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Waste Heat Recovery in the EU industry and proposed new technologies

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Abstract

In the European Union (EU), industrial sectors use 26% of the primary energy consumption and are characterized by large amounts of energy losses in the form of waste heat at different temperature levels. Their recovery is a challenge but also an opportunity for science and business. In this study, after a brief description of the conventional Waste Heat Recovery (WHR) approaches, the novel technologies under development within the I-ThERM Horizon 2020 project are presented and assessed from an energy and market perspectives. These technologies are: heat to power conversion systems based on bottoming thermodynamic cycles (Trilateral Flash Cycle for low grade waste heat and Joule-Brayton cycle working with supercritical carbon dioxide for high temperature waste heat sources); heat recovery devices based on heat pipes (flat heat pipe for high grade radiative heat sources and condensing economizer for acidic effluents).

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Keywords: Energy recovery; waste heat recovery; heat pipe; Trilateral Flash Cycle; supercritical CO2

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Nomenclature

CE	Condensing Economizer	LT	Low temperature
EU	European Union	MT	Medium temperature
FHP	Flat Heat Pipes	ORC	Organic Ranking Cycle
HE	Heat Exchanger	sCO_2	Supercritical carbon dioxide
HT	High temperature	TFC	Trilateral Flash Cycle
HP	Heat pipes	WHR	Waste Heat Recovery

1. Introduction

In the EU28, it is estimated that 70% of total energy use in the industrial sector is for thermal processes (furnaces, reactors, boilers and dryers) and up to a third of this energy is wasted through losses. A significant portion of this heat can be recovered and utilized to make a contribution to energy efficiency and Greenhouse Gas Emission reduction targets. According to [1], the largest amount of waste heat is in food and tobacco, pulp and paper, basic metals, chemical industry and non-metallic minerals.

The use of conventional waste heat recovery (WHR) technologies depends on the temperature of the waste heat stream, the composition of the waste heat stream and the available area. WHR technologies have been categorized into active and passive, with sub categories depending on the application to provide heating, cooling or electricity [1].

Heat recovery technologies can be classified into (i) recovery as hot air or steam, (ii) conversion to chemical energy as fuel, and (iii) thermoelectric power generation [2]. Alternatively, the following classification for WHR methods has been also given: (i) Direct utilizing: heat delivery to district heating or cooling or preheating; (ii) Power utilizing: electricity generation using generator; and (iii) Cascade utilization: combining heating, cooling and power [3].

WHR processes can be classified according to temperature range as high (HT), medium (MT) and low (LT), with LT usually referring to temperatures reaching 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. A deeper insight on the temperature of the gases of the various processes of several industries can be found in [4], where it is concluded that among the mentioned industries, 50% of them correspond to low grade waste heat whose temperatures are mainly below 300–350°C, corresponding to MT processes.

Methods for WHR include (i) transferring heat between exhaust gases and combustion air for its preheating, (ii) transferring heat to the load entering furnaces, (iii) generation of steam and electrical power, or (iv) using waste heat with a heat pump for heating or cooling facilities.

WHR devices work on the principle of heat exchange. During heat exchange the thermal energy of the exhaust gases gets transferred to some other fluid medium. This exchange of heat reduces the temperature of the exhaust gases and simultaneously increases the temperature of the fluid medium. The heated fluid medium is either recycled back to the process or utilized in the production of some utilities such as steam or power, and so on [5]. Heat exchangers (HEs) are most commonly used to transfer heat from combustion exhaust gases to combustion air entering the furnace. Since preheated combustion air enters the furnace at a higher temperature, less energy must be supplied by the fuel.

The benefits of using WHR devices are multiple, namely economic, resource (fuel) saving, and environmental; more specifically: (i) saving of fuel, (ii) generation of electricity and mechanical work, (iii) reducing of cooling needs, (iv) reducing of capital investment costs in case of new facility, (v) increasing of production, (vi) reducing of greenhouse gas emissions, and (vii) transforming of the heat to useful forms of energy.

2. Conventional technologies

WHR is mostly based on conventional heat recovery equipment such as HEs, recuperators and regenerators. However, these technologies have not been adopted widely by industry for heat recovery as they should be, because of high costs and long payback periods, material constraints – particularly for high temperature streams, high chemical activity for streams to be cooled below the condensation temperatures, bespoke designs that increase design and manufacturing costs, corrosion, low efficiencies and in many cases unavailability of obvious or convenient end-use of the waste heat.

Electrical power generation from WHR, particularly from LT sources, is still in its infancy. Even though a number of Organic Rankine Cycle (ORC) based power generation systems have been installed, the efficiency of these systems has not been high enough to motivate wide adoption by industry.

In general, heat recovery technologies can be grouped into:

(i) Technologies that recover heat from a primary flow and make it available as heat of a lower or similar quality in a secondary flow. Typical example technologies are HEs, recuperators and regenerators.

(ii) Technologies that recover heat from a primary flow and upgrade this to a higher temperature useful heat using another heat source as input.

(iii) Technologies that recover and convert heat from a primary flow to electricity. Typical examples are the conventional Steam Rankine Cycle and the ORC. Other potential systems at different stages of research, development and application include the Organic Flash Cycle (OFC), the Kalina Cycle, the Trilateral Flash Cycle (TFC) and the Supercritical CO_2 (sCO_2) Brayton Cycle.

Typical WHR devices used for air preheating include recuperators, furnace regenerators, recuperative and regenerative burners, passive air preheaters, shell and tube HEs, finned tube HEs or economizers, rotary regenerator or heat wheel, preheating of load, waste heat boilers, and heat pumps.

3. Proposed WHR technologies

The aim of the I-ThERM project is to develop and demonstrate technology solutions to address heat recovery from a wide range of primary flow streams extending from temperatures of around 70°C to 1000°C and the optimum utilization of this heat for heating, power generation or a combination of both. The four proposed systems Flat Heat Pipes, Condensing heat pipes, TFC and sCO_2 correspond to different temperature ranges, serving different applications for various industrial processes. This approach is shown schematically in Fig. 1

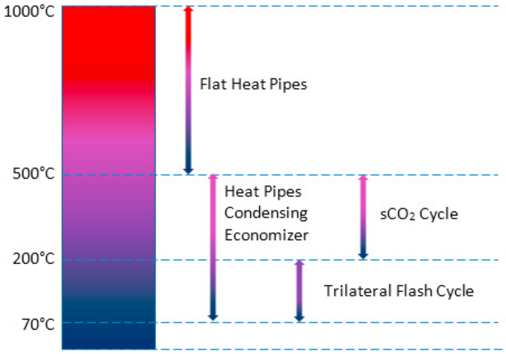

Fig. 1. Heat Recovery Range and Technologies in I-ThERM.

The heat recovery solutions are based on innovative heat pipes (HPs) whose design will be optimized for a wide range of fluid stream types, temperatures and flow rates as well as uses of the recovered heat. The standardization on HPs is motivated by the advantages they offer over other conventional heat recovery technologies, as well as the standard plug and play or easily customizable solutions they offer for a wide range of applications, including condensation of vapors in the exhaust flows to maximize heat recovery potential. Heat pipes are generally cylindrical, but the evaporator or condenser can be flat as well. In this case, they are called flat HPs. The flat heat pipes (FHPs) have severe advantages over the conventional cylindrical HPs, which are related to the isothermal characteristics and flat evaporator surface that maximizes the radiation absorbing area. FHP heat recovery systems are a new innovation (UK patent application No. 1410924.3 and 1410933.4). The innovation potential of FHPs is significant as at present there are no such systems in the market. Depending on the selection of the working fluid and material for the HP, these systems can absorb or reject heat over a very wide temperature range from sub-zero to temperatures in excess of 1000°C.

The FHP system is designed to recover heat mainly by thermal radiation from sources at temperatures greater than the temperature of the surface of the heat pipes. The radiation is absorbed by the outer surface of the FHP and transferred by conduction through the HP evaporator wall to the inner surface. When the working fluid reaches the saturation temperature, it vaporizes and flows upwards to the condenser. The heat is then transferred to the cooling fluid via a shell and tube HE system, which condenses the working fluid. Finally, the condensate flows back to the evaporator section under gravity.

Since FHPs represent a new concept of HPs, there are not many studies available in the literature. In [6] a designed and manufactured FHP was shown able to recover heat by thermal radiation from sources at temperatures greater than the surface of the heat pipes. In [7] a novel FHP based photovoltaic thermal (PV/T) system called a 'heat mat' was developed and validated and performed as a building envelope. The authors experimentally examined the effects of cooling cycles on the electrical output and the temperature of the HP PV/T panels.

The condensing economizers (CE) provide new heat recovery opportunities due to their very high heat transfer coefficient, the extremely high heat transfer surface area and the low gas side pressure drops. I-ThERM proposes standardized HP based designs for heat recovery from exhaust gases to (a) enable easy application with minimum process disruption, (b) minimize space requirements, (c) minimize heat transfer area requirements and costs through the two-phase heat transfer capability of HPs, (d) allow for condensation to maximize heat recovery through the appropriate selection of materials and coatings, (e) provide easy cleaning and reliable and low maintenance operation, and (f) provides the opportunity to install the CE systems in harsh environments with acidic exhaust gases.

The TFC is a thermodynamic power cycle whose expansion starts from the saturated liquid state rather than a vapor phase. By avoiding the boiling part, the heat transfer from the heat source to the liquid working fluid is achieved with good temperature matching. The advantage of TFC over an equivalent steam ORC system is that its power recovery potential is high, twice that of ORC [8].

The sCO_2 operates in a similar manner to other turbine cycles but uses CO_2 as the working fluid. Unlike other working fluids, CO_2 undergoes drastic density changes over small ranges of temperature and pressure and this allows a large amount of energy to be extracted at high temperature using relatively small size equipment, an order of magnitude smaller than steam or gas turbines. The intention in I-ThERM is to develop and demonstrate a small supercritical sCO_2 power system that can be easily employed for a variety of HT heat recovery to power conversion applications.

Depending on the needs of a plant or the needs of the over the fence users, the recovered heat can be used directly, can be employed to drive a power generation system or a combination of the two. In HT heat recovery applications, where the sCO_2 cycle is employed, the heat rejection from the sCO_2 system will be at a high enough temperature to be used for heating or even to drive a TFC system, if the capacities of the two systems are appropriately matched.

4. Waste heat recovery in the EU28

An analysis of the energy consumption of the industrial sector of the EU28 is carried out together with a preliminary assessment of the waste heat potential. According to [9], the percentages of waste heat potential for each industry are shown in Table 1.

Table 1.Waste heat potential percentage per industry [9].

Type of industry	Waste heat potential
Iron and Steel	11.40%
Chemical and Petrochemical	11.00%
Non-ferrous metal industry	9.59%
Non-metallic minerals	11.40%
Food and Tobacco	8.64%
Paper Pulp and Print	10.56%
Wood and Wood Products	6.00%
Textile and Leather	11.04%
Other	10.38%

Fig. 2 shows the energy consumption of the industrial sector of the EU28 for the year 2016 from [10], and the estimated WH potential based on the percentages shown in Table 1. This is estimated ignoring the temperature range of each industry in each country and taking into account only the waste heat by the exhaust gases. The short names of each industry are; 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. The breakdown of the energy consumption for 13 industrial sectors was estimated to be 3217.85 TWh in 2016, while the estimated WH potential is 336.9 TWh [10].

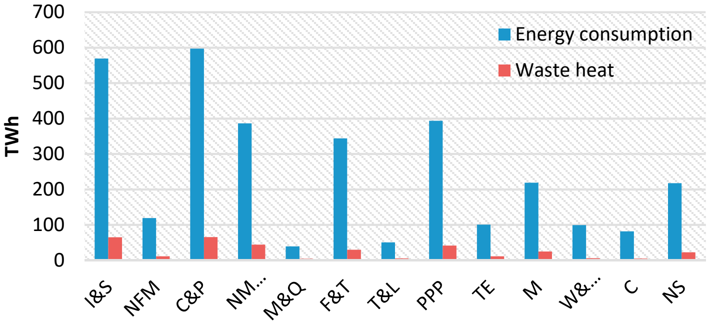

Fig. 2. The energy consumption per industry in the EU28 in 2016, and the estimated waste heat.

5. WHR potential market of the proposed systems

In this section the potential market of the proposed technologies is discussed based on the comparison with conventional WHR systems. TFC and sCO2 systems are compared with the ORC market, while for the FHP technology the potential market is estimated by finding the industrial processes where the FHP could be used.

5.1. FHP system

As mentioned above, the FHP system is designed to recover heat mainly by thermal radiation from sources at temperatures greater than the temperature of the surface of the heat pipes. There are numerous manufacturing processes in the various industries with high temperature procedures and wasted heat, but in order to be able to use the FHP system, two main conditions are required: (i) The heat should be transferred by thermal radiation; and (ii) open space near the radiant source should be available for the installation of the panels.

These characteristics are present mainly in the iron and steel industry. Five hundred steel production sites are split between 24 EU countries and around 170 million tons of steel are produced every year in Europe. The iron and steel industry produce various widely used materials such as train rails, wire rod coils, billets, blooms and slabs. As described by [11], 62% of the production is for flat products and 38% for long products.

Based on the principle of the FHP, radiant heat should be emitted from the process. Accordingly, the iron and steel industry is the best option for the use of other FHP systems due to the large amount of the wasted radiant heat during the formation of the various products from the casting, rolling and cooling processes.

The theoretical recoverable heat from radiation can be estimated through the radiation heat transfer rate equation:

$$\dot{Q}_{rad} = \sigma \mathrm{A}\left(T_h^{\,4} - T_s^{\,4}\right) \tag{1}$$

where σ is the Stefan Boltzmann constant [W m^{-2} K^{-4}], A is the surface area of the product with radiant heat [m^2], T_h is the temperature of the hot slabs [K] and T_s is the heat pipe average surface temperature (K).

The slabs, blocks and plates exit the casting machine; then they go through a roll strip where they are formed, cut, identified and picked up to the storage zone. The temperature of these products in the procedures where the utilization of the radiant heat is possible (after the rolling mill) starts from 1200°C at the exit from the rolling mill and reaches 120°C at the conveyor through the laying bed. Thus, the theoretical radiant heat transfer from the steel materials per square meter is estimated as shown in Fig. 3.

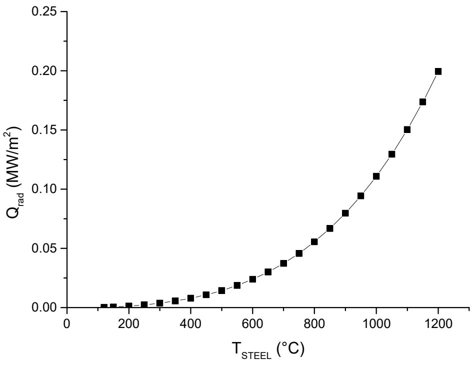

Fig. 3. The theoretical radiant heat transfer from the hot slabs in respect to the temperature of the material.

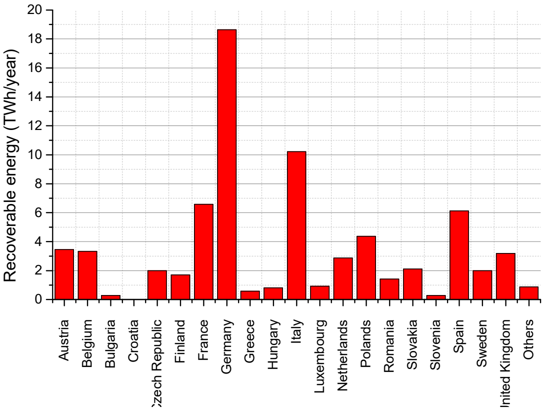

Fig. 4. Yearly technical recoverable thermal energy potential from FHP in the iron and steel industry in EU

The ideal place to try to recover the waste heat can be between the exit of the continuous casting machine and flame-cutting zone. The space availability around this zone is enough to install FHP panels. The conveyor length for flat and long products is 60–80 m and each plant may have 1–5 lines of conveyors. Thus, the potential heat recovered per plant varies. Assuming an average length of 70 m, 1.6 MW of energy can be theoretically recovered from each conveyor. Avilés steel shop has a length of about 15 m and as there are 4 slab lines, the radiation heat potential is about 3 MW. Gijón wire rod mill has a length of about 70 m and as there are 2 lines, the radiation heat potential is about 2.2 MW [6].

Using the data presented earlier in Fig. 2, the estimated technical amount of recoverable heat potential per country is estimated as shown in Fig. 4. The analysis is based on the following assumptions: Heat recovery efficiency 75%, FHP panel surface temperature 100°C, product temperature from 1200 to 120°C, conveyor length 70 m, and each plant may have 5 lines of conveyors. From the estimated amount of the theoretical recoverable radiant heat potential presented above, the theoretical recoverable amount of radiant heat per year for Europe is 0.7 TW.

Based on the 2017 crude steel production data, and considering that only 10% of this space can be covered by FHP and the WHR potential is 11.4% as mentioned above, the WHR potential for the iron and steel industry in EU is estimated to be 72 TWh/yr, which is in agreement with the value presented earlier in Fig. 2 for the iron and steel industry. Considering that 0.596 kg of CO_2 are currently produced for each kWh of electricity generated by natural gas, it is estimated that 42.5 million tonnes of CO_2 can be saved by using the recovered energy.

5.2. HPCE

Condensing economizers (CE) recover both latent and sensible heat from the flue gas and are able to raise boiler efficiencies to over 90%. A CE can increase overall heat recovery and steam system efficiency by up to 10% by reducing the flue gas temperature below its dew point, resulting in improved effectiveness of WHR.

The I-ThERM CEs will be able to be installed in harsh environment since they will have high resistance in the corrosion and acidic gases. The I-ThERM heat pipe condensing economizers (HPCE) have the following design parameters: Exhaust mass flow rate 357 kg/h, water mass flow rate 500 kg/h, exhaust average specific heat capacity 0.288 Kcal/kg °C, water average specific heat capacity 1 kcal/kg °C, exhaust inlet temperature 203°C, exhaust outlet temperature 50°C, water inlet temperature 20°C, water outlet temperature 45-48°C, recovered heat 18.349 kW.

The theoretical total (latent and sensible) heat from condensing economizer can be calculated by the following equation:

$$Q = V\rho\Delta h \tag{2}$$

where V is the air volume flow (m^3/s), ρ is the density of air (1.202 kg/m^3) and Δh is the enthalpy difference (kJ/kg).

The temperature range for HPCE by I-ThERM is 70–500°C, which applies to LT and MT. This cancels the potential of use HPCE in the iron and steel industry due to higher temperatures. Potentially it can be used in the cement industry, large volume inorganic chemicals, food, drink and milk Industry, chemicals & plastics and glass.

5.3. TFC

The proposed TFC systems can be compared with the conventional ORC units installed in MT (70°C - 200°C) processes in the industrial sector. The advantage of TFC over an equivalent steam ORC system is that its power recovery potential is high, twice that of ORC [8]. It can also eliminate the requirement for an extra cooling tower/heat rejection system, where heat in the waste stream will be rejected.

There is no way to estimate the number of TFC units to be installed in EU or the amount of energy that could be recovered by the use of the proposed TFC units. However, in order to have an idea of the size of the potential market of the proposed TFC systems, the market of the conventional ORC systems in MT is discussed.

According to [12] the three main manufacturers of ORC units are Turboden, ORMAT and Maxxtec, based on their references. Another report from the European Biogas Association lists the leading manufacturers of biogas within the EU, from which 8 of them install ORC systems [13]. From those manufacturers only one has published references for the installed plants which are located in Italy, Germany and Austria. Tartiere and Astolfi [14] presented a list with the ORC units installed in EU in 2017. The total number of units is 224, mostly installed by Triogen, Turboden and GMK. It is also stated that the main types of industries (not applications), based on the amount of ORC installed capacity share, are gas turbines (probably electric power generation), glass, metals, cement and lime.

5.4. sCO_2

The intention in I-ThERM is to develop and demonstrate a small supercritical sCO_2 power system that can be easily employed for a variety of HT heat recovery to power conversion applications. As done previously for the TFC, in order to have an idea of the size of the potential market of the proposed systems, the market of the conventional ORC systems in HT is discussed. According to [14], as of December 31st, 2016, the ORC technology represents a total installed capacity around 2701 MW, distributed over 705 projects and 1754 ORC units.

Power generation from geothermal brines is the main field of application with 74.8% of all ORC installed capacity in the world; however, the total number of plants is relatively low with 337 installations as these applications require large investment and multi-MW plants. As a result, only a few companies (ORMAT, Exergy, TAS and Turboden) have been active in this capital-intensive sector. ORMAT is the indisputable leader in this field with more than 75% of installed capacity and plants, Exergy and TAS are following with around 13% and 6% of the market respectively while Turboden has recently penetrated the geothermal market with about 2% of the installed capacity.

Waste heat recovery is an emerging field for ORC with an interesting potential for all unit sizes: all the big players are active on that market with medium – large size plants recovering heat from gas turbines, internal combustion engines or industrial processes. Most of the other manufacturers are focused on small WHR applications with products ranging from 10 to 150 kWe. Waste Heat recovery applications cover 13.9% of the total market with a relevant number of operating plants. However, it is worth noting that about 800 of these units are very small (<4 kW) plants installed by ORMAT for valve operation and cathodic protection along pipelines in remote areas.

6. Conclusions

The waste heat potential in the EU has been estimated to be 300–350 TWh/year based on the energy consumption breakdown. This is an important amount of energy saving compared to the 3217.85 TWh energy consumption of 2016, corresponding to CO_2 emissions saving as well. Regarding the cost of the WHR technologies proposed in I-ThERM, it is expected to have 25% extra cost over the conventional technologies, which is balanced by a significant improved performance due to higher efficiency. The basic industrial sectors where the proposed technologies can be marketed are the iron and steel and cement industries.

The potential market of the proposed technologies is discussed in terms of the market of the conventional technologies that can be replaced by the proposed ones. For the FHP system, there is no related conventional system to compare the size of the market, so the analysis is made based on the industries with radiative heat losses. The main radiative heat is observed in iron and steel industry and the size of the market is estimated based on production data in EU and various assumptions. From the analysis it turns out that 72 TWh/year of waste radiant heat can be potentially recovered from the iron and steel industry, which corresponds to 42.5 million tonnes of CO_2 that can be saved if the requested energy is covered by the recoverable energy.

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