NO WASTE HEAT, A SUSTAINABLE FEAT

Andrea De Finis and Sara Milanesi, Exergy International srl, explore the benefits of ORC technology over steam Rankine cycle systems and consider the importance of turbine design and configuration.

When it comes to reducing carbon emissions and increasing sustainability in industry, cement falls in the hard-to-abate sector. This is due to the challenge the cement industry faces to simultaneously curb CO_2 emissions while meeting an increasing global demand. Even though cement production dropped drastically in 2022 (down 5% to 4158 million t) this will not always be the case, as developing countries experiencing economic growth will need new infrastructure, consequently, there will be a higher demand for cement production.

Given that the CO_2 intensity of cement manufacturing slightly increased by 1% in 2022 and the same happened for electricity intensity, (reaching around 100 kWh/t cement in 2022) reducing energy demand by means of energy efficiency improvements is one of the crucial and most effective measures to both decrease the cement sector's energy intensity and tackle CO_2 emissions. The target set in the IEA NZE Scenario requires that the carbon intensity should fall by 4% by 2030.

This explains why waste heat recovery (WHR) technology is gaining prominence in the cement sector and is expected to grow at a CAGR of 12% by 2032 (Global Market Insight).

This shift toward deployment of heat recovery technologies is further driven by the growing adoption of Organic Rankine Cycle (ORC) based systems, which can recover a significant amount of heat from low-temperature sources.

WHR systems employed in the cement industry to convert the thermal energy contained in waste gases and exhaust air from the preheater and clinker cooler into electricity fall into two categories: steam Rankine cycle and ORC. Compared to

Rankine cycle technology, ORC has the advantage of recovering heat even from low-temperature resources, hence adding profitability to resources that were previously unexploitable. In addition, ORC features higher flexibility of application, eliminating the use of water and the consequent associated costs for water treatment and make-up. Other benefits of ORC for WHR over steam Rankine cycle systems include:

- Compact and automated systems which do not require dedicated personnel onsite.
- Higher performance in off-design conditions.
- Design adaptability which gives the option to use the most efficient working fluid to extract the maximum power from the resource.
- Simple and reliable product maintenance adding longevity to a power plant life.

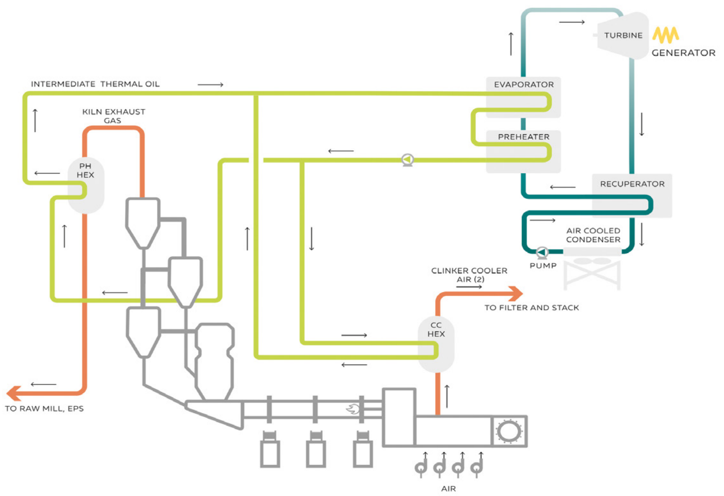
A WHR solution based on an ORC system for cement applications involves the WHR unit transfering the heat from the exhaust gases to the intermediate fluid and the ORC cycle, which receives the heat from the WHR intermediate loop and converts it into electricity by means of a turbine. The intermediate fluid usually used in the WHR unit is thermal oil or water.

A typical ORC cycle consists of several key components:

- The turbine: the key component of the plant, producing mechanical energy to be converted into electricity by a generator directly coupled with the turbine shaft.
- The heat exchangers: they extract the heat from the intermediate thermal fluid. Shell and tube heat exchangers are usually applied but the geometry and configuration can vary depending on the energy source and the total thermal input.
- The oil circuit and feed pumps: this brings the organic fluid from the condensation pressure to the maximum pressure of the cycle.
- The condenser: with the direct air to fluid heat exchanger, the organic fluid is cooled and liquefied before entering the pump. The use of an air condenser has several advantages as it eliminates the need for water, reduces the condensing pressure of the cycle, leading to higher power production, and reduces the equipment to install, thus minimising plant costs.

When required, a water-cooled condenser can also be used.

An Exergy Radial Outflow Turbine in the workshop.



Example of a WHR ORC cycle in a cement plant.

Turbine configurations

The turbine is the core of the ORC technology. The most common choice of turbine configuration for ORC systems employed by ORC suppliers are axial or radial inflow turbines. Exergy International, one of the main ORC suppliers with more than 500 MWe in its portfolio, studied and introduced the use of the Radial Outflow Turbine (ROT) applied to the ORC cycle in 2010. This technology is still unique today to Exergy's ORC systems.

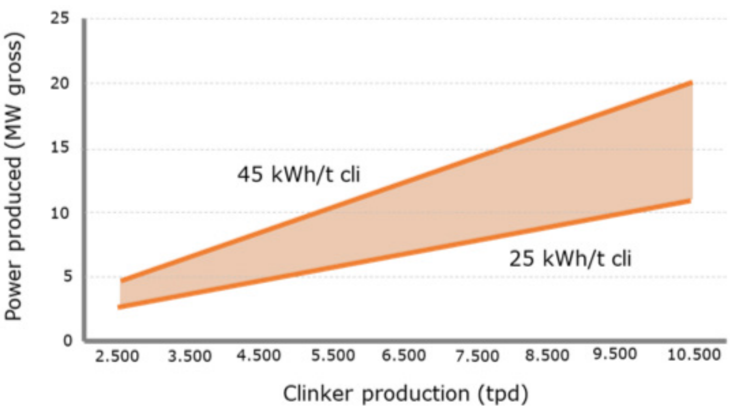
Employing the ROT technology in an ORC system for WHR applications is a simpler, more efficient, and economically viable solution:

- It has a higher efficiency over axial turbines by up to 6%. This higher performance relates to the nine stages on a single disk, reducing the size and length of the turbine compared to axial turbine, less tip leakage and disk friction losses, and a minimal 3D effect due to the low blade height and low blade height variation.

- No gearbox is needed due to to the low rotational speed (1500 – 3000 rpm) that allows a direct coupling with a generator with two or four poles and more reliability for the overall system.
- There is less limitation on cycle pressure and on blade manufacturing leading to a superior flexibility extending the range of application.
- Simpler construction technology, which is more compact and easier to transport and install.
- Maintenance is easy and of a low cost. The mechanical group of the turbine containing the bearings, oil lubrication system and seals can be easily removed without the need to drain the organic fluid away from the cycle, thus, reducing the downtime of the plant to one day compared to approximately one week or more when using other turbine technologies.

Table 1. Cement plant case study.

Plant capacity: 5000 tpd	Flow of kiln exhaust gas: 330 000 Nm^3/h
Type of process: Dry	Temperature of kiln exhaust gas (1): 335˚C
Fuel used: Coal	Flow of clinker cooler air (2): 300 000 Nm^3/h
Application: Waste heat recovery in cement production.	Temperature of clinker cooler air (2): 300˚C
Model used: EPSd 730	Cooling agent: Air cooled condenser
Flue gas outlet temperature (1,2): 170˚C	Electrical generation: 7000 KWe



Waste heat potential referred to plant capacity. (Plant capacity (tpd): 5000; kCal/kg clinker: 800; kg raw material/kg clinker: 1.6).

The typical cycle efficiency of a WHR ORC system at full load is around 25%. With a ROT, even in conditions of 60% of nominal load, 90% of relative efficiency is still achieved (22.5%).

How ORC WHR systems for cement plants work

As mentioned before, exhaust streams from the clinker cooler and the kiln preheater contain exploitable thermal energy that can be converted into power. In dry process cement plants, nearly 40% of the total heat input is available as a residual resource. Clinker coolers release large amounts of hot air ranging in temperature from 250 – 380˚C, corresponding to a range of heat from 330 – 540 MJ/t of clinker. Kiln preheaters release flue gases in a temperature range of 300 – 450˚C, corresponding to a range of heat of 750 – 1050 MJ/t of clinker. Once the portion required for drying purposes is deducted, typically by raw and coal mills, the residual heat can be then transferred to the ORC and converted into power, with no impact on the normal operation and production capability of the cement plant.

The exhaust gas or hot air from the process enters a WHR unit where in the heat recovery exchanger, the thermal power is transferred to a thermal vector, typically thermal oil. The thermal oil vehicle delivers the load to the organic fluid of the ORC cycle. The organic fluid circulates in a closed circuit where, when in liquid phase, is increased in pressure by a pump, heated up and evaporated respectively in the preheater and in the evaporator, receiving heat from the thermal oil vehicle, and finally expanded in a turbine. Then the exhaust vapour condensates in the regenerator and cools down in the air cooler before restarting the working cycle.

The use of the working fluid in the ORC cycle is important to obtain higher efficiency or to respond to specific cement manufacturing needs. More than 12 different type of fluids have been tested already by Exergy and ORC suppliers, and a big focus from R&D is currently dedicated to the hot gas filtration with ceramic candles for by-pass applications, potentially providing exploitable heat at higher temperatures.

In cement applications, the selected organic fluid is usually cyclopentane because it is well matched to the thermodynamics of the process, thus improving the cycle's performance. But in some cases, due to safety or environmental regulations in place in several countries or regions, such as the Seveso III directive (2012/18/EU) in Europe, the use of refrigerants or a non-flammable fluid can be a solution. Exergy has already designed and successfully applied an ORC solution that utilises a refrigerant as a working fluid for an application in a cement plant in Italy with a capacity of 2600 tpd and an installed power of 3.6 MW.

ORC benefits for cement

An ORC system represents a very effective and viable solution to:

- Decrease the energy demand of the cement manufacturing process producing clean power onsite that can be employed to feed the cement manufacturing process needs. It is estimated that up to 30% of the internal process' needs could be covered by self-production from an ORC-WHR system. Electrical consumption can also be reduced through the cooling fans on the air/air heat exchangers on the clinker cooler side, because with WHR installation, the cooling is performed by the boiler.
- Decrease the operating costs connected to the reduction of the energy bills for the demand of electricity from the grid.
- Increase the sustainability of the manufacturing process by reducing indirect CO_2 emissions associated with the demand for conventional electricity from the grid. Another environmental indirect benefit derived from the use of ORC relates to the saving of water in the Gas Conditioning Tower (GCT). The GCT normally uses water to cool down the gases, yet, with ORC, such waste of water can be avoided.
- Increase competitiveness and attractiveness on the market by deploying measures that increase the energy efficiency and respond to the call for the reduction of carbon footprints.
- Facilitate access to electricity with independent microgrids for remote or isolated sites.

Case study and economics

Exergy has designed and studied many WHR systems for the industrial sectors employing the ROT and has 11 WHR power plants from industrial applications in its portfolio. Exergy's ORC systems can be applied to cement plants of any size, from small modular units up to tailored power plants for a total power installed of 50 MWe.

One example of an ORC WHR system for cement application that EXERGY has studied for a possible customer is a 7 MWe ORC unit which recovers the exhaust gases from the kiln and clinker cooler of a cement plant with a capacity of 5000 tpd.

From kiln exhaust gases at the temperature of 335˚C with a flow rate of 330 000 Nm^3/h and exhaust clinker cooler air at 300˚C and a flow rate at 300 000 Nm^3/h, it is possible to generate 7 MWe (Table 1). This solution is designed with an Air-Cooled Condensing system and based on Exergy's ROT technology.

An Exergy ORC WHR cement plant, Italy, 2020.

Return on investment

An ORC WHR system installation for a cement plant has a typical payback time of 4 – 6 years depending on the electrical output of the ORC required, the cement plant configuration, the price of electricity and local government incentives such as carbon credits, green certificates, and any additional premium for saved CO_2 emissions that can sensitively contribute to reducing this time-frame.

Conclusion

With the increasingly pressing climate crisis, it is becoming more urgent for the cement sector to reduce its carbon emissions and energy consumption. Several countries are already moving to adopt policies and roadmaps to accelerate the decarbonisation of this sector, but more cooperation between advanced and developing economies is needed to accelerate this process. As the IEA reports, "cement emissions remain stubbornly high and the development and deployment of new technologies is essential to get on track with the NZE scenario."

In this context, WHR represents a valuable opportunity and a key technology for the cement sector to give an immediate answer to the challenges of carbon and energy intensity reduction, whilst supporting the transition to other technologies currently under development. ■

About the authors

Andrea De Finis has a degree in Engineering from Politecnico di Milano. He has gained throughout his career an extensive experience in sales activities of industrial plants with a focus on cement.

Sara Milanesi is a communications professional with 15 years of experience working for the energy sector. She is skilled in communications and in B2B marketing strategies to support sales growth.