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# Enhanced efficiency, sustainable power generation, and $CO_2$ emission reduction in energy-intensive industries through Organic Rankine Cycle Technology

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## Abstract

Energy efficient solutions in energy-intensive sectors such as oil and gas, cement, glass and iron and steel production are required in order to tackle $CO_2$ emissions and meet the growing energy demand. Using energy more responsibly is a good way to counter these issues. There are several ways to improve energy efficiency for energy-intensive industries, most notably Organic Rankine Cycle (ORC) technology, which allows to convert residual low grade heat into electricity. This speech highlights the ORC heat recovery projects in the energy-intensive industries. Furthermore, an overview of other potential applications of the ORC technology coupled with renewable sources, for $CO_2$ reduction projects, are also examined.
*Keywords: Organic Rankine Cycle, waste heat recovery, waste heat to power, cement, glass, iron and steel, oil and gas.*

## 1 Introduction

Generally, industrial processes waste a significant amount of heat in the environment. While facing strong international competition along with environmental limitations and increasing energy prices, energy-intensive industries strive to develop solutions in order to recover heat from their processes. Bendig *et al.* [1] define waste heat in industrial processes comparing waste heat reserve and waste heat resource. "*Waste heat as a reserve* is the net exergy that unavoidably leaves or is lost within an existing process after its integration, minus the exergy that cannot be recovered for technical or economic reasons. *Waste heat as a resource* is exergy that unavoidably leaves a process or is lost within it independent of the technological choices made within the process.” It is also worth notice that the recovery of other ways dispersed heat falls in a number of European directives, as the industrial emissions [2] and energy efficiency [3] ones. Throughout this paper, we refer to waste heat as reserve. Although the recovered heat can be transformed into several useful forms such as electricity and district heating, the priority should be given to the direct use of energy to avoid further losses.

A flowchart is analyzed in this paper to prioritize the valorization of heat recovered in section 2. Even though direct use of recovered heat is neither technically nor economically feasible, it is the absolute way to valorize it.

The flow rate and heat source temperatures form the most common technical limits for waste heat to power (WHTP) applications. Among one of the most efficient technologies, Organic Rankine Cycle (ORC) is the most efficient technology where source temperature is below 400°C [4]. In section 3, a typical scheme for an ORC application in waste heat to power is described. In most applications, a heat carrier loop is necessary, but latest developments in technology enables direct heat exchange between the source and the working fluid.

Benefits and barriers of waste heat to power are presented in sections 4 and 5 respectively. Finally, conclusions are presented in section 6.

## 2 Heat recovery flowchart

There are different uses for the heat recovered via industrial processes, but to grant the most efficient use, Weng *et al.* [5] proposes an energy flow diagram for evaluating the potential for waste heat recovery (fig. 1). The primary energy is consumed by the industrial process itself, and only a portion of it can be considered as effective energy. Among the waste heat recovery potential, improving the optimization of the control system and production process should be prioritized to focus more on avoidable waste heat. When the optimization is not technically and economically effective anymore, the waste heat should be utilized by reusing on site via heat exchangers, heat pumps, heat storages and/or absorption cooler systems. In pursuance of avoiding energy losses, the last resort is to reuse the waste heat off site. This can be achieved through heating/cooling grids, or by transforming it into electricity (Waste Heat to Power – WHTP). The following flowchart is proposed by the authors to compile the priorities for heat recovery (Fig. 2).

As highlighted in fig. 2, in most cases, industrial processes are optimized and there are no other possibilities to utilize thermal energy then converting it into electricity. A high number of studies have been carried out in the recent past to evaluate the best performing technology for waste heat to power systems. As previously mentioned, when the heat source temperatures vary between 200 and 400°C, Organic Rankine Cycle technology is regarded as one of the most efficient [4].

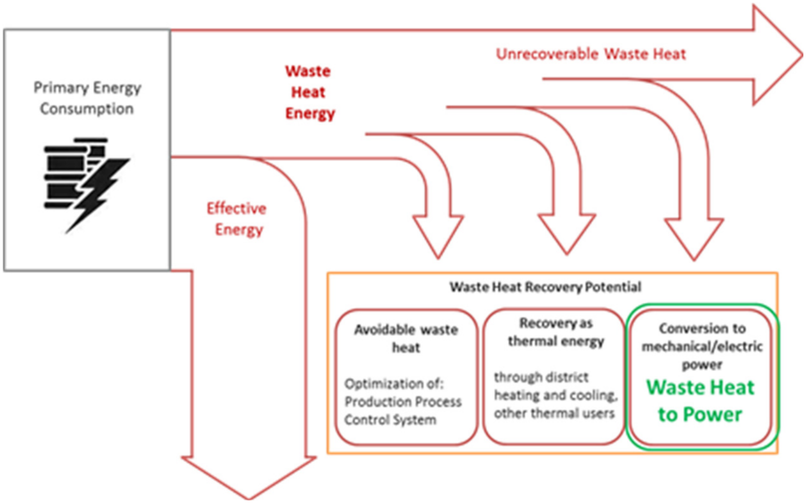


Figure 1: Energy flow diagram for evaluating waste heat recovery potential [5].

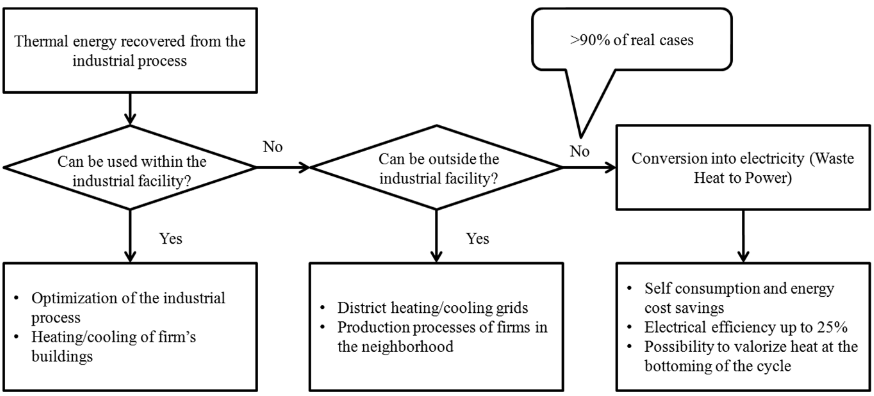


Figure 2: Flowchart of waste heat recovery priorities.

# 3 Waste Heat to Power with ORC technology

## 3.1 Typical schema

In fig. 3, a typical schema of a waste heat to power system is displayed.

Heat is wasted in the atmosphere through exhaust gases of fuel combustion or other hot streams by several industrial processes. When conditions of heat source temperature, flow rate and chemical composition are met, heat exchangers can be installed. Generally, the energy of the heat source is exchanged by a heat carrier

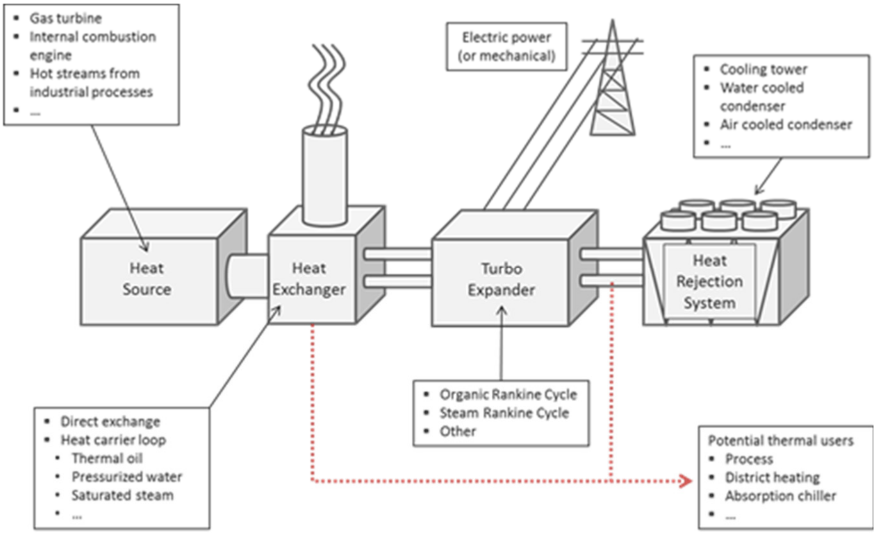


Figure 3: A typical schema of Waste Heat to Power system.

loop – usually thermal oil, saturated steam or pressurized water – for the sake of avoiding deteriorations in the working fluid caused by temperature peaks. A heat exchanger can be placed between the heat source and the working fluid, as long as the heat source is not corrosive and the process has temperature peaks within working fluid limits. This method is referred as "direct exchange". The Organic Rankine Cycle is shown in fig. 4.

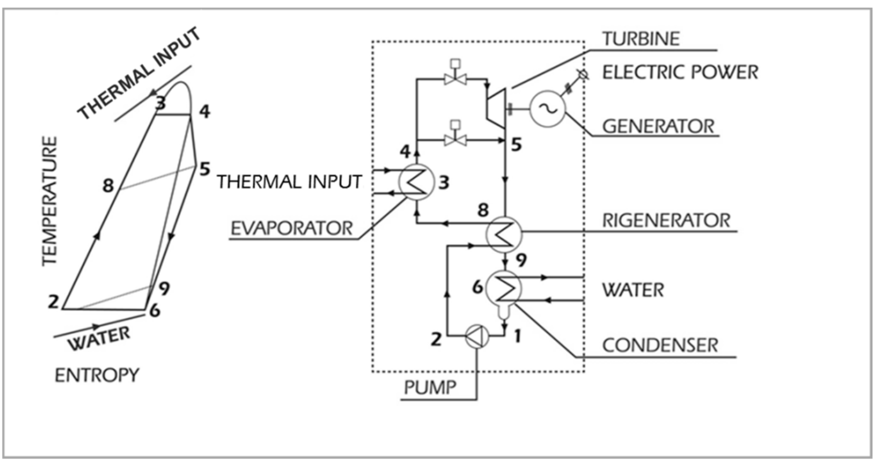


Figure 4: The typical configuration of Organic Rankine Cycle.

Hot temperature thermal input is used by the turbogenerator to pre-heat and vaporize the organic fluid in the evaporator (8→3→4). The organic fluid vapour powers the turbine (4→5), which is directly coupled to the electric generator through an elastic coupling. The organic liquid is heated (2→8) by the exhaust vapor which flows through the regenerator (5→9). Then, the vapour is condensed in the condenser (cooled by the water flow) (9→6→1). Finally, the organic fluid liquid is pumped (1→2) into the regenerator and then to the evaporator, thus completing the sequence of operations in a closed-loop circuit.

### 3.2 Heat transfer: heat carrier loop and direct exchange solutions

A circuit filled with thermal oil, saturated steam or equivalent is utilized by the ORC technology. The reason for this is to avoid the deterioration of the properties of the organic fluid in applications which temperature peaks are present. Furthermore, in some industrial processes, the cooling system operates with such fluids, which in turn makes it more convenient to feed the ORC system. However, a heat carrier circuit requires a higher investment due to complexity of the pipes and the increase in the self-consumption of the plant caused by the consumption of pumps and auxiliaries. Recently, an ORC manufacturer has come up with a solution consisting of a direct heat exchange between the source and the organic working fluid. The first direct heat exchange application in the field was launched in 2009, recovering exhaust has from an internal combustion engine running on biodiesel. Later, two other ORC units was introduced to projects alike. The second application using the same method was started up in February 2013; a project in which heat is recovered from rolling mills re-heating the furnace in a steel plant. Further projects concerning gas turbines and cement factories are currently under development.

## 4 WHTP benefits

The competitiveness of the industry can be enhanced through using the dispersed heat from waste, which is a valuable source of energy. When the heat of the dispersed gases is reduced through recovery, the temperature of the energy discharged to the environment reduces just as the necessity to cool the gases before the treatment. It is easily conceivable why several European directives noted wasted heat as an important resource. Although the Industrial Emissions Directive [2] involves no limits for heat emissions, the heat is numbered not only among emissions, but also among pollution. Heat recovery is stated as one of the typical measures in the reference documents which are developed in the framework of the directive for several industrial fields. The Energy Efficiency Directive [3] requests the wasted heat to be recovered for heating and cooling purposes when the benefits exceed the costs. The costs and emissions of heat generated by other sources, mostly non-renewable, are replaced by the costs and emissions of the recovered heat. In cases which the recovered heat is transformed into electricity, the emission-free energy brings down the necessity of withdrawing electricity from the grid, along with ruling out emissions and costs associated to the electricity that

Table 1: ORC heat recovery plant in energy intensive industries.

| Year | Site | Process | Currently in operation | ORC supplier | ORC gross power [MW] |
|---|---|---|---|---|---|
| 1999 | Heidelberg Zement, Germany | Clinker production | unknown | Ormat | 1.5 |
| 2010 | Italcementi - Ciment du Maroc, Marocco | Clinker production | Yes | Turboden | 1.8 |
| 2012 | Holcim Romania | Clinker production | Yes | Turboden | 4 |
| 2013 | Jura Cement, Switzerland | Clinker production | No | ABB | 2 |
| 2014 | Holcim Slovakia | Clinker production | Yes | Turboden | 5 |
| 2015 | Heidelberg Carpatcement Romania | Clinker production | Yes | Turboden | 4 |
| 2016 | Jura Cement, Switzerland - revamping | Clinker production | UC | Turboden | 2 |
| 2011 | Vetrerie Sangalli Manfredonia, Italy | Float glass | No | Ormat | 2.0 |
| 2012 | AGC Cuneo, Italy | Float glass | Yes | Turboden | 1.3 |
| 2014 | Sisecam, Targovishte, Bulgaria | Float glass | Yes | Exergy | 5.0 |
| 2014 | Sisecam, Meresin, Turkey | Float glass | Yes | Exergy | 5.5 |
| 2014 | Sisecam, Yenisehir, Turkey | Float glass | Yes | Exergy | 3.2 |
| 2015 | Owen Illinois, Villotta di Chions, Italy | Container glass | Yes | Turboden | 0.5 |
| 2013 | Natsteel, Singapore | Steel hot rolling mill | Yes | Turboden | 0.7 |

Table 1: Continued.

| Year | Site | Process | Currently in operation | ORC supplier | ORC gross power [MW] |
|---|---|---|---|---|---|
| 2013 | Natsteel, Singapore | Steel hot rolling mill | Yes | Turboden | 0.7 |
| 2013 | Feralpi ESF Riesa, Germany | Steel EAF | Yes | Turboden | 2.7 |
| 2013 | Trafilerie Gnutti, Italy | Brass furnace | UC | Exergy | 2.4 |
| 2014 | Fonderia di Torbole, Italy | Cast iron cupola furmace | UC | Turboden | 0.7 |
| 2014 | ABS Udine, Italy | Steel EAF | Yes | Exergy | 1.0 |
| 2015 | Ori Martin Brescia, Italy | Steel EAF | Yes | Turboden | 2.2 |
| 2014 | Undisclosed Germany | Aluminium furnace | UC | Turboden | 1.7 |
| 2016 | Aichi Steel, Japan | Steel EAF | UC | Turboden | 2.2 |
| 2016 | Arvedi Cremona, Italy | Steel EAF | UC | Turboden | 10.0 |
| 1991-2011 | Canada (7) USA (13), Spain (2) | Gas Compressor stations | Yes | Ormat | 3.5 - 7.0 |
| 2011 | Rosetown, Saskatchewan GCS, Canada | Gas Compressor station | Yes | Turboden | 1.0 |
| 2015 | Lokoil Osa Perm, Russia | Flare gas | Yes | Turboden | 1.8 |
| 2014-2015 | Canada (1), Brunei (1), Thailand (1), China (3) | Gas Compressor stations | UC | General Electric | 17.0 |
| 2013-2015 | Philippines (2) and China (2) | Petroleum industry | unknown | Kaishan | 0.4 - 1.8 |
| 2016 | Uzbekistan | Gas Compressor stations | UC | Turboden | 1 |

was used to be purchased. The WHTP system can be synergic with gas treatment, creating an environment where generating electricity from recovered thermal energy can supply the electricity requirements of the gas treatment unit, together with providing a marginal increase to the investment and reducing the payback time of the whole project. In some cases, there can also be possible synergies with the external use of recovered heat, improving the benefits. The capability and efficiency of the ORC in partial load ensures its suitability for district heating/cooling purposes since in such cases demand varies seasonally. The ORC can work at partial load in peak season and full rate in low season to optimize heat recovery all year round while minimizing the payback time of the complete system. Hence, heat recovery for electricity generation proves to be not just an alternative, but a better alternative to the heat recovery for heating and cooling, promoted by the Energy Efficiency Directive, in some cases.

### 4.1 A sustainable industry

European directives and national laws aim to reduce pollution, emissions and the energy consumption. This they require energy-intensive industries to become more sustainable. Such requirements are controlled thoroughly in emissions/environmental authorization phase, along with the evaluation of the feasibility of the connection to district heating/cooling to exploit the dispersed heat. As sustainability strengthens its impact on competitiveness through lowering the cost of energy production and increasing the sustainability of other products, its benefits on the industry is perceived more by the public.

### 4.2 Economic feasibility

There is no fuel cost in a WHTP system and the value of the generated electricity is almost equivalent that of cash flows since the electricity is not bought from the grid, but self-produced and consumed. The costs for operation and maintenance are low, often vary between 5–10% of the cash flow. Given that we focus on the WHTP system alone, there are heavy links between economic feasibility and the price of electricity. There are several calculations readily presented [6] about cement, glass, steel, and gas compressor stations which indicate a payback time of 7–9 years, when electricity purchase (0.07–0.08 €/kWh) is avoided.

Incentives and absence of higher electricity costs may reduce the payback time significantly, thus making WHTP interesting from a financial point of view.

WHTP systems can increase the competitiveness of metallurgic, glass, and cement industries by 6%, 13%, and 14% respectively [7].

A WHTP system, typically, is a part of a larger system, such as in a gas treatment unit or a district heating project. Implementing a WHTP system is an additional investment, though it reduces payback time and hikes the environmental performance of the whole system.

## 5 WTHP barriers

To begin with, energy efficiency investments can be hindered in cases where lack of certain and long-term regulatory frameworks and unrealistic targets of energy efficiency are present. Essentially, the energy efficiency directive 2012/27/EU is a promising move, although it is vital for member states to take the potential of heat recovery applications into consideration during the implementation phase, specifically referring to article 8 and article 14 in which support for recovery of waste heat is endorsed and mandatory energy audits for large enterprises are to be assigned. A WHTP system does not exclude heat recovery to feed district heating or cooling systems, proven by the case on the electric arc furnace previously presented in this paper. Such measures can catalyze investment in the market for energy efficiency, thus help to achieve the objective of 20% reduction in energy consumption. On the occasion of the energy audit, more attention should be focused on the gas cooling, often necessary before the water gas treatment, as it is possible to implement heat exchanger(s) and Rankine cycle instead of using air for the cooling down process. This method can be used to cover the electricity consumption of the waste treatment.

A system with WHTP involves cogeneration, which can be defined as "simultaneous generation in one process of thermal energy and electrical or mechanical energy" [3, 8]. The framework set up by the Directive 2004/8/EC supports [9] high efficiency cogeneration, and not every system with WHTP is supported. The directive excludes WHTP unless the heat produced is "useful heat"; production which can address an economically justifiable demand. The types of cogeneration systems which are supported by the directive conduct heat production after the electricity generation cycle, while on the other hand, in WHTP systems heat is produced before the cycle. The reasoning behind producing heat before the electricity generation cycle comes from the fact that heat loses great temperature after the cycle, resulting in a state with very limited practical uses. Thus, WHTP systems are not supported by the high efficiency cogeneration framework. Taking WHTP's different characteristics into consideration, even though a way of support is necessary to make WHTP investments appealing to investors, a supporting system designed for cogeneration might not be suitable for WHTP in particular.

Economic difficulties form the biggest issue on the path of WHTP's development, since payback times for the implementation of technologies related to WHTP are often very long for the industrial player. Hence, modifying existing support schemes or forming new ad hoc incentives might provide a solution. Taking the impact of energy-intensive industries on energy consumption into account, legislative bodies should give higher importance into designing specific provisions to finance investments in this field.

## 6 Conclusions

ORC powered WHTP systems continue to increase their numbers in energy-intensive industries and gas compressor stations. The reliable performance of the ORCs in renewable energy sector over the last three decades, combined with the credibility of widely used heat exchangers shows promising signs for the future of WHTP systems. The HREII demo project, which started-up in 2013, is a great example to prove the feasibility of waste heat recovery for power generation while contemporarily feeding a district heating. Involvement of an Electric Arc Furnace, furthermore adds complexity to the batching process.

WHTP applications are favorable in economic and environmental point of views in many sectors. Even though a longer payback time isn't admired by the industry overall, a WHTP system is a small component of a larger system in which this can be tolerated. A supporting mechanism, specifically tailored for such systems, should be introduced in order to promote the distribution of WHTP systems.

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