An 'Organic Rankine Cycle' turbine can be employed to convert, what would otherwise be 'waste' heat streams in many industrial processes, to electrical power for on-site use. Here, Riccardo Vescovo explains the processes and describes how his company is making electricity from 'free' fuel at industrial plants across Europe.

ORC recovering industrial heat

power generation from waste energy streams

Waste heat in industry is a potential resource that is often unexploited. The Turboden ORC (Organic Rankine Cycle) can supply a technical and economically feasible way to cash in on the waste heat, while keeping the industrial company focused on its core activity.

Energy is one of the major factors in today's global economy, a critical input in the industrial field and indispensable for production processes, it is a key voice in financial balances, a strategic issue in medium- to long-term decisions and – less tangible but sometimes even more important – an indicator of the environmental friendless of a company.

Among the many ways a company can better manage its energy consumption, increasing the efficiency through internal waste energy recovery appears to be one of the most effective, feasible, and profitable ones. In the current economic climate in which consumers are holding back, rather than increasing production capacity, investing in the improvement of industrial energy efficiency could be the right choice going forward.

Organic Rankine Cycle (ORC) turbines, such as those from Turboden, can be the answer to effectively and profitably pursuing efficiency in industry – by using a well-proven technology (hundreds of MW installed), internal waste heat streams (either gaseous or liquid) are converted into electricity and consequently into cost savings.

INTRODUCTION TO ORC

The ORC cycle is based on a closed Rankine cycle, performed by adopting a suitable organic fluid as the working fluid. In standard Turboden ORC units, silicon-based fluids are employed as the working medium. For geothermal and low temperature heat recovery applications, either hydrocarbons or refrigerant-based fluids are used.

The organic working fluid (confined to a closed and leak-free circuit) is pre-heated and vaporized using the heat source in the pre-heater and evaporator. The organic fluid vapour expands in the turbine (which is directly coupled with the electric generator) and is condensed using a closed water loop in the shell-and-tube heat exchanger (alternatively, ambient air can be used for cooling). The condensate is then pumped back to the evaporator, thus finishing the thermodynamic cycle.

Hot and cold sources are neither in contact with the working fluid, nor with the turbine. For high temperature applications, a regenerator (heat exchanger) downstream of the turbine is also added to further improve the cycle performance.

When compared to alternative technologies of similar sizes (0.5–5 MW production), ORC plants show the following technical advantages:

- very high turbine efficiency (up to 85%)
- low mechanical stress of the turbine, due to low peripheral speed
- low RPM of the turbine, allowing direct drive of the electric generator (without gear reduction)
- no erosion of turbine blades and casing, due to absence of moisture in the vapour nozzles
- high cycle efficiency
- long life (greater than 20 years).

These technical advantages translate into operational advantages, such as:

- simple start/stop procedures (from a remote PC in minutes)
- no extra technical knowledge needed for ORC operations (the plant is completely automatic)
- minimum maintenance requirements (time required for ORC operation is around three hours per week)

- good performances at partial load (the plants automatically operate down to 10% of the nominal load)
- very high availability, reliability and quiet operation.

ORC AND HEAT RECOVERY PROCESSES

Waste heat streams are typically in the form of hot liquid or gas. This heat is transferred to the ORC working fluid, either directly (direct exchange between waste heat and working fluid) or indirectly (with an intermediate medium closed loop) – depending upon the characteristics of the waste heat source and other constraints. Typically, waste heat liquid flows are directly coupled to the ORC cycle, while gas flows are indirectly coupled.

In the case of direct exchange, the heat source is simply connected to the ORC which converts part of the heat into electricity, as previously described.

When an indirect heat recovery scheme is employed, the heat source exchanges heat with an intermediate medium (typically thermal oil or pressurised water), and afterwards feeds the ORC cycle.

Given the importance of the original industrial process over the heat recovery system, the heat recovery plant must be conceived as a 'fail safe' device – if the heat recovery system fails (rare but possible) the primary process will not be affected. This is usually achieved by having the heat exchanger with the primary heat stream in a bypass line, with the possibility of excluding this line whenever necessary. In case cooling of the primary stream is required (i.e. for storing or filtering purposes), a redundant cooling system must be present (typically this equipment is already in place before installation of a heat recovery system).

The operation of the ORC plant is fully automatic in normal operating conditions, as well as in shut-down procedures, without the need for supervisory personnel. The heat recovery system is designed to automatically adjust itself to the operating conditions, and variations on primary heat source, temperatures and flows do not affect the functionality of the system.

STANDARD AND CUSTOMIZED PRODUCTS

Turboden produces standard systems, as well as customized solutions for low temperature heat recovery applications.

Standard systems use siloxane-based working fluids, have power outputs between 0.5 and 3 MW (multiple units can be installed in parallel to achieve greater power outputs) and are typically employed for heat recovery from waste gases via a thermal oil heat recovery loop – for waste heat streams above 250°C. Efficiencies vary depending on the heating and cooling source temperatures, typically achieving values around 19% (for hotter heat sources electrical efficiency can be as high as 25%).

Customized ORC systems are employed to recover heat from lower temperature heat sources (below 250°C) and refrigerant-based working fluids (non-flammable, non-corrosive, with low toxicity) are used in these systems. These plants are typically used for low temperature liquid flow heat recovery, and electrical efficiencies vary widely, depending upon the heat source temperatures and other specific conditions, ranging from 8% to 18%.

FIELDS OF APPLICATION FOR ORC HEAT RECOVERY

Heat recovery from ORC power plants can have many applications in the industrial sector, especially in fields where

Table 1. Three examples for potential heat recovery

Industry/application	Cement	Float glass	Steel: flat products (rolling mill)	Unit
Heat source	Kiln and clinker cooler gas	Oven exhaust gas	Preheating oven exhaust gas	
Plant capacity	2,500	500	6,000	Tons per day
Electricity cost [a]	0.09	0.095	0.06	€/kWh
Wasted thermal power in exhaust gas [b]	12	5	13	MW
Thermal power to ORC	11	4.7	13	MW
Thermal power to thermal users	1	0.3	0	MW
Net ORC electric production	1.6	1	2.4	MW
Net electricity production [d]	12,800	8,000	19,200	MWh/y
Capital expenditure indications				
ORC cost	1.8	1.3	2.4	Million €
Balance of plant [c]	2.6	1.1	1.5	Million €
Total cost (+10% project management)	4.8	2.6	4.3	Million €
Annual Cash flows [d]				
Operational expenditure	–40,000	–40,000	–40,000	€/y
Cash flow – electricity	1,152,000	760,000	1,152,000	€/y
Cash flow – heat [e]	240,000	72,000	0	€/y
Net cash flow	1,352,000	792,000	1,112,000	€/y
Results [f]				
Profit before tax	4	3.7	4.4	
Internal rate of return (10 years)	25%	27%	23%	
Net present value (10 years)	€5,333,129	€3,310,109	€4,091,971	
Avoided CO_2 emissions [g]	9,664	5,520	12,096	Tons per year

Notes:

a These values include incentives if any; differences are due to total power installed, nation, etc.
b Assuming to cool down the gas to 150/160°C
c Including heat recovery exchangers and civil works – estimated by reputable suppliers
d Assuming 8,000 operating hours/year
e Assuming a heat valorization of circa 0.03 €/kWh
f Assuming discount rate of 5%
g Assuming 0.63 kg of CO_2/kWh electric and 0.2 kg of CO_2/kWh thermal (from CH_4 combustion).

energy has an impact on the production process. Below is a list of potential fields for the ORC heat recovery systems, together with a brief description of the heat sources available and the proposed integration of ORC within the production processes.

Cement industry

The cement production process involves lime decarbonizing reactions, which being endothermic, requires great amounts of heat and high temperatures to take place.

The unused heat supplied for these reactions can be found in the combustion gas – or kiln gas – (after the raw material pre-heating) and in the clinker cooler air flow (an air stream used to cool down the clinker after it exits the kiln). These flows could, via thermal oil heat recovery circuits, be the heat sources feeding the ORC for power generation purposes.

Typical cement production plants have a production capacity between 2000 and 8000 tonnes per day, with energy consumption ranging from 3.5 to 5 GJ/tonne of clinker produced (10%–15% of it in the form of electricity).

As an indication, the power that can be produced by a Turboden ORC system in a typical cement making process can range from 0.5 to 1 MW/kilotonnes per day of clinker production capacity (assuming heat recovery from both kiln and cooler waste flows).

Using these figures, it can be estimated that the energy produced by an ORC can account for around 10%–20% of the total electricity consumed by a cement plant.

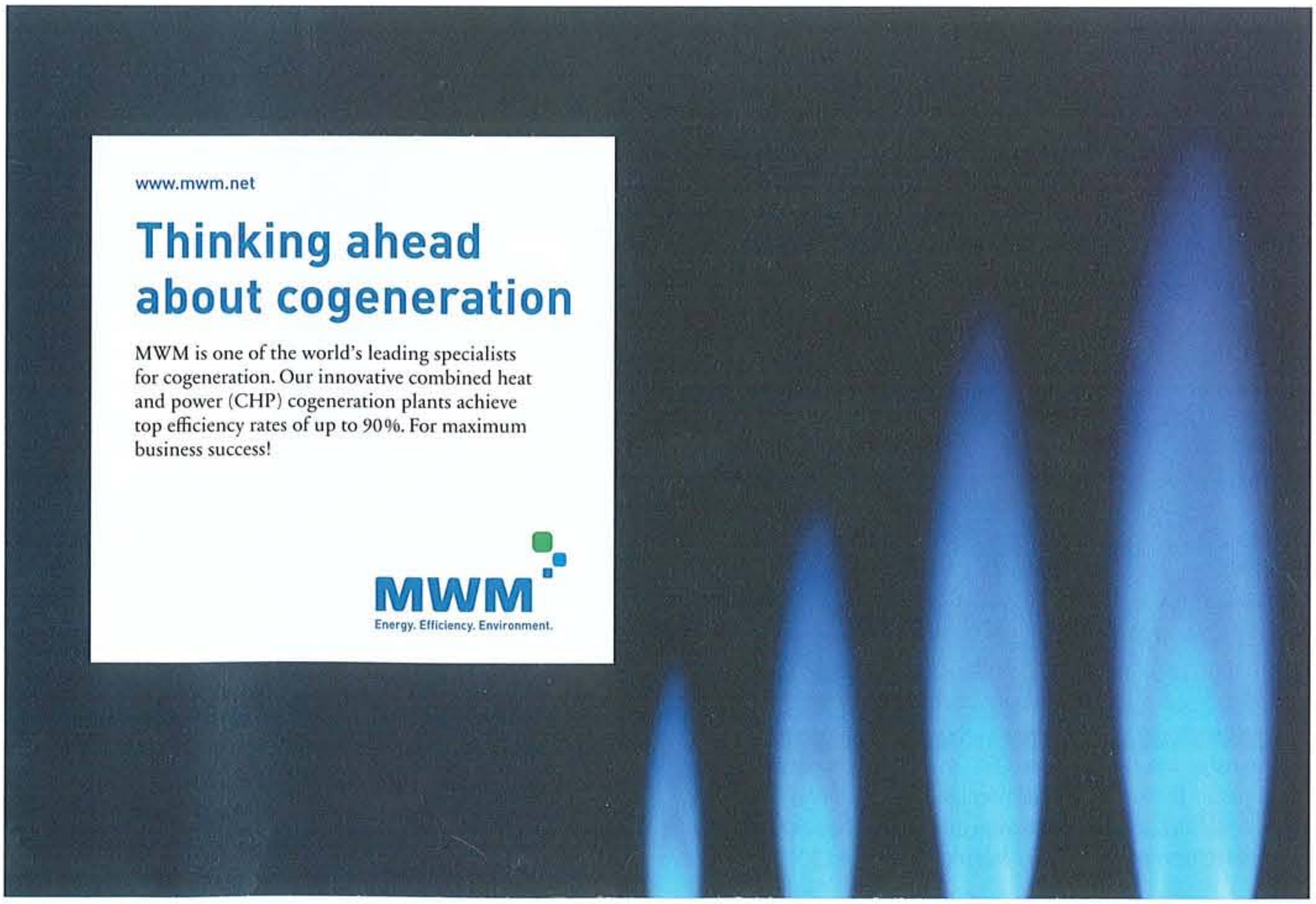
Additionally, in the case of heavy fuel oil (or similar liquid fuels) being used as a fuel (either primary or as a back-up), some of the recovered heat can also be used to keep the system at the correct working temperature.

Steel industry

In the steel production and processing industry, there are multiple waste heat sources where energy recovery with the ORC is possible. They can be divided into relatively 'clean' sources (fumes from rolling pre-heating furnaces, forging pre-heating furnaces, thermal treatments – that are typically methane-fuelled and with a relatively low dust content) and relatively 'unclean' ones (fumes from blast furnaces, electric arc furnaces, etc).

The energy produced by an ORC can account for around 10%–20% of the total electricity consumed by a cement plant

For the clean sources, heat recovery processes can rely on established technology to interface with the process (heat recovery exchangers); the second option, the exhaust characteristics (very high flows, high temperatures, high dust content, large variations in operating loads, environmental constraints) requires significant development to be carried out on the heat recovery exchangers (currently under study).



Turboden ORC unit

Heat recovery projects: case studies

The ORC systems described here are based on well-proven experience. At the end of 2008 Turboden had 85 units in operation in Europe, with a total power production of around 100 MW, with an additional 30 units under construction.

Mirom, Roeselare (B), 3 MW plant – heat recovery from hot water: Heat from a hot water stream is recovered in a waste incinerator plant to feed a district heating network. ORC was used to convert the extra heat into electricity. ORC input water is at a temperature of 180°C, output is 140°C. The condensing heat is dissipated through intermediate water cooling loop and dry air-cooling system. The system uses a refrigerant-based fluid (not flammable) as the working medium. It has been in operation since the beginning of 2008.

Oxon Italia Spa, Pavia (I), 0.5 MW plant – cogeneration power station realized by Termoindustriale: The system uses heat recovered from the exhaust gases of an 8.3 MW MAN diesel engine (fed with vegetable oils), using an intermediate thermal oil loop to transfer the heat to the ORC cycle. Condensing heat is dissipated through an intermediate water cooling loop and wet-tower cooling system. Siloxane fluid is used as the working medium. It has been in operation since mid 2008.

RHI, Radenthein (A), 1 MW plant – heat recovery from refractory production plant: Heat is recovered from a sintered magnesite production process, waste heat is available in the form of hot exhaust gas – an intermediate thermal oil loop transfers the heat to the ORC cycle. Condensing heat is dissipated through an intermediate water cooling loop and dry air-cooling system. Siloxane fluid is used as the working medium. Commissioning is scheduled for the beginning of 2009.

Italcementi, Ait Baha (MA), 2 MW plant – heat recovery from clinker production process: Heat recovery from the cement production process – waste heat is available from the kiln exhaust gas. It uses an intermediate thermal oil loop to transfer the heat to the ORC cycle. Condensing heat is dissipated through an intermediate water cooling loop and dry air-cooling system. Siloxane fluid is used as the working medium. Commissioning is scheduled for mid 2009.

Glass industry

Glass production involves the melting and refining of raw materials which takes place at high temperatures.

The unused heat supplied for glass production can be found in the combustion gas exiting the oven: this flow can be used by the ORC to generate electricity (via an intermediate thermal oil circuit).

Glass production processes can vary, i.e. the kind of product (float or hollow glass), fuel employed (methane, HFO, etc), raw materials, size, etc. This makes it difficult to develop a general rule of thumb to guess the quantity of power producible with ORC heat recovery. Generally speaking, the exhaust gas temperatures are relatively high (400°C–500°C), leading to high conversion efficiencies (up to 25%), with related economical advantages.

Small-sized combined cycles (engines/gas turbines)

(See Oxon case study, left). Turboden ORC plants are particularly suited for small combined cycle plants, thanks to the guaranteed performance, together with low operation and maintenance (O&M), and minimal knowledge necessary to run them (often it is not convenient to use traditional steam cycles, which have relatively high competences required and related O&M costs).

A typical application might include: couplings to top cycles performed with internal combustion engines, where hot exhaust gases are available as a heat source (i.e. heat recovery from diesel engines and gas engines can produce up to 10% additional power).

Turboden ORC plants are particularly suited for small combined cycle plants, thanks to the guaranteed performance, together with low O&M

Other applications

Thanks to its high flexibility and the possibility of using lower temperature heat sources (not below 100°C), other application fields for the Turboden ORC heat recovery system are: petrochemicals (refineries, chemical processes, etc.); non-ferrous metal production; refractory materials production (see RHI case study, left); waste incineration (see Mirom case study, left); and any other industrial processes involving considerable amounts of heat.

ECONOMIC FACTORS

Different from other power generation systems, heat recovery plants have the advantage of not incurring fuel costs. Therefore, once the total investment cost is outlined and energy output and O&M costs estimated, the financial results can be easily calculated (note that the income is related to the reduced electricity consumption).

Estimating total investment costs can be challenging, especially because heat recovery plants are often tied into existing production facilities – therefore, work to be done to the existing systems, layout constraints, and other factors can affect this estimation. Among the components making up the complete heat recovery system, two play key roles: the ORC module and the heat recovery exchanger.

The ORC cost and performance depends on several factors: the quantity of heat input; the temperature and kind of thermal vector used (water, thermal oil, gas, etc.); cold source temperature and type (air or water); working fluid; specific features of the thermodynamic cycle, etc.

The cost of heat recovery exchangers closely related to the exhaust gas properties – mainly heat source temperature, dust content, presence of aggressive pollutants. These factors may influence exchanger surface, material selection, exchanger geometry and, of course, costs.

Finally, the scale effects the price, making bigger installations more economical (in terms of specific cost, i.e. €/kW).

In Table 1 on page 54, three examples (based on real projects recently investigated) for heat recovery from cement, glass and steel production plants, are described. The investment costs, electricity production and financial results are presented.

There are numerous other less tangible benefits obtained from implementing an ORC power plant for heat recovery – both at project level and at a broader system level.

Clearly, energy costs saving is the primary benefit at project level: the electricity bill decreases, paying the investment back. At system level research shows that having a distributed power generation system, reduces the demand from traditional power generation plants, indirectly leading to an electricity cost reduction.

Heat recovery plants offer significant environmental benefits, even in comparison with the most efficient power production systems – the biggest advantage being that there are no emissions or fuel consumption related to it (those emissions occur independently).

Having this distributed generation system connected to the grid leads to various grid benefits: reduction of distribution losses and constraints, stabilization of grid load, so reducing the frequency of blackouts.

Furthermore, heat recovery plants reduce dependence, on a project level, on energy supply. On a system level, heat recovery plants lead to the primary fuel consumption decreasing and therefore, the reduction of imported fuel (making them less fuel import dependent).

It must be noted that these advantages, obtained by implementing ORC heat recovery systems, allow industrial companies to significantly improve their efficiency while not losing focus on their core activity.

SUMMARY

ORC heat recovery systems provide economical and environmentally friendly solutions to help reduce energy costs in energy intensive industries. Turboden plants use waste heat as the thermal input for the ORC power cycle, efficiently producing additional electric power for industries such as cement, glass and steel.

Riccardo Vescovo is a sales engineer at Turboden, Brescia, Italy.
e-mail: riccardo.vescovo@turboden.it

This article is available on-line. Please visit www.cospp.com