Heat recovery for electricity generation in industry

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Abstract

Technical economical issues pertaining to the exploitation of industrial waste heat to generate electricity through organic Rankine cycle turbo-generators are explored.

A considerable amount of heat is wasted in many industrial plants. The origin of this heat not utilized or dissipated is usually linked to economic or space concerns: it is not convenient or not possible to recover, store or transport it to other processes or users. When the heat is to be dissipated it requires cooling systems too, thus other costs for the system, operation and maintenance. In many cases the waste flows are polluted and have to be cooled before the needed treatments.

If certain quantity, quality and constancy of the waste heat are met, it can be economically convenient to utilise an organic Rankine cycle (ORC) – a closed cycle operated by sealed organic fluid with a low round per minute turbine – in order to produce electricity, usually self consumed in the plant.

In the Life+ HREII (Heat Recovery in Energy Intensive Industry) project (www.hreii.eu) the potential electricity generation from heat recovery of Italian energy intensive industries and other activity sectors have been investigated. The activity was carried out through around 50 targeted energy audits in the most promising sectors. For the others a compatibility index combining accessibility, availability, temperature, flow rate, cleanness of the gas and presence of other heat recoveries was used. For iron and steel, cement and glass sectors the savings are prudentially estimated in over 800 $GWh_{electric}$/year and $500.000*10^3$ kg of CO_2.

A number of feasibility studies have been carried out for plants around the world. The simply payback time of an ORC can typically range from 3 to 10 years, according to many variables (electricity price, hours/year, waste heat characteristics, etc.).

An ORC plant fed by recovered heat has low operational and maintenance costs and its lifetime is over 20 years. Considering also the savings in terms of imported fossil fuels and avoided CO_2 emissions, it is interesting to increase the diffusion of these plants. In Italy the waste heat recovery is included in the white certificate system. The results of this support will be evaluated.

Introduction

The paper will illustrate the situation of the ORC for electricity generation from waste heat recovery, starting with general consideration about its low diffusion and the main barriers in the first part. Different supporting measures carried out and under development in the framework of two projects at Italian and European level will be described. In the second part, the specific characteristics of the ORC turbo-generators and their suitability for medium–low temperature and irregular heat flows are presented. In the third part, the methodology and some of the results of the evaluation of the electricity generation and greenhouse gasses reduction potential with the application of ORC in Italy in some interesting sectors is illustrated. In the last part, there are four technical economical evaluation of the application in different sectors, considering also the benefits in term of payback time, of the Italian white certificate system.

Electricity generation from heat recovery

The waste heat recovery in industry is a paradigm to enhance the efficiency and reduce the costs, the pollutants and greenhouse emissions. It falls, more or less directly, in the action range of a number of EU directives (ETS, IPPC, ESD, CHP and future EED[1]), but it is not always a viable solution, because of the lack of internal or external heat demand, the costs of plant and operation, the characteristics of the waste, etc. When there are no other economical uses for the waste heat, its conversion to a more transportable form of energy such as electricity has to be evaluated. There are very promising estimates of the electricity generation potential in the energy intensive industries [[1]], but these are theoretical, to address research and development, not referred to a commercial technology. Among the few new technologies arrived to the market in the last decades, the organic Rankine cycle (ORC) turbo-generator is spreading and at least in the cement sector there are some applications [[5], [6]]. It is evaluated to be more economical than other traditional generation technologies [[9]] and is now considered a reference, being inserted in the sectorial BREF (Reference Document on Best Available Techniques) [[2]]. In the glass sector as well as in the iron and steel sector there is at least one application, which is reported as a good practice [[7], [8]]. In general, when waste gas treatment is necessary for environmental reasons, considering that textile filters are limited in temperatures, cooling is necessary. This task can be accomplished by dilution or through heat exchangers, but mixing with false air (dilution air) increases the flow rate, the size of the filters and the consumption of the fans. If heat exchangers are applied, the synergies with electricity generation have to be considered.

The main barriers for a more wide spread exploitation of this zero emission electricity resource are knowledge, lack of specific policy and governance actions, financial issues, payback time and most of all the perceived technical risks. The search for provisions in favour of this practice at EU level did not had any result (excluding [[2]]), and only general indications regarding heat recovery are present in few of the second NEEAPs[2] (National Energy Efficiency Action Plans). This is probably due to the undervaluation of the potential application and benefits. To overcome these barriers, and starting from a bottom-up approach with a ready for the market technology, two projects are underway, "HREII" [[10]] at Italian level and "HREII demo" [[11]] at European level. In "HREII" a framework of supporting actions are developed, starting from the evaluation of the national potential of waste heat to electricity generation, also involving the energy managers[3], passing through guides to explain authorizations and incentives, till actions on the policy makers to create more favourable conditions. Two significant results were obtained in Italy, thanks to the project, because of which waste heat recovery is now enclosed in NEEAP, besides a specific incentive is available under the White Certificate framework. The just started "HREII demo" project (www.hreii.eu/demo), beyond the policy action at European level following the Italian results, will develop and test an innovative heat recovery system for the electricity generation in the iron and steel industry, because in this industry sector more than elsewhere, every one wants to be the first, after the application has been demonstrated in the field.

The organic Rankine cycle

The evolution of the electrical market (the electricity bill became a key-factor in energy intensive industries income statements) and the increasing attention on the energy efficiency, lead to study the possible solutions to recover this heat and, in this scenario, the ORC (Organic Rankine Cycle) applications for heat recovery systems, are emerged.

ORC technology refers to the utilization of the Rankine thermodynamic cycle, used in conventional steam power plants, where instead of steam an organic working compound (siloxane, hydrocarbons, refrigerant fluids, alkyl benzene, etc.) is used. The thermodynamical characteristics of these working fluids allow to develop heat recovery systems that produce electricity, where conventional steam cycles are inoperative, as in the case of low temperature/high variability waste heat streams in industrial processes.

Nevertheless, since the cycle operates at lower temperatures, the total efficiency of these systems is only around 10 to 25 %, relying on the condenser and evaporator temperature. However, it is important to underline that the efficiency of a thermodynamical cycle (as the Rankine cycle) is related to the temperature levels between which the cycle is developed; therefore, low temperature cycles are inherently less efficient than high temperature cycles, indeed the overall efficiency is much lower than the more common high-temperature steam power plant (30 to 40 %).

Considering a Carnot cycle, limits on efficiency can be expressed as $1-T2/T1$, where T1 is the higher temperature and T2 is the lower, and this represents the ideal/maximum efficiency for a heat engine operating between two temperatures.

A Carnot cycle – developed with a heat source at 250 °C and a condensation source at 30 °C – has an efficiency of only around 40 %. In this context, an efficiency of 20 % is a substantial percentage of the ideal efficiency.

Let's take a look at the thermodynamical details of the ORC technology.

The power cycle, the ORC turbogenerator is feed by the available thermal power, either exploiting directly the heat source, or indirectly with a heat carrier (depending on the specific project's characteristics). In the evaporator (8 → 3 → 4 in figure 1) the thermal flow pre-heats and vaporizes a suitable organic working fluid. The organic fluid vapour powers the turbine (4 → 5), which is directly attached to the electric generator through an elastic coupling. After the turbine, the working fluid, still in the vapour phase – thanks to the shape of the liquid-vapour equilibrium curve on the T-S (temperature-entropy) diagram of organic fluids flows through the regenerator (5 → 9) where it heats the organic liquid (2 → 8). The vapour enters in the condenser (cooled either by the water flow or by

1. Emission Trading Scheme directive 2003/87/EC and 2009/29/EC, Integrated Pollution Prevention and Control directive 2010/75/CE, Energy Services Directive 2006/32/EC, Combined Heat and Power directive 2004/8, Energy Efficiency Directive: 2011/0172 COD Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on energy efficiency and repealing Directives 2004/8/EC and 2006/32/EC.

2. National Energy Efficiency Action Plans of 2011, developed by member states accordingly to the 2006/32/EC

3. Energy managers are compulsory in Italy accordingly the law 10/1991 for industrial users with consumptions over 10.000 toe/years and non industrials over 1.000 toe/year.

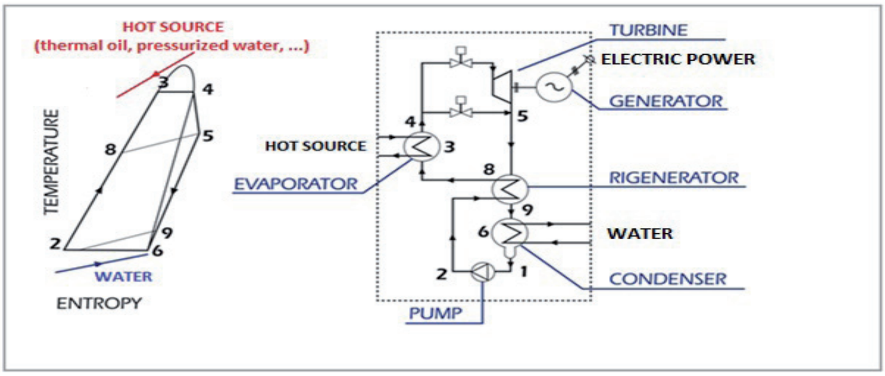

Figure 1. Process flow diagram of a Turboden ORC turbogenerator (source Turboden).

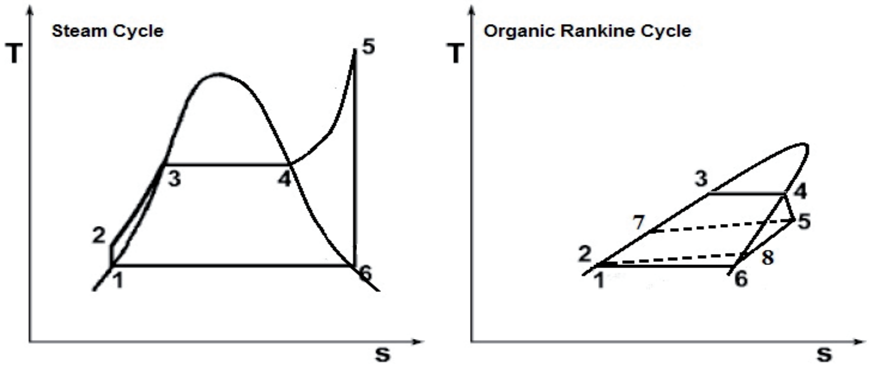

Figure 2. Comparison between steam cycle and ORC on the T-s diagram (source Turboden).

air, depending on the cooling system employed) (9 → 6 → 1) and at its exit the organic fluid liquid is pumped (1 → 2) to the regenerator and then to the evaporator, thus completing the loop of the closed circuit.

To better understand the ORC characteristics it is important to compare it with a standard steam Rankine cycle (Figure 2).

As represented in Figure 1, the Organic Rankine Cycle is characterized by a lower enthalpy gap on the turbine; this, with the high molecular mass of the working fluid, leads, for a same power output, to an higher mass flow of working fluid in case of ORC ($P_m = \dot{m} * \Delta h$), Mechanical power = mass flow times enthalpy gap.

The higher mass flow leads to several technical advantages of the ORC unit, compared to a classical steam cycle, namely:

- Very high turbine efficiency (up to 90 %);
- Low mechanical stress of the turbine thanks to the low peripheral speed;
- Low round per minute of the turbine allowing the direct drive of the electric generator without reduction gear.

The high molecular weight of the fluid leads to low critical speed and the low Δp/p so it is possible to reach lower pressures and complete the expansion in only a couple of action stages. In addition, there are some other advantages, related to the different shape of the liquid-vapour equilibrium curve on the T-S (temperature-entropy) diagram of organic fluids. The right branch of the curve of an organic fluid has a positive slope (tends to be parallel to the left branch) while the water has a negative slope and the characteristic bell shaped equilibrium curve (in water turbines this leads to the need of superheating). These advantages can be summarized as follow:

- No erosion of blades, thanks to the absence of moisture in the vapour nozzles;
- Low pressure and temperature of the working fluid;
- Partial load operation down to 10 % of nominal power, maintaining high efficiency thanks to the fact that in every load condition the curve shape guarantees an absence of liquid in the turbine permitting an operation which does not affect the efficiency.

All these technical advantages of the ORC are reflected into operational advantages that are key-points for developing heat recovery solution:

- The ORC units are unmanned systems because the low temperature and pressure of the cycle permit to develop a totally automatic solution, which does not require licensed/high skilled operators. In heat recovery projects this is a key-point because the production of electricity is not the core business, so, it does not have to divert employees attention from the industrial process,
- It is a closed cycle, so there are no concerns about the feeding water treatment,
- Some industrial processes are cyclical/variable (e.g. melting of iron & steel scraps), therefore, the availability of waste heat varies during the time, and consequently the heat re-

covery system must adapt its operation to the process load. Thanks to the shape of the liquid-vapour equilibrium curve, the ORC units are designed to automatically adjust themselves to the actual operating conditions permitting to work from 10 % up to 110 % of the nominal load, maintaining a good efficiency. In Figure 3, it is possible to see how, without big losses of efficiency, the ORC units adapt their operations to variations on exhaust gas temperatures and flows (in reasonable span times) related to the variability of the industrial process.

It is important to underline that this load variation does not affect the functionality of the system, but just the power output.

- The high availability of the ORC modules permits to dedicate few resources in maintaining and operating the heat recovery system and again this is a key-point for industrial operation where the employees must not be diverted from the core business.

Evaluation of Italian waste heat to electricity potential

There are several energy intensive industries that present waste heat in the internal processes, but not all these processes have the right characteristics to permit the employment of ORC based heat recovery systems.

In the HREII project a study on the waste heat to electricity potential in Italian industries and some services was carried out. Not to forget any interesting sector, at the emission trading industries were added all the industries and the services which appointed an energy manager accordingly to the Italian law 10/91, thus with consumption over 10.000 toe/year. Data from sectorial literature and interviews with energy managers were used for a first evaluation of the sectors through a compatibility index (see "compatibility index", table 4).

The potential of most promising branches was evaluated with a bottom-up approach, through around 50 targeted energy audits, to verify the characteristics of different typical technologies.

For the potential evaluation the following assumptions were used: emission factor for electricity generation 0,636 $tCO_2/MWh_{electric}$, conversion factor of 0,187 $toe/MWh_{electric}$ [13] and 5.000–8.000 h/y operating of the recovery system at rated load, thus also the average value of 6.500 h/y was used to have only one number. The latter is a mean precautionary value, while in the economic studies, referred to real cases the operating hours are around 8.000.

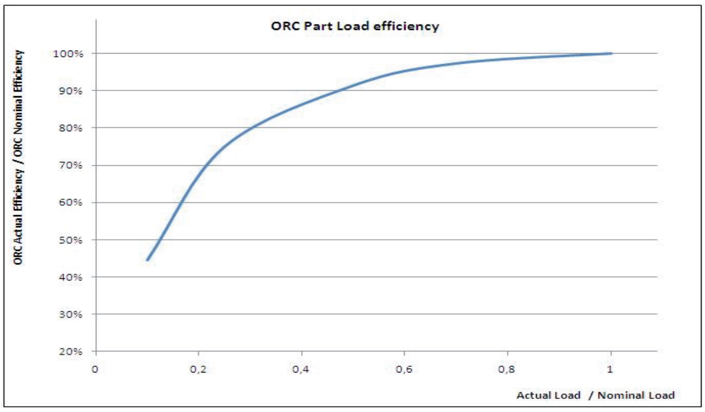

Figure 3. Characteristics at partial load of a Turboden ORC generator (source Turboden).

Table 1. Recovery potential of the glass industry in Italy.

POTENTIALITY		
plants to install (estimation)	n	24
power to install	$MW_{electric}$	22,9
energy to produce	$MWh_{electric}$/year	148.850
ENVIRONMENTAL IMPACT		
CO2 emissions avoided	10^3kg/year	94.669
Electric energy saved	$MWh_{electric}$/year	148.850
Primary energy saved	toe/year	27.835

HEAT RECOVERY IN GLASS INDUSTRIES

Plants for the manufacture of glass are divided into two main types

- Plants for producing flat glass
- Plants for producing hollow glass

The exhaust gases from the furnace of the two production processes have different features especially related to raw materials and to the type of fuel used during the casting process.

Flat glass requires a level of purity higher than hollow glass: raw materials and fuels used in the production process of flat glass lead to an exhaust gas from the oven cleaner than in the manufacturing process of hollow glass. These characteristics lead to lower investment costs for the heat exchanger exhaust gas/heat carrier.

The high temperatures of exhaust gas (only a fraction of the thermal energy contained in them can be used internally in the process) and limitations on the minimum cooling temperature (about 200–220 °C) allow heat recovery at high temperatures and the production of electricity with high efficiencies.

The energy request to manufacture a ton of flat and hollow glass is about 3,5 ÷ 6,5 GJ/10^3kg (1 ÷ 1,8 MWh/10^3kg) [4] till around 40 GJ/10^3kg for others type of products.

On average, about 30 % of the total energy supply during production is dispersed in the exhaust gases.

Assuming that only half of the thermal power available is actually recoverable, and assuming conversion efficiencies of 20 %, the amount of electricity produced is in the order of 30 ÷ 55 kWh per ton of glass.

HEAT RECOVERY FROM RE-HEATING FURNACES IN STEEL INDUSTRIES

The analysis and assessments provided in this paragraph are relative to a single process in the steel industries, that is the application of systems for heat recovery with electrical power production **from re-heating furnaces** (ex: Kilns plants rolled, forged, heat treatment). The greater potential is inherent in the melting process itself, but to date has not indifferent technological problems (Turboden hypothesized solutions also for this kind of heat recovery systems). Instead, the heat recovery from reheating furnaces does not present particular technical difficulties, except possible constraints due to the positioning of new plant and equipment within an existing production facility.

These types of process, in fact, marry particularly well with the heat recovery technology by ORC for a number of reasons, including:

- The combustion of methane gas in re-heating furnaces produces fumes virtually free of dust, which need no special treatment and filtration;
- The temperature range of exhaust gas (typically between 350 and 650 °C) enables the use of thermal oil as a carrier for the heat transfer to the organic working fluids used in ORC cycles;
- The recoverable exhaust heat output of re-heating furnaces is ideal for ORC cycles which, for electrical power between 0,5 and 5 $MW_{electric}$ have yields equal to or greater than traditional cycles with steam turbine, presenting, in addition, some benefits in terms of conducting the installation;
- The rolling mills operate typically on continuous cycles over 24 hours, and do not require frequent stops for maintenance.

For these reasons, especially in the case of furnaces for heating slabs and billets in rolling mills, it is common to find systems for heat recovery, for:

- Pre-heating the combustion air with heat exchanger placed in exhaust gas or by using burners reclamation/regeneration;
- Generation of hot water used for industrial uses inside or outside the establishment/heating of offices/city districts.

For a typical re-heating furnace, the flow of energy corresponding to the exhaust gas is slightly less than 30 % of the heat from the combustion of natural gas, which can be estimated, on average, about 1,55 GJ/10^3kg (430 kWh/10^3kg). It is clear that an additional system recovery for pre-heat combustion air, mentioned above, is at least advisable.

Where a heat recovery is not possible, or was unhelpful, the alternative electric power generation is actually interesting.

In these plants, the typical configuration for heat recovery consists of a recovery system for the interception of the exhaust gases of the reheating oven which transfers heat to the thermal oil, used as energy source and transfers the heat to the ORC module, which produces electric power.

The heat discharged from the turbogenerator for condensing working fluid is passed to a circuit of cooling water (at 25/50 °C), and may, as appropriate, be discharged into the atmosphere (through towers and evaporative air-coolers) or used for thermal loads internal to the production process.

HEAT RECOVERY FROM ELECTRIC ARC FURNACE IN STEEL INDUSTRIES

The analysis and the evaluations reported in this subsection refer to the heat recovery from process effluent of steel production towards of electric arc furnace (EAF).

The heat recovery from EAF certainly presents a great potential due to the high temperatures (1.000 to 1.400 °C) and flow rates (of 200.000 Nm^3/h up to more than 300.000 Nm^3/h) of the exhaust gases at the output; in contrast, this type of heat recovery presents some technical problems related to:

- Content of dust;

Table 2. Recovery potential of the steel industry (from rolling mill) in Italy.

POTENTIALITY		
plants to install (estimation)	n	15
power to install	$MW_{electric}$	19,3
energy to produce	$MWh_{electric}$/year	125.450
ENVIRONMENTAL IMPACT		
CO2 emissions avoided	10^3kg/year	79.786
Electric energy saved	$MWh_{electric}$/year	125.450
Primary energy saved	toe/year	23.459

- Significant variations in temperature and fumes flow inside of production cycles;
- Environmental constraints on emissions.

Currently, the increasing development in technology solves some technical and plant's criticality, then the waste heat in oven can be considered a technologically viable solution.

Considering the energy balance for an EAF of medium size (capacity of 100 tons), we obtain that the thermal energy contained in exhaust gases, which is dissipated through different cooling systems (conduit pipe to pipe, quench tower, etc.), is approximately 20 % of the energy supplied from EAF [3], so the power thermal dissipation (recoverable) is about 15 to 20 MW. From this consideration, it is clear that there is a considerable potential for heat recovery.

It should also be considered that the purification of the fumes coming from the melting process of the steel are intensive energy-consuming systems, with electrical power installed in the order of 4–7 $MW_{electric}$; the installation of a system for recovering heat aimed at the production electricity, would greatly reduce (in some cases cancel) the power consumption.

HEAT RECOVERY IN CEMENT INDUSTRIES

Typical cement production plants have a production capacity between 2.000 and 8.000 10^3kg per day, with energy consumption ranging from 3,5 to 5 GJ/10^3kg of clinker produced (10–15 % in the form of electricity).

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

The temperature of the gaseous sources after the internal use in the process (available for the recovery of heat) is relatively low (about 250–350 °C). 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. These flows could, via thermal oil heat recovery circuits, be the heat sources feeding the ORC to generate power.

Gas from the kiln are characterized by a substantial content of dust (typically 10 to 50 g/Nm^3) nevertheless several applications of heat recovery – with both steam turbine and ORC technology – in cement industry are currently working: a clear proof of the feasibility of heat recovery.

The estimation of the potential is still on going for non ferrous materials, oil&gas, etc. The cumulative potential of electricity generation from waste heat for the iron and steel, cement and glass, with an average value of 6.500 h/y at rated power, is estimated in over 800 $GWh_{electric}$/year (Figure 4) and the associated greenhouse gas savings in 500.000*10^3kgCO_2/year (Figure 5).

Table 3. Recovery potential of the cement industry in Italy.

POTENTIALITY		
plants to install (estimation)	n	25
power to install	$MW_{electric}$	30,3
energy to produce	$MWh_{electric}$/year	196.950
ENVIRONMENTAL IMPACT		
CO2 emissions avoided	10^3kg/year	125.260
Electric energy saved	$MWh_{electric}$/year	196.950
Primary energy saved	toe/year	36.830

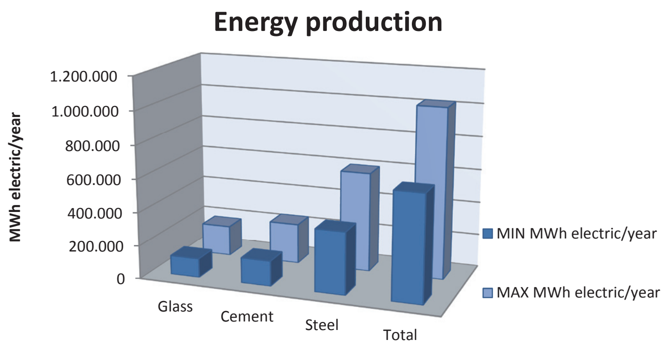

Figure 4. Italian potential of electricity generation from heat recovery (source HREII).

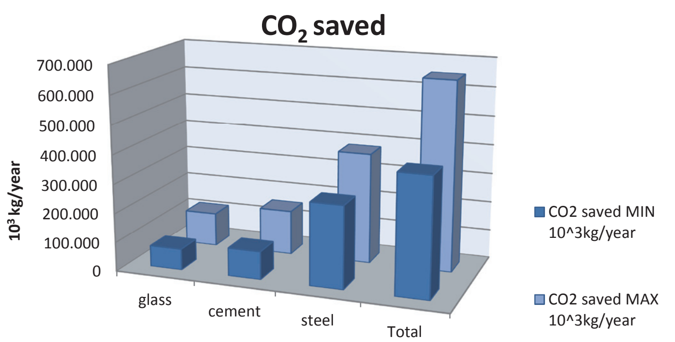

Figure 5. Italian potential of CO_2 savings due to electricity generation from heat recovery (source HREII).

COMPATIBILITY INDEX

To discern the favourable cases within the HREII project a compatibility index was defined. The index is used to discern if a process is worth of more attentions or not, it represents a qualitative indication, in a scale from 1 to 3 (where 1 means very compatible and 3 low compatible) of the grade of compatibility between the industrial process and the heat recovery system based on ORC technology.

The elements to be considered in the compatibility coefficient are:

- Presence or absence of heat recovery in internal process; where 1 indicates the total absence of heat recovery systems for the process and 3 the presence of heat recovery systems internal to the process that highly reduce the availability of thermal power.
- Access to heat source without invasive procedures for the process; where 1 is referred to the case with one discharge point for all the exhaust with an easier access (for instance, a single chimney where it is easy to install a heat exchanger) and 3 is referred to a case with multiple discharge points for the exhaust gases.
- Hours of operation per year; where 1 is referred to an amount of hours per year which ranges between 6.000 and 8.500 h/y and 3 is referred to an amount between 1.000 and 4.000 h/y.
- Technical parameters of heat source: temperature and flow rate. Concerning temperature, 1 is referred to a temperature higher than 300 °C and 3 to a temperature lower than 230 °C. Regarding flow rate, the value between 1 and 3 is defined considering the temperature, in order to attribute a 1 to flow rates that permit to achieve a high thermal power (> 3 $MW_{thermal}$) and 3 to flow rates that lead to a low thermal power available (< 2 $MW_{thermal}$).
- The quality of the heat source; where 1 indicates clean gas without presence of dust and 3 indicates dirty gas with presence of dust or other negative characteristics (presence of ash, critical dew-point, etc.).

See the example in Table 4.

To complete the energy audit kit sent to the energy managers of investigated industries and also downloadable from HREII website, there is also a simplified graph method (Figure 6) to self evaluate the potential of electricity generation of heat recovered from gases.

Entering in the diagram with the temperature and the mass flow of the exhaust gas, there is a first indication of the gross electric power obtainable with an ORC turbogenerator. If the point is below the lower curve, usually there is no practical interest to use the heat for generating electricity through a commercial ORC turbogenerator. The graph is presented also to give the order of magnitude of the possible generation potential from an exhaust gas of given characteristics.

Figure 7 shows the ranges of power and temperatures covered by the ORC turbogenerators commercially available on the market and their typical applications.

Applications and economics

As described in the previous paragraph, the heat recovery through ORC power plants can be a suitable solution for several industrial sectors, especially in fields where the industrial process is characterized by a massive need of energy. As emphasized by the HREII project, the industrial processes in which the ORC represents an high potential energy efficiency solution are the energy intensive industries such as iron & steel, glass and cement. In this paragraph feasibility analysis of ORC heat recovery power plants employable in these industries are reported.

In addition to these industrial sectors an analysis of the ORC application in a gas compressor station, to recover the waste heat contained in the exhaust gas of the turbine is also presented. The exhaust gas of the turbine drives the compressor that maintains the natural gas pressure in the pipeline, permitting its flow. This is not properly an industrial application; it is more similar to a small-sized combined cycle. However, due to the high presence of gas compressor stations in Italy and around

Table 4. Example of compatibility index calculation.

ELEMENTS	VALUE 1-3	NOTE
ATECO Sector: Melting of other non-ferrous materials – Secondary refinery		
Heat recovery in internal process	3	Usually presence of pre-heating of the raw material (billets)
Source temperature	1	Very high temperature of the exhaust
Source flow rate	2	Usually it is not so high, due to the use of electric induction furnaces for the melting process
Source quality	1	In the most cases the raw material is submitted in quite pure billets melted in induction furnaces, so the exhaust gases are quite clean
Availability heat source	2	Usually there are several little furnaces, but sometimes the exhaust are piped to a single chimney
h/y operation	2	Usually these companies work only during the weekdays and on two shifts per day
COMPATIBILITY COEFFICIENT	**2**	**Interesting sector, but only for few cases**

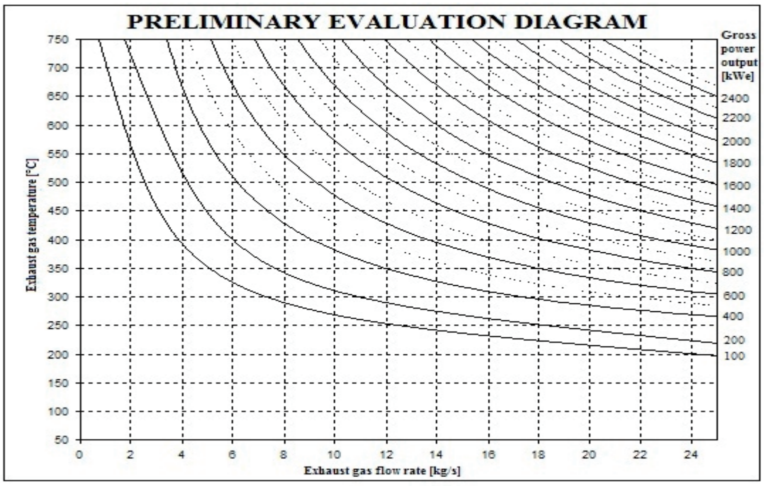

Figure 6. Preliminary self-evaluation diagram. Input data: temperature and flow rates of waste gases (source HREII).

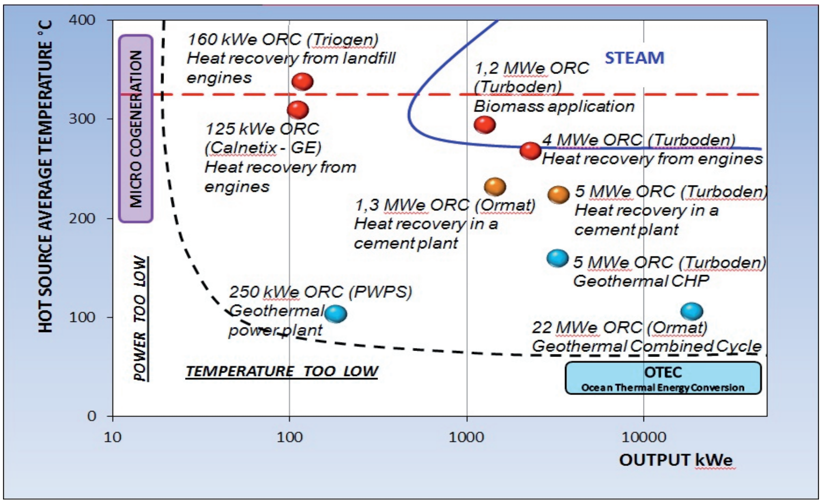

Figure 7. Some commercial application of ORC turbine for electricity generation (source HREII).

the world (the gas compressor stations are usually placed at 40 to 100 miles intervals along the high pressure pipelines), this energy efficiency solution has a huge potential in terms of primary energy savings and avoided CO_2 emissions.

Before analysing the feasibility analyses, it is important to mention in detail the main components of an ORC base heat recovery power plant:

- **The ORC turbogenerator:** The ORC can be considered a power block, which receives a thermal input and a cold source, and gives electricity as output. From an economical point of view, it must be considered that the cost of the power block is highly related to two main factors: 1) The hot source characteristics that impose the working fluid to be used and the related technical solution. Figure 8 represents a diagram which underlines the different fluids employable in function of the hot source characteristics. 2) The cooling system required, which defines the ORC cooling configuration (air-condenser or water cooled condenser). In addition it must be pointed that the size of the power plant is a key-point of the economics of a heat recovery ORC power plant. In fact, the ORC units have a high scale effect, so the higher the size, the lower the specific price of the system.
- **The heat recovery exchanger and the related ancillaries:** In several industrial applications of the ORC based heat recovery system, the heat recovery exchanger represents the more critical part of the system, due to the fact that it is the interface between the heat recovery plant and the industrial process. Particularly in processes where the heat source has critical characteristics (e.g. the exhaust gases from the kiln in a cement production process have a high abrasive dust content), the heat recovery exchanger represents a fundamental component from a technical point of view, and also a relevant cost. The ancillaries related to the heat recovery exchanger can be divided in two main groups: 1) Systems/Works on the exhaust duct necessary to insert the heat recovery exchanger, avoiding any interferences with the industrial process. The latter is a necessary condition of a heat recovery system, because the industrial process has always the priority and its reliability must not be reduced. The heat recovery section has to be conceived as a 'fail safe' device, in case the heat recovery system fails (rare but possible) the primary process will continue to work unaffected. This is usually achieved installing the heat exchanger in a by-pass line of the primary heat stream, with the possibility of excluding the exchanger automatically, if necessary, without interfering with the process. 2) Systems/works to connect the heat exchanger to the ORC. The characteristics of this part of the plant, both from a technical and an economical point of view, are highly influenced by the heat carrier utilized (e.g. thermal oil, pressurized water, etc.).
- **The cooling system:** As previously mentioned, the ORC turbogenerator has to dissipate the part of the heat not transformed into electricity. Usually, having the ORC an efficiency of 20 %, about the 80 % of the input thermal power, must be dissipated. This heat, available at low-temperature can be used, in case there are low-temperature heat demand in the industrial process or other heat demand nearby (e.g. buildings heating) or it is discharged to the atmosphere. The discharge can be either through air cooled condensers (the air-condensers will be included in the ORC power block) or through air cooled radiators/wet cooling towers (the choice between air radiators and wet towers depends on the availability of water for the make-up required by the wet towers) inserted in a closed cooling water circuit.

In Figure 9, a simplified Piping and Instrumentation Diagram for a representative ORC heat recovery power plant is reported.

In addition to the components mentioned above, there are other works that must be considered to have a complete picture of the turn-key ORC based heat recovery power plant. These activities are the civil works required by the power plant main components and the electrical connection of the ORC to the electrical grid (national grid or industry grid, depending on the project specific characteristics). The technical/economic extent of these activities is highly influenced by the specific characteristics of the project, therefore in the business analyses it has been hypothesized.

Following is reported a brief description of the analysed integration of ORC within the production processes in the four different sectors considered.

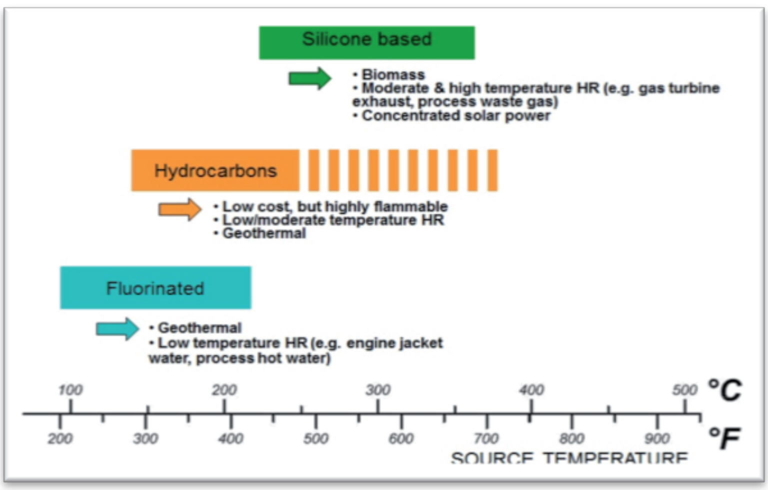

Figure 8. Type of ORC working fluids employable according to source temperature (source Turboden).

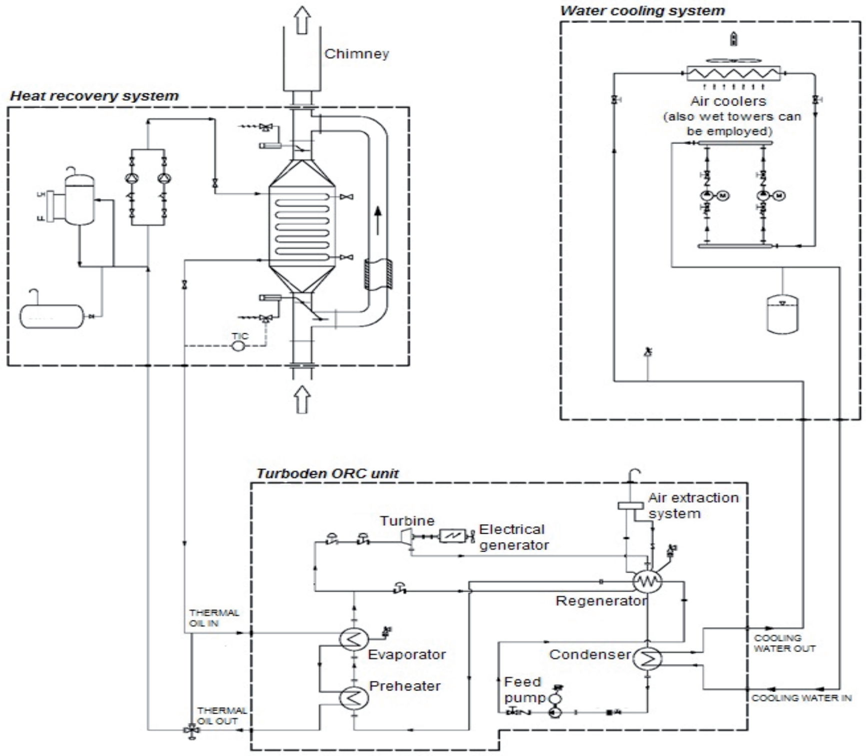

Figure 9. Representative ORC Powerplant Piping and Instrumentation Diagram, (source Turboden).

IRON & STEEL

In the iron & steel sector there are different industrial processes that present a relevant amount of waste heat, exploitable through an ORC heat recovery power plant: the scraps melting process through electric arc furnaces, the primary production with the blast furnaces, sinters and converters; the heat treatment processes; and others. For this feasibility evaluation we have considered the heat recovery from a re-heating furnace, employed in the rolling mill process.

Thanks to the fact that the exhaust gases are quite clean (combustion of natural gas) and at a relatively low temperature, a direct exchange scheme has been employed. In this configuration the ORC power-block is provided with a heat exchanger to transfer the thermal power of the exhaust gas directly to the working fluid, avoiding the intermediate loop with the heat carrier. It is important to underline that, due to the ORC working fluid characteristics (maximum operating temperature), this solution is feasible only in case the exhaust gas are not exposed at a very high temperature. In addition, due to the higher cost of the working fluid, compared with the common heat carriers; the heat exchanger working fluid/exhaust gas is designed to minimize the exchange surface (finned tubes), therefore, the exhausts have to be not excessively dirty. Finally, again for an economic reason, this solution is feasible for not too big ORC sizes (lower than 1 $MW_{electric}$), because, for big ORCs, the volume of the working fluid to be used is too high.

Regarding the cooling system, an ORC with a water cooled condenser coupled with a wet heat dissipation system with cooling towers, has been considered.

CEMENT

For the cement industry, the case analysis considers a heat recovery power plant fed by two different heat sources: the combustion gas (kiln gas), after the raw material pre-heating, and the clinker cooler air flow (air stream which cools down the clinker, final product, after it exits the kiln).

The heat transfer from these heat sources to the ORC powerblock is made by thermal oil. The heat exchanger exhaust gas/thermal oil is a critical part of the system, both from a technical and an economic point of view, due to presence of abrasive and sticky dust in the exhaust. However, to date, several applications of heat recovery with a thermal oil heat exchanger are currently working, therefore, the technology can be considered feasible and proved.

Concerning the cooling system of the ORC power block, a dry heat dissipation system, with a closed loop of water with air-coolers, has been considered.

GLASS

In the glass sector, a float glass production process has been considered. The exhaust gas of the furnace for the float glass production are quite clean, because they are produced by natural gas combustion and because the raw materials used for this kind of glass are of a good quality. Therefore, the heat exchanger installed in the exhaust gas does not represent a critical component. In addition, it must be consider that this production process is a continuous process due to the difficulties in managing furnace stops.

The power plant employed in this sector is based on an indirect scheme with the use of thermal oil as heat carrier, to transfer the thermal power of the exhaust to the ORC power block.

Regarding the cooling system, the ORC module employed has a water cooled condenser and the low-temperature heat is discharged with a closed loop of water with air-coolers.

Table 5. Summary of feasibility analyses based on Turboden case analyses and references.

Industrial process	Cement	Glass: float glass	Steel: re-heating furnace, rolling mill	Oil&gas: Gas compressor station	U.M.
TECHNICAL CHARACTERISTICS					
Heat source	Heat recovery from kiln and clinker cooler gas	Heat recovery from melting furnace for float glass production	Heat recovery from re-heating furnace in a iron&steel rooling mill	Heat recovery of gas turbine exhaust gas	-
Plant capacity	$5.000*10^3$kg/day	$600*10^3$kg /day	$100*10^3$kg /hour	11 MW (gas turbine shaft power)	-
Eectricity cost (a)	0,08	0,08	0,075	0,07	€/kWh
Waste thermal power in exhaust gas (b)	25.000	5.600	5.500	25.000	kWt
Hours per year of operation	7.900	8.100	8.000	8.000	h/y
ORC gross power output	5,3	1,3	1,1	5,4	$MW_{electric}$
Net power output of the heat recovery power plant	4,6	1,1	0,95	4,9	$MW_{electric}$
Net electricity production	36.340	8.910	7.600	39.200	MWh/y
CAPITAL EXPENDITURE INDICATIONS					
ORC cost + cooling system	5	1,5	2	6,2	M€
Heat recovery exchanger (c)	7,2	0,7	Not needed - direct exchange ORC (d)	4,5	M€
Balance of plant (e)	3,5	1,2	0,8	1,8	M€
Engineering, project management and contingencies cost (f)	1,9	0,4	0,3	1,5	M€
Total cost (adding contingencies, engineering and project management)	17,6	3,8	3,1	14	M€
ANNUAL CASH FLOW					
Operational expenditure	130.000	70.000	60.000	120.000	€/y
Cash flow-electricity	2.907.200	712.800	570.000	2.744.000	€/y
Net cash flow	2.777.200	642.800	510.000	2.624.000	€/y
RESULTS (f)					
Internal rate of return (10 years)	9%	11%	10%	13%	%
Net present value (10 years)	1.050.000	500.000	280.000	3.600.000	€
Payback time	9,2	8,4	8,8	7,2	years
Avoided CO_2 emissions (g)	22.894	5.613	4.788	24.696	10^3kg/y

(a) Differences are due to total power installed, nation, etc. – No incentives has been considered.
(b) Assuming to cool the exhaust to 150/180 °C, depending on the project.
(c) Estimated by reputable supplier.
(d) In the direct exchange scheme the ORC is fed directly with the exhaust gas.
(e) Including the ancillaries of the power plant main components and estimations for civil works, for electrical connection, for the erection and for the thermal insulation.
(f) Hypothesized equal to 12 % of equipment cost.
(g) Assuming discount rate of 8 %.
(h) Assuming 0,63 kg of $CO_2/kWh_{electric.}$

Table 6. WhC incentive and discounted payback time considering the WhC.

Industrial process	Cement	Glass: float glass	Steel:re-heating furnace, rolling mill	Oil&gas: Gas compressor station	U.M.
WhC	679.000	166.000	142.000	733.000	€/year
Payback time	7,3	6,5	6,7	5,4	years
WhC with tau=3,36	2.283.000	559.000	477.000	2.463.000	€/year
Payback time with tau=3,36	4,2	3,8	3,8	3,2	years

OIL & GAS – GAS COMPRESSOR STATION

The power plant employed in gas compressor stations is based on an indirect scheme with the use of thermal oil as heat carrier, to transfer the thermal power of the exhaust to the ORC power block. In this application the exhaust gas are absolutely clean, because generated from the natural gas combustion; therefore, the thermal oil heat exchanger is not a critical component. In addition, if compared with the standard steam combined cycle, the use of thermal oil permits to have a more simple and feasible heat recovery system, because there is not phase change in the heat recovery exchanger.

Regarding the cooling system, the ORC module employed has a water cooled condenser coupled with a wet heat dissipation system with cooling towers.

ECONOMIC EVALUATION

In the economic evaluations there are no fuel costs, and maintenance/operational costs are low. The electricity produced is self consumed, thus is considered as not bought, at the same price of the electricity taken from the grid (excluding only value added tax, excise duties, etc.). In more thorough calculation, also the value of the electricity taken from the grid could have some change, but negligible in a first approximation. In Table 5, a summary of the feasibility analyses is reported.

The payback times of 7 years and over are not very interesting for the industrial sector, moreover a strong economic crisis reduced the availability of heat (hours per years) and this also explains the low diffusion of these systems. In Italy the White Certificate (WhC) system [12] incentives for the first five years of operative life, (almost) any energy efficiency measure, thus also the waste heat recovery. For this measure no simplified method (deemed file or engineering estimates) is available, so a monitoring plan has to be set up, installing appropriate meters to measure the electricity generated and the consumption of all the ancillaries. The Italian WhC mechanism is based on the concept of additional savings, thus only the savings over the baseline can be considered. The baseline is the higher value between the efficiency of the average offer on the market and the efficiency of the previous installed equipment, if any. In the hypothesis that all the electricity generated, subtracting the ancillaries will be incentivised, it is possible to estimate the amount of WhC and of the incentive. The hypothesis is valid for the first installations, but after some installations the savings recognised for new installation will be lower or null. At the end of 2011 there were also other novelties for the WhC with the introduction [14] of a multiplying factor, tau, to recognize in 5 years the actualized savings over the entire operative lifespan of the measure. In the case of heat recovery for electricity generation tau is 3,36.

Table 6 shows the yearly contribute of the WhC for the first five years and the discounted payback time, before and after the introduction of tau coefficient. The other data are the conversion factor of $0{,}187 \cdot 10^{-3}$ toe/kWh$_{electric}$ [13] and a value of €100/toe for each certificate sold on the market.

The WhC without tau recognise a contribution of around 20 % of the investment if cumulated and actualized over 5 years. With the tau the contribution grows in the worst case over 50 %, with discounted payback periods of around 4 years. It is important to underline that this incentive system, thanks to the concept of additional savings is self regulating: it guarantees an higher sustain to new technologies/measures in their first steps in the market and it lowers with their spread.

Conclusion

The evaluation shows an interesting potential of electricity generation from heat recovery in Italian industries. There are already working examples of plants around the world in many of the most interesting sectors considered. Many of these plants employ organic Rankin cycle turbogenerators which demonstrated their suitability for this application and their reliability. At the moment the application of these systems for waste heat recovery in Italy is limited to two realizations in the glass sector, but the future is promising thanks to the attention for industrial heat recovery in the national energy planning and to the support of the "renewed" white certificates system. The latter, with the novelties introduced at the end of 2011 represents a very interesting incentive, hopefully capable to boost the diffusion of electricity generation from heat recovery.

Glossary

BREF:	Reference Document on Best Available Techniques in the framework of Integrated Pollution Prevention and Control
CHP:	Combined Heat and Power
EAF:	electric arc furnace
EED:	Energy Efficiency Directive
ESD:	Energy Services Directive
ETS:	Emission Trading Scheme
HREII:	Heat Recovery in Energy Intensive Industry project
IPPC:	Integrated Pollution Prevention and Control
NEEAP:	National Energy Efficiency Action Plan
ORC:	Organic Rankine Cycle
T-S diagram:	temperature-entropy diagram
toe:	ton of oil equivalent
WhC:	White Certificate

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