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Performance evaluation of an ORC unit integrated to a waste heat recovery system in a steel mill

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Abstract

Waste heat revalorization creates interesting opportunities to energy intensive industries. In the present project, a large-scale ORC pilot plant along with a waste heat recovery unit (WHRU) in a steel mill has been designed, commissioned and operated. The plant is part of the European Commission funded PITAGORAS project and it has been installed at ORI MARTIN in Brescia (Italy). Waste heat is recovered from the fumes of the Electric Arc Furnace (EAF) to produce saturated steam which is then delivered to a district heating (DH) network during heating season and to the ORC for electricity generation during the rest of the year. The main challenge was the integration of these systems in a single plant since the heat source is highly unstable and steady heat load is preferable for the DH and ORC for their safe operation. A steam accumulator of $150m^3$ volume was implemented between the WHRU and the ORC/DH systems to maintain a steady discharge pressure, to reduce the fast transients and to extend the supply over longer periods. The ORC has a nominal power output of 1,8MW and the preliminary results of the first weeks of operation of the ORC unit resulted in a net efficiency of 21.7%. Currently the plant is undergoing monitoring campaign which will provide additional data to further evaluate and optimize the system.

Keywords: ORC; Waste heat recovery; steel industry; EAF; district heating

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1. Introduction

Waste heat revalorization technologies offer great opportunities to several energy intensive industries towards achieving the energy and environmental objectives. The recovery of waste heat for power production is an interesting application when large thermal loads required nearby are not available. Industrial waste heat is typically characterized by being a highly fluctuating stream and the technologies for its revalorization need to be suitable for these boundary conditions. For industrial waste heat, available at low/medium temperature, the ORC is identified as the best performing technology [1]. A comprehensive study was developed in 2013 to estimate the ORC market potential in cement, steel, glass and oil & gas industries in the EU-27 and steel industry was showed to have very interesting possibilities for the application of ORC generators, for heat recovery from the exhaust gas of Electric Arc Furnaces (EAF) and in other high temperature processes like rolling mills furnaces [2].

PITAGORAS (Sustainable urban Planning with Innovative and low energy Thermal And power Generation frOm Residual And renewable Sources) is a research project co-funded by the European Commission framed into FP7 – Smart Cities program. The Pitagoras project focuses on the efficient integration of city districts with industrial parks and particularly as a waste heat recovery solution based on ORC technology for electricity and district heat production has been developed. This paper presents the main results of the real scale pilot plant implemented at the steel mill owned by ORI Martin and located in the city of Brescia (Italy).

ORI Martin Group is specialized in high quality long products steel production. The special steel unit is situated in Brescia where it produces continuously cast billets, wire rod, bars and bars in coils for special applications in the automotive and mechanical industry. The melting process of steel scrap is done in an EAF, which is an energy intensive process. The energy contained in the off-gas of an EAF represents around 25-30% of the power input to the EAF [3]. The new plant allows the recovery and revalorization of this energy that would otherwise be wasted.

ORC plants for waste heat revalorization are relatively new. The first application of ORC in an EAF was done in a steel mill in Riesa (Germany) [4] within H-REII Demo project [5] at the end of 2013. The plant built in Brescia follows its steps and goes further: ORI MARTIN waste heat recovery plant from the EAF process using ORC technology is the first one operating in Italy and feeding the local DH network.

The figure 1 shows schematically the system concept based on waste heat recovery with ORC technology.
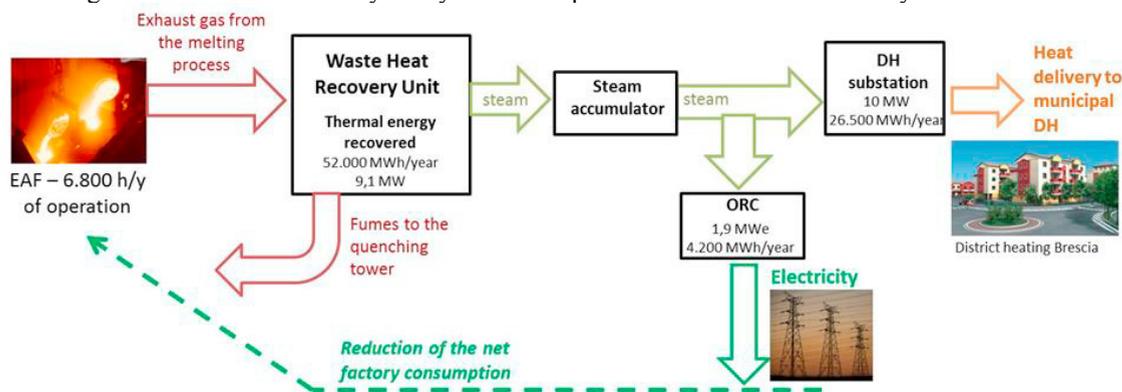
Fig. 1. Waste heat recovery system concept as implemented in the ORI MARTIN steel mill.

Originally, the flue gases were cooled in a quenching tower, filtered in a bag-filter and expelled through the chimney. With the implementation of the new plant the fumes are first passed through the Waste Heat Recovery Unit (WHRU) (iRecovery® system developed by Tenova). Within the WHRU thermal energy is transferred to the water producing saturated steam. Steam is used as heat carrier between the heat source (EAF) and the ORC evaporator. The use of thermal oil was also considered but it was discarded both for safety reasons and for the electric energy required for the thermal oil pumping system.

The plant enables a double utilization of the waste heat recovered: during the cold season (from mid-October to mid-April) the thermal energy recovered is delivered to the existing district heating (DH) network of Brescia; in addition, during the warm season (from mid-April to mid-October), the thermal power recovered is delivered to an

ORC turbo-generator to produce electricity used for self-consumption in the steel mill.

The main challenge to overcome is the discontinuous availability of the waste heat. The EAF works as a batch process due to the melting phase and the tapping phase. During this period the available waste heat and therefore the steam production is drastically reduced. In order to smooth the fluctuations in the steam supply and provide the required quality of heat input to the ORC-generator a steam accumulator with a volume of 150 m^3 has been added to the process.

Nomenclature		Symbols		
DH	District Heating	m	Mass flow rate [kg/s]
EAF	Electric Arc Furnace	H	Enthalpy [kJ/kg]
HT	High Temperature	W	Power [kW]
LT	Low Temperature	Q	Heat load [kW$_{th}$]
ORC	Organic Rankine Cycle	ρ	Density [kg/m^3]
WHRU	Waste Heat Recovery Unit	η	Efficiency [%]
GHG	Green House Gases		
PE	Primary Energy		

2. Pilot plant description

2.1. ORC and DH process units

The Brescia´s pilot plant consists of the WHRU, the steam accumulator, the deaerator, the ORC unit and auxiliary cooling systems. In figure 2 the process flow diagram including the main components of both the WHRU and ORC unit is shown. Temperature, pressure and flow rate values are monitored at the points numbered on the diagram.
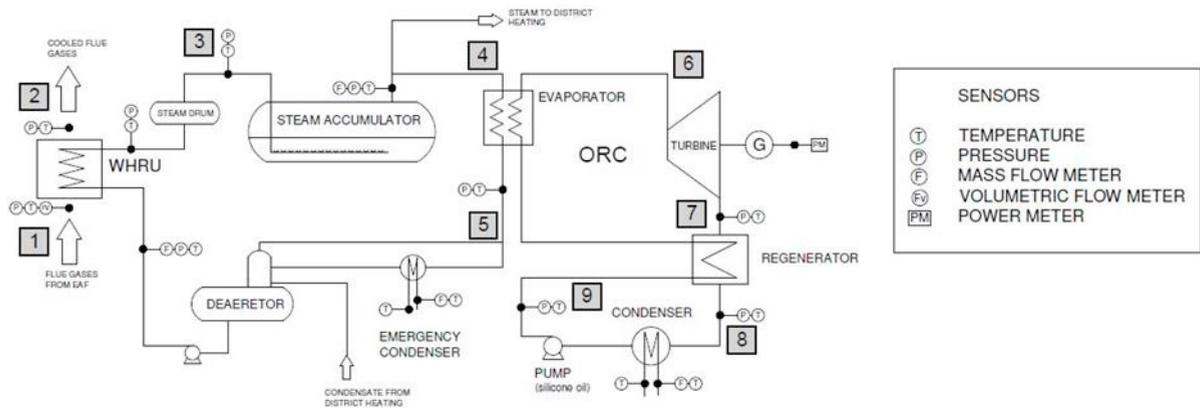
Fig. 2. Process flow diagram: Waste heat recovery, steam generation and storage, ORC and auxiliary systems.

The volume rate of the exhaust gases from the EAF process (2) is highly fluctuating due to the different phases of the furnace. The input exhaust gas design temperature to the WHRU (1) is 500ºC. After exchanging the heat with the water condensate, the temperature of the fumes at the WHRU outlet (2) drops to around 200ºC. Saturated steam between 16 and 24 bar(g) at a temperature between 204ºC and 224ºC is produced, passes through the steam drum (3) and is stored in the steam accumulator. The steam then is either condensed in the ORC´s evaporator or in the DH substation providing thermal energy. The condensate is finally collected within the deaerator and pumped to the WHRU to begin again the cycle.

The steam accumulator is the key component for the stable operation of the plant, minimizing the steam fluctuations caused by the discontinuous supply. Its operation is based on the liquid-vapor equilibrium of the condensate/steam

mixture: if the amount of steam receiving is greater than its delivery, the internal pressure drops and this causes a flash evaporation of the liquid, which results in steam available for the users. It is designed to operate under 10 to 24 bar(g), between 185ºC and 224ºC and has a storage capacity of 6 MWh. The steam accumulator allows meeting the following requirements:

- Accumulation of the recovered thermal energy and controlled release to the ORC unit or DH heat exchangers in periods with none or insufficient thermal energy from the WHRU. In this way, it is possible to supply thermal energy to the ORC with relatively small fluctuations
- Ensuring a controlled reduction of the heat load transferred to the heat receivers in a phased manner in accordance with the safety operation strategies (cases of sudden stops/failure of the WHRU or the EAF)
- Keeping the steam pressure in the Steam Drum as stable as possible, even though the temperature or flow of the exhaust gases are highly fluctuating
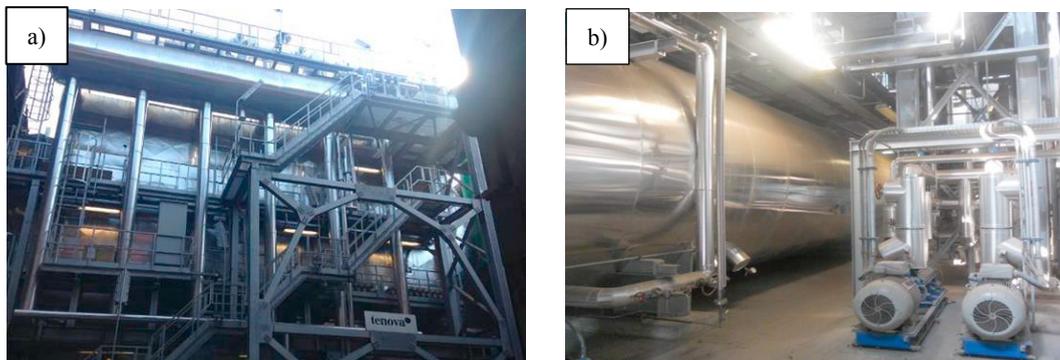
Fig. 3. (a) Picture of the WHRU with the steam drum at the top. (b) Side view of the 150m³ steam accumulator.

The operation of the ORC ends in mid-October when the steam is directed to the DH system. The required feed-in temperature for the DH network varies during the year, from about 95ºC to 120ºC. The actual heat delivery is regulated by the set point given by the DH operator which depends on heat demand and external factors.

2.2. Technical specifications of the ORC generator

The working fluid employed by the ORC is silicone oil (hexamethyldisiloxane), which was chosen due to its relatively low cost, medium working fluid pressures, high market maturity, good experiences at similar plants and comparably good efficiencies. The ORC unit supplied by TURBODEN [6] consists of the typical components of an ORC, namely the evaporator, turbine, regenerator, condenser and pump. In the regenerator, the silicone oil at the outlet of the turbine transfers heat to the stream coming from the condenser. In this way, the thermal energy released by the condenser to the cooling circuit is reduced, which reduces also the heat transferred from the steam at the evaporator. The ORC is capable to work with steam flows between 4 and 16 ton/h, automatically adapting the operation to the EAF melting cycle. Further technical data of the ORC unit are shown in table 1.

Table 1. Design technical specifications of the ORC generator installed by TURBODEN.

	Units	Nominal Values
Thermal power input	kWth	10420
Heat carrier (steam) pressure inlet	bar(a)	15
Heat carrier (steam) temperature inlet	°C	204
Total power input (incl. auxiliary electric demand)	kW	10477
Thermal power to condenser	kWth	8460
Cooling water temperature inlet / outlet	°C	32 / 42.2
Turbine inlet / outlet pressure (working fluid)	bar(a)	7.8 / 0.18

Losses (thermal power)	kWth	133
Gross electric power output	kWe	1885
Net electric output	kWe	1828
Net electric efficiency	%	17.5

2.3. Monitoring and data analysis

The pilot plant is under an extensive monitoring campaign since September 2016. The monitoring will be carried out for at least a full year of operation, covering both the district heating and the ORC operation modes. Until the 15th of October 2016 the recovered waste energy was used for power generation through the ORC. After this date its operation changed to winter mode and the plant supplied heat to the municipal DH network. This operation will continue till mid-April 2017, then it will be changed again to the ORC power generation mode. This report comprises the first results based on the monitoring data available for the first weeks that the ORC has been under commissioning phase. More data representing the operations in continuous will be available after the restart of the ORC in April 2017.

The performance characteristics of the WHRU and the ORC units were determined using the data collected by a monitoring system. Sensors provided accurate readings of the main parameters such as temperature, pressure and flow rate of the main components of the system. The plant is monitored in a 24-hour basis and the data collection is activated every 60 seconds. Pressure and temperature readings were used to determine the fluid properties such as enthalpy and entropy. Flow rate values facilitated the calculation of the heat loads of the flue gases, the steam and cooling water circuits.

The heat load transferred from the flue gases to steam within the WHRU (Q_{fg}) was calculated from the measured normal volumetric flow rate of the flue gases (V_{fg}), its density (ρ_{fg}), and the enthalpy of the inlet/outlet of the gases ($H_{in/out}$) as shown in Eq.(1).

$$Q_{fg} = V_{fg} \cdot \rho_{fg} \cdot (H_{in} - H_{out}) \tag{1}$$

The heat delivered (Q) to the WHRU, the ORC, the district heating loop and all auxiliary heat exchangers was calculated using the measured flow rates (m) and temperature data as presented in equation Eq.(2). The enthalpy was calculated using the temperature monitored in each heat transferring component.

$$Q = \dot{m} \cdot (H_{in} - H_{out}) \tag{2}$$

The power consumption of the ORC plant ($W_{ORC\_consumption}$) was monitored during the operation period as well as the power generated (W_{OUT}). Therefore the net power output of the ORC (W_{ORC_net}) was calculated using the equation Eq.(3). Then it was possible to calculate the net efficiency of the ORC ($\eta_{ORC\%}$) using the equation Eq.(4), where Q_{evap} represents the heat load of the evaporator.

$$W_{ORC,net} = W_{OUT} - W_{ORC,Consumption} \tag{3}$$

$$\eta_{ORC}\% = \frac{W_{ORC,net}}{Q_{evap}} \tag{4}$$

3. Operation mode and performance assessment

The operation of the EAF plant is discontinuous due to the different phases that characterize the process particularly the melting/refining phase. This process causes constant changes of the flow of the flue gases that pass through the WHRU for steam generation which results in steam output short cycling. This operation mode has a direct impact on the ORC unit which requires a constant thermal energy input for optimum operation [7]. Moreover, without the steam accumulator the ORC would have to operate at the power that the flue gases provide causing dynamic power changes

and extremely short period of cycles [8]. To overcome the mentioned performance issues caused by the discontinuous process a steam accumulator was implemented, which allowed maintaining a constant steam discharge avoiding high peak fluctuations.

The ORC output is dependent on the flue gases coming from the EAF plant. Heat is transferred to the steam condensate in the WHRU and saturated steam is driven to the steam accumulator. From the accumulator the steam is sent to the ORC unit and its flow is controlled to maintain pressure and flow as constant as possible. This relatively steady discharge allows the ORC to provide a power output with only minor oscillations, as it can be seen in Figure 4(a). The high peaks of the steam arriving to the accumulator as well as the falls have no important effect on the steam discharge and therefore on the ORC power output.

The steam accumulator is capable to provide continuous discharge for longer periods than the EAF furnace´s charging stops. Figure 4(b) shows clearly the extended steam discharge time which allows the ORC to generate power for an extra period of 40 to 50 minutes before the steam pressure drops to the minimum design pressure.
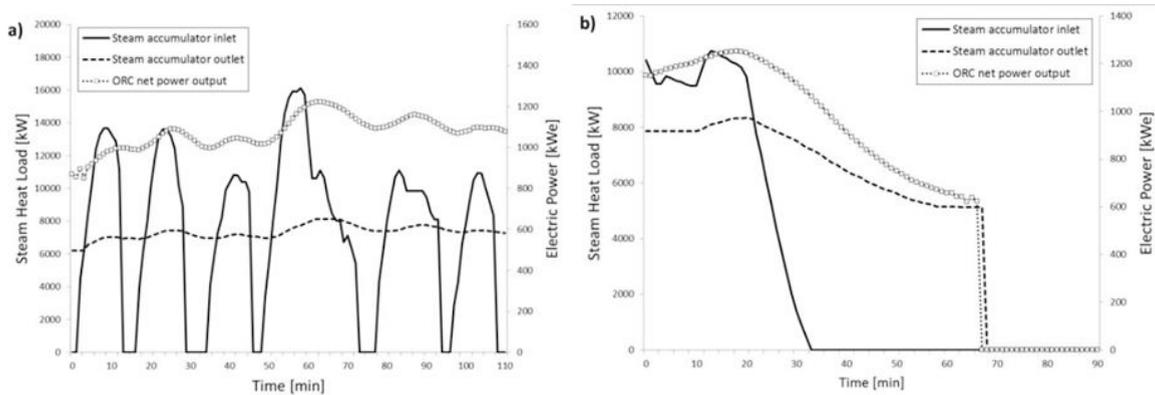
Fig. 4. (a) Steam accumulator discharge and ORC power output during normal EAF operation and fluctuating waste heat recovery. (b) Extended steam supply and ORC generation after the EAF operation. Heat loads of the steam produced, the steam supplied to the ORC unit and its power output during the EAF long stops.

Figure 5(a) and 5(b) show the performance of the ORC and the heat load during the monitoring campaign. The results show that the ORC operated from a heat load of 1.7MW which corresponds to approximately 16% of the evaporator´s capacity and 22,7% of the turbine´s maximum output. These results show that the plant can operate perfectly under partial loads. This lower end load is limited by the minimum pressure value that must be maintained in the steam side cycle for the system´s safe operation.

The average ORC´s net efficiency during the operating period was 21.7% as shown in Figure 5(b). The maximum net power output of the ORC was approximately 2.1MW under 10.5MW of heat load in the evaporator.
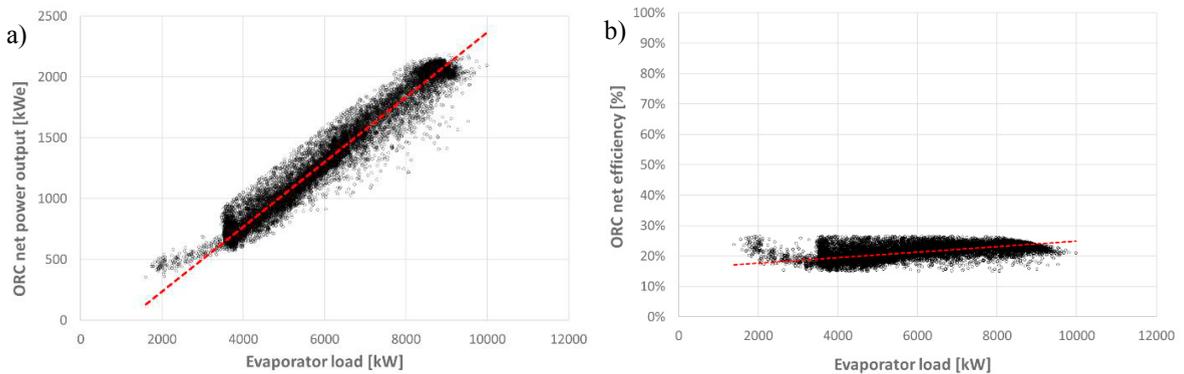
Fig. 5. (a) ORC´s power output under partial heat loads; (b) ORC´s net efficiency during the plant operation.

The average inlet and outlet temperature of the flue gases were 504.5°C and 194.6°C respectively, with a volumetric flow rate of 49830 Nm^3/h as shown in Table 2. The average heat load in the evaporator was approximately 5.9MW and the ORC power output was about 1.3MW.

Table 2. Average values during the first stage of operation of the demonstration plant.

	Units	Nominal Values
Flue gases inlet/outlet temperature	°C	504.5 / 194.6
Flue gases flow rate	Nm^3/h	49830
Evaporator inlet temperature (steam)	°C	181.3
Evaporator inlet pressure (steam)	bar(g)	8.1
Turbine inlet/outlet temperature (working fluid)	°C	162.2 / 44.3
Turbine inlet/outlet pressure (working fluid)	bar(g)	4.1 / 0.2
Heat load ORC evaporator	kW	5906.8
Average Power self-consumption	kW	26.6
Average ORC net power output	kW	1283.5
ORC net efficiency	%	21.7

It is important to mention that the plant at the time of publishing this work has been operative for a limited period. The ORC was monitored on regular operation for a total of 598 hours and during this period some changes and adjustments have been performed on both the controlling and monitoring systems. Results from the whole operating season will be available at the end of the year.

During the data collection period the total amount of energy recovered by the WHRU was 13964GJ. The thermal energy transferred to auxiliary systems and partly dissipated through heat losses summed a total of 3924GJ. The heat delivered to the ORC evaporator was in total 10040GJ and the total electric energy generated was 605MWh. From the values obtained there are indications of heat loss through the auxiliary cooling system and the WHRU itself. That was caused because the pilot plant is under continuous optimization and the controlling system has been adjusted in several cases. For the next operation periods to come the losses will be limited and the learned lessons will help to optimize the controlling system

The environmental impact assessment of the plant also showed interesting results. According to the Life Cycle Assessment that has been performed, the embodied impacts of the new plant account to 677 ton CO2-eq and 2430 MWh of primary energy. The impacts are distributed among the main components as shown by Figure 6. The avoided impacts due to the produced energy (electricity and heat) have been estimated in 7990 ton CO2/year and 40360 MWh/year, considerably higher than the energy invested to build the plant.
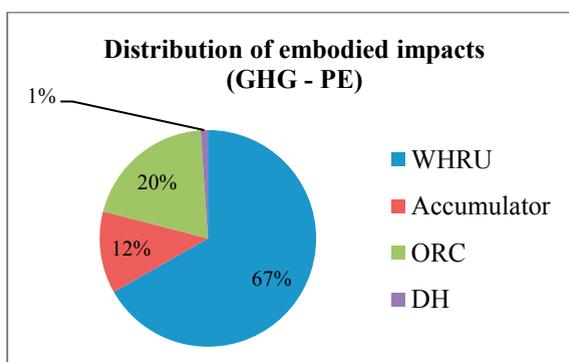
Fig. 6. Embodied impacts of the main components of the waste heat recovery plant in Brescia.

4. Conclusions

The described industrial ORC was installed in a steel mill in Brescia (Italy) as part of a waste heat recovery pilot plant. The heat recovered from the flue gases of the EAF is delivered to a DH network during winter season (from mid-October to mid-April) and to the ORC during the non-heating season (from mid-April to mid-October). The power produced by the generator is delivered to the plant for self-consumption.

Due to the discontinuous mode of operation of the EAF the waste heat coming from the fumes could be supplied only in intervals. In addition, the short stops of the EAF and the high peaks of heat delivered during its starts were also an issue to overcome. Moreover, the needs of an automatic start and stop of the ORC without any interferences with the industrial process was mandatory. The installation of a steam accumulator of 150m^3 at the outlet of the WHRU was the solution to overcome such a discontinuous process. As a result, both the heat delivered to the district heating and the ORC unit could properly operate under a steady heat supply.

Results on the performance of the plant during the first months of operation have shown promising values. The steam accumulator provided a steady discharge of steam of about 8 bar(g) to the ORC evaporator, allowing a stable electric power output even during high peak fluctuations of heat source. Steam could still be supplied during the EAF charging periods when the flue gases were not passing through the WHRU. The extended time of operation of the ORC was approximately 50 minutes. The average temperature of the flue gases was 529.6°C and the net average ORC efficiency was 21.7%.

Further monitoring of the plant and data analysis will provide enough information to identify possible performance improvements. The data collected from the units will help to optimize the function of the steam accumulator in combination with the ORC and DH units.

Acknowledgements

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