Waste heat recovery in the steel industry: better internal use or external integration?

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Abstract: Heat recovery in energy intensive industries represents one of the greatest opportunity to reduce the consumption of primary energy while increasing their competitiveness and sustainability. In steel industry, in particular, approximately 30% of the input energy to the electric arc furnace, one of the most employed technology for steelmaking, is lost in the off-gas. Energy recovery solutions can be grouped by considering the adopted heat recovery approach, which can be direct, indirect or innovative. The recovered energy can be employed by a user that can be internal or external to the steelmaking plant. Many technologies have been developed for the internal use of the recovered energy, such as scrap preheating and power generation. However, the technical challenges related to the electric arc furnace intermittent process limit the profitability of such heat recovery solutions. External uses of the recovered heat, such as industrial symbiosis and district heating have the potential to achieve better performances. After providing an overview on the potential and limits of the available energy recovery solutions, a decision support framework for the identification of the best options for future heat recovery projects in steel industry is proposed, as well as evolutionary paths within it.

Keywords: Waste Heat Recovery, Energy Efficiency, Industrial Symbiosis, District Heating, Steel Industry

1. Introduction

According to the International Energy Agency (IEA, 2016), energy efficiency should be at the centre of the energy policy of any country since it is far from fulfilling its potential. Among the energy efficiency measures, energy recovery from the waste heat discharged by industrial processes represents one of the greatest opportunity to reduce the consumption of primary energy and the related emission of greenhouse gases (GHG). Energy recovery positively impacts the efficiency of production processes by reducing operating costs, increasing the plant productivity and reducing the emission of pollutant. The benefits (i.e. operational, energy, economic, environmental and social) related with energy recovery fully embrace the sustainability concept in its triple bottom line dimensions (Elkington, 1998), indeed energy recovery has now become a common practice when easy to implement. Sources of waste heat include hot combustion gases discharged into the atmosphere, heated products from industrial processes and heat transfer from hot equipment surfaces. The exact quantity of industrial waste heat is still poorly quantified, but various studies have estimated that as much as 20 to 50% of industrial energy consumption is ultimately discharged as waste heat (US Department of Energy, 2010).

In 2012, the steel industry consumed about 5% of all primary energy produced worldwide contributing to 7% of all global CO_2 emissions due to a high share of coal in the industry fuel mix (Laplace-Conseil, 2013). World steel production increased from 28 million tons in 1950 to nearly 1.6 billion tons in 2015 (Word Steel Association, 2016). Although recently significant improvements have been achieved, this sector has the potential to further reduce of 20% both energy consumption and greenhouse gas emission. In particular, steelmaking process adopting electric arc furnace (EAF), which accounts for the 28% of the worldwide steel production (Rizwan Janjua, 2014), releases as waste heat from 15% to 35% of the total energy provided to the process (Kirschen et al., 2009). Figure 1 shows a typical energy balance of an EAF.

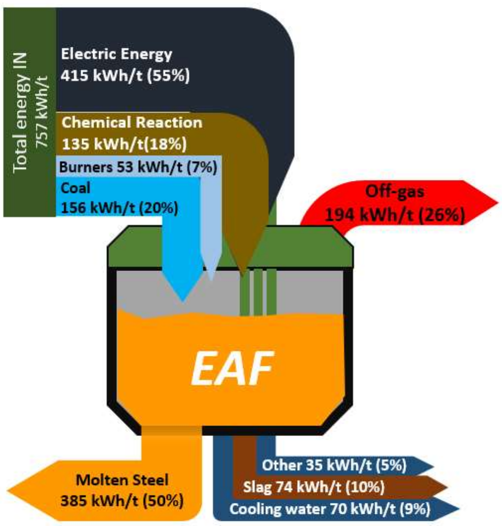

Figure 1: Energy balance of an electric arc furnace (Santangelo et al., 2015)

The main waste heat source in the EAF process is represented by the off-gas, which is characterised by an average temperature of about 750 °C and an average specific energy content of about 200 kWh/t (Born and Granderath, 2013). Since typical production capacity of EAF furnace varies from 50 to 300 t/h, a waste heat recovery potential ranging from 10 to 60 MW can be estimated.

Energy recovery solutions can be grouped by considering the adopted heat recovery approach, which can be direct, indirect or innovative. The final use of recovered heat can be internal or external to the industrial facility. Many technologies have been developed for the internal use of the recovered heat (e.g. scrap preheating). However, the technical challenges related both to the EAF intermittent process and pollutant emissions limit the profitability of such heat recovery solutions. Furthermore, current heat recovery solutions focus just on high temperature waste heat because no opportunity to exploit low temperature waste heat exists within the steelmaking plant. It is worth noting that low temperature waste heat currently represents a cost for the steel industry, which must spend further energy to dissipate it. The opportunity to recover such a low temperature waste heat and to transfer it to an external user, such as a district heating network, represents a huge chance to achieve higher exploitation of the waste heat and, thus, better performances. The article proposes an overview on the potential and limits of the available energy recovery solutions, with the aim of identifying a framework for the best options for future heat recovery projects in energy intensive industries. The paper is structured as follows. In section 2, an overview on waste heat recovery technologies is presented, highlighting advantages and criticalities of the existing and innovative solutions. Then, in section 3 a decision-making framework for the selection of the most appropriate waste heat recovery solution is proposed, while in section 4 conclusions are outlined.

2. Waste heat recovery technologies

Table 1 shows the classification of current technologies for waste heat recovery from EAF process, emerged from a literature review of journal and conference papers, as well as technical reports.

The proposed classification is based on the adopted heat recovery approach, which can be direct, indirect or innovative. Technologies based on direct heat recovery recirculate the waste heat directly into the EAF process. Indirect energy recovery technologies employ a heat transfer fluid (HTF) to recover the waste heat of the EAF off-gas. Innovative heat recovery technologies are those solutions which have been proposed and analysed in literature, but are still in their development phase, with no actual application to refer to. Innovative technologies can be considered as an evolution of the indirect heat recovery technologies. In particular, innovative technologies mainly aim at increasing the efficiency of power generation.

In the following subsections a detailed description of each category is reported.

Table 1: Current technologies for waste heat recovery from electric arc furnace

Recovery approach	Sub-category	User	
		Internal	External
Direct	Continuous charge	Scrap preheating	-
	Discontinuous charge	Scrap preheating	-
Indirect	Steam	Internal processes	Industrial symbiosis
		-	District heating
		Power generation - Steam Turbine - ORC Turbine	Electricity grid
	Hot Water	Power generation - ORC Turbine	Electricity grid
		-	District heating
Innovative	PCM-based devices	Power generation - Steam Turbine - ORC Turbine	Electricity grid
	Molten salt	Power generation -Steam Turbine	Electricity grid

2.1 Direct heat recovery technologies

In direct heat recovery technologies, the waste heat is recovered by preheating the scrap before its charging into the EAF furnace. The modality of scrap charging further classifies such technologies into two groups: continuous and discontinuous charge (see Table 1). Two technologies are mainly used to directly recover the heat in discontinuous charging: shaft furnace and twin-shell. The shaft furnace is available in two main arrangements: single and double shaft (Schmitt, 1997). In the single shaft furnace, the shaft (water cooled and refractory lined) is situated on top of the EAF. The double shaft consists of two EAF furnaces, each one with a shaft and one common electrode mast and set of electrodes to serve both furnaces. The twin-shell technology is similar to the double shaft technology, including two EAF vessels with a common arc and power supply system (U.S. Environmental Protection Agency, 2012). Consteel®, Ecoarc® and EPC® are the main technologies for direct heat recovery in continuous scrap charging.

Consteel® technology conveys the process off-gas into a tunnel where the scrap is pre-heated and continuously fed into the EAF by means of a charge conveyor (Memoli and Bianchi Ferri, 2007). The off-gas enters the tunnel at around 750°C and leaves it at around 500°C, leading to a heat recovery efficiency of about the 34%. The upgraded version of Consteel® technology consists of wider conveyors and a different tunnel profile to improve the heat exchange as well as a new tunnel section equipped with burners, to enhance the input of chemical energy (Giavani et al., 2012). Ecoarc® technology continuously fed the scrap into the preheating shaft where it is constantly in contact with the molten steel in the furnace; during the melting phase the furnace including the shaft is tilted backwards (Yamaguchi et al., 2000). The preheating chamber with its telescopic feeder and the charging deck where a hopper operates are the two main components of the EPC® technology. In this case, the preheating chamber is installed beside the EAF upper shell and the preheated scrap is charged continuously by the telescopic feeder system into EAF for melting (Rummler et al., 2012). Direct energy recovery technologies have significant advantages (Lawrence Berkeley National Laboratory, 2010), such as the reduction of the tap-to-tap (TTT) cycle time, the decrease of power requirements, and the reduction of CO2 emissions (Tenova Spa, 2011).

Nevertheless, a broad adoption of these technologies has been hindered by the difficulties related to the increased plant complexity, surface oxidation of the charge and its partial melting as well as high emission factors for dioxins (Remus et al., 2013). It is worth noting that information about the investment costs for these technologies are difficult to find as they derive from private negotiations between suppliers and customers.

2.2 Indirect heat recovery technologies

Indirect energy recovery technologies employ an HTF, such as steam or hot water (see Table 1), to recover the waste heat of the EAF off-gas. Such technologies requires a thermal energy storage (TES) to provide a constant heat supply to the downstream systems (Steinparzer et al., 2012).

In current state-of-the-art EAF fume treatment plant (Remus et al., 2013) off-gas are cooled down to around 600°C through water cooled ducts (WCD). A quench tower is usually installed downstream to quickly reduce off-gas temperature down to 200°C in order to allow bag filters operation while preventing dioxins production. The heat absorbed by the cooling water, whose temperature increases from 30°C to 50°C, is typically dissipated into the atmosphere by means of evaporative towers thus representing an additional operative cost.

Technologies such as Clean Heat Recovery® (Santangelo et al., 2015), employ superheated water to recover the EAF waste heat and to feed an Organic Rankine Cycle (ORC) system. This system has been implemented by Danieli Officine Meccaniche Spa in the ABS steel plant in Italy. In order to mitigate the issues related to the temperature fluctuations of EAF off-gas, an innovative tank of superheated water, called Thermal Stabilizer Unit (TSU), has been developed by Danieli Officine Meccaniche Spa in collaboration with the University of Udine (Nardin and Dal Magro, 2012). The TSU system is able to smooth the thermal power fluctuations thanks to multiple water inlets and outlets, which are specifically positioned to mix the hottest water with the coldest one.

Hot water could be used to feed district heating networks with a supply temperature of around 90°C. However, to the best of author's knowledge, recovered heat by hot water has not been used to feed district heating yet.

Some other systems, e.g. SMS Siemag AG (Ester, 2009) and Tenova iRecovery® (Born and Granderath, 2013), are based on steam generation through evaporative cooling of the off-gas ducts. Currently, evaporative cooling represents the best solution for off-gas heat recovery because of its flexibility. In fact, the generated steam can be exploited in many ways, serving both internal and external users. According to (Born and Granderath, 2012), in most European countries steam generated by heat recovery allows the achievement of a cost saving of 25 € per ton of generated steam.

An example of internal application of the generated steam is to use it to carry out secondary metallurgy process (e.g. steel degassing by means of steam-driven vacuum pumps) or to drive turbines for energy conversion. The electricity generated by the turbines can then be used within the same steelmaking plant (i.e. self-consumption) or sold to the electricity grid (i.e. external use). The steam can also be used directly to feed an external user such as a district heating network (Trunner and Steinparzer, 2015).

The most successful and spread waste heat recovery system based on steam generation is the iRecovery® Level 1, which has been firstly developed by Tenova from the well-known evaporative cooling system within the GMH EAF revamping project, where about 20 t/h of steam are continuously produced to feed internal users (Schliephake et al., 2010). The main advantage of this solution is the operational stability, which is enabled by the constant temperature of water evaporation, and the robustness to temperature peaks of the off-gas. Such a robustness is due to the spare capacity of the boiling water/saturated steam mixture flowing in the cooling system. This system is able to cool down the off-gas up to 600°C. Considering an average inlet off-gas temperature of 750°C, a heat recovery efficiency of about 21% can be estimated. In waste heat recovery systems based on steam generation, Ruth's steam accumulators are used as TES systems.

At ESF steel plant in Riesa (Germany), the presence of more favourable conditions in terms of steam demand gave Tenova the opportunity to develop the iRecovery® Level 2 technology (Baresi, 2012; Bause et al., 2015) to further exploit the off-gas waste heat. In this case, the off-gas is cooled down up to 200°C, leading to a heat recovery efficiency of approximately 75%. This opportunity has been accomplished by adding a waste heat boiler located downstream the evaporative cooling ducts and installed on the primary EAF off-gas line in parallel to the existing quenching tower. Critical problems such as dioxins de novo synthesis and the extremely high dust concentration required remarkable design efforts. The Riesa project represents a successful example of industrial symbiosis since the generated steam is sold to Goodyear Dunlop Tires Germany GmbH to feed its tyres production plant, which is located nearby (Bause et al., 2015). Part of the generated steam is used to supply an ORC unit for power production. The produced electricity is self-consumed by the steelmaking plant.

Another interesting example of energy recovery system has been implemented in Brescia (Italy) at the ORI Martin steel shop, where a new Consteel® EAF has been installed together with a iRecovery Level 2 waste heat recovery system coupled with an ORC unit (Monti et al., 2015). During the winter, such a waste heat recovery system feeds the existing district heating network and generate electricity, while during the summer only electricity is generated. Due to its technical features and energy performances as well as to the many references worldwide, Tenova iRecovery®, whose general layout is represented in Figure 2, might be rewarded as the current best available technology within the indirect heat recovery options.

For what concerns power generation technologies, two main options are available: steam and ORC turbine. When adopting these technologies in EAF waste heat recovery systems, steam turbine results to be cost-effective when the electric nominal power is higher than 15 MW, while ORC turbine becomes economically viable at an electric nominal power 5 MW, whose specific capital cost is approximately 1,000 € per kW of electric nominal power (data provided by local supplier).

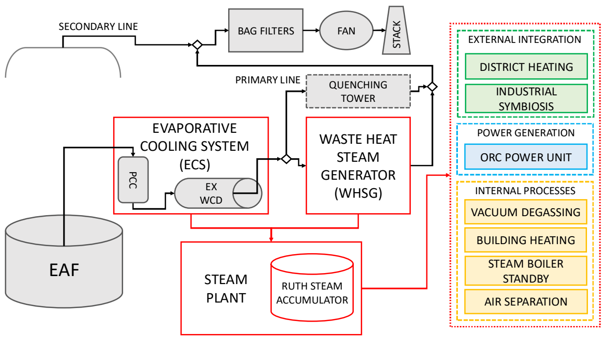

Figure 2 Waste heat recovery through steam production: benchmark plant layout and possible uses

For what concerns the application of indirect heat recovery technology, strategic and technical issues should be carefully evaluated when considering external uses of the recovered energy. Thus, a system perspective should be adopted to guarantee the success of the project. A recent work (Simeoni et al., 2018) evaluated an Italian case study by analysing the opportunity to recover the waste heat from a steel casting facility to satisfy the heating needs of the southern part of Udine Municipality through the realization of a new district heating network. Different district heating layout scenarios have been analysed to consider the impact of connecting different city areas and users. The authors highlighted that a district heating project exploiting waste heat involves several stakeholders, each driven by different and often conflicting objectives. Typically, besides the industrial facility providing the waste heat, the main actors involved in such a project are: an energy services provider managing the district heating network, end users (e.g. other industrial facilities or civil buildings), policy makers and investment funds. Each of them is the bearer of different instances, such as minimization of pay-back period, profit maximization, minimization of the energy bill cost and minimization of GHG emissions. Results showed that for a given industrial waste heat recovery opportunity, it is possible to simultaneously meet the objectives of the various stakeholders involved, resulting in a win-win solution, if a trade-off between the different sustainability perspectives is adopted, thus leading to remarkable economic and environmental performances.

2.3 Innovative heat recovery technologies

Innovative heat recovery technologies aim at increasing the energy conversion efficiency. Two main innovative solutions have been proposed in the past: one using molten salt as HTF and other employing phase change materials (PCM).

The use of molten salt as heat transfer and storage media has been tested in a pilot plant installed in a Simetal EAF Quantum (Steinparzer et al., 2014).

Besides sensible energy storage system (e.g. hot water tank, molten salt), latent heat storage (LHS) technologies exploiting phase change materials (PCMs) are considered to be a promising solution able to store energy as latent heat and release it at a constant temperature during phase transition (Agyenim et al., 2010). According to (Farid et al., 2004), latent heat storage is one of the most efficient ways of storing thermal energy. Unlike sensible heat storage, LHS provides much higher storage density with a smaller temperature difference between storing and releasing heat. However, in (Kenisarin, 2010) it is highlighted that LHS technologies for recovery of high-temperature waste heat have not been given great attention despite their large potential. LHS systems for high-temperature waste heat recovery in steel industry have been proposed in (Maruoka et al., 2004), where metals, such as lead and copper, are adopted as PCM in order to supply constant heat to an endothermic reaction.

Another system exploiting metals as PCM has been proposed in (Nardin et al., 2014). In this case, the aim of the system is to reduce the variability of the off-gas temperature to allow an efficient downstream energy recovery with traditional technologies such as a steam Rankine cycle. The smoothed off-gas temperature profile gains more favourable conditions of steam at the turbine inlet, thus increasing the turbine efficiency due to reduced partial load operations. Furthermore, excessive oversizing of the turbine to face high steam temperatures is avoided, with benefits on investment costs. In (Dal Magro et al., 2017), the smoothing system is coupled with steam production by means of carbon dioxide as HTF.

However, such promising solutions, even if patented (Nardin, 2012), are just at a developing phase, with no actual plants implementing them.

3. Interpretative framework

The previous section 2 has highlighted the potential and limits of current waste heat recovery technologies. Direct heat recovery technologies allow the reduction of TTT cycle time and the decrease of power requirements. However, the deployment of such a technology is mainly limited by both the increased plant complexity and dioxin emission factors. Indirect heat recovery technologies do not improve the performance of the EAF process but result to be more flexible. In fact, they can feed both internal (e.g. power generation) and external (e.g. district heating) users. Innovative solutions are an evolution of indirect heat recovery technologies, which aim is to increase the efficiency of power generation. It is worth remarking that such technologies are still in the development phase.

Involving external users into the deployment of heat recovery projects can allow a full recovery of the waste heat (i.e. from high to low temperature), thus representing a huge chance to achieve better performances.

In Figure 3 a decision-making framework for the selection of the most appropriate waste heat recovery solution is proposed. Two important decision criteria are considered in this framework: the potential demand from external users and the market value of the electricity. The potential demand could be both thermal and/or electric energy, while the external users could be the electrical grid, surrounding industrial activities as well as private and public buildings. The potential demand is related to the location of the steelmaking plant, which affects the cost of the infrastructure (e.g. district heating network) required to transfer the heat, and to the related climate conditions, which particularly affects the heat demand of buildings. The potential demand is considered high when external users can absorb entirely or almost completely the waste heat recovered in the steelmaking plant and are relatively close to it. This condition usually happens when the steelmaking plant is located inside an industrial park or is close to an urban centre. On the contrary, the potential demand is low when external users can absorb just a small amount of the recovered heat or the steelmaking plant is located away from potential energy consumers.

Market value of the electricity considers both the buying/selling price of the electricity as well as incentives rewarding power generation from heat recovery. Generally, the electricity market value can be considered high when its selling or saving leads to a pay-back period of heat recovery technology lower than five years.

It is worth noting that indirect heat recovery technologies are the most common solution (three out of four cases). This is due to the intrinsic flexibility of this technology, whose HTF allows feeding both internal and external users.

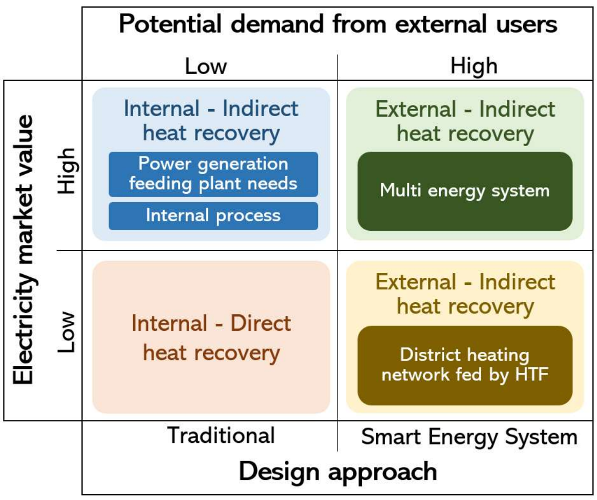

Figure 3: Decision-making framework for waste heat recovery solutions

When both the presence of potential demand from external users and the electricity market value are low, internal use of the recovered waste heat through direct heat recovery represents the best option for waste heat recovery. If the electricity market value is high and the potential demand from external user is low, indirect heat recovery technologies for internal use should be selected. In particular, if steam-based heat recovery is adopted, an internal process such as steel degassing could be fed. However, since electricity can be used in most of internal processes, power generation should be preferred over the direct use of steam.

In the case of high potential demand from external users and low electricity market value, the proposed framework recommends the adoption of an indirect heat recovery technology to cover the thermal energy demand of external users through a district heating network.

Finally, when the potential demand from external users and the market value of the electricity are high, the deployment of a multi energy system serving external users is suggested. The multi energy system considered in this case consists of an indirect heat recovery technology feeding both a turbine for power generation and a district heating network. Depending on the energy market regulation and subventions, the electric energy can be self-consumed as in the Riesa plant, or sold to the national grid as in Brescia plant. As concerns thermal energy, a municipal district heating network can be fed as in the case of Brescia. Industrial symbiosis can also be triggered as in Riesa, where the steam generated by the steel plant heat recovery is directly used for the production process of a different industrial activity in the neighbourhood.

The presence of relevant external users suggests the viability of energy recovery by district heating. If the network already exists, the solution can be more easily implemented. However, the simultaneously presence of a great amount of waste heat and a significant thermal power demand can trigger the realization of a network from the scratch, as in the case of Udine, where such solution is being explored. Such opportunity requires the active involvement of both public institutions and private stakeholders, which should cooperate in order to create the proper conditions for mutual benefits. It is worthwhile to highlight that district heating can exploit low temperature waste heat sources (e.g. cooling water) more significantly than internal recovery solutions where limited applications can be found. Thus, the possibility of developing a network should be always taken into account to reach more significant overall energy efficiency, even if the related infrastructure is not already available.

When the potential demand from external users is high, the design approach should evolve from single plant traditional sizing and management towards the smart energy system paradigm. The most recent conceptualization defines a smart energy system as an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system (Lund et al., 2017). To fully exploit the symbiotic relationship an interaction platform could be developed and grounded on technologies and concepts of Industry 4.0, ranging from power demand matching balancing to demand side management of the multiple involved users.

The proposed framework is not meant to offer a static positioning of recovery opportunities. A steel plant can, in facts, start with the lower left quadrant by initially pre-heating its scraps. Then, indirect heat recovery can be added, in order to exploit the residual waste heat to increase the energy recovery efficiency. Depending on external conditions, which can change over time, indirect recovery can embrace external users, thus moving to the right quadrants. Therefore, evolutionary paths can be recognised within the framework, leading a steel plant to dynamically change its positioning. This is the case of Brescia plant, which initially implemented direct recovery adopting the Consteel® technology and, successively, upgraded direct heat recovery with iRecovery Level 2 indirect recovery solution, feeding the municipal district heating and the ORC power production unit connected to the national grid. In this case, the evolutionary path led straightforward from the lower left quadrant to the upper-right one.

4. Conclusions

The article presented an overview of current technologies for recovering the waste heat released by EAF process, highlighting their advantages and limitations. A decision-making framework for the selection of the most appropriate waste heat recovery solution has been proposed with the aim of identifying the best options for future heat recovery projects in steelmaking industry as well as other energy intensive industries. The decision-making framework is based on two criteria: the potential demand from external users and the market value of the recovered energy. These two dimensions are suggested to guide the selection of proper waste heat recovery technology. Therefore, internal use or external integration should be evaluated on the basis of the actual context where the waste heat is available. However, recent projects highlight a trend towards the smart energy system design approach. The single plant boundaries are overcome in favour of symbiotic synergies, which allow a fully exploitation of waste energy, not reachable by internal use. Therefore, future research effort should be focused on empowering multi energy systems by means of the development of new system design solutions as well as the creation of collaborative platforms for the involvement of different stakeholders.

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