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D5 – Performance Analysis

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Author:	Marco Baresi, Luca Filippini, Silvio Formenti, Esther Setuain, Antonio Rosano, Francesco Campana			
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INTRODUCTION

Reducing energy consumption has been a constant concern of steelmakers over the years; making one ton of steel today uses about one half of the energy used in the 1970s [4]. These efforts must continue as further reductions are required in the steel industry as well as in other energy intensive sectors to minimize costs and to respect policies on greenhouse gas emissions. This is a major challenge to meet, particularly in Europe, where the price of energy is high, CO_2 reduction targets have been set by the EU and the steel industry is still suffering the impact of the economic crisis.

In electric steelmaking, which is gaining a growing percentage of world steel production, process optimization and control technologies and best practices ever more shared by EAF operators have allowed to raise substantially the benchmark productivity and energy efficiency of scrap based minimills. In this area, a further energy efficiency improvement seldom considered due to the perceived complexity of the application, is the re-use of the waste heat from the EAF exhaust gas for power production.

The challenging conditions of EAF scrap melting (a batch process with extremely variable off-gas flow in a harsh environment) require robust, flexible and automatic systems capable to recover the off-gas heat and to convert it to power leaving the EAF operator concentrated on its main job. One key component which can fully meet the required duty is an ORC (Organic Rankine Cycle) power unit coupled with reliable primary heat capture equipment. ORC power units have demonstrated their unique properties in hundreds biomass based power plants and in waste heat recovery in cement, glass or downstream of gas turbines and large reciprocating engines. Key advantages of ORC systems are high reliability, ease of operation, good efficiency, low O&M costs.

The following is an example of a new heat recovery system from EAF off-gas with ORC power production recently installed by Elbe-Stahlwerke Feralpi GmbH (ESF) in Riesa, Germany.

ELBE STAHLWERKE FERALPI

Riesa steel history and Feralpi Group

Steel production started in Riesa in 1843 and continued during all the following years, while Germany and Europe went through many different events, including two wars.

In 1980s Riesa steelworks, integrated into the planned economy of the GDR, reached 12,000 employees, but, after the German Reunification, the plant risked closure because of high production costs and environmental issues. In 1991 the Italian steel producer Feralpi acquired the steelwork, investing to build the present installations and creating ESF Elbe-Stahlwerke Feralpi GmbH.

Founded in 1968, the Feralpi Group is a leading manufacturer of steel products for the construction industry with a capacity of 5 million tons per year of steel and finished products. Feralpi plants, employing a total of 1,300 people, are located in Italy, Germany Czech Republic, Hungary and Romania.

ESF Elbe-Stahlwerke Feralpi GmbH: plant, process, production

ESF Elbe-Stahlwerke Feralpi GmbH produces reinforcing steel in the form of bars and coils. The ESF steel plant consists of a steelshop for steel billets as semi-finished product and a hot rolling mill for further processing of steel billets to re bars and coils. ESF produces up to 1,000,000 metric tons of Steel billets and up to 800,000 metric tons of reinforcing steel per year.

Figure 1. ESF plant panoramic view

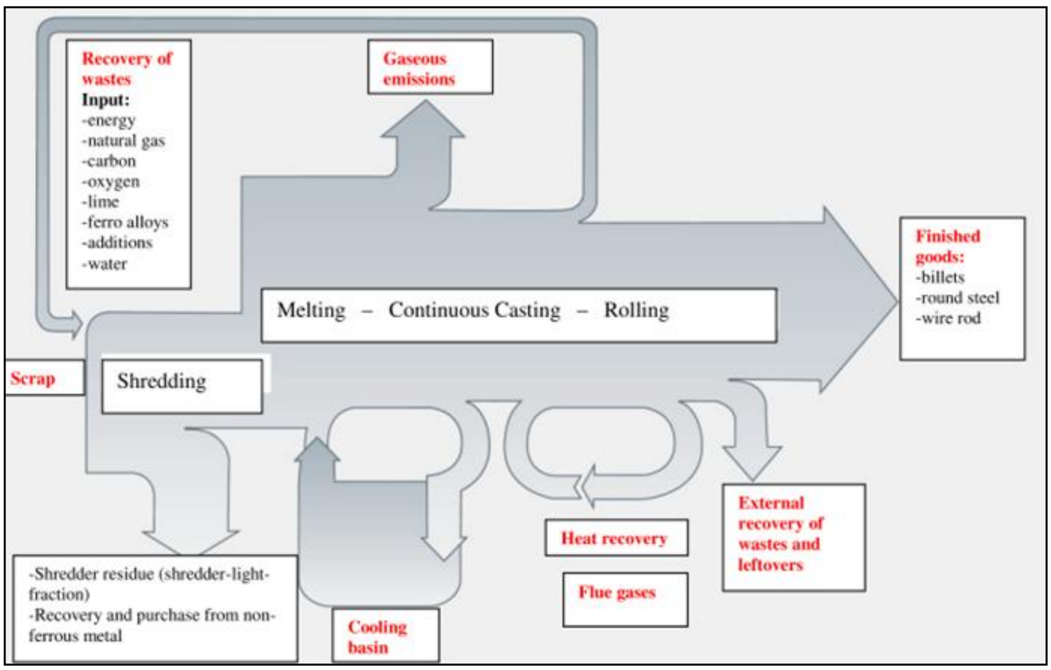


Figure 2. Material & energy flows at ESF plant

Figure 2 shows schematically the actual flow of materials at ESF plant. The feedstock for steelmaking at ESF is steel scrap, which is melted in an Electric Arc Furnace at approximately 1,600°C (2,910°F) to raw iron that is cast to billets in a continuous casting machine. The hot rolling mill includes a walking beam furnace that reheats the steel billets up to rolling temperature of approximately 1,200°C (2190°F). The reheated billets are passed to the rolling mill that can either produce round steel or wire rod by varying number of rolling stands, cylinders and choosing different paths of cooling and tying (as coils or bundles).

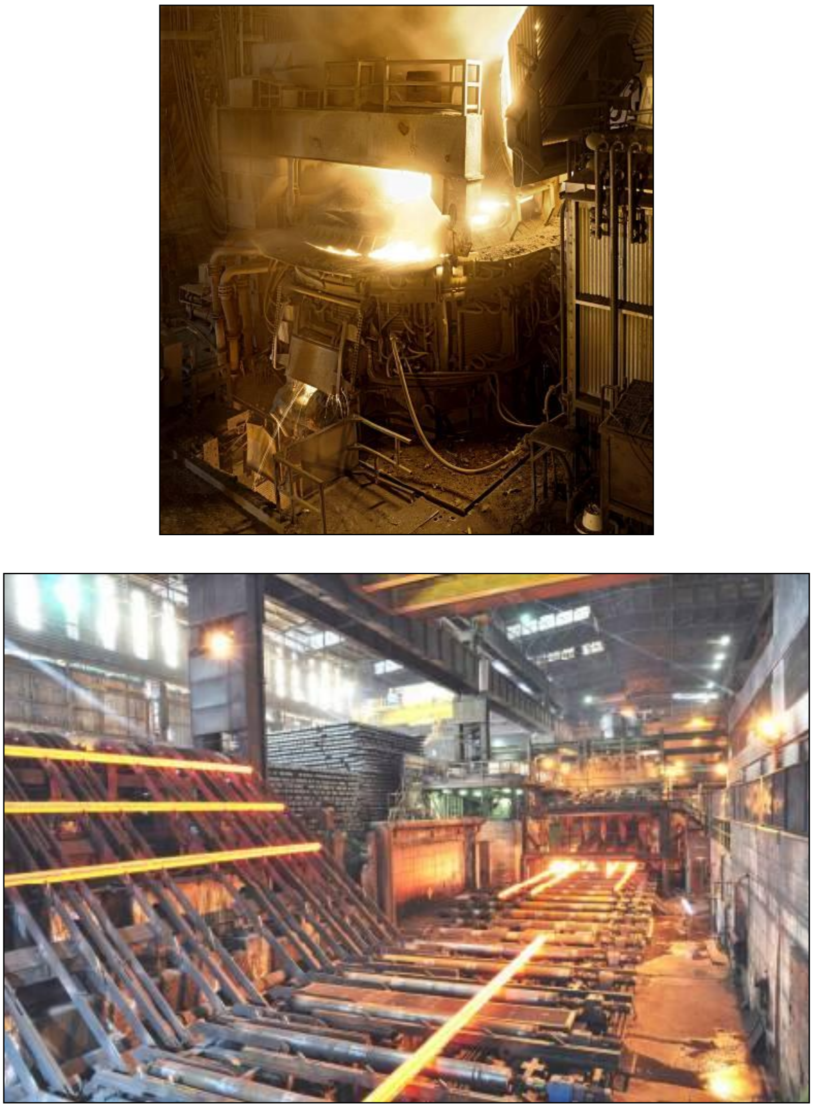


Figure 3. EAF and continuous casting machine at ESF, Riesa

A very specific feature of ESF installation is the possibility of a direct feed of hot billets from continuous casting into the walking beam furnace (Figure 3). Billets can be fed to the furnace at temperatures up to 900°C (1650°F): this leads to high energy savings at the furnace, since it only has to increase it of about 300°C (540°F) to reach the feed-in temperature of the rolling mill. Nevertheless, ESF needs around 550 GWh of electricity and the equivalent of 230 GWh from natural gas per year.

EMAS Certification

Because of cost intensity issue, as well as its environmental responsibility, in 2012 Feralpi Group decided to establish an environmental and energy management system under the European "Eco Management and Audit Scheme" (EMAS), including all companies located at Riesa site; in addition, Feralpi Riesa regularly publishes a sustainability report of the previous two years [2]. According to the policy of the management system, ESF continuously improves its environmental performance and energy efficiency. The installation of the EAF waste heat recovery is one of the key measures of energy saving and of environmental protection (CO_2 reduction) as well, due to a correspondent reduction of use of fossil fuels.

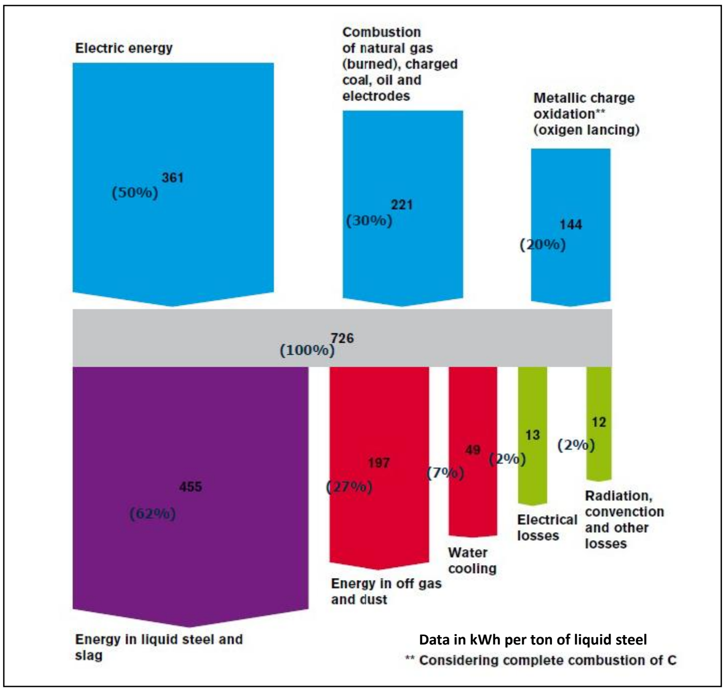


Figure 4. Typical energy balance for top charged scrap based EAF (Tenova)

HEAT RECOVERY TO POWER FROM EAF PROJECT

Feralpi objectives

The Feralpi Group, continuously striving to improve the operations in productivity, energy efficiency and environmental performance of its facilities, started considering the possibility to install a waste heat recovery system with power production at one of their electric steelmaking plants back in 2008. The objective was to further improve energy efficiency of scrap based steelmaking, lowering the EAF specific electric energy use and CO_2 emissions, with no reduction in overall plant availability and no additional personnel cost.
The identified waste energy source to be recovered was the sensible heat of the hot combusted gas stream from the EAF, normally conveyed through water cooled ducts to the primary fume treatment system, with quench tower and bag house filtering. This waste stream, typically representing more than 25% of the total energy input [3], is the most important source of waste energy in EAF steelmaking.

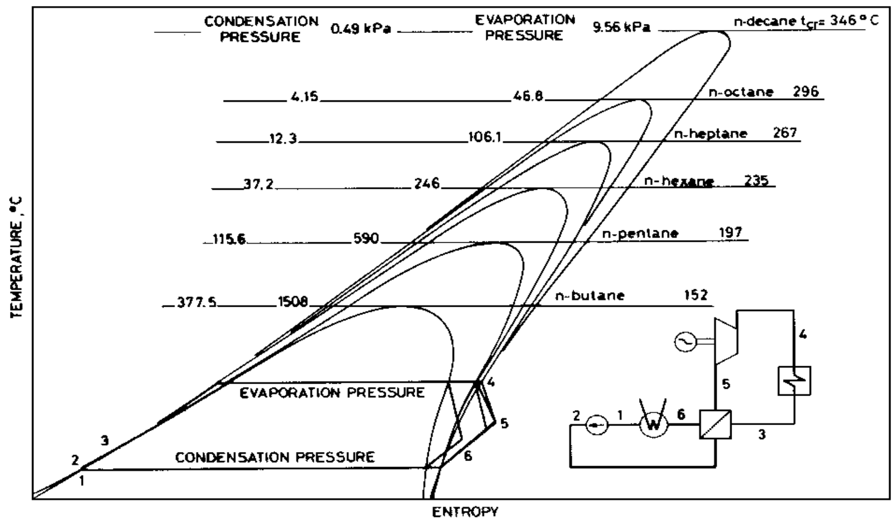
Process choice: Steam turbine vs ORC

Many existing Waste Heat to Power (WHTP) systems used in energy intensive industries with continuous high temperature processes use steam turbines to convert heat to power. Waste heat recovery boilers capture the valuable energy of the hot exhaust gases generated by the primary process to evaporate water and produce saturated or superheated steam. Steam is then expanded in a steam turbine and eventually condensed back to water. This is the classical Rankine cycle, employed, for instance, in the chemical industry, nonferrous metal making and for the production of ferroalloys.
These traditional water-steam systems are typically employed in industry for plants over 10 MW and extending up to 50 MW and above. In these cases, and where the primary calcining or metallurgical process generates a steady flow of high temperature exhaust gas, superheated steam cycles are employed to maximize efficiency in converting heat to power. Superheated steam systems require costly equipment (high temperature & pressure demand more sophisticated equipment and materials) and high O&M costs (operators must be certified steam engineers, water quality requires special care etc.). Due to the capital and running costs, superheated steam cycles are seldom convenient for WHTP plants below 15-20 MW.
At smaller capacities, less costly non superheated (saturated) steam Rankine cycle systems have been employed; also in these cases however, local codes typically require the continuous presence of certified steam engineers, increasing operating personnel costs to unacceptable levels. In addition, when the process heat source is discontinuous or highly variable, steam turbines running on saturated steam cannot be easily employed.

Due to all these factors, Feralpi decided to rule out the traditional Rankine cycle based on water-steam boiler and direct expansion steam turbine, and to consider instead using the ORC.
In fact, the ORC technology, widely employed in hundreds of renewable energy plants in Europe and North America (mostly in biomass based generation and in geothermal applications) was successfully proven also in various WHTP installations in the industrial environment [4] [3].
These ORC units, operating in cement plants and other energy intensive industries, convinced Feralpi that the ORC would be the most appropriate alternative to handle the discontinuous, extremely variable waste heat of the EAF exhaust gases, guaranteeing flexibility, ease of operation and minimum O&M.
Feralpi had one concern about the ORC technology, namely about the use of thermal oil as heat carrier between the primary heat source (EAF off-gas) and the ORC proper. Despite the fact that thermal oil is widely employed in the Oil & Gas and Marine Industry, Feralpi objected to have thermal oil near the EAF. The issue was overcome discussing with Turboden, supplier of the ORC system, and verifying that saturated steam could well be used to convey heat from EAF off-gas to the ORC evaporator. In fact, studies and proposals done by Turboden in 2009, showed that saturated steam at about 20 bar.g, as produced at Georgsmarienhütte EAF steelshop [6], was a good heat carrier/source for an ORC system.

ORC technology explained
As mentioned above, ORC is the acronym of "Organic Rankine Cycle". As the name suggests, the ORC is a thermodynamic cycle based on the classic Rankine Cycle, performed with an organic fluid instead of water. The most widely used organic fluids are hydrocarbons (e.g. pentane), siloxanes (employed also in cosmetic products) and refrigerants (more common in HVAC systems and refrigeration). In Figure 5, saturation curves for several organic fluids are reported: as the shape of curves suggest, if compared to water, organic fluids do not need to be superheated to avoid condensation in the turbine during expanding stage; moreover, the organic fluids have higher molecular weight than water. All these features lead to some very important technical advantages compared to conventional steam cycles in some specific cases:

- high turbine efficiency (around 85%)
- low mechanical stress on the turbine (low tip speed, moderate temperature)
- low turbine rotational speed allowing direct drive generator (no gearbox)
- no blade erosion (no liquid particles during expansion, due to the shape of saturation curve)
- no oxidation (some organic fluids can even be considered as lubricants themselves)
- high efficiency with low and moderate temperature sources (e.g. 24% with 300°C, 570°F hot source)



- Figure 5. Saturation curves for several organic fluids. (Turboden)

As a consequence, ORC much easier to operate than steam turbines. Ease of operation is characterized by:

- simple start-stop procedures, with quiet running and automatic and unattended operation
- high availability
- high flexibility (good efficiency at partial load, with turn-down to 10% or less of nominal power)
- long life and minimum O&M requirements

These advantages stem from the fluid characteristics, which allow to design and build relatively large and slow rotating (thus efficient and reliable) turbines, making ORC one of the best choices for small scale applications (up to 5-10 MW). On the other hand, the turbine size causes the ORC technology not to be cost-effective for most common larger applications, where superheated steam cycles are the natural choice. For this reasons the ORC technology has ever growing applications for distributed generation in geothermal power, other renewables (especially biomass based), in small combined cycles (bottoming gas turbines or internal combustion engines) and for waste heat recovery in industrial processes.
The actual configuration of ORC systems can be different depending from the specific application and site conditions such as type of heat source, demand of low temperature heat, availability of water, space constraints.
Usually, when the primary heat source are hot dusty combustion gases and cooling water is available, the heat recovery systems consist essentially of a primary heat exchanger, the ORC unit, a cooling system for dissipating heat of condensation downstream the ORC turbo-generator. The primary heat exchanger feeds the ORC turbo generator, transferring part of the waste heat from the exhaust gas to the ORC unit by means of a heat carrier (typically thermal oil, pressurised water or steam). The ORC unit converts the incoming thermal energy into electricity and heat at low temperature. The heat discharged from the cycle of power during condensation is released to the environment by means of an intermediate water circuit (or mixture of water and glycol to prevent freezing in winter), when low temperature heat is not usable. The dissipation of this heat can be in the form of a dedicated system: this can be either a dry system, with air-coolers, or a wet system with evaporative cooling towers.
Figure 6 shows a simplified scheme of the ORC. Following the cycle step by step, first the working fluid is pre-heated (7-3) and evaporates (3-4) by means of the heat carried (thermal oil, hot water or steam), and then expands in a turbine (4-5), which is usually directly coupled to the generator. The condensation (8-1) can be performed by a cooling medium (air or water). The cycle closes when liquid from the condenser is pumped (1-2) to reach the evaporation pressure. An economizer (the so called "regenerator) is placed downstream of the turbine, in order to achieve higher efficiency (5-8, 2-7).

Site selection
Feralpi Group, considering the high cost of electricity in Italy, due to the nature of the installed power generation capacity in the country (no nuclear and only about 15% coal), initially evaluated to install an EAF waste heat recovery system in one of its scrap based mini-mills near Brescia. The project would have benefitted of the Italian incentives on energy efficiency, improvements employing an innovative technology. These incentives are in practice a premium equivalent to about 6 €cents/kWh added on the price of high voltage electricity. The value of this premium (the so called "white certificates") is defined by a market mechanism where the electricity distributors must meet commitments to improve every year the average efficiency of their clients. The white certificates system is one of the measures established by the Italian legislators to meet the energy efficiency and greenhouse gases reduction targets fixed by the European Union. Notwithstanding the important saving on electricity costs, the payback time for a waste heat recovery to power system at the Italian site was considered too long.
More favourable conditions existed at Elbe-Stahlwerke Feralpi plant in Riesa (Germany) where the local utility Stadtwerke Riesa GmbH was interested to acquire directly as steam an important portion of the energy, recovered with the new installation, for one of its clients at the adjacent industrial park. The expected revenue of the steam exported, summed with the saved cost of electricity expected after installing the ORC unit, gave an acceptable payback for the investment.

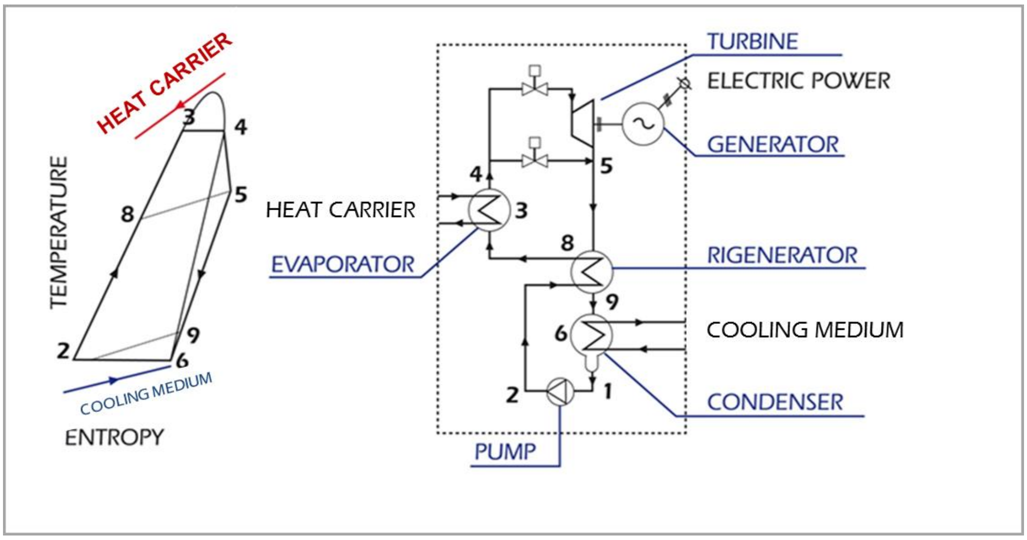


Figure 6. Typical ORC scheme and thermodynamic cycle

ESF Steelshop Waste Heat to Power System

At the end of 2011, ESF agreed with Stadtwerke Riesa GmbH to supply about 1/3 of the heat recovered from the EAF off-gas, (i.e. 10 t/hr of saturated steam at 26 bar.g) to be used by the plant of Goodyear Dunlop Tires Germany GmbH, located nearby. ESF then decided to go ahead with its cogeneration project based on recovering heat from the Electric Arc Furnace off gas, generating saturated steam and conveying this steam partly to the thermal user (Stadtwerke Riesa) and partly to the ORC power plant to produce electricity.

The first installation of this type was developed with the support of the European Commission (LIFE program, HREII Demo project), who co-financed a small part of the investment highlighting the relevance, innovation and environmental benefits of the project [7].

The plant to be built included a new EAF fume treatment and heat recovery system with evaporative cooling and saturated steam production contracted to Tenova, and a 2.7 MW ORC power plant fed with saturated steam contracted to Turboden. The simplified scheme and energy flow of the plant are shown in Figure 7 and Figure 8.

It is well known that steel melting process in the Electric Arc Furnace (EAF) is a batch process: off-gas thermal flow from the EAF roof or side opening varies during the melting cycle. During tapping and when the roof of the furnace is open, for bucket scrap charging or for repairing, the thermal power at the primary off-gas duct is close to zero.

A typical EAF melting cycle at ESF is described in Table 1.

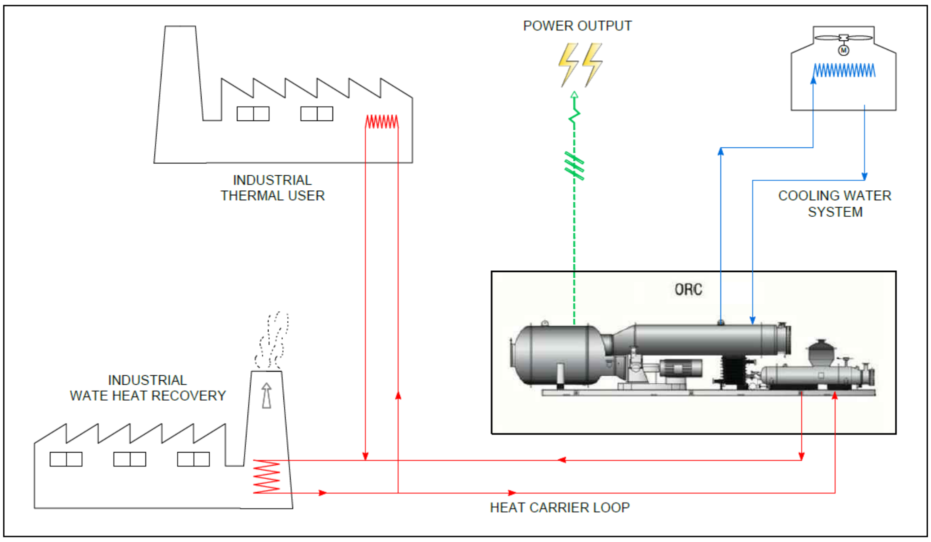


Figure 7. Simplified cogeneration waste heat recovery scheme
as applied in Riesa

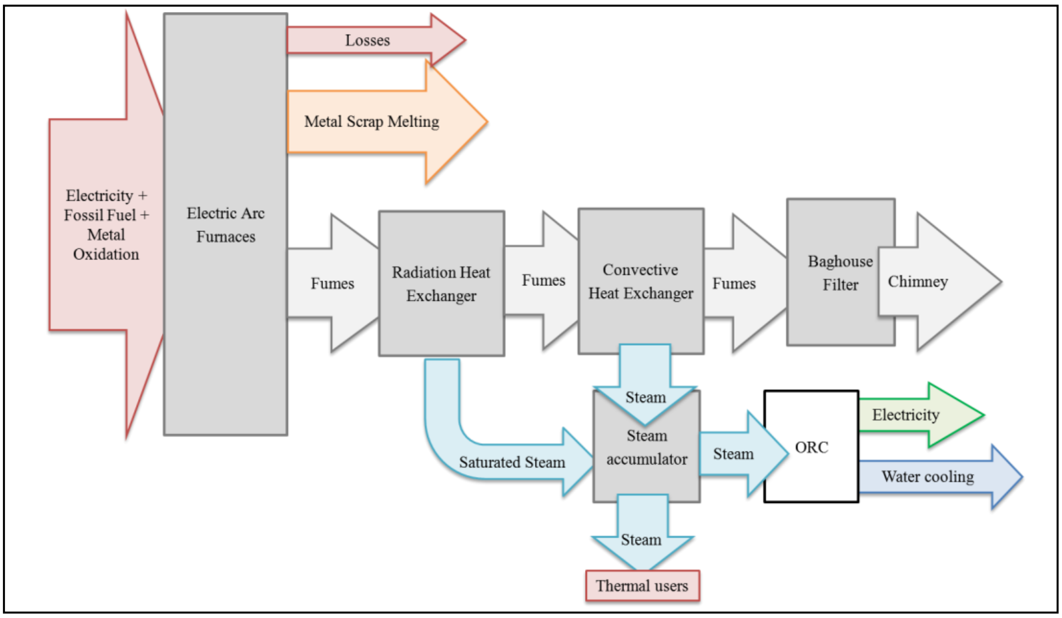


Figure 8. Heat recovery system with ORC technology from exhaust gas of Electric Arc Furnace, as applied in Riesa

Melting Phase	**Power-On time** *[minutes]*	**Power-Off time** *[minutes]*	**Average Power** *[MW]*
1st scrap bucket charging		2	-
Melting	10		70
2nd scrap bucket charging		3	
Melting	10		70
3rd scrap bucket charging		3	
Melting & refining	13		70
Tapping & repairing		7	-

Table 1. ESF Electric Arc Furnace melting cycle data

The significant values for the Fume treatment and WHTP system design are:
- Tap-to-tap time: 48 minutes;
- Longest Power-Off time: 11 minutes;
- Average Power during Power-On: 70 MW;
- Total Power-On time: 33 minutes.

EAF Heat Recovery with Evaporative Cooling System

Since the EAF off-gas has a discontinuous, highly variable heat flow, the Evaporative Cooling System (ECS) used for primary heat recovery must include a buffer, necessary to ensure that the steam conveying the recovered heat is always available, and varies within a certain range of pressure and temperature. In the case of ESF, where steam is both exported and used internally for power generation, the buffer is sized to use as much as possible the generated steam, guarantee the agreed constant steam flow to the external steam client (Stadtwerke Riesa), guarantee at least the minimum steam flow (about 10% of the design flow) to keep the ORC always in operation, producing electric power. In practice, the steam produced by be evaporative cooling system (ECS) in the primary off-gas line and separated in the steam drum has peaks of 70 tons per hour. After the steam accumulator, the average output of steam to users is equalized to approx. 30 tons per hour.

The heat recovery system has two separate sections. The first section, where the off-gas has peak temperatures of 1600°C (2,910°F), works as a radiation heat exchanger, replacing the

existing system (cold water cooled ducts and settling chamber) with a completely new system using throughout steam boiler tubes of small section for evaporative cooling. This new off-gas handling and cooling section with evaporative cooling was supplied by Tenova based on the experience gained in more than 3 years of operation at Georgsmarienhütte steelshop [6].
The second section, installed bypassing the existing water quench tower, is a convection Waste Heat Steam Generator (WHSG) with evaporators, superheater and economizer mounted, in sequence, following the gas flow, on compact modules. While the layout is similar to classical WHSG used elsewhere, the design was made considering peak loads in flow and temperatures and high dust load (20 g/Nm^3). The vertical plain tubes are cleaned automatically.

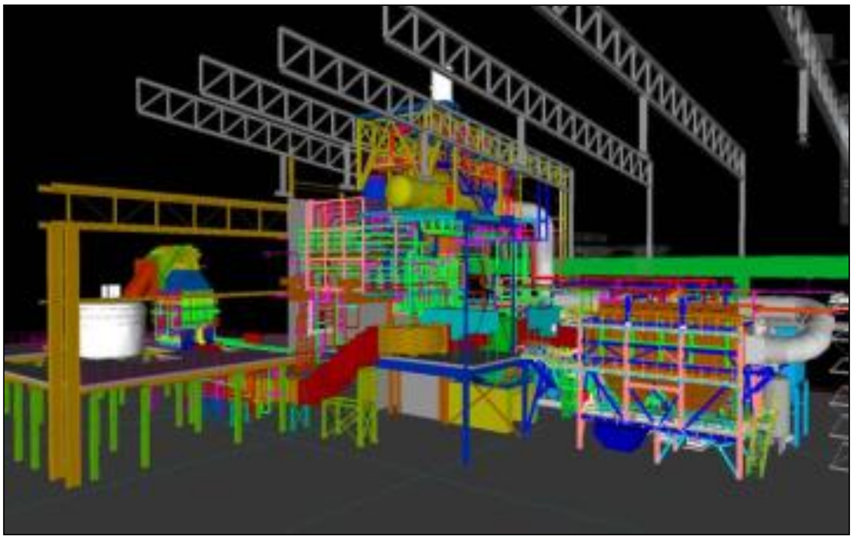


Figure 9. Waste heat steam generator rendering and installed equipment at ESF plant, Riesa

The off gas coming from the ECS cooled waste gas duct (radiation section) crosses the WHSG bundles horizontally. The dust separated inside the heat exchanger is collected and discharged into bins, by means of a chain conveyor.
In the evaporative cooling system, the cooling water at boiling point is fed from the steam drum by recirculation pumps to the evaporators, which are in fact the off-gas duct surfaces in the radiation section and the evaporator bundles in the WHSG. Once passed the evaporators, a part of such cooling water evaporates producing a water-steam mixture. The water-steam mixture returning to the steam drum is separated in two phases, boiling water, which is recirculated to the cooling system, and saturated steam, delivered to the heat users: Stadtwerke Riesa (10 t/hr) and ORC power plant (up to 20 t/hr).
Additional benefits brought by the new cooling system, other than recovering energy, are due to the fact that the (hot) Evaporative Cooling System extends the life of the off-gas ducting. This is due to several reasons:

- Normal working temperature at the internal surface of the exhaust gas path/ducting is high and far above dew point; therefore ducts and heat exchangers are protected against acid corrosion.
- All cooled parts are continuously at the same nominal temperature or exposed to a low variation of temperature. Constant, uniform temperature minimizes thermal mechanical stress to off-gas ducts.
- Through the evaporation of water, the system absorbs easily energy peaks.

Heat recovery system supplier	Tenova (Comeca subcontractor for heat exchanger parts)
ORC supplier	Turboden
Hot source	Saturated/Superheated Steam @ 26 bar.g
Inlet thermal power to the ORC	13,517 kW
Steam temperature In to ORC	228÷245°C (442÷473°F)
Condensate temperature Out from ORC	100°C (212°F)
Thermal power to the cooling water	10,640 kW
Cooling water temperatures (in/out ORC)	26°C / 44°C (79°F / 111°F)
Gross electric power output	2,680 kW
Net electric power output	2,560 kW

Table 2. ORC design data for ESF Electric Arc Furnace heat recovery plant

ESF Steam to Power system with ORC

The specific features of the waste heat recovery installation at ESF Riesa, designed to export steam to the nearby industrial user, dictated the choice of the heat carrier employed to convey heat from the EAF fume treatment and heat recovery plant to the ORC.

The use of steam, instead of the more usual thermal oil as heat source, required a modified design for the "hot" heat exchangers (preheater and evaporator) of the ORC. In fact the steam fed ORC unit of ESF looks very similar to other ORC systems using different heart carriers.

Using saturated steam at 26 bar.g and 228 to 245°C (442÷473°F) as heat carrier implies a small reduction in ORC efficiency compared to a systems fed with thermal oil normally at higher temperature (280°C / 536°F to 310°C / 590°F) .

On the other hand, as mentioned before, while thermal oil is appreciated in other industries like Oil & Gas, Cement, Biomass Power, steelshop operators are not familiar with thermal oil and may like not to use it in the EAF environment.

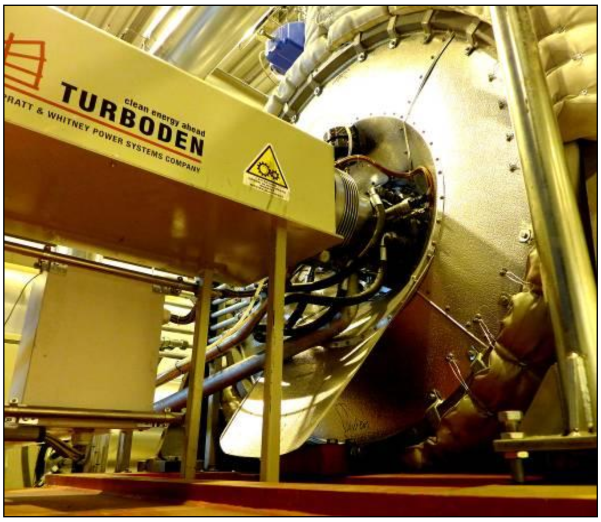


Figure 10. Organic Rankine Cycle Unit at ESF plantRiesa: overview and turbine detail

Feralpi was reassured in their decision to go ahead with a steam fed ORC after the experience of Tenova at Georgsmarienhütte steelshop [6], where Tenova supplied an EAF Waste Heat Recovery system producing saturated steam with similar parameters.

It is important to note that the saturated steam conveying heat to the ORC does not expand like in a traditional steam turbine. In this case the saturated steam just transfers heat to the ORC working fluid through surface heat exchangers, is cooled down and condenses with a small pressure drop, returning as condensate to the steelshop fume treatment to be heated and then evaporates again.

The heat carrier loop with steam at 26 bar.g and 228 to 245°C (442÷473°F) on the hot side, and 3 to 7 bar.g and 105 to 170°C (221÷338°F) condensate on the low temperature side is much less demanding than any conventional superheated steam cycle with direct expansion. The closed loop steam/condensate system is much easier to operate and maintain compared to a steam cycle with direct expansion.

The overall layout of the ESF installation shown in Figure 11 was dictated by the location of the export steam and condensate return lines, connecting the off-gas Evaporative Cooling System, the ORC Power Plant and the delivery point of steam to the Stadtwerke Riesa network and eventually the Goodyear Dunlop plant. In fact the ORC power plant and auxiliaries are located near the delivery point of steam and return of condensate at the boundary of ESF property. The steam and condensate return pipelines run for approximately 1,300 m (0,81 miles), partly on an existing pipe rack to connect the convection heat exchanger of the fume treatment plant with the ORC power plant.

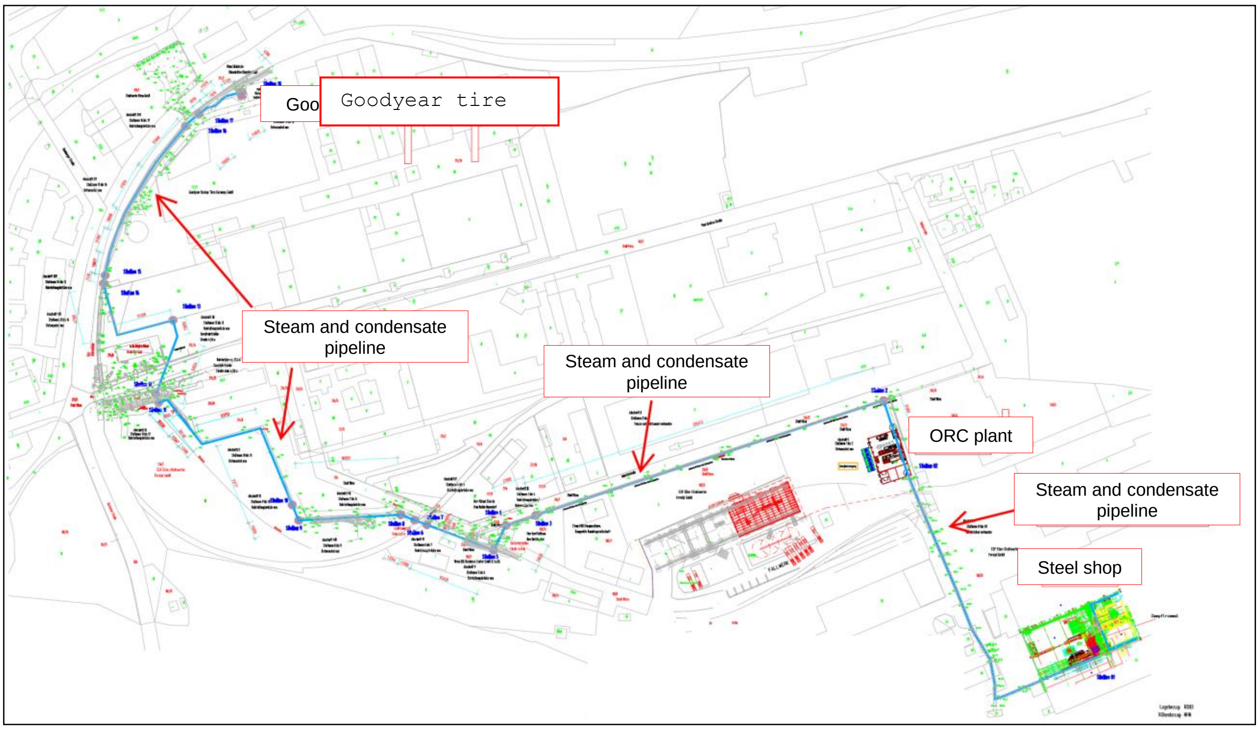


Figure 11. Steam and condensate pipelines overall layout at Riesa

Figure 12. Steam and condensate pipeline inside ESF plant, Riesa

Project schedule and start-up

The contract for the supply of the ORC unit was signed in December 2011. During the 2012 all the components were designed and manufactured, and in February 2013 the ORC units was transferred to Riesa. June and July were spent for the erection and the cabling of the ORC; in August the convection steam generator was installed and the cold test of the ORC was performed. Finally, in November the radiation heat exchanger was installed during the yearly shutdown of the steelshop.

The start-up of the new Waste Heat Recovery installation at Elbe-Stahlwerke Feralpi in Riesa occurred immediately before Christmas 2013, with some delay with respect to the original plans, mainly due to the constraints to the site construction activities dictated by the priorities of the steelmaking shop operation.

The initial operation of the revamped steelshop, with new Waste Heat Recovery installations, began in early 2014 at Elbe-Stahlwerke Feralpi in Riesa: the EAF off-gas treatment plant with evaporative cooling and steam production, the steam and condensate pipelines connecting with Stadtwerke Riesa, the ORC power plant, showed that , the new system was able to meet all the expected performance targets.

The ORC, for the first time coupled to scrap based steelmaking, confirms to be a best in class technology in challenging conditions, recovering and converting the variable energy of the EAF off-gas, improving energy efficiency and reducing CO_2 emissions. Ease of operation and great flexibility of the ORC, capable of automatically adjusting to the EAF melting cycle, are key features greatly valued by steelshop operators.

PERFORMANCE ANALYSIS

1.1 Scope of the document

Scope of this document is the description of the methodology applied in data collection and performance analysis of the heat recovery system in EAF (Electric Arc Furnace) at ESF, Feralpi group plant in Riesa, Germany.

The analysis was developed with a SCADA data acquisition system, based on a PC, in the control room. This system allows the display of various aspects of the plant ORC:

1. visualization of the plant on the screen in full graphic (colour);
2. visualization of the system components in detail;
3. display of plant condition (e.g. in operation, malfunction, warnings, etc.);
4. display of analogue values in digital and curve form (trend data).

Moreover, this system allows automatic recording of the most important analogue values. The recorded values can be displayed in a historical diagram. The time span of the diagram is completely adjustable (from about 10 sec to 30 days).

The system is equipped with a modem for data transfer to remote control, to ensure remote analysis of plant performance.

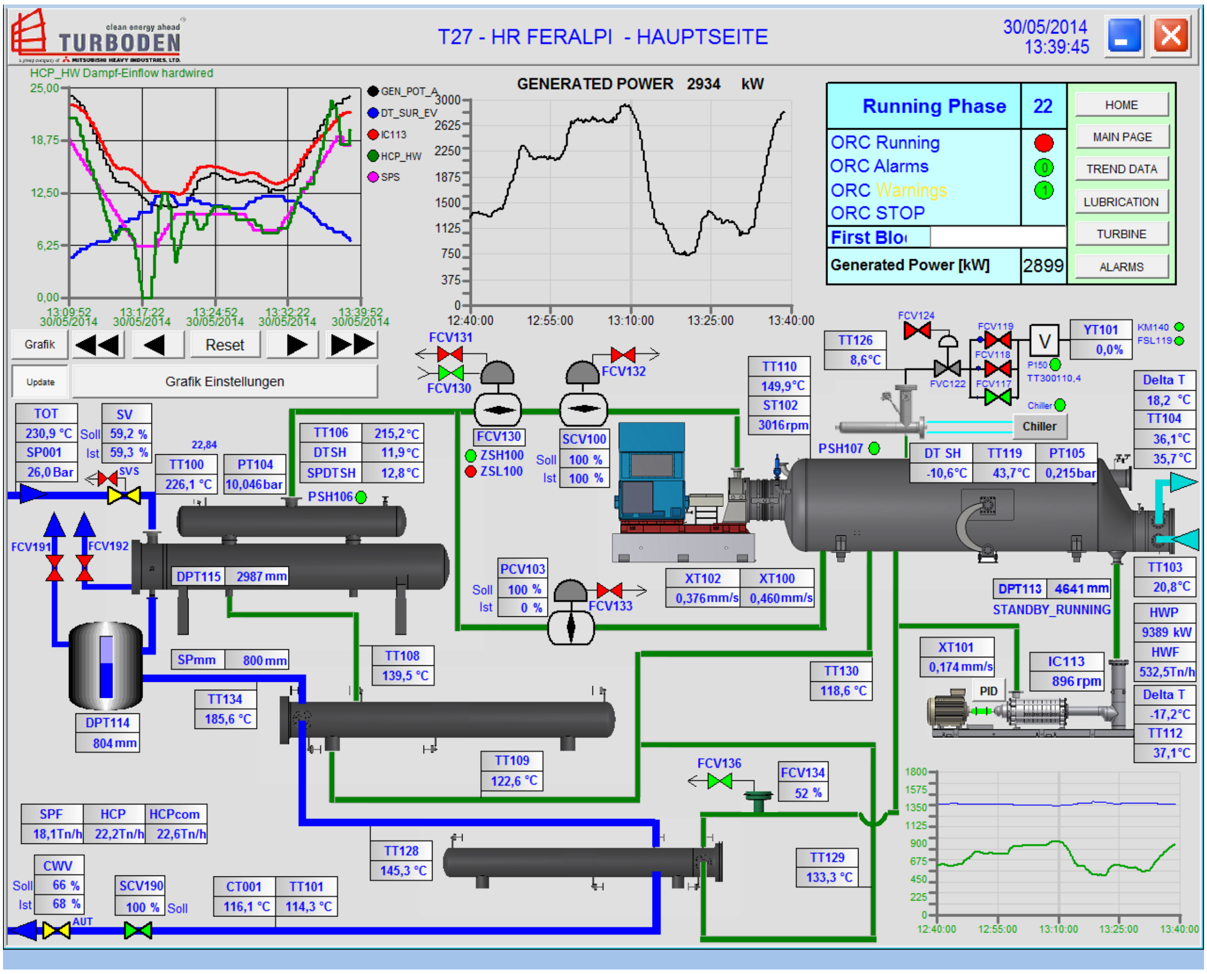


Fig. 1 – Power Plant monitoring system example

The remote control is realized with an ADSL line, with a fix IP address. An ISDN line dedicated exclusively to remote control system of the plant will be installed if ADSL is not available.
Through this remote control it is possible to monitor various parameters of ORC plant, so to develop a performance plant analysis.
various parameters are monitored using the remote control (table 1 - *Parameters monitored for the analysis of performance*).

Monitored parameters	u.m.
Inlet temperature of the heat carrier	°C
Outlet temperature of the heat carrier	°C
Mass flow of the heat carrier (steam)	t/h
Gross electric power	kW
ORC auxiliaries consumption	kW
Efficiency of the ORC system	%
Electric energy produced	kWh

Table 1 - Parameters monitored for the analysis of performance

1.2 Data collection

ORC units performances are collected in plant datalogs, that record a string every minute. Datalogs are available on daily basis, thus they need to be gathered in a complete database.
A database collecting significant information about the ORC operation has been set up. Data reported are property of Turboden srl and are very confidential, thus it is not possible to show them in details.
In figure 2 the Thermal power input (blue) and the gross electric power output (green) in the period between 2014 August, 1st and 2014 August 10th are reported.

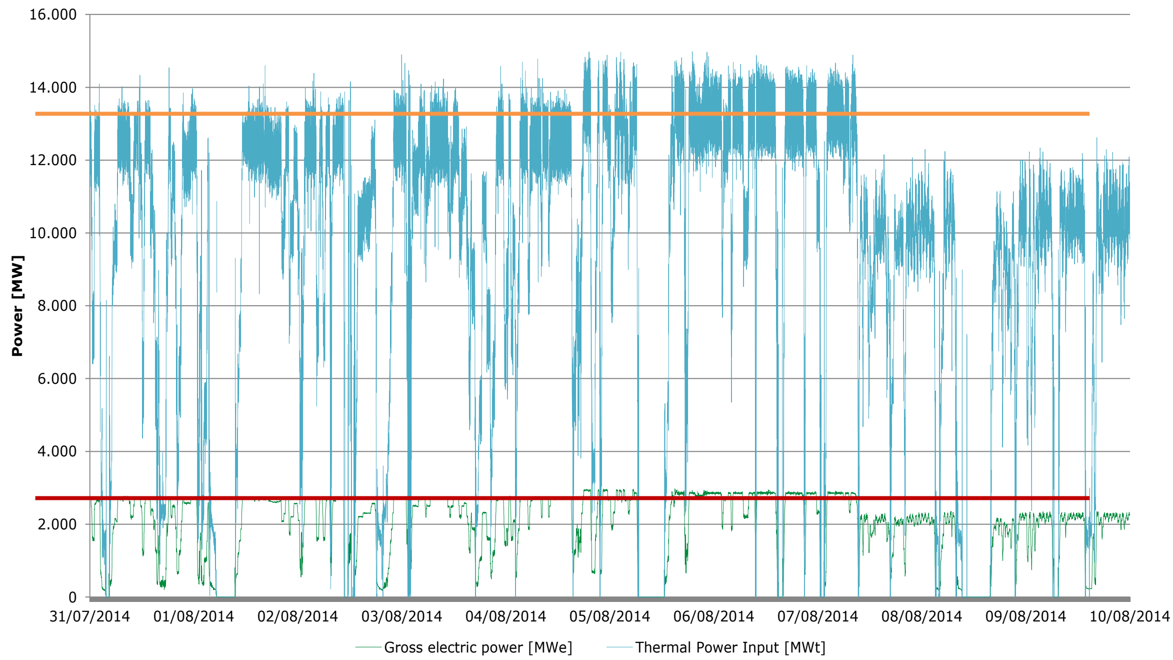


Fig. 2 – Thermal input and power output in the first decade of August 2014

The orange line represents the nominal thermal input (13500 kW) and the red one the nominal gross ORC power output (2700 kW).

Steam generator helps to keep the thermal input quite stable, but some fluctuations are always occur. The ORC shows a reactive behavior to thermal power fluctuations and good reliability in managing overloads.
It is important to note that the data may be affected by some interference that highlights fluctuations.

1.3 Performance Analysis

In order to analyze ORC performances, in figure 3 gross (blue) and net (red) electric efficiency are reported in the period between 2014 August, 1st and 2014 August 10th.

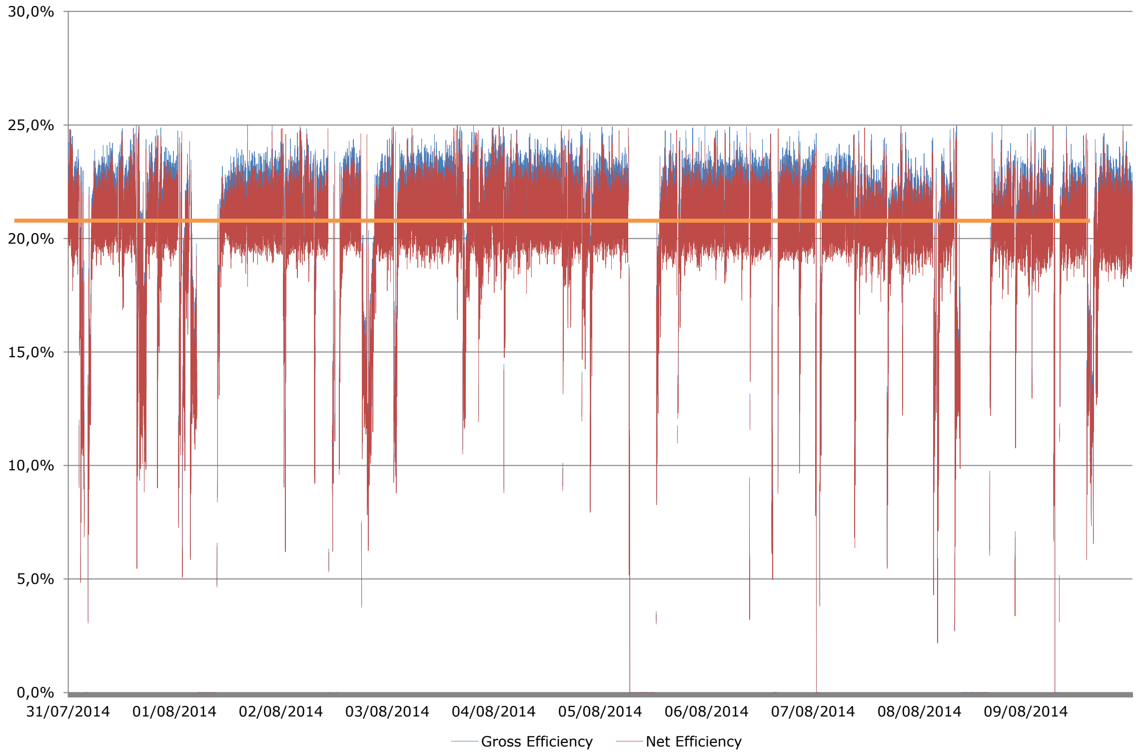


Fig. 3 – Gross and net electrical efficiency

Gross electrical efficiency is calculated as the electric power at the generator over the thermal power of the steam at ORC input.
Net electrical power is calculated as the electric power at the generator minus the electrical consumption of ORC auxiliaries. Please note that steam pumps and cooling system consumptions are not included. These values are not available.
The results of net electric power over thermal power of the steam at ORC input represents the net electrical efficiency.
Values of net efficiency calculated vary in the range of 19% and 23%.
The orange line represents the average value of net electric efficiency with the exclusion of stops (21%)
It is important to note that the data may be affected by some interference that highlights fluctuations.

1.4 Partial load performance analysis

As shown in fig. 2, thermal input available for the ORC fluctuates depending on industrial production cycle that influences the steam production. Thus the nominal input is not always available.

In order to analyze the performances of the ORC at partial load, two figures are compared:

- *Steam actual load over nominal load*: nominal thermal power (13500 kW) is not always available: this figure represents the percentage of thermal input available and it is reported on the x-axis.
- *ORC actual power over nominal power*: the figure reported on the y-axis represents the percentage of the gross ORC power output over the nominal ORC gross power (2700 kW).

14400 points registered in the period between 2014 August, 1st and 2014 August 10th are reported in fig. 4.

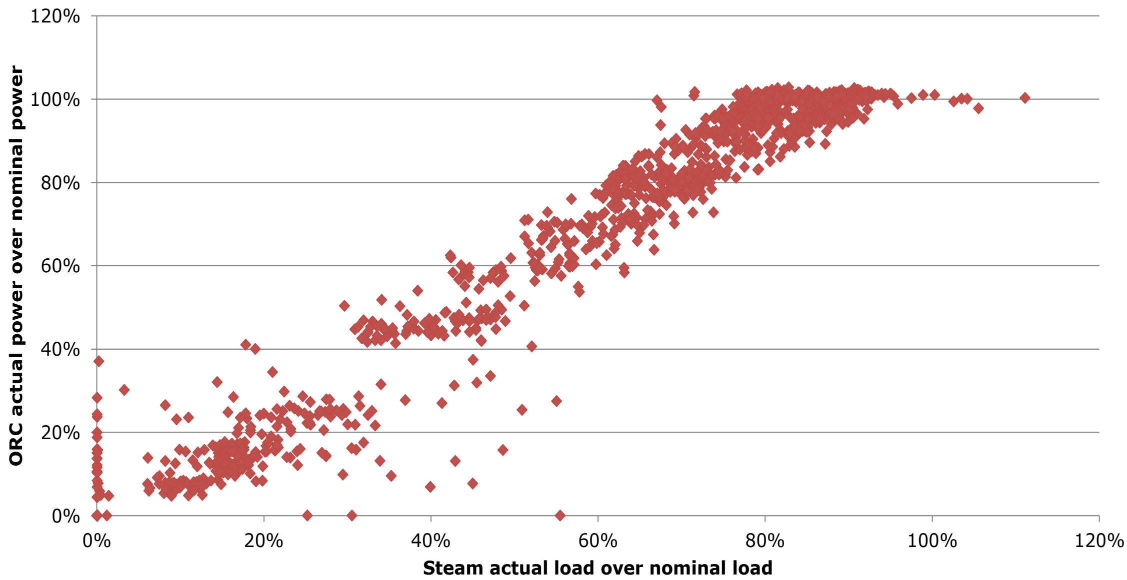


Fig. 4 – ORC performances at partial load

The graphs shows that the ORC produces 100% of its nominal power even if the thermal input is 80%.

With 70% of the nominal thermal input, the ORC still produces 80% of the nominal power output.

When the thermal input decreases below 20%, the ORC still keeps on operating, without stopping.

Points on the y-axis between 0% and 20% represent the timeframe during which the ORC generates electricity even if the thermal input is not recorded. Values outside the more concentrated areas can be assumed as information noise.

CONCLUSION

After few weeks from the beginning of commercial operation of the heat recovery system in EAF (Electric Arc Furnace) at ESF, Feralpi group plant in Riesa, Germany, the ORC performance analysis gives very interesting results:

- the ORC works properly at the design point;
- average net electrical efficiency is 21%[1];
- the ORC promptly responds to thermal input fluctuations;
- the ORC keeps its performances stable also at partial load;
- the ORC keeps on operating even if the thermal input decreases below 20%.

This performance analysis represents a first analysis. Further evaluation will be carried out considering:

- a longer operation period;
- performances of other components involved in the waste heat recovery system;
- energy balance of the whole plant;
- economic performances on business plan.

These results confirm the H-REII DEMO assumptions and represent a very important objective achievement.

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[1] Please note that steam pumps and cooling system consumptions are not included. These values are not available.