A supply chain model with integrated thermal recovery and electricity generation from industrial waste heat

Beatrice Marchi
Department of Mechanical and Industrial Engineering,
Università degli Studi di Brescia
via Branze 38
25123 Brescia
Italy
b.marchi@unibs.it

Simone Zanoni
Department of Mechanical and Industrial Engineering,
Università degli Studi di Brescia
via Branze 38
25123 Brescia
Italy
simone.zanoni@unibs.it

Marco Pasetti
Department of Mechanical and Industrial Engineering,
Università degli Studi di Brescia
via Branze 38
25123 Brescia
Italy
marco.pasetti@unibs.it

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Abstract

The industrial sector is the most energy-demanding activity in modern societies, consuming about 54 % of the world's total delivered energy. The largest amount of waste heat in the industry sector is generated by energy-intensive processes, such as the manufacturing of food, paper, basic metals (*e.g.* iron and steel), chemicals, and non-metallic minerals. Among these, the metal industry, which includes iron and steel manufacturing, aluminium production, and metal casting, covers a great share of the overall energy consumption, and present large energy efficiency potentials. In these processes, the opportunity to recover waste heat represent an effective way to reduce both energy costs and greenhouse gas emissions. Recent research streams focused on the potential of supply chain management, and of integrated network in enhancing the outcomes of energy efficiency measures. A few works analysed the opportunity to recover energy from excess heat in integrated systems, mainly focusing on active applications for the generation of electricity. In this study, this approach is extended by formulating a supply chain inventory model with integrated waste heat recovery from the exhaust gases generated by energy intensive processes. The decision-making process is firstly modelled as a decentralized policy in which the two actors aim to minimize their own total costs, and then as a centralized policy in which the actors cooperate in order to optimize the economic performance of the supply chain. The decision variables of the model are the lot size, the number of shipment from the vendor to the buyer, and the amount and use of recovered energy.

Introduction

Nowadays, integrating energy considerations in operation decision support models is acquiring increasing relevance, since energy performance are closely linked to sustainability and success issues, both in a single firm (Zanoni *et al.*, 2014) and a supply chain perspective (Bazan *et al.*, 2015). Energy efficiency measures (EEMs) in industrial processes can provide several benefits to different stakeholders of the supply chain in terms of productivity, profitability, competitiveness, and quality (Marchi and Zanoni, 2017). Improving energy efficiency gained a key role in creating competitive advantages, especially for the metal industry, which is one of the highest energy and emission intensive sector. Typical production processes, which includes iron and steel manufacturing, aluminium production, and metal casting, require in fact large amounts of energy. The electric arc furnace (EAF) steelmaking process, for instance, consumes about 436 kWh/ton of raw steel produced (Energetics Incorporated, 2000).

Several EEMs have been proposed by the scientific literature, and are currently applied in the industry, ranging from production planning, investments in energy-efficient equipment, recycling of energy in industrial production process and recovery of excess energy (Johansson and Söderström, 2014). Among them, waste heat recovery represents an effective and mature EEM for energy-intensive processes operating at high temperatures (*e.g.* steelmaking processes), in which large amounts of excess heat are produced.

Waste heat can be recovered on-site and reused in thermal processes or transformed into electrical energy for the core process or for auxiliary services, depending on the energy requirements of the industrial plant and on the maturity of the existing technologies for the specific process. Different mature technologies are already capable to take advantage of this industrial waste heat potential, and are usually categorised as passive or active technologies. In passive applications (such as heat exchangers and thermal energy storage), heat is used directly at the same or at a lower temperature level. Conversely, in active applications waste heat is transformed to another form of energy or to a higher temperature in order to provide electricity or heat useful for other processes (Brückner *et al.*, 2015). Recovered energy can be used directly from the same user, *viz.* recycled in the core process or for ancillary services, or sold to other users in the nearby through a heating network or the electrical grid, by taking advantage of the industrial synergies in the geographical proximity (Broberg Viklund and Johansson, 2014; Ivner and Broberg Viklund, 2015). The integrated approach represents a noteworthy practical opportunity since in this way the economic and environmental performance of the supply chain are optimized: a single firm perspective is likely to not perceive all the potential of energy efficiency measures (Marchi and Zanoni, 2017). For instance, the company accountable for the excess heat not always presents energy requirements in the form and in the instant of time of the available recovered energy. Instead of investing in expensive equipment to synchronize energy requirement and generation, transferring the energy recovered to nearby users can be more feasible, especially if they belong to the same supply chain.

Several studies on the waste heat recovery in industrial processes have been presented in the scientific literature, mainly focusing on on-site recovery. Noteworthy, (Biel and Glock, 2016) introduces the generation of waste heat, transformed into electricity through a ORC (Organic Rankine Cycle), into a lot size model and investigates how lot sizing policies change if waste heat is considered. Recently, (Marchi *et al.*, 2017a) introduced the concept of integrated excess heat recovery in the traditional inventory theory, by modelling the opportunity to coordinate the supply chain members in order to minimize the overall cost. Similarly, (McBrien *et al.*, 2016) considered the opportunity to recover both thermal and electrical energy with a supply chain perspective, but didn't analyse the effects that the production planning has on the waste heat recovery, and *vice-versa*. More recently, (Marchi *et al.*, 2017b) analysed potential synergies among industrial systems, utilities and public service facilities for boosting energy and resource efficiency through an industrial symbiosis approach. Specifically, in the network under analysis, several energy-intensive companies were considered which were responsible for large amount of waste heat.

The aim of the present work is thus to fill the existing gap in the literature, by proposing a lot sizing model that takes into account the integrated waste heat recovery in terms of thermal and electrical energy. In real applications, in fact, the amount of energy that can be recovered depends on the production planning. This is accounted in the proposed model by expressing the waste heat generated by the process as a function of the energy required to process the production lot. The presented model is focused on a supply chain in the metal industry, in which the vendor runs a melting process and then delivers the manufactured items to the buyer, who operates additional operations in order to satisfy the requirements of the final customers. Through the model is then possible to find the optimal flow of the energy recovered: i.e. the share of thermal energy reused to preheat the metal, the share of thermal energy sent to the buyer, and the share of energy transformed into electricity to be used to power the machine or sold to the buyer.

The remainder of the paper is organized as follows. After the introduction of the notation used throughout the manuscript, the problem is stated in its general form, by identifying the main actors and relations in the considered supply chain. Afterwards, the integrated energy and economic model of supply chain is described in detail, by defining the decision variables, the boundary parameters, and the related mathematical formulation. In the same section, a solution approach is proposed for two different policies, *viz.* decentralized and centralized decision making processes. The general model is then proposed for a specific use-case, by considering a EAF steelmaking process. Finally, the main findings of the study are summarized in the last section of the manuscript, and potential future developments are discussed.

Problem setting

This study deals with the coordination of inventory and waste heat recovery decisions in a two-stage single-vendor and single-buyer supply chain, as depicted in Figure 1. Decentralized and centralized scenarios are modelled and compared in order to analyse the effects that production planning and recovery opportunities have on each other. In the decentralized scenario, the buyer selects the order lot size (q) that minimizes its own total cost (TC_B), and then the vendor optimizes its production costs (TC_V) by manufacturing the optimal production lot (nq), by changing the number of shipments (n), and identifying the best use of the recovered energy through the parameters α, β, and γ. In the centralized scenario, the two actors act jointly in order to minimize the total costs of the whole supply chain (TC_S). The following assumptions are considered in the model:

- The inventory system involves a single item with an infinite planning horizon;
- No shortages are considered;
- The customer demand rate D is constant;
- The production rates are constant and limited by technology limits of the production processes with P1P2D.

Model development

INVENTORY MODEL

The buyer orders a lot size of q at regular time intervals and manufactures them at a production rate P_2. The vendor can manufacture an integer multiple of the order lot, nq, at a finite production rate P_1, with a single setup that is delivered to the buyer in n shipments of equal size q. The average inventory levels for the vendor, I_V, and the buyer, I_B, are given by Eq.s (1) and (2), while Eq.s (3) and (4) define the production time of the two actors. In Figure 2, an example of the inventory levels of vendor and buyer is depicted.

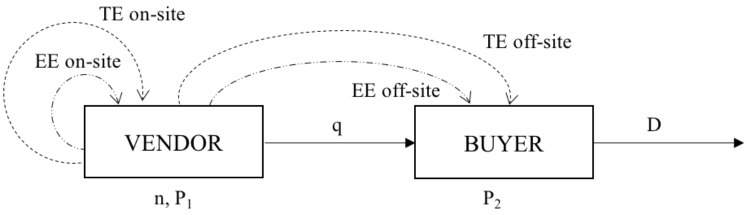

Figure 1. Supply chain diagram defining energy and material flows.

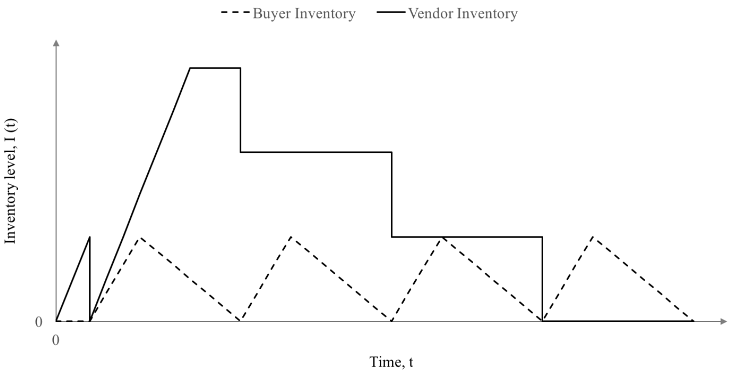

Figure 2. Inventory levels of the vendor and the buyer over time.

$$I_V = \frac{q}{2}\left[\left(1-\frac{D}{P_1}\right)n + \frac{2D}{P_1} - 1\right] \quad (1)$$

$$I_B = \frac{q}{2}\left(1-\frac{D}{P_2}\right) \quad (2)$$

$$t_{P1} = \frac{nq}{P_1} \quad (3)$$

$$t_{P2} = \frac{q}{P_2} \quad (4)$$

THERMAL AND ELECTRICAL ENERGY FLOWS

The material, and energy flows (both thermal and electrical) of the metal production process are presented in Figure 3. The model considers the following waste heat recovery opportunities: on-site load pre-heating, on-site electricity generation and reuse, and off-site transportation of recovered energy to other users with a demand for heat and/or electricity. In this study, we assumed the use of the Organic Rankine Cycle (ORC) technology for the thermodynamic conversion of waste heat into electricity. ORCs are in fact a mature and widely used technology for the exploitation of several heat sources, particularly in the case of industrial waste heat recovery (Schroeder and Leslie, 2010). Several ORC systems are available on the market, with different sizes and efficiencies, mainly depending on the temperature of the available heat source (Pasetti *et al.*, 2014).

Material losses occur during the melting operation, hence the amount of raw material, m_r, that should be processed is higher than the final product at the end of the melting process, nq. The relation among the processed raw material and the production lot size is defined by Eq. (5), where δ represents the percentage of mass flow lost during the melting process.

$$m_r = \frac{nq}{(1-\delta)} \quad (5)$$

The energy required by the process, $\dot{Q}_M$, to melt the raw material loaded into the furnace is defined by Eq. (6), where P_1 is the production rate of the vendor (ton/h), c_r the specific heat of the raw material (kJ/ton K), T_M the melting temperature (K), $T_{r,PH}$ the temperature of the raw material after the preheat process (K), and $L_{f,r}$ the specific latent heat of the raw material (kJ/ton).

$$\dot{Q}_M = \frac{P_1}{(1-\delta)}\left[c_r\left(T_M - T_{r,PH}\right) + L_{f,r}\right] \quad (6)$$

The excess heat, $\dot{Q}_{EH}$, contained in exhaust gases after a treatment in the Waste Heat Recovery Unit (WHRU) is represented as a percentage of the melting heat, $\dot{Q}_M$, as defined in Eq. (7).

$$\dot{Q}_{EH} = \omega_M \dot{Q}_M \quad (7)$$

The load preheating phase is used to reduce the heat required to melt the raw material during the production process. The heat required to reach the temperature $T_{r,PH}$ can be obtained from the heat recovered from the off-gases. If this recovered energy is not sufficient, the additional heat required is purchased from the electrical grid through a heat generator. Eq.s (8)–(10) describe the heat exchanges in the load preheating stage.

$$\dot{Q}_{PH} = \dot{Q}'_{PH} + \dot{Q}''_{PH} = \frac{P_1}{(1-\delta)} c_r\left(T_{r,PH} - T_{r,in}\right) \quad (8)$$

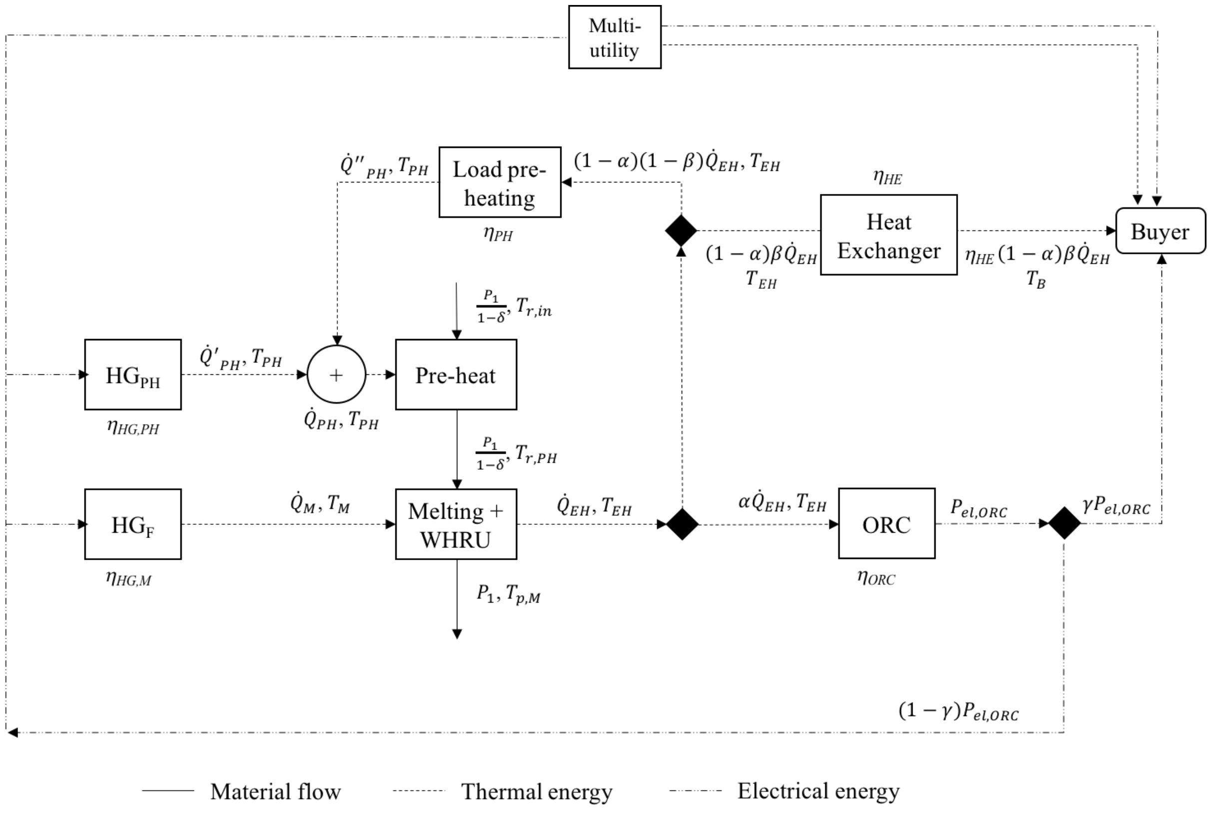

Figure 3. Energy flow diagram representing the material, thermal, and electrical energy flows of the metal production process, according to the considered waste heat recovery opportunities.

$$\dot{Q}''_{PH} = min\{\eta_{PH}(1-\alpha)(1-\beta)\dot{Q}_{EH}; \dot{Q}_{PH}\} \quad (9)$$

$$\dot{Q}'_{PH} = max\{0; \dot{Q}_{PH} - \dot{Q}''_{PH}\} \quad (10)$$

Waste heat can be also recovered and converted into electricity by means of the ORC engine. Eq. (11) defines the electrical power that can be obtained from the exhaust heat through the ORC.

$$P_{el,ORC} = 0.00028\, \alpha\, \eta_{ORC}\, \dot{Q}_{EH} \quad (11)$$

The vendor requires electrical energy to heat and melt the raw material ($\frac{\dot{Q}'_{PH}t_{P_1}}{\eta_{HG,PH}} + \chi\frac{\dot{Q}_M t_{P_1}}{\eta_{HG,M}}$), to start-up electrical equipment, and for auxiliary services (K). The buyer presents a specific energy consumption which is given by the sum of a fixed energy consumption (W) and of variable component (k), which is proportional to the production flow in the process. Eq. (12) defines the specific electrical energy consumption of the buyer, while Eq. (13) its specific thermal energy consumption.

$$SEC_{e,b} = \frac{W_{e,b}}{P_2} + k_{e,b} \quad (12)$$

$$SEC_{t,b} = \frac{W_{t,b}}{P_2} + k_{t,b} \quad (13)$$

The energy purchased from the grid is given by the energy requirements minus the amount of energy that is recovered for the specific actors and carrier. Eq.s (14) and (15) model the electrical energy purchased from the utility by the vendor and by the buyer, respectively, at every production cycle. Eq. (16) represents the thermal energy purchased from the utility by the buyer.

$$\psi_{e,V} = 0.00028\left(\frac{\dot{Q}'_{PH}t_{P_1}}{\eta_{HG,PH}} + \chi\frac{\dot{Q}_M t_{P_1}}{\eta_{HG,M}}\right) + K - EE_{on-site} \quad (14)$$

$$\psi_{e,B} = SEC_{e,b}nq - EE_{off-site} \quad (15)$$

$$\psi_{t,B} = SEC_{t,b}nq - TE_{off-site} \quad (16)$$

The heat recovered by the vendor from the off-gases can be used as thermal energy on-site (Eq. (17)), as well as off-site, by transferring it to the buyer (Eq. (18)), reducing the heat required in the preheating phase and/or the thermal energy consumption of the buyer. Heat can also be converted through an ORC into electricity, which can be reused in this case both on-site at the vendor plant (Eq. (19)) and off-site, by transferring the electrical energy generated to the buyer (Eq. (20)).

$$TE_{on-site} = \dot{Q}_{PH}'' \quad (17)$$

$$TE_{off-site} = min\{0.00028 * \eta_{HE}(1-\alpha)\beta\dot{Q}_{EH}t_{P2}i; SEC_{t,b}iq\} \quad (18)$$

$$EE_{on-site} = min\left\{(1-\gamma)P_{el,ORC}t_{P1};\ 0.00028\left(\frac{\dot{Q}'_{PH}t_{P_1}}{\eta_{HG,PH}} + \chi\frac{\dot{Q}_M t_{P_1}}{\eta_{HG,M}}\right) + K\right\} \quad (19)$$

$$EE_{off-site} = min\{\gamma P_{el,ORC} t_{P2} i; SEC_{e,b} iq\} \quad (20)$$

where $i \in [1,n]$ represents the maximum number of production cycles of the buyer that occur during the production time of the vendor, since only in this case the off-site recovery can be exploited. The synchronism is guaranteed by the following constraint:

$$i \leq \left[\frac{1}{P_1}(n-1) - \frac{1}{P_2}\right] D + 1 \quad (21)$$

ECONOMIC MODEL

The buyer incurs order cost, setup cost, inventory holding cost and the costs related to energy consumptions (both electrical and thermal). The formulation of the total cost of the buyer (TC_B) is thus given by Eq. (22).

$$TC_b = \frac{AD}{q} + \frac{S_2 D}{q} + h_b \frac{q}{2}\left(1 - \frac{D}{P_2}\right)$$
$$+ \left(c_{e\_u,b}\psi_{e,b} + c_{e\_v,b} EE_{off-site}\right)\frac{D}{nq}$$
$$+ \left(c_{t\_u,b}\psi_{t,b} + c_{t\_v,b} TE_{off-site}\right)\frac{D}{nq} \quad (22)$$

The total cost of the vendor (TC_V) is given by the sum of setup cost, inventory holding cost and the energy cost. In addition, the vendor accounts for revenues generated by the integrated waste heat recovery, since it can sell the recovered energy to the buyer. The total cost formulation is given by Eq. (23).

$$TC_v = \frac{S_1 D}{nq} + h_v \frac{q}{2}\left[\left(1 - \frac{D}{P_1}\right)n + \frac{2D}{P_1} - 1\right] + c_{e\_u,v}\psi_{e,V}\frac{D}{nq}$$
$$- \left(c_{e_v,b} EE_{off-site} + c_{t\_v,b} TE_{off-site}\right)\frac{D}{nq} \quad (23)$$

OPTIMIZATION METHOD

In the decentralized scenario, the two actors aim to minimize their own costs. Through the study of the derivatives of the total cost of the buyer (Eq.s (24)–(25)), it results that Eq. (26) is convex in the order lot size (q), and thus it is possible to define the optimal value q^*.

$$\frac{\partial TC_b}{\partial q} = -\frac{[A + S_2]D}{q^2} + \frac{h_b}{2}\left(1 - \frac{D}{P_2}\right) \quad (24)$$

$$\frac{\partial TC_b}{\partial q} = 2\frac{[A + S_2]D}{q^3} \quad (25)$$

$$q^* = \sqrt{\frac{2[A + S_2]D}{h_b\left(1 - \frac{D}{P_2}\right)}} \quad (26)$$

Substituting Eq. (26) in (23), it is then possible to evaluate the optimal value of n, α, β, and γ, by applying the following algorithm.

Step 1. Set $\alpha = \beta = \gamma = 0$, $n = 1$, and $q = q^*$ from Eq. (26).

Step 2. Calculate TC_V (n, α, β, γ) through Eq. (23).

Step 3. Repeat Step 2 for every combination of (n, α, β, γ), with α, β, γ in the range from 0 to 1 while $n \in Z+$. The values of the decision variables that minimize the total cost of the vendor (n^*, α^*, β^*, γ^*) are determined and saved as the optimal solution.

In the centralized scenario, the two actors aim to minimize the costs of the whole supply chain (TC_S), which is given by the sum of the total cost of the vendor and the one of the buyer (Eq.s (22)–(23) respectively). Through the study of the derivatives of the supply chain total cost, it results that TC_S is convex in the order lot size (q), and thus it is possible to define the optimal value q^*.

$$\frac{\partial TC_S}{\partial q} = -\frac{\left[\frac{S_1 + c_{e\_u,v}K}{n} + A + S_2\right]D}{q^2}$$
$$+ \frac{h_v}{2}\left[\left(1 - \frac{D}{P_1}\right)n + \frac{2D}{P_1} - 1\right] + \frac{h_b}{2}\left(1 - \frac{D}{P_2}\right) \quad (27)$$

$$\frac{\partial TC_S}{\partial q} = \frac{2\left[\frac{S_1 + c_{e\_u,v}K}{n} + A + S_2\right]D}{q^3} \quad (28)$$

$$q^* = \sqrt{\frac{2\left[\frac{S_1 + c_{e\_u,v}K}{n} + A + S_2\right]D}{h_v\left[\left(1 - \frac{D}{P_1}\right)n + \frac{2D}{P_1} - 1\right] + h_b\left(1 - \frac{D}{P_2}\right)}} \quad (29)$$

Substituting Eq. (29) in the supply chain total cost, it is then possible to evaluate the optimal value of n, α, β, and γ, by applying the following algorithm.

Step 1. Set $\alpha = \beta = \gamma = 0$, $n = 1$, and $q = q^*$ from Eq. (29).

Step 2. Calculate TC_S (q^*, n, α, β, γ) given by the sum of Eq.s (22) and (23).

Step 3. Repeat Step 2 for every combination of (q^*, n, α, β, γ), with α, β, γ in the range from 0 to 1 while $n \in Z+$. The values of the decision variables that minimize the total cost of the supply chain (q^*, n^*, α^*, β^*, γ^*) are determined and saved as the optimal solution.

Integrated waste heat recovery opportunities in the Electric Arc Furnace production process

The tap-to-tap cycle, which defines the EAF operations, consists in a melting process producing batches of liquid steel, which is characterized by a specific heat of 460 kJ/ton K and by a latent heat of 33,000 kJ/ton. The whole cycle is made up of the following steps:

- Charging phase: the roof of the furnace is removed and scrap metals and other iron-bearing materials are loaded into the furnace. In the same phase, some additional alloying agents (*e.g.* aluminium, manganese, chromium, and nickel) and fluxes (*e.g.* lime) are introduced through the side doors of the furnace, for a better control of the EAF process and of the quality of products;
- Melting phase: the electrodes are lowered to about an inch above the scrap metal and generate an electric arc with the

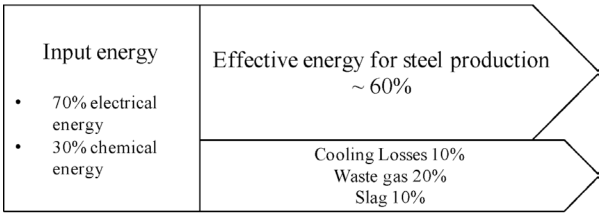

Figure 4. Energy balance of the EAF melting process (Energetics Incorporated, 2000).

roof of the furnace. The electric current in the arc provides the heat necessary for the melting process. In addition, oxy-fuel burners and oxygen lances are used to provide additional thermal energy (up to the 30 % of the total supplied energy) to the EAF process;

- Refining phase: in this phase, impurities such as aluminium, silicon, manganese, carbon, phosphorus, and sulphur are removed from the steel bath;
- De-slagging phase: impurities, in the form of slag, are removed from the furnace;
- Tapping of liquid steel: the tap hole is opened, and the furnace is tilted to pour out the liquid steel;
- Furnace turnaround: it represents the final stage of the cycle. The furnace is prepared for the next cycle and the system is inspected, mainly looking for possible refractory damages.

The melting process involves the use of the largest share of energy consumption of the whole tap-to-tap cycle, and in some circumstances, it can also generate disturbances in the power grid, such as flickers and harmonics. For that reason, the reduction of energy losses and the recovery of excess heat may represent a relevant opportunity for both the user (*i.e.* the industrial plant) and the manager of the power grid (*i.e.* the Distribution System Operator). The energy balance of the EAF melting process is depicted in Figure 4.

The exhaust gases at the output stage of the EAF furnace are responsible for about the 20 % of the power in input of the melting process. Off-gases from EAF present very high temperatures, in the range of 1,600–2,200 K, their volume rate is highly fluctuating among different stages of the operations, and they contain relevant amount of combustibles, particulates, dusts and other pollutants (BCS Inc, 2008; Energetics Incorporated, 2000; Ramirez *et al.*, 2017). For these reasons, off-gases from EAF can't be directly recovered. However, they could be recovered through a WHRU in which the thermal energy of the off-gases is transferred to water producing saturated steam (Ramirez *et al.*, 2017). The steam is then used as heat carrier between the heat source (EAF) and the recovery alternatives. The most common on-site recovery opportunities for EAF steelmakers are represented by load preheating (BCS Inc, 2008), and by the generation of electricity through an ORC power plant, with efficiency up to 15 % (Lecompte *et al.*, 2017; Ramirez *et al.*, 2017). Moreover, the thermal and electrical energy recovered can be delivered off-site through existing heating networks and power grids to other users presenting a demand for heat and/or electrical energy (Broberg Viklund and Johansson, 2014; Ramirez *et al.*, 2017).

Through a numerical study, we then analyse the behaviour of the model previously defined in order to provide some insights on the integrated energy recovery in supply chain. The other parameters used are defined in Table 1.

From the results, shown in Table 2, it is possible to observe how the shift from a decentralized scenario, in which the vendor aims at minimizing its own costs, to a centralized one, in which the objective is to optimize the economic performance of the whole supply chain, leads also to different flows of the recovered energy (i.e. different values of α, β, and γ). Specifically, in the decentralized scenario, the recovered energy

Table 1. Input parameters of the numerical study.

A	€350/order	η_{PH}	95 %
$c_{e\_v,b}$	€0.1/kWh	K	1000 kWh
$c_{e\_u,v}$	€0.15/kWh	$k_{e,b}$	25 kWh/ton
$c_{e\_u,b}$	€0.2/kWh	$k_{t,b}$	15 kWh/ton
$c_{t\_u,b}$	€0.1/kWh	P_1	100 ton/h
$c_{t\_v,b}$	€0.02/kWh	P_2	150 ton/h
D	100 ton/h	S_1	€25/setup
δ	5 %	S_2	€100/setup
h_b	€5/ton h	T_M	1810 K
h_v	€15/ton h	T_{r_in}	290 K
η_{HE}	99 %	T_{r_PH}	423.15 K
$\eta_{HG,M}$	95 %	$W_{e,b}$	250 kW
$\eta_{HG,PH}$	96 %	$W_{t,b}$	100 kW

Table 2. Results of the numerical study.

	q (ton)	n	α	β	γ	TC_v (€/h)	TC_b (€/h)	TC_S (€/h)
Decentralized scenario	232.38	*1,383*	*0.52*	*0*	*0*	3,882.37	1,077.30	4,959.66
Centralized scenario	73.49	*1,171*	*0*	*0.52*	*0*	2,710.03	1,255.12	3,965.15

is firstly used at the vendor site. While, if the two actors cooperate, the vendor prefers to transfer a share of the thermal energy to the buyer instead of producing electricity because of the very low efficiency of the ORC. In this way, the supply chain incurs in lower total costs (-20.1 %), even though not necessary both the actors incur in savings: the vendor obtains a reduction of 30.2 %, while the buyer an increase of 16.5 %. For that reasons, profit sharing mechanisms should be investigated.

Conclusions

Waste heat recovery represents a remarkable opportunity for energy-intensive processes aiming at reducing energy consumptions. Currently, different technologies are capable to recover excess heat and to provide both thermal and electrical energy. Specifically, waste heat recovery in metal industry can lead to relevant economic and environmental benefits, due to the large energy content of exhaust gases of the melting process. These gases can be recovered as thermal energy by introducing a load preheating phase, or as electrical energy through thermodynamic conversion by using ORC engines. In this study, we proposed a supply chain inventory model in which the most relevant waste heat recovery technologies for the metal industry are considered. The defined model is thus applicable to all the supply chains in which the vendor performs a melting process. The recovered energy can be used both on-site at the vendor plant, and off-site taking advantage of industrial synergies among nearby users, by transferring electrical and/or thermal energy from the vendor to the buyer.

A numerical analysis, applied to the EAF process is also proposed to highlight the relevance of the presented model and to provide some insights. The results show that how the recovered energy is used differs in the two scenario considered. If decentralized decisions are considered, the vendor is more interested to reduce its own energy costs using all the energy that can be recovered, in part as thermal energy and in part converted into electricity. Conversely, when the two actors cooperate, the priority shift to reusing the recovered energy in the form of heat, since it presents higher efficiency than the conversion process though the ORC. Moreover, a sensitivity analysis on some relevant parameters is presented in order to extend the observations to a wider range of case study.

The waste heat flow generated by the melting process is subject to a high variability. A recent study (Dal Magro *et al.*, 2015), shows that a temperature smoothing device based on phase change materials inserted into the off-gas line of a continuous charge electric arc furnace process with scrap preheating can lead to increased efficiency. The integration of this technology in the proposed work can represents a further improvement. The synchronisms of the production cycles of the two actors of the supply chain is a prerequisite for the use of recovered energy at the buyer plant. A possible future development of this study consists in introducing an energy storage system in order to uncouple the recovery of waste heat and the demand for energy (Biel and Glock, 2017). A further extension is the integration in the model of the opportunity for the vendor to sell the recovered energy to the multi-utility by dispatching it into the district heating and/or electricity grid for meeting the energy requirements of residential users.

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Appendix A

The notation used throughout the paper is defined as follow:

A Order cost of the buyer (€/order)
α Percentage of excess heat recovered through the ORC
β Percentage of recovered heat sent to the buyer
$c_{e\_v,b}$ Unit price for the electrical energy sold by the vendor to the buyer (€/kWh_e)
$c_{e\_u,v}$ Unit price for the electrical energy purchased by the vendor from the utility (€/kWh_e)
$c_{e\_u,b}$ Unit price for the electrical energy purchased by the buyer from the utility (€/kWh_e)
$c_{t\_u,b}$ Unit price for the thermal energy purchased by the buyer from the utility (€/kWh_t)
$c_{t\_v,b}$ Unit price for the thermal energy sold by the vendor to the buyer (€/kWh_t)
c_r Specific heat of the raw material (kJ/ton K)
χ Percentage of the heat required in the melting process that is fulfilled through electrical energy
D Demand rate (ton/h)
δ Percentage of mass flow loss during the melting process
$EE_{on\text{-}site}$ Amount of electrical energy recovered on-site by the vendor (kWh_e)
$EE_{off\text{-}site}$ Amount of electrical energy recovered by the vendor and transferred off-site to the buyer (kWh_e)
γ Percentage of electric power transferred to the buyer
h_b Unit holding costs for the buyer per unit of time (€/ton h)
h_v Unit holding costs for the vendor per unit of time (€/ton h)
η_{HE} Heat exchanger efficiency to reach the temperature required by the buyer
$\eta_{HG,M}$ Heat generator efficiency in the melting process stage
$\eta_{HG,PH}$ Heat generator efficiency in the preheating process stage
η_{ORC} Organic Rankine Cycle efficiency
η_{PH} Preheating from energy recovered process efficiency
I_B Inventory level of the buyer (ton)
I_V Inventory level of the vendor (ton)
K Fixed electrical energy consumption at the vendor production plant (kWh)
$k_{e,b}$ Variable coefficient of the specific electrical energy consumption of the buyer (kWh_e/ton)
$k_{t,b}$ Variable coefficient of the specific thermal energy consumption of the buyer (kWh_t/ton)
$L_{f,r}$ Latent heat for melting one unit of raw material (kJ/ton)
m_r Amount of raw material processed (ton)
n Number of shipments
P_1 Production rate of the vendor (ton/h)
P_2 Production rate of the buyer (ton/h)
$P_{el,ORC}$ Electric power generated through the ORC (kW)
q Order lot size (ton)
$\dot{Q}_{EH}$ Excess heat produced by the melting process (kJ/h)
$\dot{Q}_M$ Heat required in the melting process stage (kJ/h)
$\dot{Q}_{PH}$ Heat required for pre-heat the raw material (kJ/h)
$\dot{Q}'_{PH}$ Heat required for pre-heat the raw material purchased from the electrical energy source (kJ/h)
$\dot{Q}''_{PH}$ Heat required for pre-heat the raw material obtained through the waste heat recovery (kJ/h)
S_1 Setup cost of the vendor (€)
S_2 Setup cost of the buyer (€)
$SEC_{e,b}$ Specific electrical energy consumption at the buyer site (kWh_e/ton)
$SEC_{t,b}$ Specific thermal energy consumption at the buyer site (kWh_t/ton)
T_B Temperature of the excess heat recovered and transferred to the buyer (K)
T_{EH} Temperature of the excess heat produced in the melting process (K)
T_M Melting temperature (K)
T_{PH} Temperature of the preheating process (K)
$T_{p,M}$ Temperature of the product after the melting process stage (K)
$T_{r,in}$ Temperature of the raw material in input (K)
$T_{r,PH}$ Temperature of the raw material after the preheating process stage (K)
t_{p1} Production time of the manufacturing process at the vendor site (h)
t_{p2} Production time of the manufacturing process at the buyer site (h)
TC_b Total cost of the buyer (€/h)
TC_v Total cost of the vendor (€/h)
$TE_{on\text{-}site}$ Amount of thermal energy recovered on-site by the vendor (kJ/h)
$TE_{off\text{-}site}$ Amount of thermal energy recovered by the vendor and transferred off-site to the buyer (kWh_t)
$W_{e,b}$ Fixed coefficient of the specific electrical energy consumption of the buyer (kW_e)
$W_{t,b}$ Fixed coefficient of the specific thermal energy consumption of the buyer (kW_t)
ω_M Percentage of heat in the melting process that is wasted
$\psi_{e,V}$ Electrical energy purchased from the utility by the vendor (kWh_e)
$\psi_{e,B}$ Electrical energy purchased from the utility by the buyer (kWh_e)
$\psi_{t,B}$ Thermal energy purchased from the utility by the buyer (kWh_t)