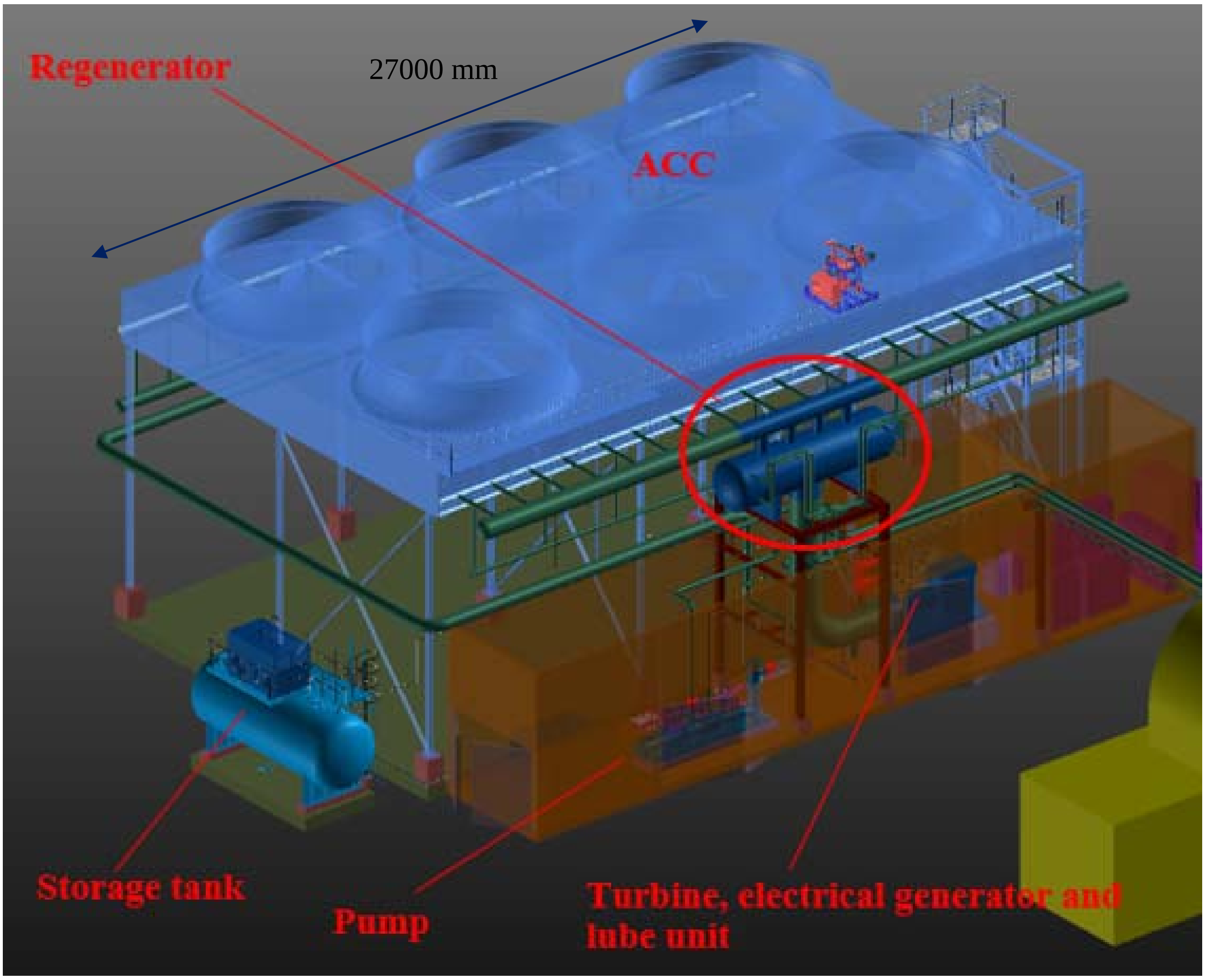

Figure 4 Overall view of main ORC components

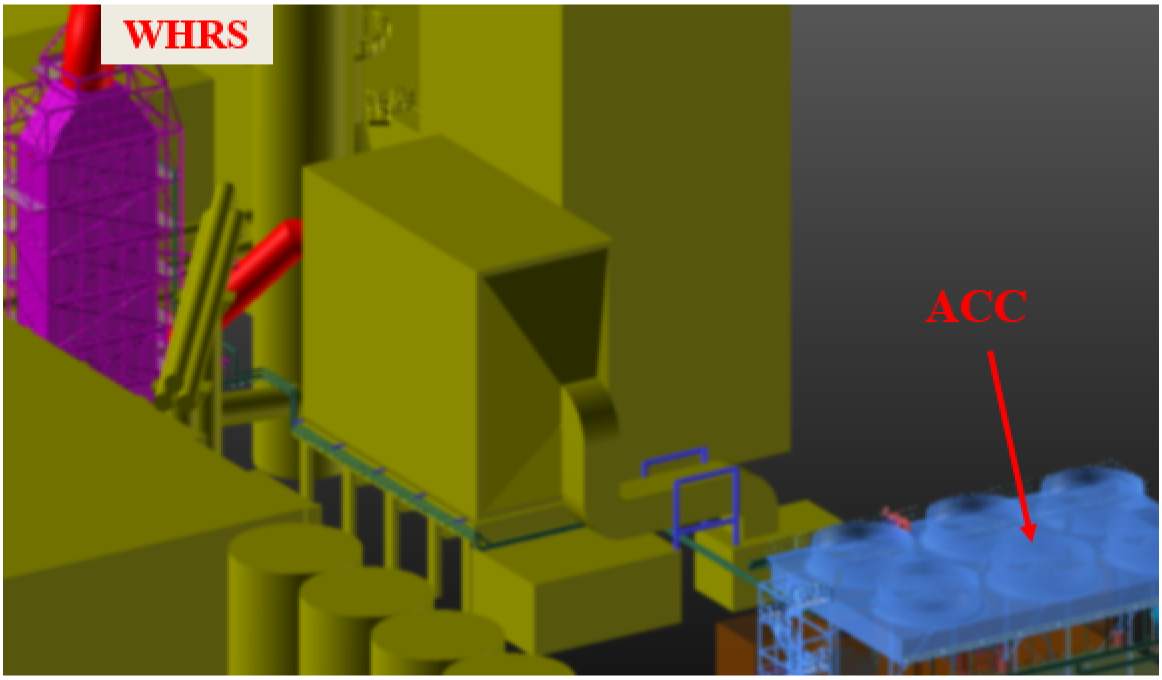

Figure 5 Overall view of main ORC components

3.1 Pump

The feed pump of organic fluid is activated by a 3-phase motor and controlled by a frequency converter in order to achieve optimal control and minimize consumption as much as possible. Organic fluid is pressurized by means of a multistage centrifugal pump, moved by an electrical motor. An inverter allows varying rotational speed of pump.

Figure 6 Pump skid

3.2 Regenerator

In the regenerator, organic liquid pressurized by the pump is preheated by the vapour coming out the turbine; regeneration phase is needed to increase ORC efficiency. The regenerator is composed by a shell; vapour flows inside the shell, where finned tubes are placed. Organic liquid flows inside these tubes.

In figure 7 the finned exchange battery is shown. It will be place inside a carbon steel shell, shown in figure 8.

In figures 9 and 10, regenerator shells during fabrication process.

The shape of this regenerator is not usual for Turboden ORC; it is a consequence of available space and position of ACC.

In figure 11, it can be seen the completely assembled regenerator.

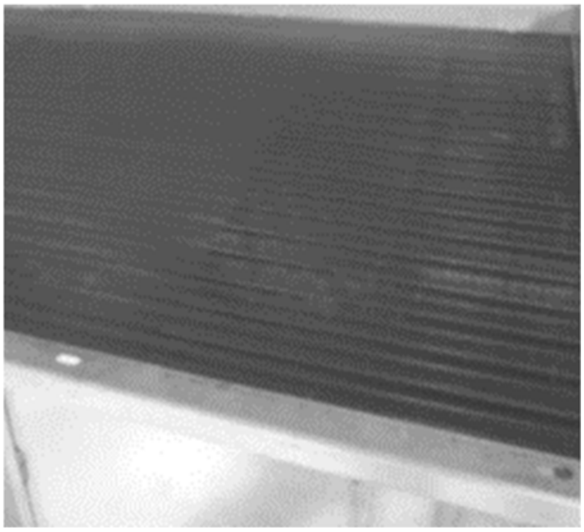

Figure 7 Finned regenerator battery

Figure 8 Regenerator shell

Figure 9 Regenerator shell

Figure 10 Regenerator outlet shell

Figure 11 Completed regenerator

3.3 Turbine

ORC turbine is an axial multistage turbine. An axial turbine allows working large vapour flow with good performance. It is a cantilever turbine, so bearings are placed only to one side of the turbine. This configuration is suitable to reduce stress due to heat deformation and to simplify maintenance.
Turbine is completely designed and assembled by Turboden. Turbine speed is 3000 rpm.
Turbine casing is shown in figure 12. At the top, there is the inlet nozzle, while turbine outlet is in the opposite side, not shown in figure 12.
In figure 13 it is shown with structures needed for pressure test.
Turbine blades have been re-designed according to the new fluid and thermodynamic cycle.
In figure 14 the turbine is completely assembled and coupled to the electrical generator.

Figure 12 Turbine casing

Figure 13 Turbine casing with tools for pressure test

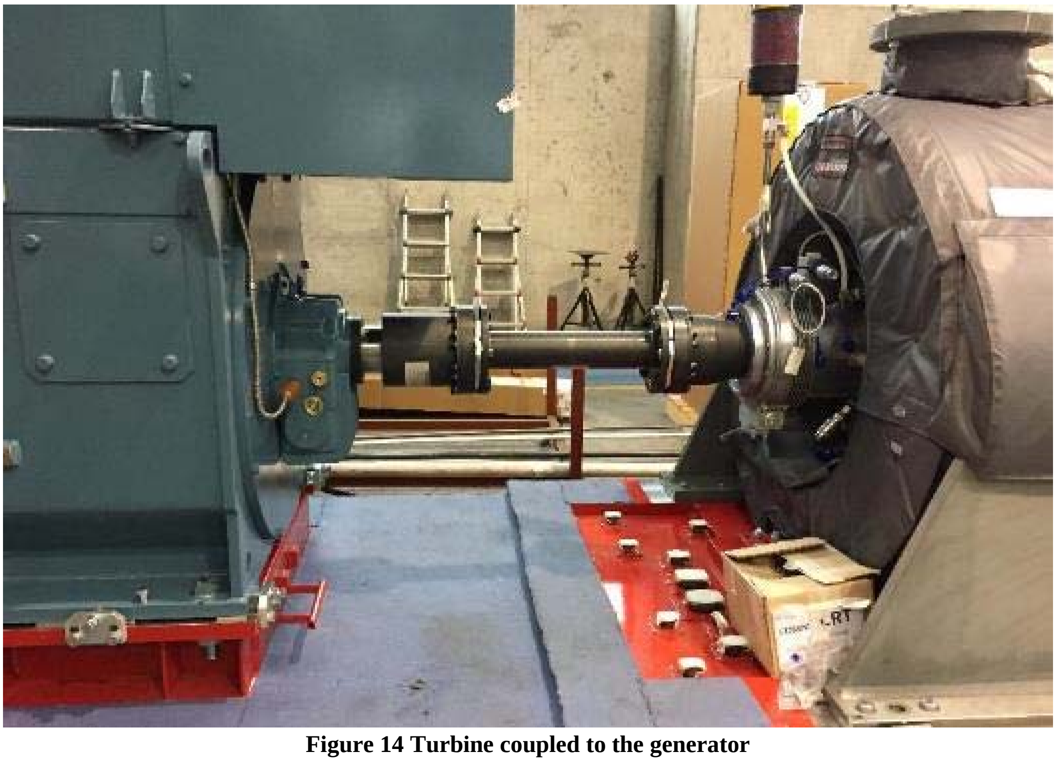

Figure 14 Turbine coupled to the generator

3.4 Lube unit

Lubrication oil is pressurized and sent to ORC turbine in order to lubricate bearings and seals. A circuit goes to an air cooler in order to dissipate heat stored by oil. Temperature control of oil is important because temperature influences oil viscosity, hence its lubrication capacity.
Lube unit is supplied with all pumps, motors, valves and filters required.

Figure 15 Lube unit

Figure 16 Lube unit

3.5 Electrical generator

The electrical generator converts the mechanical energy into electrical energy with high efficiency. Electrical generator is a squirrel cage generator with a rated output of 2600 kW. Voltage is 690 V and frequency 50 Hz.
It is directly coupled to the turbine without any reduction gear (it is a two poles generator, so it rotates at 3000 rpm).

Figure 17 Electrical generator

3.6 Electrical cubicles

Electrical cubicles are needed both for power transmission from generator to grid and for feeding all ORC auxiliaries.
They are provided also with lamps and emergency buttons. An indicator of turbine speed and electrical parameters is present.

Figure 18 Electrical cubicles

Figure 19 Electrical cubicles

3.7 Storage tank

Storage tank is needed to store organic fluid during first start-up and possible invasive maintenance operations. Because of organic fluid low boiling point, it would vapourize if maintained outside a vessel at atmospheric conditions.

Figure 20 Storage tank

3.8 Air cooled condenser (ACC)

Vapour after being cooled in the regenerator goes to the air cooled condenser through a suitable duct. Vapour is distributed through a collector to the tube bundles which are cooled by forced air generated by six fans.

Besides WHRS, air cooled condenser has a consistent footprint. Turboden standard condenser is a water condenser, so standard condenser appears as a simple shell&tube exchanger fed by cooling water; obviously downstream, water has to be cooled down by:

- an air cooler, which is anyway smaller and cheaper than an ACC; in the air cooler, liquid water flows inside finned tubes which are cooled by means of fans.
- a wet cooling tower, in which water is sprayed in air in order to reach wet-bulb temperature, which is lower than ambient temperature. This is good for cycle efficiency because condensation temperature decreases, but it requires water consumption and accurate control of water composition.

ACC is more efficient than a water condenser + air cooler because organic fluid exchanges heat directly with air, so a heat exchange is avoided. On the other side, it has not the disadvantages of a cooling tower.

ACC disadvantage is its large footprint and cost (related to dimensions but also to quality of materials, e.g. pressure resistance, certified welding…).
ACC are usually used in geothermal plants.

ACC will be assembled on site.
In figure 21, ACC is shown during fabrication.

Figure 21 ACC

3.9 Direct WHRS

The direct heat exchanger is composed of 2 sections.

The first section is used for heating thermal oil, which is used for thermal purposes inside the facility (preheat fuel oil).
Because of the high content of dust, tubes bundle are made with bare tubes for both sections.
The second part is used to vapourize a working fluid with a very low Global Warming Potential. This fluid is not flammable nor toxic.

Heat exchanger bundle is divided in a certain number of transportable sections, which will be welded together on site.

Considering the type of dust, the pipes are plane and an automatic cleaning system is installed.

Gas enters from the top of heat exchanger and exit from the bottom, after a change in direction of 180° in proximity of dust removal system. At inlet and outlet of heat exchanger shut-off valves are installed in order to block gas flowing inside the heat exchanger in case of emergency or maintenance. Suitable compensators are installed to prevent stresses caused by thermal expansion.

Figure 22 DHE

Figure 23 DHE casing

WHRS will be assembled on site.

3.10 Control and supervision of the ORC

ORC turbo-generator operation is automatically controlled by a PLC that adapts the operation to the vary feeding condition (variations in process conditions including the thermal load variation)
The system works by monitoring the process conditions and of the auxiliaries through the electro-instrumental components of the field, by performing the calculations with a control algorithm, and by acting on the control valves and rotating speed of the feeding pump.
In charge of the control system there are both the automatic start sequence (in which have been made all electric, instrumental and process controls) and the plant stops.
The control system also performs basic process monitoring functions (Basic Process Control System), implementing blocks in case of reaching the pre-alarm thresholds on some external parameters (for example not available electrical network, low temperature of the hot source, etc.) or internal (for example, over-speed of the turbine, etc.). In this case the system will be switched off immediately and the alarm will be registered in the remote supervisory system.
The operation of the PLC control is independent from data acquisition and display system: in case of failure of the Personal Computer or supervision of the connection cable to the PLC control the ORC turbogenerator is not disabled.

3.11 Conclusion

Almost all main ORC components are ready for the installation.
The construction of largest components, as direct exchanger and ACC, will be completed on site, during erection phase.