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Assessment of energy potential for heat recovery in the EU industry

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Assessment of energy potential for heat recovery in the EU industry

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Abstract. Thermal processes account for 70% of the EU industry final energy, with 30% thereof being wasted through losses. This fact has been a motivating factor toward applying various technologies and methods for waste heat recovery. Already such technologies exist and are applied in many industrial sectors, while some "new" technologies have also been tested or suggested. It is therefore useful to obtain insight information into such processes, together with their temperature ranges and, hence, assess the potential market for each industrial sector. Here such an attempt is made, based on existing literature. Estimates on the total energy that can be recovered through the EU industry are given and a special case study on the important Iron and Steel industry is presented. This kind of information can be useful for the improvement of existing and the development of "new" technologies or techniques.

Keywords: waste heat recovery; WHR potential estimation; WHR technologies; iron and steel.

1. Introduction

The European Union (EU) is currently responsible for over 11% of the world final energy consumptions and the world final CO_2 emissions, with the EU industry accounting for the 26% and 48% of the final EU energy consumptions and CO_2 emissions respectively [1]. Moreover, 70% of the EU industry final energy is for thermal processes, with 30% thereof being wasted through losses. However, a significant portion of this heat can be recovered through various methods and technologies [1–3].

There is, hence, an increasing global interest in the development and application of waste heat recovery (WHR) systems. The WHR market is currently well over €45 billion, with EU Europe dominating this market [2]. For the industrial sector and, consequently for the environment, to benefit from these developments, technological improvements and innovations that increase energy efficiency of WHR equipment and reduce installation costs should continue to take place (see [3]).

Conventional WHR technologies, active or passive, depend on the temperature of the waste heat stream and other factors, and can be classified into (i) recovery as hot air or steam, (ii) conversion to chemical energy as fuel, and (iii) thermoelectric power generation, while an alternative classification for WHR methods has been given as (i) direct utilizing: heat delivery to district heating or cooling or preheating, (ii) power utilizing: electricity generation using generator, (iii) cascade utilization: combining heating, cooling and power [4–6]. WHR processes can be classified according to temperature range as high (HT), medium (MT) and low (LT), with LT usually meaning 100°C or less. The temperature classification of the various processes is an effective way to select the appropriate WHR technology for each industry and each process [1].

The main aim of this work is to present an insight on the potential for WHR available in the EU industry with regard to type of industry and WHR technology as well as WHR methodology.

2. Main industries assessment

When considering different technologies for using the industrial WHR potential, it is useful to first determine whether it is the theoretical/physical potential, the technical potential or the economic/feasible potential. The theoretical potential considers physical constraints only (e.g., the heat must be above ambient temperature), the technical potential depends on the technologies considered (e.g., the required minimum temperature), while the feasibility of the technology considered should be further analyzed using economic criteria [2].

There exist several attempts in the literature for the estimation of WHR potential through various, albeit similar, methodologies [7–9]. The identification of the WHR processes is the key parameter to evaluate the WHR potential. There are 18 industries where WHR can be achieved, namely (i) the Iron and Steel industry, (ii) the Large Combustion Plants, (iii) Large Volume Inorganic Chemicals: Ammonia, Acids and Fertilizers, (iv) Large Volume Inorganic Chemicals: Solids and Others industry, (v) Food and Tobacco, (vi) Production of Glass, (vii) Production of Organic Fine Chemicals, (viii) Production of Non-Ferrous Metals, (ix) Production of Cement, Lime and Magnesium Oxide, (x) Production of Polymers, (xi) Ferrous Metals Processing, (xii) Production of Pulp, Paper and Board, (xiii) Surface Treatment Using Organic Solvents, (xiv) Tanning of Hides and Skins, (xv) Textiles industry, (xvi) Waste incineration, (xvii) Waste Treatment, and (xviii) Wood-based panel production.

The main processes and their temperature levels that implicate waste heat in the steelmaking process are: the blast furnace/basic oxygen furnace route (HT), the direct melting of scrap (electric arc furnace) (HT), the smelting reduction (HT) and the direct reduction (HT). Large combustion plants include several processes for general fuel heat conversion (HT), gasification/liquefaction (HT), steam generation process (MT, HT), co-generation/combined heat and power (LT), combined cycle plants (HT).

Large volume inorganic chemicals (ammonia, acids and fertilizers) include conventional steam reforming (e.g., desulphurization process) (HT), sulphuric acid process (e.g., sulphur combustion SO2 production process) (HT). Large volume inorganic chemicals (solids and others) include sulphur burning process (MT), tank furnace process (HT) and sodium silicate plant (HT).

The Food and Tobacco industry uses many processes that involve heat in various ways, some of which are crude vegetable oil production from oilseeds (LT), utility processes (MT), heat recovery from cooling systems (LT), high temperature frying (HT), solubilization/alkalizing process (MT). Production of glass uses mainly heating the furnaces and primary melting processes (HT). Production of organic fine chemicals includes processes of energy supply (LT) and thermal oxidation of VOCs and co-incineration of liquid waste (HT).

Production of non-ferrous metals includes processes of primary lead and secondary lead production (MT), smelting process (HT) and zinc sulphide (sphalerite) (HT). Production of cement, lime and magnesium oxide includes processes of kiln firing (HT) and clinker burning (HT). Production of polymers includes mainly thermal treatment of wastewater (LT). Ferrous metals processing uses mainly hot rolling mill (HT). Production of pulp, paper and board includes processes of chemical pulping (LT-MT-HT), mechanical and chemimechanical pulping (LT-MT), papermaking and related processes (LT).

Surface treatment using organic solvents includes processes of printing (HT), drying and curing (HT), waste gas treatment from enameling (HT), manufacturing of abrasives (LT-HT), coil coating (MT). Tanning of hides and skins uses mainly drying (LT). Textiles industry includes processes of dirt removal (HT), optimization of cotton warp-yarn (LT-MT), dyeing (LT), oxidation (HT), drying (MT). Waste incineration includes processes of drying and degassing (MT), pyrolysis (MT-HT), gasification (HT), oxidation (HT), combustion (HT). Waste treatment includes processes of thermal treatment (HT), drying (LT), regeneration of carbon (HT), incineration (HT), catalytic combustion (MT-HT), dying of wood particles (MT-HT). Finally, wood-based panel production includes processes of drying of wood fibers (MT), pressing (MT), lamination (MT).

An analysis of the energy consumption of the EU industry together with a preliminary assessment of the WHR potential can be found in [2], where the percentages of WHR potential for each industry have been estimated, as shown in Table 1.

Table 1. Waste heat potential percentage per industry [2]

Industry Type	**WHR potential (%)**
Iron & Steel	11.4
Chemical and Petrochemical	11.0
Non-ferrous metal	9.6
Non-metallic minerals	11.4
Food and Tobacco	8.6
Paper Pulp and Print	10.6
Wood and Wood Products	6.0
Textile and Leather	11.0
Other	10.4

Moreover, figure 1 shows the energy consumption of EU industry for the year 2016, and the estimated WHR potential based on the percentages shown in Table 1. In 2016 the total energy consumption for 13 industrial sectors was estimated to be 3217.85 TWh, with the estimated WHR potential at 336.9 TWh [1]. The Iron & Steel industry is chosen as a case study for a more analytical explanation on how to perform WHR in that industrial sector with regard to method, technology and temperature, in section 3.

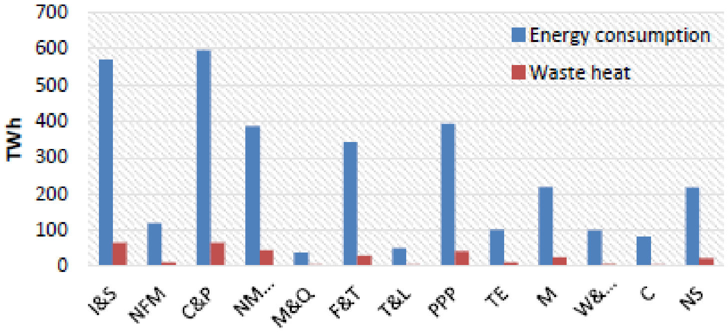

Figure 1. The energy consumption per industry in the EU in 2016, and the estimated WH (I&S: Iron and Steel, NFM: Non-Ferrous Metals, C&P: Chemical and Petrochemical, NMM: Non-Metallic Minerals, M&Q: Mining and Quarrying, FT: Food and Tobacco, T&L: Textile and Leather, PPP: Paper, Pulp and Print, TE: Transport Equipment, M: Machinery, WWP: Wood and Wood Products, C: Construction, NS: Not Specified) [1].

3. The case of the iron and steel industry

Iron and Steel (I&S) production is separated into different processes and each process has different temperature range and potential WHR. There are five main operation processes, namely: (i) the sinter process, (ii) the pelletization plants / induration process, (iii) the coke oven plants, (iv) the blast furnace, (v) the basic oxygen steel making. Temperature ranges in the I&S industry are in the HT range, with temperatures ranging from 900 to 1500 °C between processes. Higher temperatures of the waste heat to be recovered correspond to a higher quality and economic efficiency of the heat, regardless of the method used [10]. To examine the technical and economic feasibility of the WHR it is essential to match supply with demand [11].

There are different methods employed to take advantage of the waste heat energy from the processes. Barati et al. have classified WHR technologies into recovery as hot air or steam, conversion to chemical energy as fuel, and thermoelectric power generation [5]. The methods are generally applied into three categories, as mentioned in the Introduction: (i) Direct utilizing; heat delivery to district heating or cooling or preheating; (ii) Power utilizing; electricity generation using generator; (iii) Cascade utilization; combine heating, cooling and power.

Direct utilization can be achieved using heat exchangers. The heat exchangers are most commonly used for heat transfer from the combustion exhaust gases to the air entering the furnace; this process is known as preheating or recovery from hot air. The heat pump systems can be classified in mechanically driven heat pumps, absorption heat pumps and other sorption technologies [4]; they include open cycle vapor recompression systems, absorption heat transformers, compression-absorption heat pumps, and adsorption and desiccant systems. More details on the techniques used in the WHR of the I&S industry and the process of which each technique is applicable can be found in [12]:

The convectional way to recover heat is with the use of water quenching [13]. Molten slag exhausted is the most common WHR source of energy in the I&S industry and the systems/processes used are described in [14].

Regarding the procedure of slag crushing, it is required to take advantage of the waste heat and is certified into three physical methods: mechanical crushing, air blast and centrifugal granulated.

An extended list of the all available processes is as follows: (1) Solid slag impingement process, (2) mechanical stirring process, (3) rotating drum process, (4) air blast process, (5) rotating cup atomizer (RCA) process, (6) spinning disk atomizer (SDA) process, (7) rotating cylinder atomizer (RCLA) process, (8) direct electrical conversion devices (WHR by either phase change materials (PCMs) or by thermoelectric materials).

Generating electrical power from waste heat energy is achieved by converting the heat energy to mechanical energy in order to drive an electric generator. The temperature of the waste heat affects and limits the efficiency of the power generation and is only available to mainly HT (as in the case of the IS industry) and in some cases to MT waste sources.

Generating power via mechanical work in the I&S industry can be achieved using the following well-known principles: (1) Steam Rankine Cycle, (2) Organic Rankine Cycle, (3) Kalina Cycle.

Finally, chemical methods are classified into two processes, namely the methane reforming reaction process and the coal gasification process. The chemical processes, despite the sensible heat conversion of molten slag into chemical energy with high energy values, exhibit limitations. The gas product, for example, is hard to be purified and as raw materials for the chemical processes cannot be directly obtained from the I&S manufacturing plants, the process will have an increased cost. At the moment there is no available information of large-scale applications in the I&S industry.

3.1. Performance and Potential

Different methods at different processes can yield different performance and WHR for a specific system. It would be more accurate to present the available performance potential of each system.

Table 2. Summary for the granulation processes and WHR methods from [14].

Granulation	Slag type	Heat exchanger	WHR rate (%)	Reference
Solid impingement	BF slag	Fluidized bed	65	[15]
Mechanical stirring	BF slag	Partition wall type heat exchanger	50	[16]
Mechanical stirring	BF slag	Partition wall type heat exchanger	50	[17]
Single rotating drum	BF slag	Fluidized bed	60	[18]
Twin drum	BF slag	Partition wall type heat exchanger	40	[19]
Air blast	Steel slag	Partition wall type heat exchanger	41	[20]
Air blast	BF slag	Fluidized bed	48	[21]
Rotating cup	BF slag	Fluidized bed	59	[22]
Spinning disc	BF slag	Packed bed		[23]
Spinning disc	BF slag	Chemical process		[24]
Rotating cylinder	BF slag			[25]

The processes and the techniques have been discussed in the previous sections. The energy recovery from the granulation/ slag type and heat recovery rate are presented in table 2.

The WHR potential of the I&S industry is presented in table 3.

Table 3. I&S waste heat recovery potential [26].

		Heat source	**Heat Supply (KWh/ton)**	**Temperature (^{o}C)**
Coke Ovens	Sensible Heat in the Coke Ovens	Gas	82	980
Coke Ovens	Exhaust gas from combustion of CO gas	Gas	58	200
Coke Ovens	Heat Recovery from solid radiant coke	Solid	62	800
Blast Furnaces	Sensible heat in the blast furnace	Gas	28	100
Blast Furnaces	Exhaust gas from blast stoves	Gas	82	250
Blast Furnaces	heat recovery from slag	Solid	100	1300
BOS	Heat recovery from BOS gas	Gas	141	1700
BOS	Heat recovery from BOS slag	Solid	6	1500
EAF	Electric Arc Furnace	Gas	44	1200
Casters	Heat Recovery from hot slab	Solid	352	1600
Hot Rolling	Heat recovery from coil	Solid	1395	400
		Total	**2350**	

A case study of hot blast stove flue gas sensible heat recovery and utilization has been presented in [27]. An absorption heat pump was firstly run using the flue gas, and later was used to preheat the Blast Furnace gas. The system performance was optimized using the energy saving rate and the profit rate by the authors. The results indicated that the system could achieve an energy saving of 16.5% and a reduction of CO_2 at 16.5%. Lemmens and Lecompte have also investigated the economic effect of flue gas heat recovery using organic Rankine cycle (ORC) [28]. The flue gas has a maximum temperature of 240–250 °C that amounts to approximately 2.8 MW of thermal power. The IRR of the project was calculated at 12.6%, which is higher than the discount rate scenarios, yielding hence a positive NPV value. A sensitivity analysis was conducted by the authors stating that the project results altered most by changes in the electricity price and the annual load hours of the system. Arash et al. have presented a comparative thermodynamic analysis of two waste heat recovery cycles, organic Rankine cycle and Kalina cycle for a cogeneration system [29]. The authors have observed that optimum pressure value for the ORC is much lower than that of the Kalina, which leads to lower cost levels for materials and sealing of ORC. Additionally, the Kalina cycle requires a lower turbine size than that of the ORC. Another study on the performance between ORC and Kalina cycles has been investigated in [30] through the use of multi-stream WHR techniques.

A study contacted in Japan has presented the economic analysis of the WHR devices (see Table 4).

Table 4. Economic analysis of WHR devices [31].

WHR Device	**Investment cost (million €)**	**Economic effect (million €/ year)**	**Estimated Payback Period (years)**
Sintering machine cooler	29	1.1	25.8
Hot stove	1.2	0.5	2.8
Blast furnace top-pressure recovery turbine	6.6	8	1.8
Converter gas	4.8-9	0.6	8.3–15.2
Converter gas sensible	5.65	0.7–1	5.6–7.8

The authors have presented the calculated results with maximum waste stream temperature of 180 °C, concluding that for straight and concave waste heat with R not less than 0.2, Kalina cycle is better than ORC, while for convex waste heat, ORC is preferable.

4. Conclusions

As mentioned above, the WHR potential in the EU has been estimated to be 300–350 TWh/year, which is about 10% of the EU energy consumption of 2016. This constitutes a highly motivating factor for the development of WHR technologies. Having obtained sufficient insight information into such processes, together with their temperature ranges, used in all industrial sectors in the EU [1–3, 8–9], the next step is to assess the potential market for each industrial sector. The idea of improved and ‘‘new’’ technologies with regard to recovery techniques has been suggested in [1], [3]. To this end, the functionality and usage of technologies as well as their advantages and shortcomings has been thoroughly evaluated and described in [3]. Equally important is to obtain further knowledge on any related barriers (e.g., financial, technological, legislative) and how these can be overcome.

For the interested reader, more details on the subject can be found in [1], [2], [9].

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