Harnessing Hidden Heat

Sara Milanesi, Exergy, explores the deployment of ORC waste heat recovery as a mature and scalable pathway to lower cement sector emissions.

The carbon footprint of cement production remains exceptionally high, reaching approximately 1.57 billion t of CO_2 emissions in 2023, corresponding to more than 25% of total industrial-sector emissions worldwide.[1] This makes cement manufacturing one of the most carbon-intensive industrial activities and a critical focus area for global decarbonisation strategies.

The main sources of CO_2 emissions in cement production are structurally embedded in the process itself. Approximately 60 – 65% of emissions originate from the calcination of limestone during clinker production, 30 – 35% result from the combustion of fuels – still predominantly fossil-based – required to achieve the high process temperatures, while the remaining 5 – 10% are associated with electricity generation and consumption (Figure 1). In terms of energy intensity, cement manufacturing accounts for nearly two-thirds of total energy use within the non-metallic minerals sector, underlining the central role of energy efficiency in any viable decarbonisation pathway.

Based on the multi-source nature of emissions, it is evident that decarbonising cement production is particularly challenging and necessitates the parallel deployment of several complementary mitigation technologies. In addition, the inherently long operational lifetimes of cement plants slow down technology turnover, limit flexibility, and tend to reduce R&D investment intensity.

Several decarbonisation levers across the cement value chain – such as carbon capture, utilisation, and storage (CCUS) and recycled raw materials – are either not yet fully mature at an industrial scale or remain economically challenging under current market conditions. Consequently, the pace of adoption of such technologies is strongly dependent on public support mechanisms, including grants, tax incentives, and carbon pricing frameworks, as well as on the long-term economics of carbon sequestration.

WHR: a mature and rapidly deployable decarbonisation lever

Within this context, waste heat recovery (WHR) emerges as one of the least disruptive, most

market-ready, and widely proven solutions for reducing the carbon footprint of cement manufacturing, particularly addressing the 5 – 10% of emissions linked to electricity consumption. By converting otherwise wasted thermal energy from process exhaust gases into on-site electricity, WHR systems enable significant reductions in purchased power, associated emissions, and operating costs.

Globally, the theoretical waste heat potential is estimated at over 3100 TWh_{th} per year, of which approximately 300 TWh_{th} originate from the cement sector.[2] Capturing even a fraction of this potential represents a substantial opportunity for improving energy efficiency and lowering emissions in the near term.

The two main technologies applied for WHR in the cement industry are the conventional steam Rankine cycle (SRC) and the organic Rankine cycle (ORC). The latter differs fundamentally through the use of an organic working fluid – typically a hydrocarbon – rather than water. Over the past two decades, ORC technology has increasingly established itself as the preferred option for cement applications due to its superior flexibility, enhanced safety, and higher efficiency across a wide range of operating conditions.

ORC WHR system design and integration in cement plants

In a typical ORC-based WHR configuration for cement plants, an intermediate heat-transfer loop is employed to separate the ORC cycle from the dusty, abrasive exhaust gas streams. Heat exchangers recover thermal energy from the preheater and clinker cooler exhausts and transfer it to a thermal oil circuit, which subsequently feeds the ORC evaporator.

The design of these heat exchangers is a critical engineering task, requiring careful consideration of dust loading, particle abrasiveness, gas velocity, fouling behaviour, operating pressure, temperature gradients, and cleaning strategies in order to ensure long-term reliability and sustained heat-transfer performance. Depending on plant layout and available heat sources, the thermal oil loop may be arranged in parallel or series configurations.

Within the ORC itself, the working fluid – most commonly cyclopentane, although refrigerants may be selected where non-flammability is required – is pressurised, preheated, vaporised, and expanded through a turbine. The exhaust vapour is subsequently condensed using either an air-cooled or water-cooled condenser. All auxiliary systems, including pumps, cooling fans, control and safety systems, and electrical interfaces, are fully integrated with the plant's architecture to ensure synchronised operation and high availability.

ORC advantages for cement applications

The competitiveness of ORC technology relative to both conventional steam cycles and alternative decarbonisation solutions lies primarily in its technological maturity and rapid deployability. A WHR-ORC system can typically be designed, installed, and commissioned in around 12 months, enabling cement producers to realise environmental and efficiency benefits in a short timeframe, with average investment payback periods from 4 to 8 years.

A key barrier commonly associated with decarbonisation technologies in hard-to-abate industrial contexts – namely operational disruptions and kiln shutdowns – is effectively avoided with ORC WHR systems. ORC plants operate as fully stand-alone

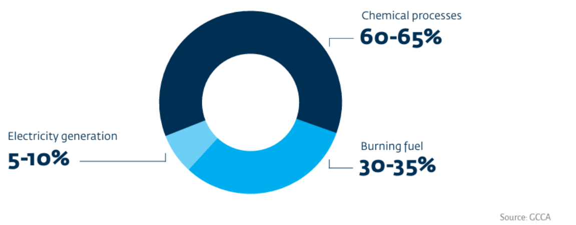
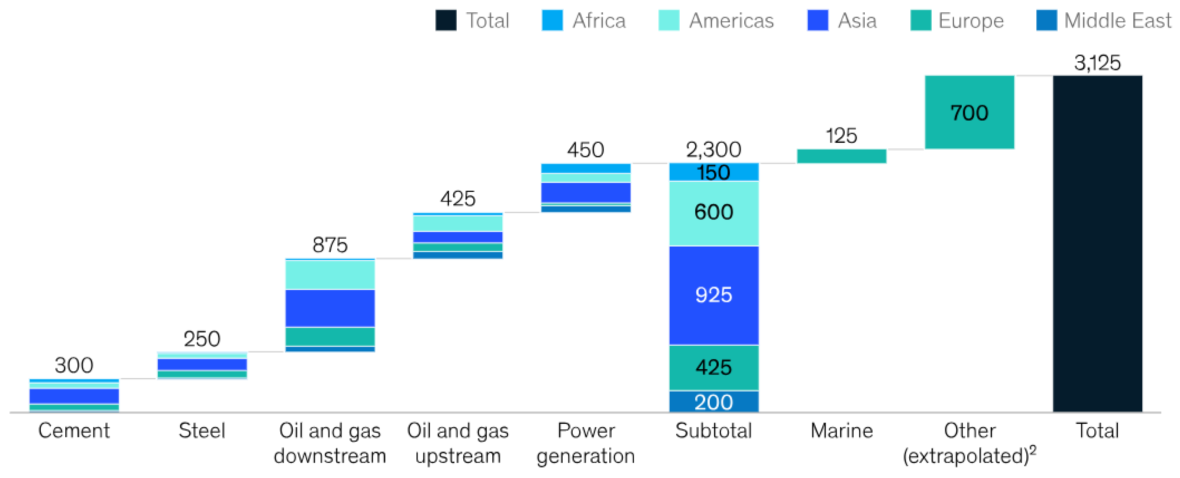


Figure 1. CO_2 emission source of cement production.



[1]All numbers rounded to the nearest 25 TWh_{th}.
[2]Extrapolated global potential for chemicals, non-ferrous metals, and pulp and paper.
Source: Estimating the waste heat recovery in the European Union Industry, Energy, Ecology and Environment, September 2019; McKinsey analysis

Figure 2. Current global recoverable waste heat potential by sectors and regions (TWh_{th}).[1]

power-generation units, eliminating interference with the kiln, preheater, or clinker cooler and thereby minimising operational risk. Furthermore, ORC systems offer high flexibility and modularity, allowing staged implementation and progressive scaling in line with operational or financial constraints. From a technical standpoint, ORC systems offer several advantages over SRCs:

- Efficient exploitation of low- to medium- temperature heat sources (≥150˚C).
- High efficiency and operational stability under off-design and partial-load conditions.
- Elimination of turbine blade erosion associated with steam condensation, resulting in lower maintenance requirements.
- Possibility of zero water consumption through air-cooled condenser configurations.
- Fully automated operation with remote monitoring, minimising operator intervention.

As an energy-efficiency measure, WHR also delivers substantial benefits to cement producers:

- Reduced operating costs through on-site electricity generation, potentially covering up to 30% of plant power demand.
- A stable source of clean electricity with a high-capacity factor and a smaller footprint per installed capacity compared to other renewables, such as solar PV and wind.
- Lower maintenance costs compared with steam-based systems.
- Improved return on investment when combined with carbon credits, incentives, or feed-in tariffs.

There are also significant environmental benefits, including:

- Reduced fossil fuel consumption.
- Lower energy intensity, directly supporting decarbonisation objectives.
- Reduced CO_2 emissions associated with electricity generation.
- Avoidance of water usage in water-scarce regions.

In countries with carbon pricing, taxation, or emission trading schemes (ETS), avoided CO_2 emissions further translate into tangible financial savings. Indicative CO_2 reduction figures based on 25% plant efficiency are summarised in Table 1.

ORC solutions for the cement sector

Exergy is a supplier of tailor-made ORC systems for WHR worldwide, in sizes from 1 up to 60 MWe on a single turbine, optimising each installation to maximise cycle efficiency while accommodating project-specific constraints. A key differentiator of Exergy's technology is the use of its radial outflow turbine (ROT), which combines high efficiency with compact design and reduced maintenance requirements.

More recently, Exergy has expanded its portfolio with the ORC-lite series, consisting of modular, pre-engineered, preassembled solutions aimed at accelerating project implementation. For cement applications, the ORC-lite series offers a compact 1.1 MWe high-temperature module, enabling faster delivery, a low footprint, and reduced upfront investment while maintaining high efficiency of the cycle. The unit is also ideal for pilot projects and flexible installations, with the option to expand to higher power capacities via modular configuration. Key features include:

- High-temperature modules (up to 310˚C at ORC inlet), deployable in dual or multiple configurations.

Table 1. Indicative CO_2 emission reduction from WHR based on 25% plant efficiency.

Case	MWth	MWe	CO_2 tpy saved
1	25	6.25	25 200
2	40	10	29 100
3	16	4	11 600

Figure 3. 3D model of high-temperature ORC-lite unit.

Figure 4. Exergy's WHR system installed at Cementi Rossi, Italy.

- Compact footprint (25 × 12 × 9 m) for limited-space installations.
- Cyclopentane as the standard working fluid.
- Plug-and-play system.
- Reduced construction and commissioning time.

The availability of both fully customised large-scale ORC systems and small modular ORC-lite solutions allows Exergy to address a broad spectrum of WHR project requirements and accelerate market adoption.

Table 2. Case study: hot source conditions and ORC performance.

Source		CC	PH
		Hot air	Exhaust gas
Exhaust gas flow rate	Nm³/h	210 000	350 000
T at heat-exchangers inlet	°C	310	340
Composition by Vol%	N_2	79.05	59.09
	CO_2	0	30.25
	H_2O	1.38	6.85
	SO_2	0	0
	Ar	0	0
	O_2	20.95	3.26
T at heat-exchangers outlet	°C	140	220
Net thermal power recoverable	MWt	12.8	18.0
ORC gross electric power	MWe	7.7	
Net electric power WHR	MWe	6.8	

Case studies

Exergy has implemented 11 WHR projects in energy-intensive sectors, including cement, steel, glass, chemical industries, and others.

In Table 2, a case study is presented that Exergy has engineered for a potential cement customer to assess the integration of an ORC-based WHR system recovering heat from both clinker cooler (CC) and kiln preheater (PH) exhaust streams. The analysed configuration considers clinker cooler hot air at 210 000 Nm³/h and 310°C, combined with preheater exhaust gases at 350 000 Nm³/h and 340°C.

After heat recovery, exhaust temperatures are reduced to 140°C (CC) and 220°C (PH), enabling the recovery of approximately 12.8 MWt and 18.0 MWt of thermal power, respectively.

The recovered heat feeds a single ORC unit designed for variable operating conditions, delivering a gross electrical output of approximately 7.7 MWe and a net WHR power generation of about 6.8 MWe.

Conclusion

WHR systems represent a proven and efficient way to decarbonise the cement sector, offering significant reductions in fossil fuel consumption, electricity costs, and CO_2 emissions. ORC solutions provide operational flexibility, minimal maintenance requirements, and compatibility with both high- and medium-temperature heat streams.

Their stand-alone configuration ensures no interference with cement production, mitigating operational risks typically associated with process-integrated solutions.

As the cement sector faces tightening regulatory requirements, rising energy costs, and competitive pressures, the deployment of WHR-ORC systems provides both environmental and economic benefits, supporting compliance, energy efficiency, and long-term competitiveness. Technology providers with proven industrial expertise and the ability to customise solutions to plant-specific conditions play a critical role in enabling rapid, reliable, and efficient WHR adoption in the cement industry. ■

Table 3. ORC-lite table performance for various source conditions.

Hot oil (Therminol 66)	310°C		300°C		280°C		250°C	
Heat source inlet temp. (°C)	310	310	300	300	280	280	250	250
Heat source outlet temp. (°C)	150	150	150	150	150	150	150	150
Heat source flow rate (tph)	48.9	47.6	52.6	50.7	63.4	60.1	88.6	83.1
Air temperature (°C)	20	10	20	10	20	10	20	10
Gross power (kW)	1100	1100	1100	1100	1100	1100	1100	1100
Net power (kW)	1000	1000	1000	1000	1000	1000	1000	1000

References

1. 'Annual CO_2 emissions from cement', (2024) – https://ourworldindata.org/grapher/annual-co2-cement#explore-the-data
2. 'Estimating the Waste Heat Recovery in the European Union Industry' *Energy, Ecology and Environment*, McKinsey analysis, (2019).