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Waste heat recovery projects using Organic Rankine Cycle technology – Examples of biogas engines and steel mills applications

G. David[1], F. Michel[2], L. Sanchez[3]
[1]*ENERTIME SAS, Paris, France*
[2]*ENERTIME SAS, Paris, France*
[3]*ENERTIME SAS, Paris, France*

Abstract/Resume

The objectives of this paper is to present ORC technology and to show that for several waste heat recovery applications it is both technically and economically viable to decrease environmental impact from industrial and energy production by producing electricity with waste heat.

A presentation of ORC technology will be carried out on such topic as : organic fluids, technical parameters, current actors and solutions, strengths and weaknesses of the technology compared to other waste heat recovery solutions. Applications in industry (recovery of thermal power available in steel mill and from a landfill gas engine exhaust) will be described - ORC technical design based on heat source characteristics, location analysis, regulatory review, safety implications and the impact on industrial process, and evaluation of investment and O&M costs – in order to evaluate the technical and economical feasibility of both applications.

The study demonstrates the technical feasibility of ORC solutions and its relevance from an environmental point of view in terms of resources optimizations and reduction of greenhouse gas emissions. However, economic feasibility of projects must still be considered on a case by case basis depending on the characteristics of the heat sources (available power, temperature) but also on the resale price of electricity. Through the example of France, authors show that modules producing electricity on biogas engine exhausts already have a good pay-back time due to interesting feed-in-tariffs for electricity produced from landfill gas. On the other hand, it shows that waste heat recovery projects in industry are economically viable except where very low prices of electricity paid by industries and when lack of appropriate support measures make it non-viable.

In addition to the fact that waste heat recovery is a CO2 free electricity production technology, support measures for the reduction of electricity consumption in factories

makes economical sense because any additional electricity production capacity will generate power at a higher cost compared to the prevailing power production cost. Avoiding such higher production costs by limiting the additional capacity that needs to be built is in the interest of the distributor of electricity.

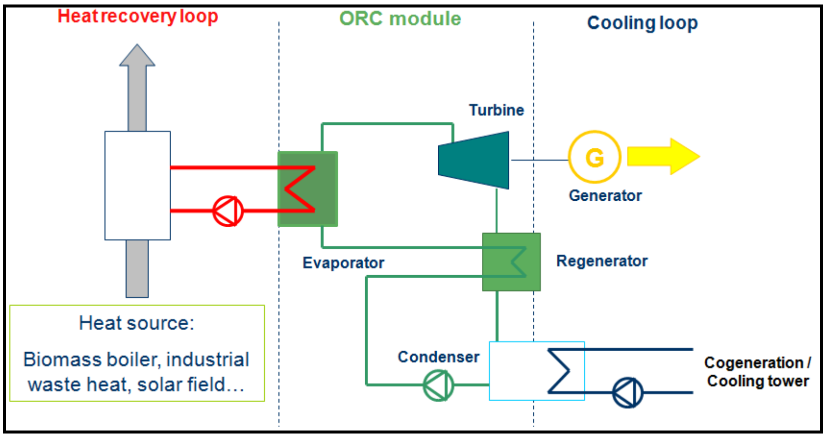
Organic Rankine Cycle technology

Overview

Organic Rankine Cycle (ORC) technology refers to the use of the Rankine thermodynamic cycle used in conventional steam power plants, where instead of steam an organic working fluid (refrigerant fluid, alkyl benzene, siloxane etc.) is used. The large range of available fluids allows the development of innovative solutions for all types of heat recovery and its conversion into electricity, particularly for low temperatures and small sizes, where conventional steam cycles are inoperative.

A power generation installation using organic Rankine cycle technology combines three loops:

- A loop using a transfer fluid (pressurized water, thermal oil) for recovering thermal energy from a heat source (boiler biomass, solar energy or waste heat).
- A loop using organic fluid to produce mechanical work through a Rankine thermodynamic cycle;
- A cooling circuit for condensation of the organic fluid.



Organic fluids

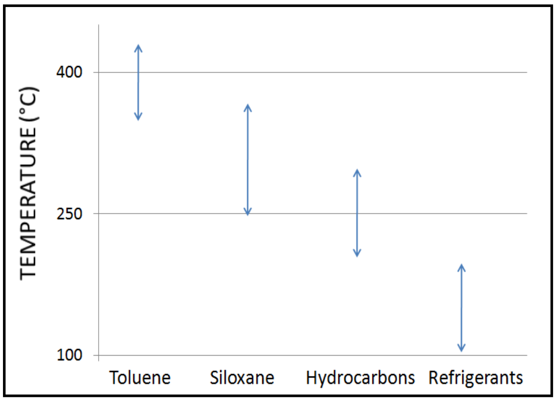
ORC working fluids are chosen according to the application and the temperature of the available heat source. Cycle efficiency is one of the most important criteria of any Project, but other criteria have to be taken into account as well, such as:

✓ The auto-ignition temperature must be well above the maximum working temperature ;

- ✓ The enthalpy loss in the turbine has to be maximal in order to minimize the mass flow of the fluid flowing in the pump. Pump consumption will be therefore lower, increasing the net cycle efficiency ;
- ✓ On the entropy versus temperature diagram, the inclination of the curve has to be as close as possible to the isentropic curve (vertical) to avoid excess overheating at the outlet of the turbine and the use of an expensive recuperation exchanger
- ✓ The ODP or GWP environmental impact has to be minimal;
- ✓ The cost of the fluid is a parameter to be included in the analysis.

ORC modules available on the market use one of the following working fluids depending on the temperature of the hot source:

- ✓ Refrigerants (R245fa, R134a) are used at low temperatures (100-180°C);
- ✓ For medium temperatures sources (between 200 and 250°C), hydrocarbons such as pentane and hexane are chosen;
- ✓ For higher temperatures (250-350°C), a class of fluids called siloxanes achieves efficiencies of around 20%.
- ✓ Finally, for temperatures above 350°C, some manufacturers use Toluene.

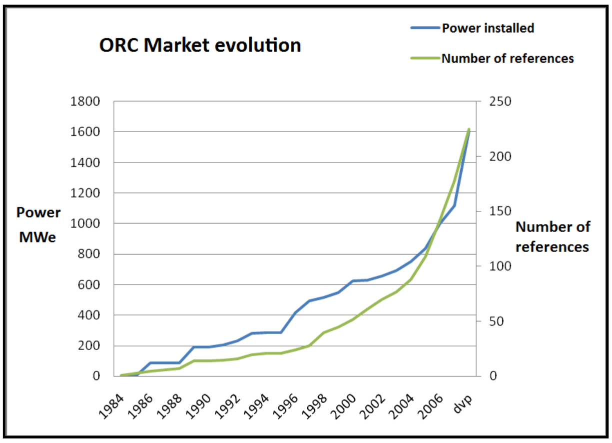


Market and key players

The markets covered by the ORC technology are primarily:

- ✓ Small power plants using biomass (the ORC module is generally connected to a thermal oil boiler);
- ✓ Valorisation of geothermal sources at low and medium temperature where steam plants are inefficient;
- ✓ Small solar thermal power plants using parabolic troughs or linear Fresnel collectors;
- ✓ Waste heat recovery power plants with heat sources at temperatures down to 90°C, a market covered by this paper.

ORC technology has been widely used during the last 20 years, with more than 300 units installed for a total capacity of more than 2,000 MWe, most of them designed for temperatures greater than 150°C and mainly geothermal applications. The most important players in the market are American Companies (ORMAT, Pratt&Whitney, GE Heat Recovery), Italian but US-owned (Turboden owned by Pratt&Whitney), German



(Maxxtec, GMK), and Dutch (Tri-O-Gen).

Strengths and weaknesses

Obviously the biggest weakness of the technology is the apparent low conversion efficiency (between 10 and 20%). However the main reason of this low value is the low operating temperature: for the same operating temperatures a steam cycle will not achieve a higher efficiency.

The use of certain fluids also causes more stringent security measures compared to the steam cycle because of their flammability, explosiveness and toxicity in some cases.

The main advantages of the ORC technology compared to steam plants are:

- ✓ Large inlet temperatures distribution from 450°C down to below 100°C;
- ✓ ORC modules are easy to install (compact, skid-mounted standard module), easy to operate, and reach great availability (>98%);
- ✓ ORC modules require low maintenance (no droplet erosion in the turbine, low pressure evaporator, automation);
- ✓ Small units (down to 30kWe) are available allowing valorisation of many thermal sources;
- ✓ Sizes range from a few kWe to several MWe. For power capacities lower than 2MWe, steam power plants are usually not well adapted. In particular, the operation and maintenance costs of the equivalent steam power plant are higher and its efficiency is lower.

Example 1: Waste heat recovery projects in steel mill

Potential overview

In 2007, the energy consumption of industry in France represented 23% (37 million toe[1]) of the total energy consumption[2]. Due to the efforts of and changes in industrial activities, its portion has been decreasing since the 1970s (when industry represented 36% of total energy consumption). However, it seems that the sector's consumption has reached a plateau since the early 2000s.

In France, the main industrial consumer of energy is the steel industry (18% of total consumption), followed by the agro-industry (14%) and the organic petrochemical industry (13%). In the steel industry, **most of the stages in the production process (Cowper, slab kilns, Coking Plant, etc.) release a large amount of energy in the form of wasted heat.** These sources are at different temperature levels (between 50°C and 350°C), which are

[1] Ton oil equivalent
[2] French government data

too low to be valorised through a steam cycle. Due to the lack of technical solutions (high investment costs, in-sufficient efficiency, safety issues…) these sources have been left un-valorised. Some heat sources with similar characteristics can be found in **cement and glass factories[3].**

Outside of the industrial production field, recovering heat from the exhaust of gas turbines or gas or diesel engines to generate additional electricity is also feasible using ORC technology.

The capability of ORC modules to valorise low temperature heat sources allows the use of this technology for numerous waste heat recovery projects in industry for power generation. **Potential sources are high temperature sources from kilns as well as heat flux at around 100°C. The potential for project implementation is tremendous.** Just in continental France, over 50MWe could be implemented in steel factories and more than 15MWe in cement factories[4].

Some successful examples of ORC implementations can already be seen around the world for waste heat recovery in industry or from gas engines. ORC modules are appreciated for their ease of implementation and operation. Modules do not disturb the industrial process and are automatically turned off when the process is off.

This first example presents an overview of a waste heat recovery study carried out in 2009 and focuses on evaluating the possibility of low heat valorisation in a French steel mill by ORC technology.

Waste heat recovery particularities

In the case of industrial waste heat recovery projects, the design phase is absolutely critical. T**he industrial process is the priority and should not be disturbed.** The industrial process might fluctuate, and therefore the characteristics of the heat source (flow, temperature, etc.) might also be modified. For this reason it is necessary to select a module that will enable the highest electrical power production, which is not always the one with the highest efficiency[5]. A module operating at low temperatures will have a lower efficiency, but will enable to recover more thermal energy (flue gas will be released at a lower temperature from the heat exchanger) and may therefore produce more power than a high temperature module.

One of the strength of ORC technology is the availability of a large range of fluids and potential cycles, allowing the optimization of the performance of the waste heat recovery installation, taking into account the characteristics of each source.

Case study heat source presentation

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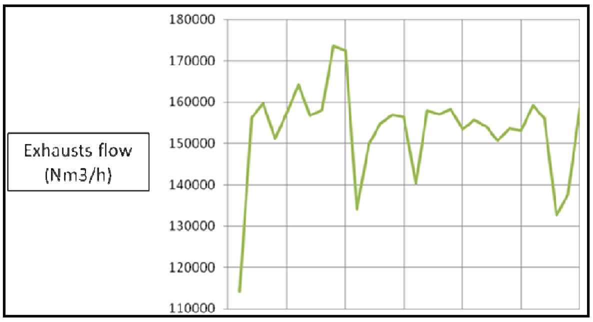
[3] Engin T.& Ari V., Energy auditing and recovery for dry type cement rotary kiln systems–A casestudy, Energy Conversion and Management 46 551–562, 2005
[4] French Chemical Society, 2005
[5] Joost J. Brasz, 2008, Assessment of C6F as working fluid for organic Rankine cycle applications.

A coke plant transforms coal into coke, using a pyrolysis process. The coke produced has the physical and mechanical characteristics needed by a steel furnace. The heating of the coke ovens is provided by the combustion of process gas (coke oven gas, steel furnace gas or natural gas). A large quantity of thermal energy resulting from the combustion of the gas escapes through the exhaust.

The coking plant under study emits around 150 000 Nm3/h of flue gas at a temperature of 150°C. The flow rate is relatively stable and the coking plant is never stopped. Another particularity of the exhaust is the high sulphur content (level of H_2S sometimes reaches $3g/Nm^3$). This element is corrosive for piping and heat exchanger.

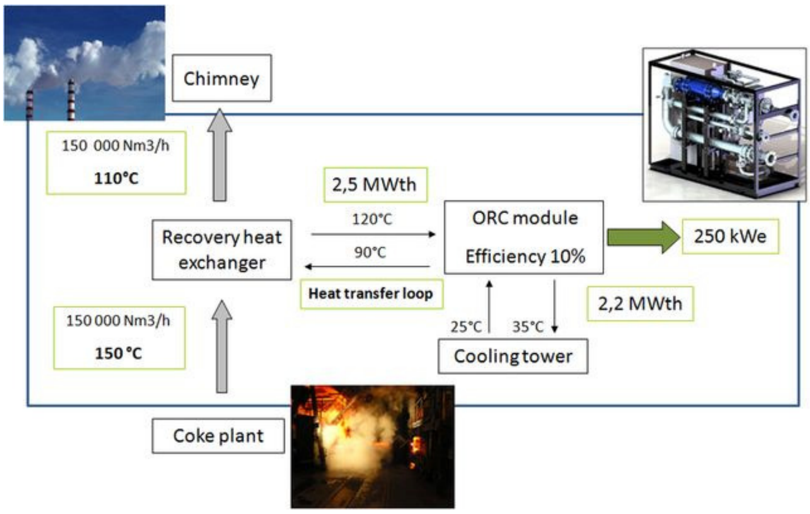
Average daily exhaust flow rate (30 day period)



Due to the high sulphur content, it is not possible to cool the exhausts below 110°C. Thus, the potential recoverable thermal energy is around 2,5MW[6].

Project sizing

Analysis of the data showed an ORC potential of 250kWe by recovering the heat of the exhaust gases through an intermediate loop (pressurized water between 90 and 120°C).



For this temperature and power, 2 Clean Cycle units of 125kWe gross (produced by Calnetix, recently purchased by General Electric) would fit. The gross efficiency of such a module for this heat source would reach 10% with a cooling loop at 25/35 °C (using a cooling tower).

Auxiliary' electrical consumption represents around 50kWe (20% of the gross power): 30kWe for the ORC modules circulating pump, 15kWe for the cooling loop (pump and cooling towers) and 5kWe for heat transfer loop circulating pump. **Thus we expect a net production of 200kWe.**

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[6] Calorific capacity of exhausts is evaluated at $1,45kJ/°C/Nm^3$

Regulatory review, location analysis and impacts on industrial process

For low temperature projects, the fluids used are safe and non flammable (water for heat transfer and cooling loop; R245fa for the ORC module) which facilitates implementation in the industrial environment. The regulatory and authorisation phases are simplified. In France, the only equipment requiring an administrative declaration are wet cooling towers for sanitary reasons[7].

Such waste heat recovery projects would require 50m² of ground surface as follows:

- 15 m² for the two ORC modules
- 10 m² for the waste heat recovery exchanger and loop
- 25 m² for the cooling system.

Finally, a by-pass loop is installed on the existing exhaust circuit. The recovery heat exchanger would be installed on that bypass loop to disconnect the industrial process from the heat recovery projects. **Using such precaution, a problem with the ORC system would not impact the coking plant.**

Investment and O&M costs

Due to the relatively small size of the Plant, specific costs of the project are relatively high: at around 1100k€ for 250kWe gross, or more than 4 000€/kWe. The major part of the investment is devoted to the 2 ORC modules (around 50%).

On the other hand ORC installations are well-known for their very low operation and maintenance costs. Current projects show average O&M costs of 1c€/kWh and availability above 95%[8]. In the following analysis we will consider a conservative assumption of 3c€/kWh.

	Ex-Works	**Transport**	**Assembly**	**Total**
Recovery heat exchanger	200	15	15	230
2 ORC modules	500	10	10	520
Cooling tower	100	5	5	110
Electrical auxiliaries	40	5	5	50
Mechanical auxiliaries	50	5	5	60
Civil works	0	0	40	40
Project costs	0	0	0	70
Total	890	40	80	1 080

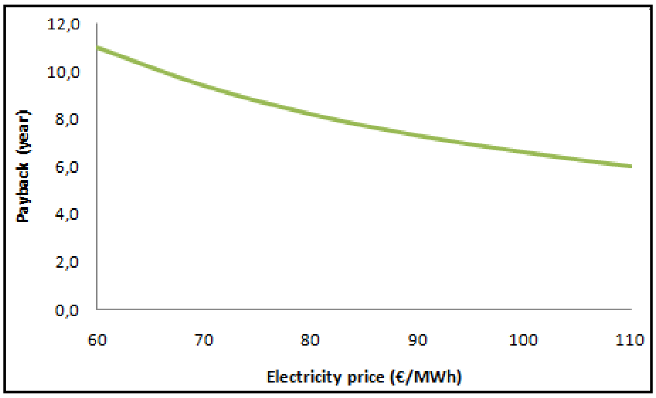
Expected investment costs (k€)

[7] Legionella problems

[8] G.Holdmann, ORC Technology for Waste Heat Applications, Diesel Heat Recovery and Efficiency Workshop, December 2007

Economic analysis

Calculation of the annual data of available thermal energy in the exhausts combined with the expected performance of the ORC results in a net expected production of 1550MWh per year.



Other assumptions used for the economic analysis are ; a plant lifetime of 15 years, the absence of any subsidy (feed-in-tariff, green certificates or subvention) and an inflation rate of 2%.

The proposed figure shows the evolution of the payback time with the price of electricity paid by the industrial party.

In France, average price of electricity for industrial companies is very low - between 50 and 75€/MWh – because of the predominance of nuclear in the energy mix. Unfortunately, despite the advantages and the strengths of the ORC solution, the price level does not allow this kind of project to be financed as the payback time of the investment would be above 8 or 9 years.

However an increase of the price of electricity is expected in the coming years to a level where investors may be interested in financing projects on behalf of industrialists. In some European countries, such level has been reached (Germany, Italy) and interesting waste heat recovery projects are already running.

Example 2: Waste heat recovery on biogas engine exhausts

Introduction

The major constraint for a waste heat recovery project is the price of the electricity produced. In the first example, because no feed-in-tariff was guaranteed and grid electricity price was low, the project was not economically viable in the target country (France). In this third part we will study alternative waste heat recovery projects which might be implemented in countries with cheap electricity prices, as in France as the electricity produced will benefit from a special tariff. In this case, the tariff applies to electricity produced via the recovery of heat from engines or micro-turbines running on biogas. We will focus in particular on a project valorising thermal energy from a Jenbacher JMS 612 biogas engine.

Heat source characteristics

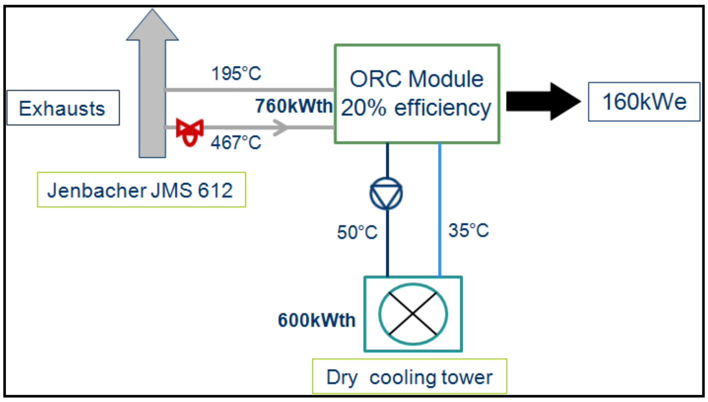
Biogas engines have two sources of thermal energy at two levels of temperatures:

- Exhaust gas: generally at a temperature above 400°C: it can be cooled down to 180 ° C without any risk of condensation of corrosive components. Potentially recoverable thermal energy represents roughly 20% of the input power ;
- Engine cooling loop (hot water at 90°C): depending on the engine size, the potentially recoverable thermal energy represents roughly 25% of the input power.

These two sources can be recovered by ORC technology. Exhaust gas can be used to run a high temperature module (like Tri-O-Gen) with a high conversion ratio (around 20%). The water loop combined with the exhaust gas can also be used to run a module operating at a lower temperature (like Calnetix)

As with the coke plant project, a bypass loop is installed on the exhaust to allow recovery of thermal energy without disturbing the biogas engine operation.

Project sizing



The engine studied produces around 1 450kWe with an efficiency of 39%. The amount of recoverable energy in exhaust gases is around 800kWth between 470 and 180°C. This energy is in our case lost as no potential thermal consumer has been identified. The characteristics are sufficient to consider the installation of a high temperature ORC module such as the one proposed by the Dutch manufacturer Tri-O-Gen (see the picture on page 8) to improve electrical production by 8%.

The module produces 160kWe gross (145kWe net) at full load with an efficiency of 20% using Toluene as the working fluid. Toluene does not require specific safety devices as the module contains a relatively small amount of fluid (~300l) and the manufacter has already taken all the necessary measures to avoid leakages. The installation requires a cooling loop between 35 and 50°C (using a dry cooling tower). A particularity of this module is the possibility to avoid the usual intermediate loop between the heat source and the module: the exhaust directly feeds the evaporator.

Investment and Economic analysis

Investment costs are evaluated at around 540k€. The proposed waste heat recovery solution improves the efficiency of the biogas plant from 39 to 42%. It is interesting from two points of view:

1. With the same amount of biogas the annual production of electricity goes from 14 600MWh to 15 800MWh;
2. In France electricity from biogas can be sold at a price which depends on the efficiency of the plant: improving it by 3% leads to an increase of around 2 €/ MWh in the electricity tariff for the entire plant (engine and ORC)

Thus, the ORC installation increases the existing tariff and therefore existing revenue by 25k€ and the additional electricity produced by the ORC module give an additional earning of 85k€. The **Payback time for the investment is therefore below 5 years.** A very interesting figure for energy suppliers, which is why several projects are already under development or running in France, Netherlands and USA.

	Ex-Works	Transport	Assembly	Total
Recovery heat exchanger	10	5	5	20
ORC module	400	5	10	415
Cooling tower	25	5	5	35
Mechanical auxiliaries	10	5	5	20
Civil works	0	0	20	20
Project costs	0	0	0	30
Total	445	20	45	540

Conclusion

This paper presents two case studies of waste heat recovery projects: valorization of hot gases from a coking plant in a steel mill and valorisation of exhaust from a biogas engine. The first one suffers from a low electricity price in the targeted country (France) but should be viable in the coming years or immediately by targeting other European countries. The second one is already economically viable due to a special feed-in-tariff or equivalent supporting measure.

Other industrial sectors, which may be targeted are the glass industry (hot gas leave the furnace at around 400°C), and cement industry (one study showed that 40% of the energy used in the cement industry was lost in waste heat[2]). Nevertheless the first targeted projects should preferentially be located in countries where industries suffer from high electricity costs or electricity supply problems (electricity grid failure, damageable variations of electricity frequency) and where operating a dependable in-house system for electricity production is a solution. Exhaust gases from large diesel engines producing electricity on non-connected grids (e.g. on island for example) can also power an ORC module in order to improve the efficiency of these systems and reduce fuel consumption:

in this case the economic advantages of ORC modules are directly linked to the price of oil.

References

1. French government data
2. Engin T.& Ari V., Energy auditing and recovery for dry type cement rotary kiln systems–A case study, Energy Conversion and Management 46 551–562, 2005
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