Industrial excess heat exploitation in energy intensive industries

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Abstract

Resource efficiency is a matter of survival especially for the energy intensive industries, as the international competition gets tougher and environmental concerns rise in line with the COP21 agreement. Due to their relevant energy expenditure, the energy intensive industries are usually very active in energy efficiency and in most cases have already picked the low "hanging fruit", implementing efficiency measures that have low investments and short payback time.

In many energy intensive industries it is possible to recover considerable amounts of heat otherwise wasted to the environment, considering that the internal demand for lower temperature heat, if any, is usually already satisfied. The external use of this heat, if a civil or industrial demand exists, can be an opportunity, but requires large investments has long payback time and requires co-operation by external user(s). If the recovered heat has temperature above 250 °C, a way to generate value from it is to convert it into electricity, usually self-consumed by the industrial plant. The diffusion of waste heat recovery for electricity generation differs by sector: in the glass and scrap based steel production (electric arc furnace) sectors there are about 10–20 plants installed worldwide[1]. The situation is quite different for the cement sector with over 800 waste heat recovery plants installed around the world, mostly in Asia and about five in European Member States.

This paper analyses the configuration, specification, working data, economics and emission reductions of some ORC based waste heat recovery systems in Europe in each of the three above sectors. Some of these systems are also connected to a district heating network, an interesting synergy with local initiatives. The paper also draws possible further developments of the ORC based waste heat recovery for electricity generation systems increasing the recovered energy, the efficiency of transformation and lowering the investment cost making these systems more appealing for decision makers.

Introduction

There are various definitions of industrial excess heat [1], hereafter it is used to indicate the heat discharged directly or indirectly into the environment by an industrial process [2]. This heat can have many names (e.g. waste industrial heat, residual industrial heat, recovered heat, etc.) and be considered in different ways, a "by product" that can be reused or sold [3], "waste heat to satisfy economically justified demand" [4] or an "emission" or "pollution" [2].

The term industrial excess heat was preferred discussing of waste heat recovery for electricity generation in order to avoid potential confusion with "waste to energy", indicating also the electricity generation from waste incineration.

Of the energy entering into an industrial process (Figure 1), only a fraction is effective energy, used by the process, the rest, the excess heat, returns to the environment. It is possible to reduce the share of excess heat working on the process, but once the technical and economical optimization of the process has

1. For glass and steel it wasn't possible to find information on the plants in India and China, so it can be an under estimation.

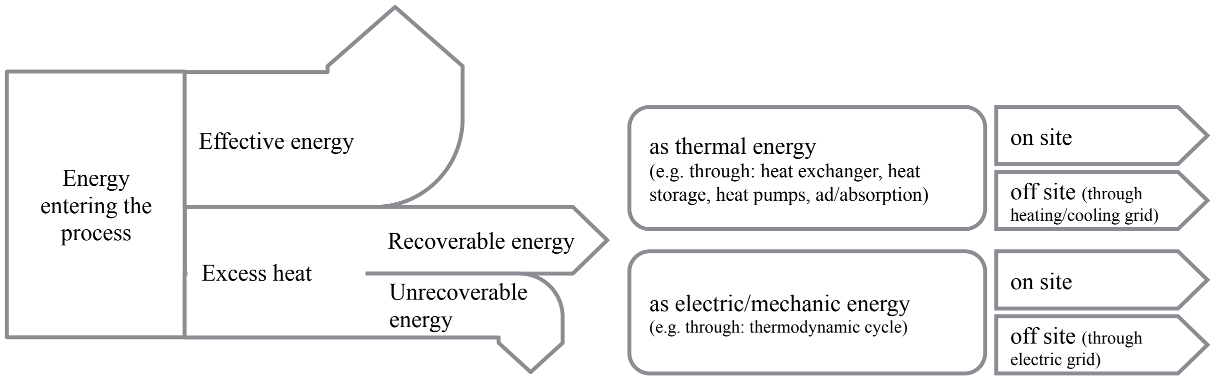

Figure 1. Energy flows and excess heat recovery options.

been reached, it should be considered how to exploit the excess heat. The recoverable part of the excess heat is a function of the availability of user(s) of the recovered energy and of the costs of recovering, eventually converting and delivering it. The priority goes to the use of heat on site through heat exchangers, heat storage, heat pumps to upgrade the heat or ab/adsorption system for cooling/conditioning or refrigerating, since the investment costs for these solutions is lower. If there are no on site uses of thermal energy, off site use of thermal energy or its conversion in another form of energy should be considered. The recovered thermal energy can provide heat or cool for external users connected directly or trough heating and cooling networks. The conversion of the heat in electric or mechanic energy usually allows to use it on site, even if the electricity can also be exported to the grid. The conversion can be preferable to external use since it doesn't impose bonds or links, but the two uses aren't only alternative, but can also coexist with interesting synergies [7]. The topic is of particular interest due to the recent deadlines of the energy audit for not SME[2] requiring in many cases an assessment of the technical and economic feasibility of connection to an existing or planned district heating or cooling network according to article 8 energy efficiency directive and on the previous comprehensive assessment according to article 14. Various comprehensive assessments give some information on ORC applications or even give some evaluations, but as noticed in one [5] of them, there is a lack of sectorial overview of the profitable ways to exploit the excess heat, including the ORC and especially for ORC a lack of knowledge among companies and consultants.

The paper gives an overview of the most interesting opportunities of excess industrial heat recovery for electricity generation and cogeneration, also combined with district heating networks, taking in account only heat recovery for electricity generation systems with an electric power of 0.5 MW and above. Under this size the specific cost of ORC and heat recovery systems becomes higher, making excess heat recovery applications less appealing unless specific supporting mechanisms are present. It is worth mentioning that are available on the market ORC of various sizes, around and under 100 kWe and that those sizes will probably benefit in the future of cost reductions due to the higher standardization and number of unit produced.

The particular features of ORC machines match the characteristics of many excess industrial heat recovery application around Europe, where industrial plants have usually smaller sizes compared to the ones in Asia and thus it is not economically justified to have dedicated personnel to manage the system. The dimension of the plants is one of the reasons for the wide diffusion of steam cycle in the cement and iron&steel (e.g. sinter plants) sectors in Asia. In particular in China there are over 700 of the over 800 excess heat to power system in the cement sector worldwide [6] also thanks to the fact that this measure is so effective for the cement sector that it has become compulsory by law.

ORC characteristics

The characteristics making the ORC particularly apt for medium and low temperature heat recovery for electric power generation applications are linked to the high molecular weight and specific saturation curves of organic fluids, making the shapes of the cycles of water and organic fluid sensibly different (Figure 2). Not going to a detailed comparison of the two cycles [7], the main distinctive characteristics of ORC systems making them particularly interesting for heat recovery and power electricity generation are: lower operating pressure, low enthalpy drop across the turbine (leading to more efficient turbines, lower number of stages required, lower speed), flexible operations to variable loads, high efficiency also at partial load, high overall efficiencies, no risk of blade erosion also at very low load (down to 10 % of nominal load), completely automatic systems, low O&M requirements, no water consumption, being a closed cycle. To raise the efficiency the ORC, the turbogenerator is usually equipped with a regenerator. The heat exchanged in the regenerator is represented in Figure 5 by the dotted line.

ORC based industrial excess heat exploitation in Europe

CEMENT INDUSTRY

The first and so far the only example of ORC excess heat recovery for electricity generation present in a BREF (Best Available Technique References in the framework of [2]) is the ORC installed at the cement plant in Lengfurt, Germany. This was the first ORC application in the cement industry and

2. Article 8.4 of the energy efficiency directive [4] requires the Member States to ensure that enterprises that are not SMEs undergo a high quality, independent energy by 5 December 2015 and then every four years. Moreover according to art. 8.7 Member States may require, within the energy audit, an an assessment of connection to an existing or planned district heating or cooling network.

recovers only the energy of the clinker cooler (CC), 9 MW at 300–350 °C, covering 9 % to 12 % of the electricity needs of the plant [8]. The other ORC systems installed in cement plants in Europe (Table 1) have a two step heat recovery scheme, with also a second heat exchanger (HX) recovering heat at about 300 °C from the exhaust gases downstream the cyclone preheater (CP). As represented in the scheme below (Figure 3), when both CC and CP heat sources are available, a very efficient heat recovery system can be deployed, making the ORC cycle following very well the shape of the heat source minimizing the exergy losses, allowing to achieve overall net efficiencies (thermal power to electric power) above 22 %. Such configuration was installed in plants in Slovakia and Fieni (Romania).

Thanks to this and other optimizations of the heat recovery system, an ORC based heat recovery system can produce as much as about 20 % of the plant electricity consumption.

To better exploit the heat at lower temperature from the clinker cooler heat exchanger (gas temperatures drop from 300 °C to around 100 °C) there are two thermal oil to organic fluid heat exchangers (Figure 4). The organic fluid running the cycle was selected to optimize the double thermal oil to organic fluid heat exchangers configuration: the almost parallel profiles of thermal oil and organic fluid minimizes the exergy losses hence improves the overall efficiencies. In Figure 5 it is represented the cycle of the organic working fluid (in black), with the lower part that is run in the regenerator. The left curve of the cycle over the regenerator and the profile of the thermal oil are almost parallel [9].

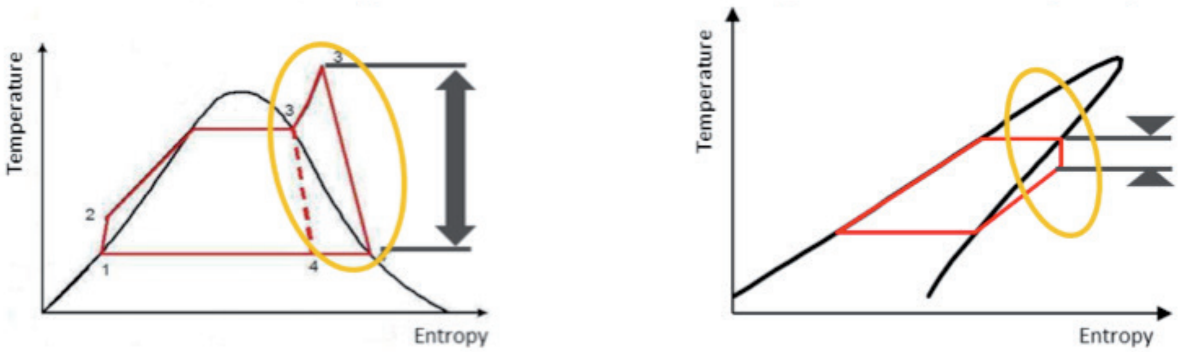

Figure 2. Rankine cycles of water/steam (on the left) and organic fluid (on the right).

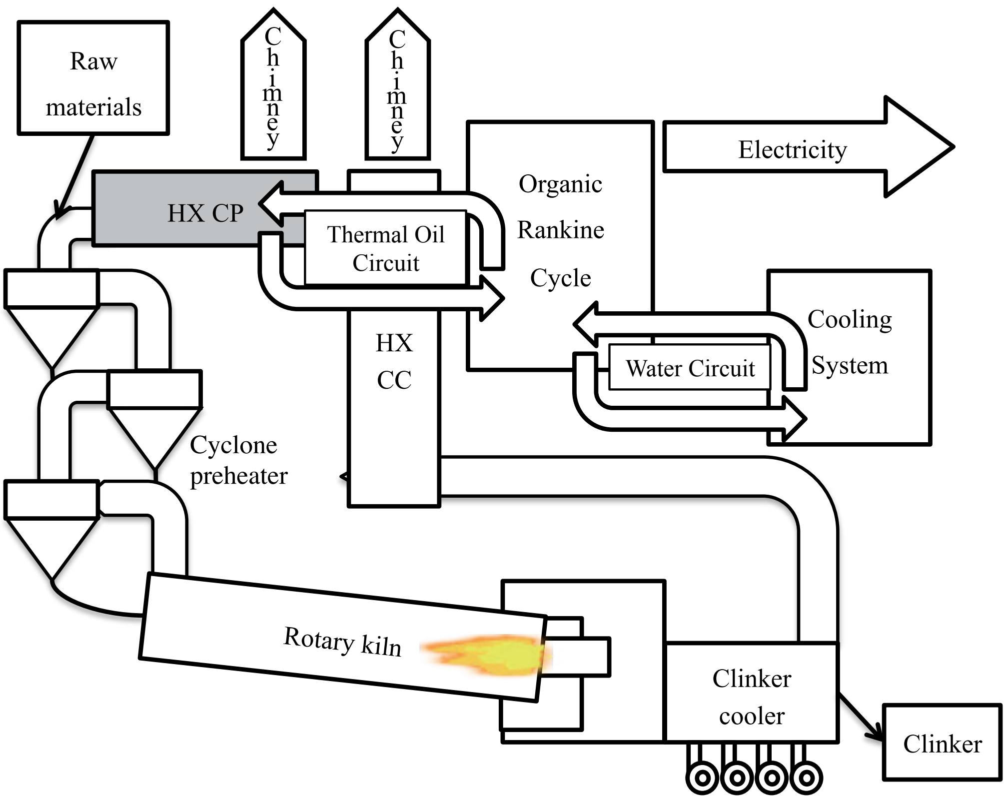

Figure 3. Scheme of heat recovery system in cement plants. The parts in grey are not present in all the systems.

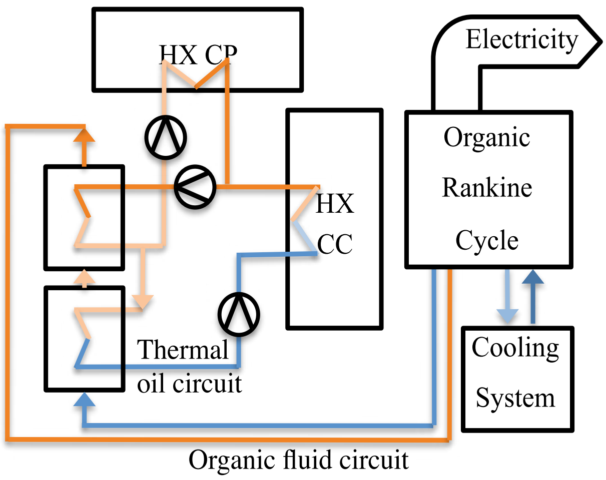

Figure 4. Configuration of heat exchangers for gaseous flows to thermal oil and for thermal oil to organic fluid.

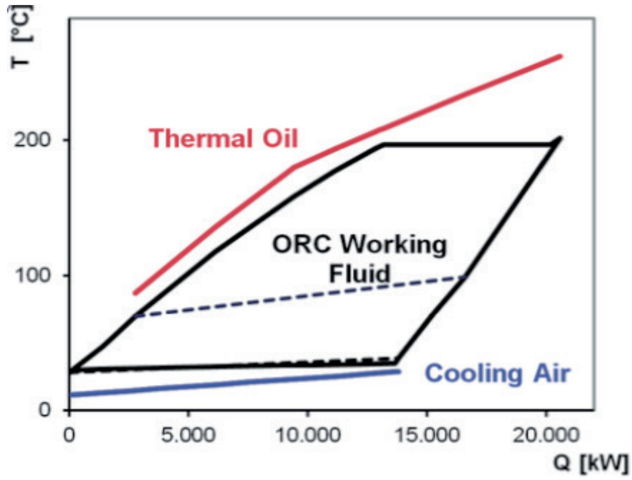

Figure 5. ORC Thermodynamic cycle for a heat recovery system in a cement plant in Temperature-Power diagram.

Table 1. ORC heat recovery plants in the cement industry in European Member States plus Switzerland.

Year	Cement Plant	ORC Manufacturer	ORC gross power [MW]
1999	Heidelberg Zement, Lengfurt, Germany	Ormat	1.5
2012	Holcim, Aleșd, Romania	Turboden	4
2012	Holcim, Untervaz, Switzerland	ABB	2
2013	Jura Cement, Wildegg, Switzerland	ABB	2
2014	Holcim, Rohoznik, Slovakia	Turboden	5
2015	Heidelbergh Cement, Fieni, Romania	Turboden	4
2017 (*)	Undisclosed, Italy	Turboden	2

(*) Under construction when writing the paper.

Table 2. ORC heat recovery plant in the refractory industry in European Member States.

Year	Refractory production	ORC Manufacturer	ORC gross power [MW]
2008	RHI GROUP, Radenthein – Austria	Turboden	1

REFRACTORY INDUSTRY

A process somehow similar to the cement production is the production of refractory, a type of material used for high temperature applications (above 500 °C).

In this production process the raw material is "cooked" in tunnel ovens at relatively high temperatures, leaving exhaust gas available for heat recovery. An ORC for waste heat recovery has been effectively employed to recover heat from these combustions gasses at about 400–500 °C (Table 2).

GLASS INDUSTRY

Glass production processes can be divided into two main types, flat glass and hollow glass. The exhaust gases of the oven usually firstly exchange heat with recuperative or regenerative burners and eventually with other heat exchangers to preheat the combustion air, though it is still possible to recover heat at temperatures over 300 °C, even considering a limit to the lower cooling temperature to avoid the risk of pollutants condensation in the heat recovery exchanger. The temperature and recoverable heat from a single production line aren't usually sufficient to feed a reasonable size steam turbine [10], so ORC is an interesting solution where there is only one furnace. The first ORC systems (Table 3) were installed in flat glass plants, since the flue gases are cleaner and the oven works continuously for 15 years. It is possible to estimate 30–55 kWh of electricity generated per ton of glass produced [11].

In 2015 the first installation of ORC waste heat recovery in the hollow glass was installed. Hollow glass production plants are typically smaller than flat glass ones and the production is more discontinuous, hence leading to smaller ORC sizes (e.g. less than 1 MWe), though the number of hollow glass plant is considerably greater than flat glass (e.g. 10 times more), making hollow glass heat recovery a very interesting opportunity for heat recovery.

It's worth to mention also the two glass plants realized in 2015 in Turkey (Table 4).

METAL INDUSTRY

Steel production

The metal industry counts a very large number of potential processes that could be subject of excess heat recovery. This paper present the processes with existing ORC heat recovery systems, while for the other processes summarizes the most relevant ones in terms of production volumes deepening the analysis for the most attractive production processes. By far the most important process is steel production, counting hundreds of production sites worldwide. The steel production can be divided in two main sources, either primary or secondary production. Primary steel production uses iron ore as raw material: after a first sintering process to acquire the proper physical characteristics needed in the following production steps, the ore is fed to a blast furnace for the production of cast iron. Cast iron is finally converted to carbon steel in Basic Oxygen Furnace (BOF). In the secondary production scarp steel is used as raw material, which is melted in Electric Arc Furnaces (EAF) [12]. Thanks to its flexibility and simplicity of operation also in part load conditions, the most appealing applications for ORC based heat recovery in the steel production are from EAF, BOF and sinter processes.

Figure 7 represents an ideal heat recovery scheme for ORC based heat recovery systems coupled to EAF and BOF furnaces.

Hot fumes exiting EAF and BOF furnaces are at temperature ranging, when operating at nominal load, between 1,000 and 1,200 °C. These processes are highly discontinuous: at the end of each melting cycle the vessels containing the melted steel must be emptied and the process is stopped for some minutes. A heat recovery system coupled to these heat sources will be made of two sections, one at higher temperature (e.g. above 600 °C) mostly driven by the radiant heat exchange with the suitable exchanger geometry (e.g. the so called "pipe-to-pipe" heat exchanger), and a second, at lower temperature (e.g. below 600 °C) mainly driven by a convective heat exchange.

Many EAF suppliers (e.g. Tenova, Primetals, etc.) have developed improved systems that allow to use the hot gasses to pre-heat the scrap steel and also to make the process more continuous and stable. In these cases the fumes for heat recovery are available at about 600–800 °C, therefore only the convective section is typically pursued.

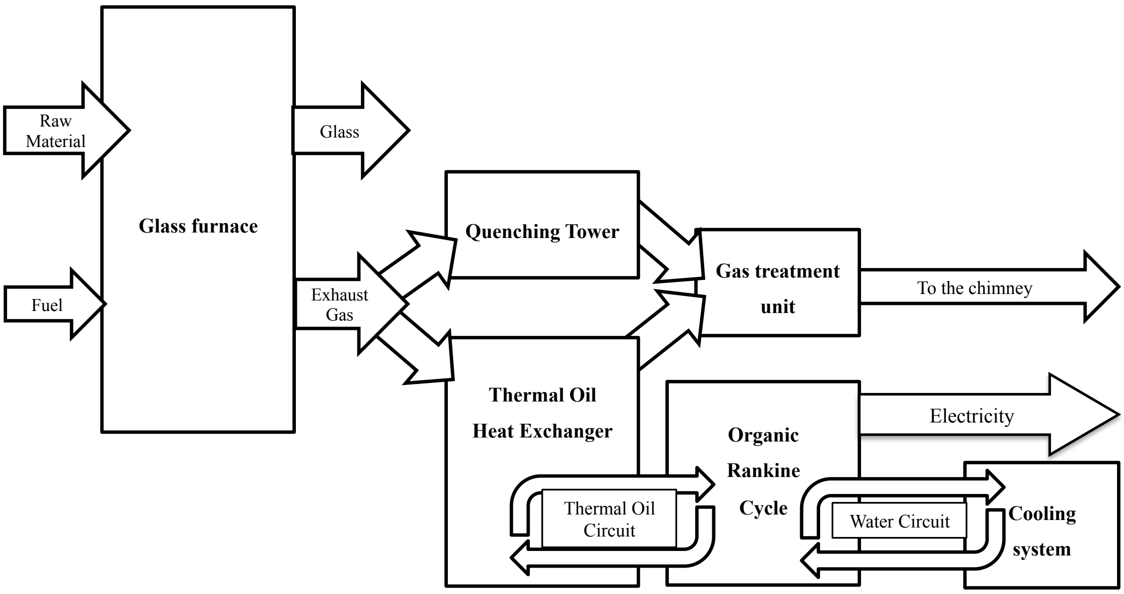

Figure 6. Scheme of heat recovery system in glass plants.

Table 3. ORC heat recovery plants in the glass industry in European Member States.

Year	Glass Plant	ORC Manufacturer	ORC gross power [MW]
~~2011~~	~~Vetrerie Sangalli, Manfredonia – Italy*~~	~~Ormat~~	~~2.0~~
2012	AGC, Cuneo – Italy	Turboden	1.3
2015	Şişecam, Targovishte – Bulgaria	Exergy	4.8
2015	Undusclosed, Italy	Turboden	0.5

** The glass plant closed due to the economic crisis.*

Table 4. ORC heat recovery plants in the glass industry in Turkey.

2015	Şişecam, Yenisehir – Turkey	Exergy	4.8
2015	Şişecam, Mersin – Turkey	Exergy	5.5

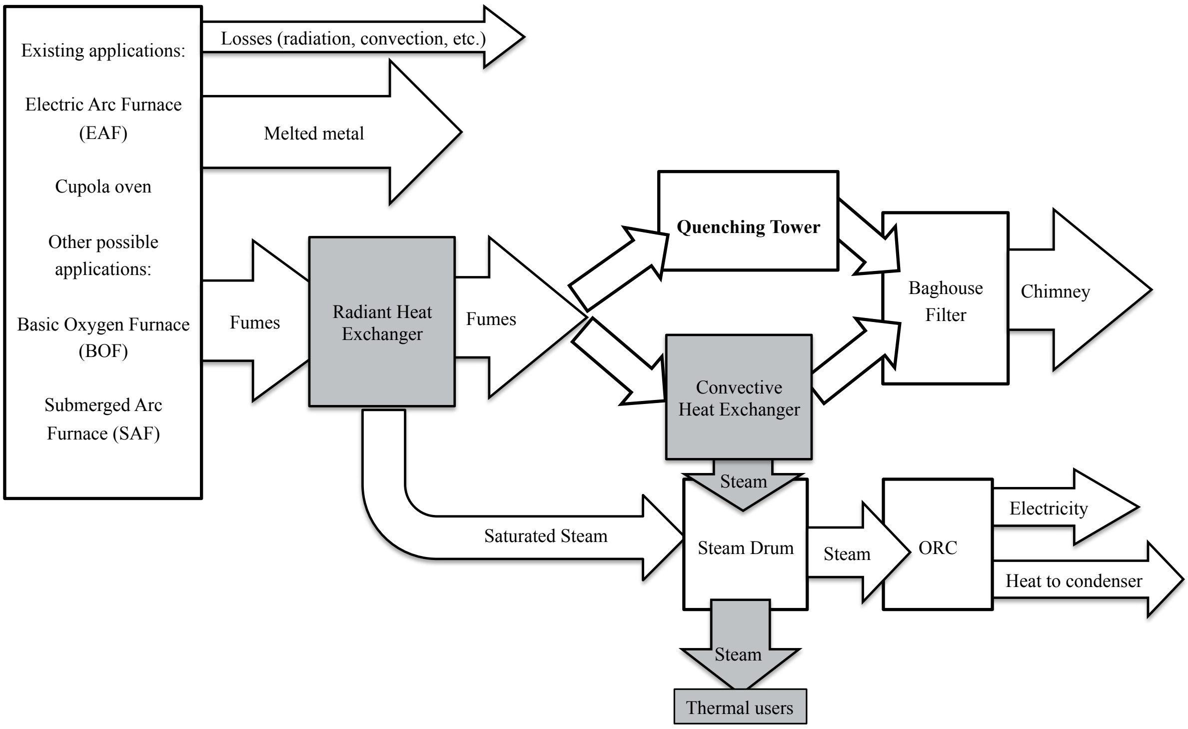

Figure 7. General scheme of heat recovery system with ORC from EAF, cupola oven, BOF and SAF in the iron & steel sector. The parts in grey are not present on all the systems.

Table 5. ORC heat recovery plants in the steel industry in European Member States.

Year	Iron and steel. Electric Arc Furnace	ORC Manufacturer	ORC gross power [MW]
2013	Elbe-Stahlwerke Feralpi, Riesa – Germany	Turboden	2.7
2015	Acciaierie Bertoli Safau, Udine – Italy	Exergy	1
2016	Ori Martin, Brescia – Italy	Turboden	1.9
2016 (*)	Arvedi, Cremona, Italy	Turboden	10

(*) Under construction when writing the paper.

Table 6. ORC heat recovery plants in the iron industry in European Member States.

Year	Other metals	ORC Manufacturer	ORC gross power [MW]
2013	Cast Iron – Cupola oven FMGC, Soudan France	Enertime	1
2016 (*) (**)	Cast iron – Cupola oven Fonderia di Torbole, Italy	Turboden	0.7

(*) Under construction when writing the paper.

(**) Fonderie di Torbole, Italy had a pilot plant in the 1996 and now the revamping with a 0,7 MW is under construction.

Table 6 provides some indication about the energy that can be recovered in relation to the EAF capacity.

Cast Iron

Primary cast iron is produced in the form in large ingots from blast furnaces (see previous paragraph). These ingots are used to produce the final products: they are melted in cupola furnaces and cast to acquire the wanted final shape. Being cast iron a material used for many purposes, there are many potential industries that could benefit employing an ORC based system to recover the waste heat present in the combusted gases.

Aluminium

The main processes for primary aluminium production involve a chemical reaction and an electrolysis process. Neither of these processes releases significant amounts of heat at high temperatures so they are not very interesting for ORC based heat recovery systems. Additionally, since the electrolysis process is a great electricity consumer, typically primary aluminium plants are installed where the cost of electric energy is very low, lowering the convenience of electricity self-generation by means of heat recovery but rather a dedicated power plant is present.

Secondary aluminium is more interesting for ORC based heat recovery systems to recover heat downstream the melting furnaces. Indicatively, the electric output that can be generated with an ORC based heat recovery system coupled to a secondary aluminium production plant is about or 4–6 kWe per ton of capacity, corresponding to about 3–5 % of the furnace installed power (Table 8).

Copper

The primary copper production comes from conversion of sulphide ore, involving a very large amount of hot gas generated in the smelting furnace. Since the smelting process is relatively stable and the plants relatively large, often the most traditional steam based Rankine cycle is often used to exploit the waste heat recovery. However, ORC based systems could be deployed as an alternative to steam cycles.

Secondary copper, especially its alloys, can be divided in two families: either those cases in which the raw material is relatively clean, or when the raw material is widely mixed with waste material like plastics and oil. While for the former cases an inductive kiln can be used, leveraging the high conduction capability of copper and leading to very high energy efficiency practically leaving no space for heat recovery, the latter involve both combustion and post combustion of the fuel and waste contaminants present with the raw material, leading to a relatively high amount of heat wasted to the chimney. An interesting application for an ORC based heat recovery system (Table 9).

Metal Silicon

Metal silicon is produced by reducing silica to silicon. This reaction takes place at very high temperatures in Submerged Arc Furnace (SAF) using carbon-based reductants. SAF process is relatively similar to the EAF (Figure 7): main differences are the lower exhaust gas temperature and dust content.

As EAF for steel production, SAF for metal silicon offers a potential for ORC heat recovery.

Others

There are various other metallurgic processes interesting for the application of excess heat recovery for electricity generation, but the number of plants is low or null in Europe. For example, in 2015 a 5 MW ORC at a platinum conversion process was installed in South Africa.

OIL & GAS

ORC technology can be a very interesting technical solution for waste heat recovery from oil and gas infrastructure equipment. Many are the potential application fields, such as: hat recovery in gas compression stations downstream gas turbines (in Northern America there are various installations), leveraging the combustion heat of Associated Petroleum Gas (APG) or flare gas, heat recovery from hot streams in production/refining processes (e.g. hot streams out coming distillation columns, etc.), cooling power heat recovery (e.g. in regasification processes), heat recovery from the hot water present from exhausted oil wells (similarly to geothermal applications), etc. [13].

CARBON BLACK

Carbon black is a chemical product mainly used in the tyre production. It is produced by thermal decomposition of hydrocarbons at high temperatures. As reported in Figure 8, there are several opportunities to recover heat in the production process to feed an ORC based system: after the reaction

Table 7. ORC power as function of the EAF capacity and of the heat exchangers.

		EAF capacity				
		60t	90t	110t	200t	300t
Convective only heat recovery	MWe at generator terminal	1	2	2.5–3	5	7
	ORC specific cost [€/kW]	1,300	1,100	950	800	700
	Overall CAPEX [€/kW]	3,500	3,200	3,000	2,800	2,500
Convective and radiant heat recovery	MWe at generator terminal	2	3	4	7	9
	ORC specific cost [€/kW]	1,100	950	850	700	600
	Overall CAPEX [€/kW]	3,200	3,000	2,800	2,500	2,200

Table 8. ORC heat recovery plant in secondary aluminium industry in European Member States.

Year	Secondary aluminium	ORC Manufacturer	ORC gross power [MW]
2014	Undisclosed, Germany	Turboden	2

Table 9. ORC heat recovery plant in secondary copper industry in European Member States.

Year	Secondary copper	ORC Manufacturer	ORC gross power [MW]
2015	Brass Gnutti, Chiari – Italy	Exergy	1.2 + 2.4

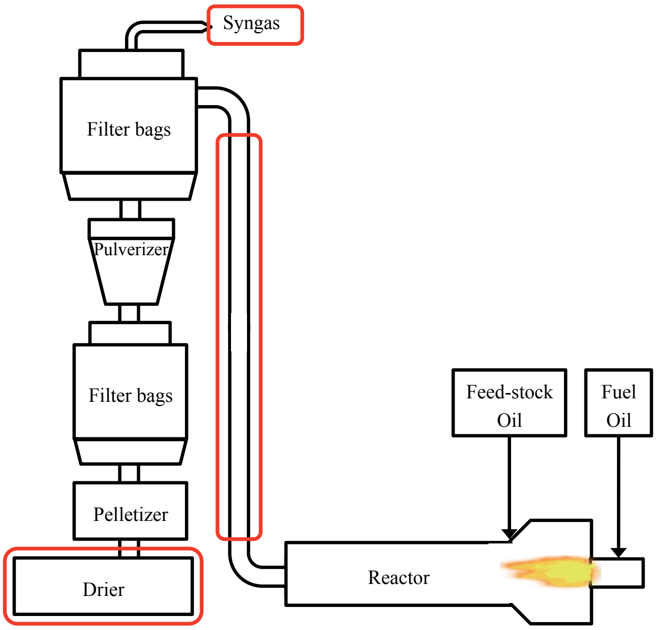

Figure 8. Furnace black manufacturing process summarized, with circled in red the potential sources for ORC mechanical or power generation.

to cool down the syngas, downstream of the dryer or directly using the syngas formed as by-product in the production process.

Figures, economics and avoided emissions

The total installed electric power of the plants presented in the previous tables is around 40 MW at the end of 2015, but will reach 50 MW at the end of 2016 taking into consideration the plants under construction when writing the paper (Figure 9). The cement sector, the first to install ORC for excess heat recovery represent around 50 % of the installed power in 2015, but the steel sector is rapidly growing and considering all the metals together they will equal the installed power of the cement sector at the end of 2016.

By analysing the working data of three of the plants presented in the previous tables it is possible to calculate the average yearly net electricity generation efficiency (considering also the consumptions of diathermic oil pumps and coolers) and their availability of the waste heat recovery and electricity generation system.

PERFORMANCE AND AVAILABILITY

- Heidelbergh Romania: Indicative ORC Efficiency over 22 %, availability in the last year of operation >98 %.
- Feralpi Germany: Indicative ORC efficiency around 20 %, availability in the last year of operation >96 % (not considering the downtime related to the failure of an electric component external to the ORC unit).
- AGC Italy: Indicative ORC efficiency around 23 %, availability in the last year of operation >98 %.

In Table 10 are summarized the main characteristics of the installation in the three sectors, with typical power range of the ORC generator, annual working hours, range of investment, annual operation and maintenance costs and characteristics of the flue gases.

To evaluate the economics (Table 11) of these applications, since those are heavily influenced by the price of electricity, it has been decided to calculate the present specific cost of the electric MWh produced, obtained dividing the total present expenses (investment plus operation and maintenance) actualized with an interest rate of 4 % by the total electricity produced on a period of 20 years (15 for float glass). Two cases are presented for the usual maximum number of hours and 5,000 hours per year.

The avoided greenhouse gas emissions are evaluated considering the emissions of the thermo electric generation, since in case of additional production or on the other way around of lower withdrawn of electricity from the grid, it is plausible to consider that there will be a lower production from thermo electric plants feed with natural gas, oil, coal, etc. and not from renewable or nuclear generation plants. The lower limit is around 400 gCO_2/kWhe, considering all thermoelectric gener-

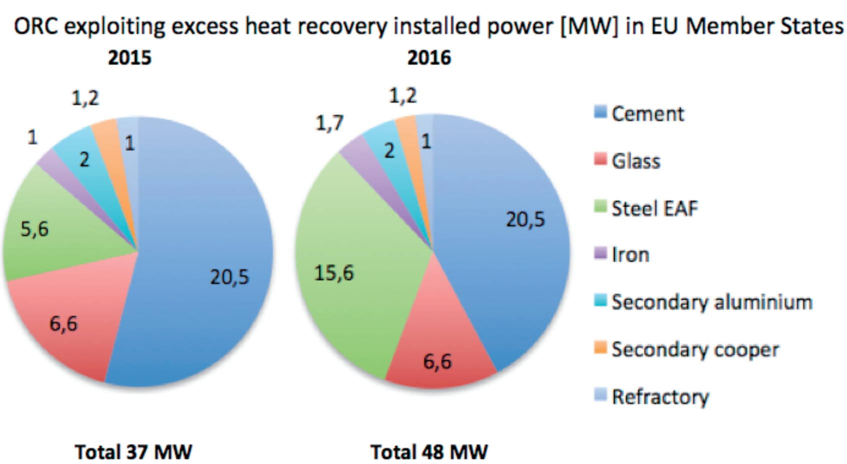

Figure 9. Total installed ORC excess heat recovery to electricity generation power in European Member States by sector.

Table 10. Main figures of ORC systems installed in cement, metal and glass sectors.

Criteria ↓ / Application →	Cement	Iron & steel EAF	Glass
Power output [MWe]	3–5	2–10	0.5–3
Annual working hours	Up to 7,900	Up to 7,500	Up to 8,500
Investment cost (1) [€/kW]	2,000–3,500	2,000–4,000	1,500–4,000
Operation and maintenance costs	About 2 % of investment cost	About 2 % of investment cost	About 2 % of investment cost
Typical heat source temperatures & characteristics	300 °C–350 °C Several sources High dust content Dry dust	700 °C–1,200 °C Cycling High dust content	350 °C–450 °C Constant flows Moderate dust content Sticky dust

(1) Referred to turn key installation without civil and electric connections.

Table 11. Electric production, costs and avoided emissions of ORC based excess heat recover systems in cement, metal and glass sectors.

		Cement				Iron & steel EAF				Glass			
Power output [MWe]		4				6				1.5			
Investment cost (1) [k€/MWe]		2.2		4.2		2.2		4.8		1.7		3.6	
Investment cost (1) [M€]		8.8		16.8		13.2		28.8		2.6		5.4	
O&M [k€/year]		176		336		264		576		51		108	
Present Value [M€]		14.3		27.2		21.4		46.6		4.1		8.7	
Working hours [khours/year]		5.0	7.9	5.0	7.9	5.0	7.5	5.0	7.5	5.0	8.5	5.0	8.5
Production [GWh/year]		20.0	31.6	20.0	31.6	30.0	45.0	30.0	45.0	7.5	12.8	7.5	12.8
Avoided emissions [$ktCO_2$/year]	(400 $kgCO_2$/MWh)	8.0	12.6	8.0	12.6	12.0	18.0	12.0	18.0	3.0	5.1	3.0	5.1
	(900 $kgCO_2$/MWh)	18	28	18	28	27	41	27	41	7	11	7	11
Production [GWh/20 years]		400	632	400	632	600	900	600	900	150	255	150	255
Present production cost [€/MWhe] 20 y		35.6	22.5	68.0	43.0	35.6	23.8	77.7	51.8	27.5	16.2	58.3	34.3
Present production cost [€/MWhe] 15 y										32.1	18.9	68.0	40.0

Note: the ranges given are related to the several factors that could influence the cost, primarily the size but also the specific layout, the type of cooling system, the specific process characteristics, etc.

(1) Price indication for the overall investment is estimated based on similar projects. Detailed analysis shall be carried out case by case in order to identify fumes and exchangers equipment to be integrated/supplied.

ation by natural gas feed combined cycle, the situation of Luxemburg. The upper limit of around 900 gCO_2/kWhe considers thermoelectric mixes of some Member States with a relevant share of steam cycles feed by coal or shale oil.

Further developments

The application of ORC technology high temperature industries can be considered relatively young, with the first prototype plants started up in the mid-nineties and most of the plants built in the 2010s. The on-going developments are moving toward increasing the recovered energy, the efficiency of transformation and lowering the investment costs, making these systems more appealing for final investors. Here below some of the most promising are outlined and briefly described.

DIRECT EXCHANGE

One of the characteristics that differentiated in the past ORC systems from traditional water-steam Rankine cycle was the necessity for ORC plants to have an intermediate thermal media (such as thermal oil, pressurised water, saturated steam) between the primary heat source (typically hot gases) and the ORC working fluid.

Recent developments brought to the market direct exchange solutions: ORC cycle in which the primary heat source (hot gas) exchanges heat directly with the organic media. Such systems were applied with success and are already commercially available for 'clean' heat sources (e.g. exhaust gas coming from reciprocating engines and gas turbines). Future applications of direct exchange solutions will be in the cement and glass industries, while in steel the fist application was realised on a reheating furnace of a rolling mill in 2013 in Singapore [7].

Direct heat exchange systems, compared to the traditional solutions employing intermediate heat transfer loop, promise a further simplification of the systems, eventually leading to a cost reduction (thanks to the reduced number of components) as well as an efficiency improvement (thanks to an avoided temperature reduction of the heat source related to the intermediate fluid) while keeping the typical ORC advantages (low O&M, high flexibility and efficiency).

As preliminary indications, cost savings due to the direct exchange solution may range between 5 and 15 % depending on the specific application, while net power production may improve by 5 to 10 %. Overall, direct heat exchange could lead to improvements in the ORC based solution with a reduction in the overall specific cost (€/kWnet) between 10 and 20 %.

Keeping these potential advantages in mind, it must be said that direct heat exchange becomes less appealing when dealing with discontinuous and very high temperature heat sources, since peaks of temperature may deteriorate the organic fluid. In these cases the advantages of direct exchange solutions are offset and intermediate thermal media solutions are preferable.

DIRECT MECHANICAL DRIVE

Another development that promises technical and economic advantages is to employ an ORC system for heat recovery in industrial plants not just to generate electric power but rather to directly providing mechanical power to other machines within the same industrial plant.

Example of installations following such scheme would be:

- Heat recovery from a hollow glass plants to generate mechanical power directly moving an air compressors (hollow glass plants are relevant compressed air consumers),
- Heat recovery downstream process reactors in carbon black production processes to generate mechanical power to directly drive the induced draft fan of the process itself,
- Heat recovery in natural gas compressor stations to generate mechanical power to drive a natural gas compressor.

Such a scheme is advantageous thanks to the improved energy saving that it allows: in fact, in comparison to a traditional heat recovery system for electric power generation only, the direct drive avoids the two power transformations mechanical – electrical and electrical-mechanical that take place first on the ORC machine feed by recovered heat and secondly on the user. Considering typical electric generator, motors and VFD (Variable Frequency Drive) efficiencies, a direct drive solution could lead to an energy saving between 5 and 10 %.

Direct dive solutions are not new, being very common in the natural gas compressor application (in which the compressors are driven by gas turbines) and already used with traditional steam cycles. The promising potential of the direct drive combined with ORC systems is related to the automatic operation and high availability that the ORC technology guarantees leading to potentially very reliable and easy to operate systems. Moreover this kind of solutions can become very interesting where the electricity generation, even if self consumed, is subject to bonds or heavy taxation.

STEEL PRODUCTION, WASTE HEAT RECOVERY WITH ORC AND DISTRICT HEATING

Combining an ORC based heat recovery system with a district heating network can be a way to further increase the overall energy efficiency and an interesting synergy with local initiatives to promote the acceptance of industrial plants from local communities. The two applications should not be considered as alternative to each other, since in many cases they can be complementary making the whole initiative more sustainable also from the economic point of view (Figure 10): the ORC increases the exploitation of the heat exchanger, the most cost intensive component, when the demand of district heating network is low. In this way even if the initial investment is higher, the payback time can be sensibly lowered [7].

A first example of district heating in parallel with the ORC is the Feralpi plant in Riesa (Germany), in which the waste heat from a steel EAF feeds with steam in parallel an ORC unit for power generation and an industrial thermal user located about 3 km away. Another representative example is the new ORC plant in EAF energy recovery delivered to ORI Martin (Brescia) started-up in April 2016.

ORI Martin is a leading European supplier of engineering steel in bars for the automotive industry and for other mechanical applications. The ORC is a 1.9 MW unit integrated as a retrofit in the electric steel melt shop being revamped with a new Consteel® EAF furnace. Similarly to the plant installed at ESF Riesa, the heat recovery system is based on saturated steam being partly destined to Brescia citywide district heating network of the local utility and partly to the ORC power unit (Figure 7). Since the steam demand of the district heating varies both seasonally and daily, the ORC will utilize and convert the remaining available steam portion. The flexible operation of the ORC, automatically adjusting to the available heat load with a guaranteed turndown to 10 % of the nominal load, were also key factors for this plant.

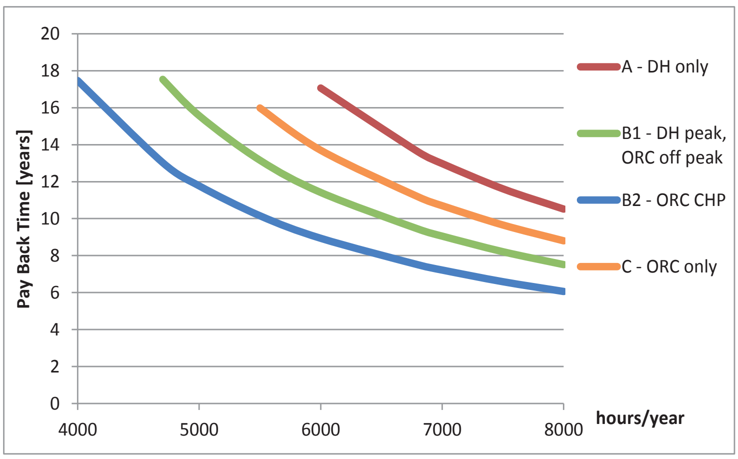

Figure 10. Excess heat recovery for: A district heating (DH), B1 DH in parallel to ORC, B2 DH in series to the ORC and C ORC only. Source [12].

The new heat recovery system will improve the energy efficiency, sustainability and economics of the ORI Martin Steel plant, maintaining a competitive industrial activity within the city of Brescia [14].

There are various supporting tools available around European Member States to foster the exploitation of excess industrial heat, as dedicated guides summarising the available technical solutions and local and sectorial potential [15] or even specific for ORC [16] and as interactive Geographic Information System showing the availability of excess heat and the demand at district level (e.g. [17], [18], [19]) or even at block level ([20]). Those maps can help local planning and also to meet demand and offer of heat.

Conclusions

The Energy Union Strategy considers the energy efficiency to be an energy source in its own right. This is particularly true for the recovery of excess heat, a source of heat usable by the process or saleable to other users, convertible in other form of energy as electricity and possibly in the future also of mechanical energy and listed as a fuel for cogeneration systems [21]. There are various examples of successful implementation of ORC based industrial excess heat recovery systems around Europe and promising applications not yet implemented in specific subsectors. These systems can also be cogenerative and should be evaluated also in combination with the exploitation of the excess heat in an external network, since this can boost the economics and the sustainability of the initiatives. The provision of articles 8 and 14 of the energy efficiency directive will surely help to highlight the opportunities to the public and private decision makers, but excess industrial heat, in particular when exploited for electricity generation and/or for external heat uses needs a specific support, at least till when its diffusion on larger scale and the confidence in the available financing options [22] won't become stronger.

Glossary

APG	Associated Petroleum Gas
BOF	Basic Oxygen Furnace
BREF	Best Available Technique References
CC	clinker cooler
CHP	Combined Heat and Power
CP	cyclone preheater
EAF	Electric Arc Furnace
GIS	Geographic Information System
HX	Heat Exchanger
ORC	Organic Rankine Cycle
VFD	Variable Frequency Drive

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