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D2.3 Report on estimation of energy, environmental and economic potential for heat recovery in EU28

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Executive Summary

The benefits of using Waste Heat Recovery (WHR) devices are multiple, namely: (i) economic, (ii) resource (fuel) saving, and (iii) environmental; more specifically: (i) saving of fuel, (ii) generation of electricity and mechanical work, (iii) reducing cooling needs, (iv) reducing capital and investment costs in case of new facility, (v) reducing greenhouse gas emissions.

Typical WHR devices used for air preheating include: recuperators, furnace regenerators, recuperative and regenerative burners, passive air preheaters, shell and tube Heat Exchangers (HEs), finned tube HEs or economizers, rotary regenerators or heat wheels, waste heat boilers, and heat pumps.

This deliverable gives a brief description of the various conventional WHR technologies as well as a description of new innovative WHR and Heat to Power (H2P) technologies proposed in the ITHERM project. These are the Flat Heat Pipe (FHP), the Heat Pipe Condensing Economiser (HPCE), the Trilateral Flash Cycle (TFC) system and the Supercritical Carbon Dioxide Cycle (sCO_2).

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.

I-ThERM developed standardized FHP based designs for heat recovery from radiant waste heat sources to enable easy application with minimum process disruption, minimise heat transfer area and space requirements, and costs through the two-phase heat transfer capability of HPs. The project also developed Heat Pipe based Condensing Economiser designs to make use of the latent heat contained in combustion exhausts.

For low temperature waste heat to power conversion applications, I-ThERM is developing the TFC technology which has the capability of converting low temperature waste heat, down to 70°C, to electrical power. The system has the advantage of generating higher power outputs for a given heat input compared to Organic Rankine Cycle systems.

For high temperature waste heat to power applications the I-ThERM project is also developing a supercritical sCO_2 heat to power conversion system that can be easily employed for a variety of heat recovery to power conversion applications. The sCO_2 cycle offers the potential for higher conversion efficiencies compared to ORC systems, and uses a non-flammable and non-toxic working fluid which has a very low global warming potential of 1.

The technologies under development in the project are suitable for use in most industrial sectors: Metals, Chemicals, Cement, Ceramics, paper and pulp, food and drink, etc. This report presents an analysis of the energy consumption of the major industrial sectors of the EU28 and a preliminary assessment of the waste heat recovery potential.

The waste heat recovery potential can be classified according to temperature range as high, medium and low. A high temperature (HT) process is one with temperatures above 400°C, a medium temperature (MT) process is one with temperatures ranging from 100–400°C and a low temperature (LT), a process with temperatures below 100°C.

From this analysis it was concluded that the iron and steel industry as well as the non-metallic mineral products industries are the most energy intensive industries with the highest amounts of waste heat and accordingly the greatest heat recovery potential.

After the preliminary assessment, the potential market of the most intensive industrial sectors is identified. For the FHP, the iron and steel industry offers the largest potential market. For the HPCE the potential market is the whole market for commercial and industrial boilers that do not include their own in-build condensing economisers. In particular the application for the HPCE is suited to industrial applications with dirty and acidic exhausts, particularly in the petrochemical industry. Other potential application fields include the Cement and Glass Industries, and the Steel and food industries. Condensing economisers can recover 10-25% higher energy than non-condensing economisers and therefore their applications will be primarily in areas of high cost primary fuels.

TFC systems will compete with ORC systems. However, they offer the advantage of higher output per unit heat input and higher heat recovery potential. Market will be in low temperature heat to power conversion applications (75-200°C). The sCO_2 technology is aimed at high temperature >400°C to power conversion applications. It offers advantages over ORC systems of higher energy conversion efficiency and direct heat recovery without the need for a secondary heat exchanger. Suitable applications for heat recovery and power conversion are in the steel, glass and petrochemical industries. Other application areas include nuclear power generation and concentrated solar collector power plants.

The report describes potential application areas of all the technologies being developed in the I-ThERM project. It also provides indication of the heat recovery potential of the industrial sectors in which the I-ThERM technologies can be applied to. Final potential market in terms of units will depend on the capacity of each unit, cost and readiness of the market to accept a new technology.

The Period 3 Review considered the review of Waste Heat Recovery and Conversion Technologies in Deliverable D2.3 to be satisfactory. However, a recommendation was made to define the baseline performance and efficiency of conventional technologies and compare the potential performance and efficiency of the technologies being developed in I-ThERM against the baseline.

To address this, more information is given in the revised D2.3 report on the baseline performance of conventional technologies. The expected performance of the technologies being developed in I-ThERM against the baseline and potential payback periods are detailed in Table A below.

Table A – Comparison of Performance of I-ThERM Technologies Against the Baseline

	Temperature Range	**Potential Efficiency**	**Heat recovery/Power output**	**Installed cost per power output**	**State of the art competing technology**	**Conventional system efficiency**	**Conventional system cost per power output**
Flat Heat Pipe System (FHPS)	0-1000°C[1]	75%[2]	200[3] KWth	€300/kWth[4]	No alternative[5]	Not available	Not available
Heat Pipe Condensing Economiser (HPCE)	Exhaust gas temperature from combustion 200-500°C	Heat recovery effectiveness Sensible 78% Latent 36%[6]	200 kWth	€250/kWth	Bespoke condensing economisers for industrial process exhausts 200-500°C	Heat recovery effectiveness. Similar to HPCE, Sensible 78% Latent 36%[7]	Similar costs to HPCE €150/kWth[8]
Trilateral Flash Cycle (TFC)	70-120°C	6-10%	~100 kWe	Estimated at €2000-€2500/kWe	ORC	5-8% [9]	€2000/kWe
Supercritical Cycle (sCO2)	300-500°C	16-20%	~50 kWe	€6000/kWe [10]	ORC at 300°C	10%	€2000/kWe

Projected Payback Period of I-ThERM Technologies

	Heat recovery/ power output	Energy saved per annum KWh	Price of fuel €/kWh	Cost savings €	Installed cost of technology €	Payback period Years
FHPS	200 kWth	1750000	0.04[11]	70080	60000	0.9
HPCE	200 kWth	175000	0.04	70080	50000	0.7
TFC	100 kWe	876000	0.12[12]	105120	250000	2.4
sCO2	50 kWe	438000	0.12	52560	300000	5.7[13]

[1] The temperature range will depend on the material of the FHPS and the fluid used in the Heat Pipes
[2] The efficiency will depend on many design parameters and in particular the temperature of the heat source. Also the size of the FHPS. The largest the size the higher the quantity of heat that can be recovered and the higher the cost.
[3] Value of thermal output specified in grant agreement.
[4] At present costs cannot be estimated accurately. This will depend largely on infrastructure necessary for the installation of the technology and the utilisation of the heat recovered. For a 200 kWth unit it is estimated that installed cost will be approximately €250/kWth.
[5] No alternative units are currently available in the market for this application. Hence, comparison cannot be made with the proposed FHPS.
[6] Sensible heat recovery effectiveness for designed 200 kWth HPCE, 78% and latent 36%.
[7] Conventional economisers can be designed to provide similar heat recovery effectiveness as the HPCE
[8] Cost assumed to be equivalent to the HPCE. The HPCE offers a number of additional advantages to conventional economisers. Potential smaller size and lower maintenance costs.
[9] This is an estimate for low temperature heat to power conversion.
[10] The cost is an estimate for a proof of concept system. For large capacity systems the cost will be a lot lower.
[11] Price of natural gas
[12] Price of electricity
[13] Payback period is long due to the small power output of pilot system.

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Abbreviations

BOF	Basic Oxygen Furnace
CDM	Clean development mechanism
CE	Condensing economiser
EAF	Electric arc furnaces
ESI	Emergy sustainability index
EU	European Union
FHP	Flat heat pipes
GHG	Greenhouse gas
HP	Heat pipes
HPCE	Heat pipe condensing economiser
HPHE	Heat pipe heat exchanger
HT	High temperature >400°C
HRSG	Heat recovery steam generator
IRR	Internal rate of return
LT	Low temperature <100°C
MT	Medium temperature 100-400°C
NPV	Net present value
ORC	Organic Rankine Cycle
PBP	Payback period
PCM	Phase change materials
PRC	Organic Rankine Cycle
PV/T	Photovoltaic Thermal
RCA	Rotating cup atomizer
RCLA	Rotating cylinder atomizer
SDA	Spinning disk atomizer
TFC	Trilateral flash cycle
US	United States
WHRSG	Waste heat recovery steam generator
WHR	Waste Heat Recovery

Industries

C	Construction
C&P	Chemical and Petrochemical
FT	Food and Tobacco
I&S	Iron and Steel
M	Machinery
NS	Not Specified
NMM	Non-Metallic Minerals
NFM	Non-Ferrous Metals
M&Q	Mining and Quarrying
PPP	Paper, Pulp and Print
TE	Transport Equipment
T&L	Textile and Leather
WWP	Wood and Wood Products

Countries

AU	Austria
BE	Belgium
BG	Bulgaria
CR	Croatia
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GB	Great Britain
GR	Greece
HU	Hungary
IE	Ireland
IT	Italy
LV	Latvia
LT	Lithuania
LU	Luxemburg
MT	Malta
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia

1 Introduction: Objectives of D2.3

Deliverable 2.3, for Task 2.3: ***Estimate energy, environmental and economic potential in EU28.***

Based on the findings from previous tasks in WP2, Task 2.3 compares the conventional waste heat recovery technologies with the proposed technologies in the I-ThERM project. In Task 2.1 prepared by CUT, the streams of waste heat in the EU28 were identified with an extensive report on the industrial energy needs in all 28 EU countries.

In this report, a comparison of the proposed and conventional heat recovery technologies is provided, together with discussion on other parameters such as, the projected energy, cost and CO_2 emission savings from the application of the proposed heat recovery technologies in the EU28. The information can also be used to determine target energy performance and capital and installation costs to increase the attractiveness of the technologies to be developed for wide adoption by industry.

2 Conventional WHR technologies

Waste heat recovery methods include capturing and transferring the waste heat from a process with a gas or liquid back to the system as an extra energy source. The waste heat can be rejected from the various processes at any temperature. Regarding the potential of the recovery of the waste heat, conventionally the higher the temperature of the rejected heat, the higher the quality of the waste heat and the easier the optimization of the WHR process.

Therefore, it is important to recover the maximum amount of heat and ensure the achievement of the maximum efficiency from a WHR system. There are various WHR systems for each temperature range of the wasted heat. A review of the various WHR systems was presented by Jouhara et al. (2018). The presentation of the various WHR technologies in this section is based on this review. Another study on the potential use of various WHR technologies for LT waste heat sources was presented by Huang et al. (2017), considering case studies from China and Singapore only.

Industrial furnaces are used for various processes that requires heat. Heat in the furnace can be provided by: (i) fuel energy, (ii) chemical energy, (iii) electrical energy or (iv) a combination of these. Gases that are generated during the process leave the furnace at a temperature equal to the internal temperature of the furnace and hence have a high sensible heat content. Sometimes the exhaust gases carry some chemical energy, which raises the temperature of exhaust gases further due to post combustion. The heat energy contained in the exhaust gases is the waste energy since in the majority of cases is damped to the environment. However, it is possible to recover some part of this energy if investments are made in WHR devices.

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 of the facilities.

WHR devices work on the principle of heat exchange. During heat exchange the heat 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, etc.

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

Heat exchangers 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. 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, waste heat boilers, and heat pumps.

2.1 Thermodynamic cycles

The use of thermodynamic cycles that employ organic working fluids enables a cost effective and promising way of energy recovery from moderate grades of waste heat sources. Organic Rankine cycle (ORC) and Kalina cycle are the main technologies to recover waste heat for power generation.

A typical Rankine cycle consists of a pump, a condenser, an evaporator and a generator. Fuel is burned in the evaporator and the water as the working fluid is heated to generate superheated steam. This is then directed to the turbine to generate power and then passed through the condenser, losing heat and turning back into its liquid state. The liquid water is then pumped into to the evaporator and the cycle is repeated.

Similar to ORC, the Kalina cycle is a variant of Rankine cycle that uses the working fluid in a closed cycle to generate electricity. This system however, commonly uses a mixture of water and ammonia as the working fluid in a process that usually consists of a recuperator and separator in addition to other components of a Rankine cycle to generate steam and power.

According to Wang et al. (2017), Kalina cycle system shows a better performance when compared to ORC. Based on literature (Luo et al., 2017; Peris et al., 2015); Prananto et al., 2018); Ramirez et al., 2017), the efficiency of the thermodynamic cycles varies from 6–21.7%.

2.2 Heat Pumps

The heat pump system is a vapor compression system consisting of four main components: the compressor, the condenser, the expansion valve device and the evaporator. A heat pump takes sensible and latent heat at low thermal level from the exhaust gas and reintroduces it into boiler with return fluid but at higher temperature without increasing the boiler fuel consumption. Because the operation of heat pumps requires additional energy consumption, the WHR technology is called active (Baradey et al., 2015). Depending on the design, heat pumps can serve two functions: either upgrading waste heat to a higher temperature or using waste heat as an energy input for driving an absorption cooling system. Heat pumps are most applicable to LT product streams found in process industries including chemicals, petroleum refining, pulp and paper, and food processing. In general, heat pumps are most cost effective where they serve simultaneous heating and cooling requirements.

Industrial heat pumps, using waste process heat as the heat source, deliver heat at higher temperature for use in industrial process heating. However, the installation of a heat pump corresponds to an additional investment cost and leads to savings on operating costs. The profitability depends on the initial investment cost and energy prices.

2.3 Summary of WHR technologies

A very descriptive summary is presented by Jouhara et al. (2018), as shown in Table 1.

Table 1. WHR technologies with benefits and limitations given by Jouhara et al. (2018).

Technologies	Temperature range used	Benefits	Limitations
Regenerative Burners	HT	Saving fuel by preheating the combustion air and improving the efficiency of combustion.	The system requires additional components such as a pair of heat exchange media and several control valves to function, which can be complex.
Recuperative Burners	HT	Both the exhaust gas and waste heat from the body of the burner nozzle are captured and more heat from the nozzle is generated.	The burner and the nozzle need to be inserted into the furnace body, which may require installation and modification of the furnace.
Economizers	LT, MT	The system maximizes the thermal efficiency of a system by recovering low-medium temperature heat from the waste flue gas for heating/preheating liquids entering a system.	The system may need to be made out of advanced materials to withstand the acidic condensate deposition, which can be expensive.
Waste Heat Boilers	MT, HT	The system is suitable to recover heat from medium – high temperature exhaust gases and is used to generate steam as an output.	An additional unit such as an auxiliary burner or an after burner might be needed in the system if the waste heat is not sufficient to produce the required amount of steam.
Recuperators	LT, HT	The technology is used for applications with low – high temperatures and is used to decrease energy demand by preheating the inlet air into a system.	To maximize heat transfer effectiveness of the system, designs that are more complicated may need to be developed.
Regenerators	MT, HT	The technology is suitable to recover waste heat from high temperature applications such as furnaces and coke ovens and for applications with dirty exhausts.	The system can be very large in size and has high capital costs.
Rotary Regenerators	LT, MT	Rotary regenerators are used for low – medium temperature applications and could potentially offer a very high overall heat transfer efficiency.	The system is not suitable for high temperature applications due to the structural stresses and the possibility of deformations that can be caused by high temperature
Run around coil (RAC)	MT, HT	This unit is used when the source of heat is away from the point of use to employ a direct recuperator and when cross contamination between the two flow sources needs to be prevented.	This system is found to have a very low effectiveness when compared to a direct recuperator and needs a pump to operate, which requires additional energy input and maintenance
Heat Recovery Steam Generator (HRSG)	HT	The system can be used to recover the waste heat from the exhaust of a power generation or manufacturing plant to significantly improve overall efficiencies by generating steam	The system requires several components to function and may require an additional burner to improve the quality of the recovered waste heat. The

Technologies	Temperature range used	Benefits	Limitations
		that can be used for process heating in the factory or for power generation.	system is also very bulky and requires on site construction.
Plate Heat Exchanger	MT, HT	Plate HEs have high temperature and pressure operating limits and are used to transfer heat from one fluid to another when cross contamination needs to be avoided.	Parameters such as frequent variation in temperature and load must be studied and based on that suitable HE design must be chosen to avoid failure of the structure of the HE for the application
Heat Pipe Systems	MT, HT	Heat pipes have very high effective thermal conductivities, which results in a minimal temperature drop for transferring heat over long distances and long life that requires no maintenance, as they incorporate passive operation. They have lower operation costs when compared to the other types of HEs.	To achieve an optimum performance from the HE, appropriate design, material, working fluid and wick type based on the application and temperature range of the waste heat must be studied and chosen.
Thermoelectric Generation	MT, HT	The system produces electricity directly from waste heat and eliminates the need for converting heat to mechanical energy to produce electrical energy.	The system has a very low efficiency of 2–5%. However, recent advances in nanotechnology have allowed electrical generation efficiencies of 15% or greater to be achieved.
Thermo Photo Voltaic (TPV) Generator	LT, HT	These devices are used to directly convert radiant energy into electricity and offer a better efficiency when compared to other direct electrical conversion devices.	The device is found to have a limited operating temperature range and their efficiency decreases as the temperature increases. Having said that, high efficiency PV cells that can withstand high temperatures are also available but they have high capital cost.
Heat Pump	LT, MT	Heat pumps transfer heat from a heat source to a heat sink using a small amount of energy and can be used to offer economical and efficient alternative of recovering heat from various sources to improve overall energy efficiency. Heat pumps in particular are good for low-temperature WHR, as they give the capability to upgrade waste heat to a higher temperature and quality.	In order to use this system, the method of capturing the waste heat based on its source and grade must firstly be analyzed and in that respect, appropriate HE and system installation needs to be set up.
Direct contact condensation recovery	MT, HT	The system uses a direct mixture HE without a separating wall and can be used to transfer heat from immiscible liquid – liquid and solid – liquid or solid-gas.	Due to absence of a separating wall in this HE, particles from the flue gas can be mixed with the water, which may require filtering before exiting the HE.

Technologies	Temperature range used	Benefits	Limitations
Indirect contact condensation recovery	MT, HT	The system provides the advantage of eliminating cross contamination of the flue gas and water and can be designed to work as a filter of a process.	The system consists of a HE which in order to minimize corrosion from acidic condensate should be made from advanced materials and can be expensive.
Transport membrane condenser	MT, HT	The system works by extracting and delivering the hot water back into the system feed water directly from the exhaust gas through a capillary condensation channel. This way, the water is extracted through a membrane channel rather than directly from the flue gas and so the recovered water is not contaminated and does not require filtering.	The system employs a capillary condensation channel, which in order to minimize corrosion from acidic condensate, may need to be made from advanced materials and can be expensive.

2.4 Case studies of various WHR technologies in EU

Spirax Sarco (2017) installed a gas to water HP HE in Ireland to solve the problem that a dairy factory was facing since the exhaust being fired from heavy fuel oil was high in sulphur and hence unsuitable to be used due to surface condensation and corrosion. Three HP gas to water units were installed, recovering 488kW, saving €87,000 per annum with a payback period of 19 months.

Seck et al. (2015) investigated the impact of heat recovery using heat pumps in industrial processes up to 2020 in the French Food and Drink industry. The results showed that the implementation of heat pumps in the food and drink sector achieved a final energy consumption reduction of about 12% by 2020 compared to 1990 levels, which represents around 8.1 TWh in total (13% compared to 2001), with a CO_2 emissions reduction of about 9% (around 2Mt of emissions).

Hita et al. (2011) carried out a study to assess the potential of heat recovery in food and drink industry by the use of the TIMES model. TIMES is an energy prospective model usually applied to the analysis of the entire energy sector, but it may also be applied to study in detail single sectors, like the food and drink industrial sector in this case. In industry, it is possible to find heat source in the temperature range of 30–60 °C on several equipment like air compressors, chillers and other thermal end uses. This heat is at too low temperature to be recovered by an exchanger and used directly in industrial processes. So, this heat is currently wasted, and heat pumps represent a way to recover it. The price of a heat pump is very dependent on their working conditions. Standard machines for temperatures of up to 100 °C or up 140 °C cost 1500 €/kW and 1800 €/kW respectively. The TIMES model calculated the amount of heat that can be recovered from different processes as follows:

- Heat recovered in air compressors = 50% * input energy
- Heat recovered in the chillers = 70% *(2.5 + 1) * input energy

- Heat recovered in thermal end uses = 15% * input energy

A study conducted at two steel manufacturing factories in Asturias, Spain using heat recuperation process based on a steam Rankine cycle has been conducted by Alvarez et al. (2012). There are two Blast Furnaces in the factories and slag production represents almost 80% of the by-products. Most of the slag is transformed into granulated slag where the remaining are left to cool down on open air. The authors have presented a proposal for waste heat recovery for the specific case scenarios. The calculated energy potential by the authors is given at 1300 TJ per year. The inlet temperature at the steam turbine is 453 °C and the amount of slags are 1.09 Mton per year. The recuperator efficiency was selected at 80% and the calculated IRR was 10.69% with a payback period of 7.7 years. Following on, the authors noted that the recuperator efficiency is uncertain in the technical development and considered and presented efficiencies between 60–90%. Finally, a CO_2 reduction of 0.04–0.063 ton of CO_2 per ton of steel with power production between 5.7–8.7 MW.

The Slite cement plant in Sweden uses a steam turbine to generate electricity (European Commission, 2013). The recoverable heat from the process is sent to an existing electricity plant situated to the cement works, operated by a third party who re-utilizes a steam turbine to generate electricity. The steam is generated in a two-step heat recovery boiler system, one at the clinker cooler and one in the down duct of the kiln. In 2007, the plant took approx. 30 MW of heat out of the system; it was initially designed for 9 MW and now supplies, after optimization, about 6 MW. The investment costs, calculated in 1999, were 8x106 euro for the boiler and steam distribution system, 25% of which was subsidized. However, no costs were stated for the re-used existing steam turbine that contributed significantly to the economics of the installation. The annual electricity production is now approx. 50 GWh, equaling 25% of the plants total power need.

Another case study is the Lengfurt plant in Germany that uses a LT ORC process (European Commission, 2013). This process is essentially based on the use of an organic motive medium (pentane) that evaporates at significantly lower temperatures than water instead of using steam as the motive medium. The basic principles of this technique have been used successfully for a long time in refrigeration techniques. The ORC technique is used mainly for generating power from geothermal heat sources; however, the use of this process in a cement plant is a world first. The results have shown that 1.0 MW (net) electrical power can be generated with the given mode of operation. The achieved availability was 97% of the operation time of the cement kiln. The clinker cooler has a waste heat output via the clinker cooler exhaust air of 14 MW and an exhaust gas temperature of between 300–350 °C, and approx. 9 MW on average is extracted. At times, due to certain operating conditions of the kiln and kiln grate clinker cooler, the output of the turbine is lower than initially designed for. In 2007, the waste heat power generating plant covered up to 9%; however, in future this plant will make it possible to cover up to 12% of the electrical power requirement necessary for a cement plant. In this way, CO_2 emissions from the combustion associated with the generation of power can be reduced by between approximately 3000 to 7620 ton/yr.

Campana et al. (2013) carried out a study analyzing the potential use of ORC WHR systems in the European energy intensive industries. It is stated that there are 259 cement plants in the then EU27 with overall capacity of 247.81 million of metric tons. Not all 259 but 241 plants were considered in their study due to various process limitations and missing information from the rest. Regarding the steel industry, there were many processes and techniques in production. ORC application was considered more suitable for heat recovering from the exhaust gas of electric arc furnaces (EAF) and rolling mills. There are over 190 EAF located in EU. Three different layouts can be conceived: HEs can be placed just outside the furnace (300–1600°C), before the quenching tower (200–900°C) or recovering heat from the fluid used in the quenching tower. Inlet gases into conditioning system have temperature values of 150–350°C

Amiri Rad and Mohammadi (2018) carried out energy and exergy analyses on the Rankine cycle for WHR in a cement factory. They mention that cement industry is one of the largest industries regarding the energy consumption, and the use of ORC systems for heat recovery system has a good potential. In their study, a steam cycle was designed in order to generate power from the waste heat of the chimneys of a cement factory in Sabzevar. The working fluid (the steam) was superheated by the waste heat of the kiln chimney that was at a temperature of 380 °C in order to enter the Turbine at a higher temperature. An air condenser was used to cool the steam exiting in the Turbine due to the water scarcity in Sabzevar. The proposed steam cycle was optimized based on the energy and exergy analyses. The total exergy and energy efficiencies of the recovery system occurred at the recovery boiler pressure of 1398 kPa. At this recovery boiler pressure, the highest values were 16% and 39%, respectively.

Ahmed et al. (2018) presented a design methodology for an ORC, based on actual data of a cement factory. An ORC combined with a gas turbine to convert the gas turbine waste heat into electrical power was examined, with working fluid R134a. It was concluded that the effectiveness of the ORC HE using the R134a working fluid can increase up to 93%.

A study on the direct power generation from an ORC from waste heat is presented by Zhang et al. (2018) through an emergy analysis. The results show that the emergy yield ratio (EYR) and emergy index of sustainability (ESI) of an ORC are 197.52 and 3.97, respectively. The sustainability of the ORC system is less than that of wind, hydro and geothermal power plant, but much greater than that of fossil fuel power plants. The emergy proportion of the working fluid R134a accounts for 13.3% to the total input flows in the construction phase.

Ramirez et al. (2017) carried out a performance evaluation of an ORC unit integrated to a WHR system in a steel mill in Italy. Waste heat is recovered from the fumes of the Electric Arc Furnace (EAF) to produce saturated steam, which is then delivered to a district heating (DH) network during heating season and to the ORC for electricity generation during the rest of the year. The ORC installed has a nominal power output of 1.8 MW and the preliminary results of the first weeks of operation showed a net efficiency of 21.7%.

Engin and Ari (2005) studied the case of heat recovery in a dry type cement rotary kiln system by proposing a WHR Steam Generator (WHRSG). The heat streams used in the proposed scheme were the waste heat from the clinker cooler and the kiln exhaust gas, which have an average temperature of 215 °C and 315 °C, respectively. Both streams are supplied to the circulating water inside the WHRSG unit, so that steam is produced that subsequently drives a turbine, resulting to the generation of electrical energy. The authors calculated the savings and found that up to 8 GWh/year could be saved, resulting to a total savings of 560000 $/year and a payback period of 17 months, assuming a total implementation cost of $750000.

Lemmens and Lecompte (2017) have also investigated the economic effect of flue gas heat recovery using ORC. The flue gas has a maximum temperature of 240–250 °C that amounts to approximately 2.8 MW of thermal power. The Internal Rate of Return (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.

Peris et al. (2015) used ORC technology in a ceramic industry for low grade heat recovery. The recovery facility consists of a recuperator, a HE and a heat transfer loop for transferring heat from the furnace (heat source) to the ORC unit. A gross electrical efficiency and a net electrical efficiency of 12.47% and 10.94%, respectively, were achieved. A feasibility study of the application was also carried-out and showed an annual electricity generation of 120886 kWh, a Net Present Value (NPV) for 15 years of €138286, an Internal Rate of Return (IRR) of 22.88% and a payback period (PBP) of 4.63 years.

Forni et al. (2012) studied the application of the ORC in industries such as Cement and Glass. In the cement industrial plant, two heat sources were used for the heat recovery system. The waste heat streams were the gas of the kiln after the pre-heating of the raw material and the clinker cooler, which cools the final product (clinker) once it exits the kiln. Thermal oil is used for transferring the waste heat to the ORC module. For the cement plant, the results showed a net electricity generation of 36.340 kWh/year, an IRR of 9% for 10 years, an NPV of €1.050.000 for 10 years and a PBP of 9.2 years. In the glass industrial plant, WHR during the float glass production process was studied. Specifically, the waste heat from the exhaust gas of the float glass furnace is transferred to the ORC with the aid of a HE and a thermal oil. The results in this application showed a net electricity production of 8.910 kWh/year, an IRR of 11% for 10 years, a NPV of €500.000 for 10 years and a PBP of 8.2 years.

Casci et al. (1981) used ORC technology in a ceramic production plant, during the ceramic firing process in a tile tunnel kiln. Using the exhaust gases at middle range temperatures the heat was transferred to the ORC engine using thermal oil as the heat transfer liquid. The test results showed that an overall efficiency of 80% was achieved. Finally, the economic analysis showed a minimum and maximum PBP of 2.86 and 4 years for an operational time of 7000 hours/year, and a minimum and maximum PBP of 2.5 and 3.5 years for an operational time of 8000 hours/year. An IRR of 18% is also possible for a life expectancy of 5 years.

A comparison study between ORC and Kalina cycles is presented by Wang et al. (2017). Two parameters, the ratio of the heat above and below the most salient/concave point (R) and the temperature of that point, are used to roughly express the features of waste heat. With the efficiency from waste heat (exergy) to power as energy performance indicator, the calculation results for waste heat with maximum supply temperature 180 °C show 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.

Nemati et al. (2017) presented a comparative thermodynamic analysis of two WHR cycles, ORC and Kalina cycle for a cogeneration system. The authors observed that the 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.

A case study of hot blast stove flue gas sensible heat recovery and utilization was presented by Chen et al. (2015). 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. The results indicated that the system could achieve an energy saving of 16.5% and a reduction of CO_2 at 16.5%.

In 2000, Umeå Energi Ltd. built a power plant combined with a municipal/ industrial wood waste burning facility. The plant uses a heat recovery system with an integrated 14 MW compression heat pump that recovers waste condensing heat in the flue gas and transfers this waste heat into the district heating system. The plant also separates ammonia slip produced as a result of thermal NOx-reduction. Ammonia is recovered and recirculated to the boiler for reuse (Arzbaecher et al., 2007).

Hebenstreit et al. (2014) studied the integration of electric driven heat pumps with wood chip and wood pellets boilers. The results showed a decrease in operating costs between 2% and 13%, increase in energy efficiency of 3–21 % and a payback period of 2–12 years.

Mukherjee et al. (2017) carried out a study on food processing and technology focusing on the baking processes in the food manufacturing sector that use gas fired ovens. Only about one-third of the total energy used in these ovens adds value to the final product. The remaining two-thirds is discharged with the exhaust gases at 150–250 °C and thus represents an opportunity for heat recovery. However, the LT range, fouling and presence of corrosive materials in the exhaust streams make heat recovery technically challenging and uneconomical. The existing low-grade heat recovery technologies mostly use gas to liquid heat transfer to produce hot water for use in other areas of the manufacturing plant. The design enables recovery of up to 50% of the energy available through the exhaust stack, increasing the energy efficiency of the overall process to 60% and reducing food manufacturing costs by one third.

Table 2 summarizes various case studies found for WHR systems in the EU.

Table 2. Summary results of literature.

WHR Technology	Industry	Temperature [°C]	Process	Efficiency [%]	Production	NPV [€]	IRR [%]	PBP [yrs]	Reference
ORC	Ceramic (Spain)	200-300	Furnace	10.94	120886 kWh/yr	138286	22.88	4.63	Peris et al. (2015)
	Cement (Italy)	200-300	Kiln & clinker cooler	20	36340 MWh/yr	1050000	9	9.2	Forni et al. (2012)
	Glass (Italy)	170	Float glass furnace	20	8910 MWh/yr	500000	11	8.4	
	Steel mill (Italy)	250	Steel production	21.7	1283.5 kW	N/A	N/A	N/A	Ramirez et al. (2017)
	Cement (Iran)	320	Kiln chimney	16	4014 kW	N/A	N/A	N/A	Amiri Rad and Mohammadi (2018)
	Ceramic	300	Tile tunnel kiln	N/A	N/A	N/A	18	4	Casci et al. (1981)
Kalina	Geothermal power plant (Japan)	150-180	Electricity generation	13.2	1660.3 kW	N/A	N/A	N/A	Prananto et al. (2018)
Steam cycle	Glass (Norway)	500	Glass-melting furnace (regenerative)	10.9[2]	430 kW[3]	390000	18.7	3.7	KOROBITSYN (2002)
		900	Glass-melting furnace (recuperative)	21.2[2]	1085 kW[3]	1130000	21.6	3.4	
		1450	Glass-melting furnace (oxy-fuel)	25.9[2]	934 kW[3]	970000	21.6	3.4	
WHRSG	Cement		Dry-type rotary kiln	48.7(2)	8000000	N/A	N/A	1.38	Engin and Ari (2005)
	Cement		Preheater, Calciner, Kiln, Cooler	10(5)	4400	N/A	N/A	2	Khurana et al. (2002)

[1] Overall efficiency [2] Heat recovery efficiency [3] Electrical Power [4] Of total primary energy efficiency

3 Proposed WHR technologies

Most WHR is 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 low temperature sources, is still in its infancy. Even though a number of 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.

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. This approach is shown schematically in Figure 1.

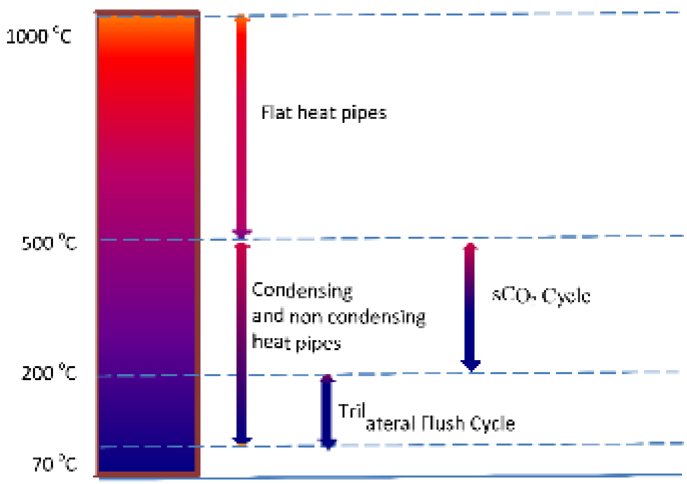

Figure 1. Heat Recovery Range and Technologies in I-ThERM

The heat recovery solutions are based on innovative HPs whose design will be optimised 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 described in Section 2 above, and to enable the offer of standard plug and play or easily customisable solutions for a wide range of applications, including condensation of vapors in the exhaust flows to maximize heat recovery potential.

Depending on the needs of specific plant or over the fence users, the recovered heat can be used directly, 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.

The ambition of this project is to develop and demonstrate heat recovery technologies that overcome many of the disadvantages of conventional technologies and create a pathway for much wider adoption of heat recovery by industry.

3.1 Flat heat pipes

Heat pipes (HP) are among the most popular passive heat transfer technologies over the last years, due to their high efficiency. Heat pipes have high thermal conductivity that enables uniform temperature along its heated and cooled sections.

The basic structure of HP consists of an evacuated tube partially filled with a working fluid that exists in two phases, vapor and liquid, at the same time. Accordingly, an important parameter to determine the efficiency of a HP is the working fluid selection and the casing material as well.

HP have a broad market of usage, from LT cryogenic applications to HT applications, where efficient heat transfer is required. Thus, HP can be used in a range of applications, such as nuclear and low temperature applications. Low temperature applications include the industrial sectors such as pharmaceutical, food processing, biotechnology as well as chemical and medical industries.

Although the technology of HPs is very promising and efficient for many applications in the industry, there are still factors that need to be considered, such as the cost and the technology development. Compared to conventional heat transfer methods, HPs have higher initial cost.

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 (FHP) (Figure 2) 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).

Figure 2. Flat heat pipes application.

However, FHPs which is a new and promising idea based on the HP technology, have the same benefits as the conventional HPs, but due to their geometry they can be used in specific applications more efficiently. For example, the combination of flat pipes and PV/T panels is a successful combination as stated by Jouhara et al. (2017b), since it can reduce the manufacturing cost and increase the viability of mass production.

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.

Heat pipe technology has slightly higher cost than the conventional technology, but it has advantages over the conventional technology systems in terms of maintenance and replacement of pipes.

Since FHPs represent a new concept of HPs, there are no studies available in the literature. Jouhara et al. (2017a) designed and manufactured a flat HP, able to recover heat by thermal radiation from sources at temperatures greater than the surface of the heat pipes. The overall dimensions of the flat HPHE are 1 m high and 1 m wide. The HPHE consists of 14 stainless steel pipes linked by a bottom header and a tube HE at the top. The prototype was tested in laboratory conditions as well as in industrial steel process. It was concluded that the flat HPs are promising for WHR in the steel industry but there are also some challenges needing further investigation.

Jouhara et al. (2016) developed and validated a novel flat HP based photovoltaic thermal (PV/T) system called a 'heat mat', which performs 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 electrical efficiency was increased by 15% with the use of an active cooling cycle in the panels. Moreover, the temperature of the panels decreased from 40–58 °C to 28–33°C. The thermal efficiency of the heat mat without the PV layer was around 64%, while the efficiency of the heat mat with the PV layer was around 50%.

Flat HPs can also be used for heat recovery from medium and low temperature sources. Flat HPs that can be manufactured in different configurations, can also be used as a first stage heat recovery from high temperature exhausts. They can also be used for temperature control of spaces and liquid baths.

3.2 Condensing economizers

In the previous section, it is stated that there are different types of HEs for different applications but with similar functionality. These types are the finned tubes, the coiled tubes, the non-condensing and condensing economizers. The last two are mainly used to increase the efficiency of boiler systems. Boilers equipped with condensing economizers can have an overall efficiency that exceeds 90%. A condensing economizer 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 condensing economizers (Figure 3) provide new heat recovery opportunities due to their very high heat transfer coefficient, the high heat transfer surface area and the low gas side pressure drops.

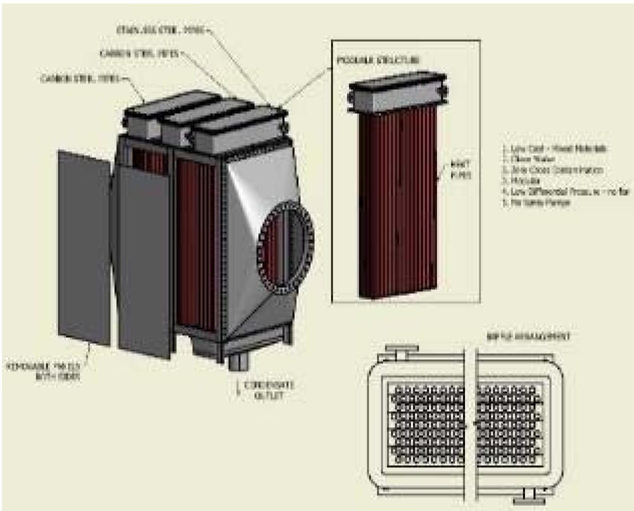

Figure 3. Condensing economizers schematic representation.

There are two types of condensing economizers: of indirect and of direct contact. The indirect contact condensing economizers remove heat from the hot gases by passing them through HEs. The direct contact condensing economizers offer high heat transfer coupled with water recovery capability since heated water can be collected for boiler feed water, space heating, or plant process needs. Recovered water will be acidic and may require treatment prior to use, such as membrane technology, external HEs, or pH control.

I-ThERM will produce standardized HP based designs for heat recovery from gaseous exhausts 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 for easy cleaning and reliable and low maintenance operation.

Similar to the flat HPs, innovations in this area will also involve investigation and specification of optimum material coatings and HP fluids for the different temperature ranges, approaches to improve primary (exhaust/process) fluid heat transfer coefficient, for the different temperature ranges, a design tool for the design and specification of condensing HPs in general and in particular for the application in this project.

3.3 Trilateral Flash Cycle

The Trilateral Flash Cycle (TFC) is a thermodynamic power cycle whose expansion starts from the saturated liquid state rather than a vapor phase (see Figure 4). 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 (Paanu and Niemi, 2012). It can also eliminate the requirement for an extra cooling tower/heat rejection system, where heat in the waste stream will be rejected. The TFC cycle has been under consideration for more than 30 years but the low efficiency of expander technology and high pump power have hindered its development to commercialisation.

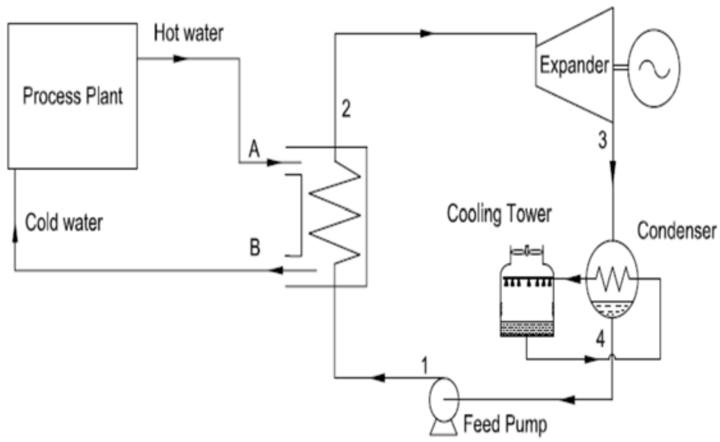

Figure 4. The trilateral Flash cycle schematic representation.

The efficiency of the system is also dependent on the efficiency of the two-phase expansion process and this has been the main obstacle in the development of the TFC cycle to commercialization stage. Another problem is the relatively high pump power that limits the net electrical power available from the system. Recent studies and laboratory investigations have, however, shown that it is possible to achieve adiabatic expansion efficiencies of more than 70% (Ho et al., 2012).

A small capacity TFC system with 5 kW electrical power output was developed and tested by Spirax Sarco at its premises in Cheltenham, UK. This system uses the thermal energy from the waste stream to provide the pumping energy for the cycle, thus overcoming the high pumping power disadvantage of TFCs. This should make TFC an attractive system for power generation from low temperature heat sources, as low as 70 °C.

The I-ThERM contribution is on the optimization of turbine steam expanders already developed by Spirax for low capacity steam power systems to operate efficiently at low heat source temperatures of about 70°C.

With this system the heat recovery increases, but low temperature should be needed.

3.4 Supercritical Carbon Dioxide Cycle

In recent years, significant research and development has been carried out on ORC systems and a number of manufacturers are currently researching systems for a range of applications. While the current state of the art shows a maturity for the first generation of ORC systems, typical efficiencies from 6% to 16%, there is still room for further research and development to increase efficiencies to 20% (Ramirez et al., 2017).

A technology that has the potential to provide higher thermal energy conversion efficiency compared to ORC is the supercritical CO_2, Brayton Cycle system (sCO_2), illustrated in Figure 5.

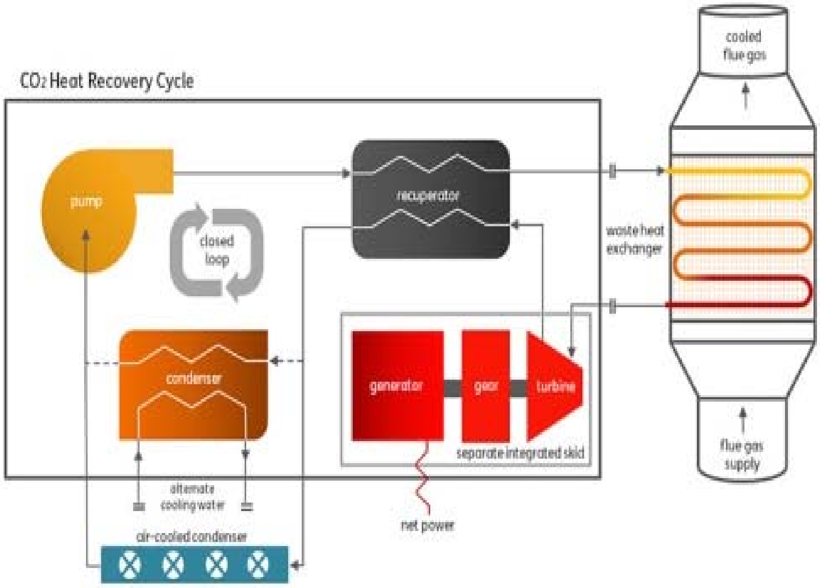

Figure 5. The supercritical carbon dioxide cycle schematic representation.

The sCO_2 operates in a similar manner to other turbine cycles but uses Carbon Dioxide 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. It has been demonstrated through modelling and laboratory studies that the sCO_2 cycle can provide, depending on operating pressures and temperatures, energy conversion efficiency of 30% (Kacludis et al., 2012).

According to Ahn et al. (2015), the supercritical CO_2 Brayton cycle has been gaining a lot of attention for application to next generation nuclear reactors. It is mentioned that this cycle has a big potential to be used for WHR as well.

Supercritical CO_2 cycle systems are currently under research and development by large power system manufacturers such as Mistubishi Electric, Siemens, etc. A large, 7.5 MWe system, Echogen EPS100, is currently under research and development for large industrial fuel-fired processes, utility-scale power generation, and concentrated-solar thermal utility applications.

The intention in this project is to develop and demonstrate a small modular supercritical sCO_2 power system that can be easily employed for a variety of HT heat recovery to power conversion applications.

The sCO_2 cycle is proposed in this project because of its size, 10 to 100 times smaller than Rankine, its efficiency that exceeds 30% and because of the nice properties of the working fluid, CO_2. It is non-flammable, nontoxic and has a global warming potential of 1.

A 5kW CO_2 cycle system has recently been developed by Enogia SAS and installed in a specially designed test facility at Brunel University London for further testing and development. For the purposes of this project, a 50 kWe system will be developed by Enogia with input from BUL and installed for power generation using heat recovery from a biomass boiler.

4 Impact of the proposed technologies

The energy and cost saving potential is closely linked to the flow of heat in the plant in most cases. The basic idea behind WHR is to try to recover maximum amounts of heat in the plant and to reuse it as much as possible, instead of just releasing it into the air or a nearby riverhis project, considers the following solutions:

- Flat HPs with appropriate selection of materials and working fluid will be able to recover heat primarily by radiation but also by convection at temperatures > 200°C and utilize this heat for power generation through the sCO_2 cycle.
- Condensing and not condensing HPs (economizers) can be used to recover heat efficiently from exhausts and use this heat for power generation through the sCO_2 cycle at temperatures down to 200°C. Below 200°C the TFC Cycle will be employed. Where liquid waste streams are available at suitable temperatures below 100° C, standard HEs will be employed (plate, shell and tube, etc.).
- The heat to power generation technologies developed, the TFC system for low temperature (70–200°C) and the sCO_2 for medium temperature (200–500°C) and the combination of these with HP heat recovery technologies will maximize the potential for power generation from waste heat streams.

Benefits from these implementations:

- Reduction of the parasitic losses of the cycle and improvement of the overall thermal efficiency, with the TFC system.
    - The principles of this innovation can also be applied to other power systems such as ORC cycles.
- Will be the first in Europe and most probably internationally in the small capacity range, up to 100 kW, with the sCO_2 system.
- Can absorb or reject heat over a very wide temperature range from sub-zero to temperatures in excess of 1000°C with the use of the Flat HP systems.
- Will improve primary (exhaust/process) fluid heat transfer coefficient, for the different temperature ranges and increase quantity of recovered heat, with the Condensing HPs.

Thus, I-ThERM will contribute towards:

- energy efficiency for a sustainable industry
- increasing industrial competitiveness
- promoting a new European supply chain for export of WHR technologies
- helping in saving, and creating new jobs

The Main industrial sectors for the application of the project's technology solutions are:

- Most industrial sectors (heat to power generation - heat source temperatures: 70–200°C.

- Sectors with high temperature waste heat sources (heat to power generation-exhaust temps: 200–500°C): Metals, Chemicals, Cement, Ceramics, paper and pulp, food and drink, etc.
- High temperature sectors such as the petrochemical and metal manufacturing, for temperatures up to 500°C.

Benefits for industries from WHR processes:

- Save fuel and reducegreenhouse gas emissions
- Generate electricity and mechanical work
- Sell heat and electricity
- Reduce cooling needs
- Reduce capital investment costs
- Increase production
- Transform the heat to useful forms of energy

5 Potential of the WHR technologies to the EU28

5.1 Industrial energy consumption of the EU28

Table 3 shows the energy consumption of the industrial sector of the EU28 for the year 2016 from European Commission (2018). The short names of each industry are as follows:

- 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

5.2 Industrial processes and temperature ranges

Table 4 shows the most energy consuming industrial sectors and various processes of each sector, characterized by their temperature ranges based on the classification given for the WHR processes to LT, MT and HT.

Table 3. Breakdown of the energy consumption of the EU by Industrial sector in TWh in 2016 by European Commission (2018).

Country	I&S	NFM	C&P	NMM	M&Q	F&T	T&L	PPP	TE	M	W&WP	C	NS	**Total**
AU	28.4	2.9	11.1	11.1	1.6	9.4	0.8	19.6	1.3	7.4	7.9	6.3	2.2	**109.85**
BE	29.1	3.5	50.0	16.3	0.0	17.4	2.3	8.1	2.3	2.3	2.3	2.3	4.7	**140.72**
BG	1.3	1.5	9.7	6.5	1.4	2.8	0.8	2.8	0.2	1.5	0.7	0.7	0.8	**30.71**
CR	0.1	0.1	1.8	3.7	0.2	2.4	0.3	0.9	0.1	0.9	0.6	1.1	0.5	**12.63**
CY	0.0	0.0	0.1	1.7	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.1	0.1	**2.48**
CZ	21.8	1.0	11.1	12.5	1.0	6.7	2.0	6.9	5.3	7.9	2.7	2.3	4.4	**85.62**
DK	1.0	0.0	3.0	5.3	0.9	7.0	0.2	0.9	0.2	2.6	0.8	1.9	1.2	**24.92**
EE	0.0	0.0	0.4	0.8	0.1	0.8	0.1	0.7	0.1	0.4	0.7	0.7	0.3	**5.28**
FI	14.4	2.9	12.1	3.6	2.3	4.8	0.3	70.5	0.8	3.6	6.0	4.5	2.6	**128.38**
FR	61.1	12.8	51.2	38.8	4.4	55.2	3.4	27.6	12.3	21.9	6.6	17.7	28.6	**341.63**
DE	152.0	27.3	173.7	75.1	4.4	58.9	5.5	64.5	35.2	61.0	22.4	0.0	30.9	**710.85**
GR	1.5	15.9	1.8	2.1	0.9	5.2	0.5	0.6	0.2	0.3	0.3	1.5	5.2	**36.01**
HU	5.2	1.4	12.8	6.2	0.3	6.8	0.5	2.4	2.6	4.7	0.9	2.7	3.1	**49.54**
IE	0.0	5.7	2.9	4.9	1.2	5.4	0.2	0.3	0.3	3.5	1.8	0.1	2.1	**28.45**
IT	55.3	7.6	40.8	53.8	1.4	32.8	12.8	26.9	4.9	39.6	5.4	4.1	18.9	**304.35**
LV	0.0	0.0	0.3	1.3	0.1	0.9	0.1	0.1	0.1	0.2	5.2	0.4	0.2	**8.72**
LT	0.0	0.0	4.0	1.6	0.1	2.2	0.4	0.4	0.0	0.3	1.2	0.5	0.8	**11.50**
LU	3.4	0.0	0.7	1.8	0.0	0.3	0.4	0.1	0.0	0.1	0.3	0.3	0.5	**7.83**
MT	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.2	**0.51**
NL	28.0	3.0	79.2	7.0	1.3	24.4	1.1	6.7	1.2	6.0	0.9	7.0	4.5	**170.45**
PL	30.7	5.1	29.3	33.1	4.8	22.8	1.4	19.0	4.8	8.6	11.3	1.9	8.9	**181.66**
PT	2.2	0.3	4.3	11.9	0.7	5.3	3.4	15.9	0.7	1.8	1.4	1.9	0.7	**50.38**
RO	20.3	0.0	14.6	11.6	0.4	6.6	1.7	1.6	2.5	4.2	3.9	4.1	2.0	**73.50**
SK	24.8	3.0	4.3	5.4	0.1	1.6	0.3	5.3	2.0	2.5	0.5	0.3	1.6	**51.75**
SI	1.7	1.9	1.9	2.1	0.2	0.8	0.2	1.9	0.4	1.6	0.6	0.3	0.8	**14.46**
ES	37.5	13.3	31.4	37.9	5.1	27.7	4.3	19.1	5.3	11.0	6.3	11.3	10.4	**220.64**
SE	17.7	3.8	7.2	3.8	6.1	4.3	0.3	66.7	2.4	3.9	6.7	1.3	8.8	**132.97**
GB	31.8	6.1	37.5	26.5	0.1	30.8	7.4	24.2	15.5	20.7	2.5	6.4	72.6	**282.05**
EU28	**569.25**	**119.11**	**596.91**	**386.38**	**39.24**	**343.71**	**50.76**	**393.56**	**100.84**	**218.98**	**99.49**	**81.90**	**217.69**	**3217.85**

Table 4.The most consuming industries and examples from their processes and temperature ranges classified to LT, MT, HT.

Industry	Processes	Temperature range (°C)	Temperature range (LT, MT, HT)
Iron & Steel industry	Sinter Process	1300–1480	HT
	Pelletization Plants - Induration process	Straight grate:1300–1350	HT
		Grate kiln: 1250	
	Coke oven plants - Jewell - Thompson oven	1150–1350	HT
	Blast furnace - Hot Stoves	900–1500	HT
	Basic Oxygen Steelmaking	1200	HT
Large Combustion Plants	Combustion process -	430–630	HT
	Gasification / Liquification process		
	Steam process - Boiler	Coal and Lignite fuels: 540–570	HT
		Liquid fuels: 120–140	
	Co-generation/combined heat and power	100	LT
	Combined cycle plants	430–630	HT
Large Volume Inorganic Chemicals (Ammonia, Acids and Fertilizers) industry	Conventional steam reforming - Desulphurization process	350–400	HT
	Conventional steam reforming - Primary and Secondary reforming	Primary: 400–600	HT
		Secondary: 400–600	
		Exhaust gas: 1000	
	Ammonia Partial oxidation - Gasification of heavy hydrocarbons and coal	N/A	N/A
	Ammonia Partial oxidation - Sulphur removal	N/A	N/A
	Sulphuric Acid - Sulphur combustion SO2 production process	900–1500	HT
	Sulphuric Acid - Regeneration of spent acids SO2 production process	400–1000	HT
	Sulphuric Acid - Spent acid from TiO2 production and roasting of metal sulphates	850+	HT
	Sulphur burning process	145	MT

Industry	Processes	Temperature range (°C)	Temperature range (LT, MT, HT)
Large Volume Inorganic Chemicals (Solids and Others) industry	Tank furnace process	430–650	HT
	Sodium silicate plant (revolving hearth furnace) process	600	HT
Food & Tobacco	Seed oil extraction process	65	LT
	Solubilisation / alkalizing process	45–130	MT
	Utility processes - CHP	60–115	MT
	Heat recovery from cooling systems	50–60	LT
	Frying	180–200	MT
Glass Producing industry	Heating the furnaces and primary melting	750–1650	HT
Organic Fine Chemicals industry	Energy Supply	45–130	LT
	Thermal oxidation of VOCs and co-incineration of liquid waste	950–1000 (SNCR) or SCR	HT
	Recovery and abatement of acetylene	N/A	N/A
Non-ferrous Metals industry	Primary lead and secondary lead production	200–400	MT
	Smelting Process	400–1200	HT
	Zinc sulphide (sphalerite)	900–1000	HT
Cement, Lime and Magnesium Oxide industry	Kiln firing	≥ 2000	HT
	Clinker burning	1400–2000	HT
Polymers producing industry	Thermal treatment of waste water	N/A	N/A

Industry	Processes	Temperature range (°C)	Temperature range (LT, MT, HT)
Ferrous Metals processing industry	Hot rolling mill	1050 – 1300	HT
	Re-heating and heat treatment furnaces	N/A	N/A
Pulp, Paper and Board Production industry	Kraft pulping process (chemical pulping)	155–175 (Cooking and delignification)	MT
		90–100 (Oxygen delignification)	LT
	Sulphate pulping process (chemical pulping)	800–1100 (calcination reaction - lime kiln)	HT
	Mechanical pulping and Chemimechanical pulping	95–125 (Grinding- Pressure Groundwood pulping)	LT-MT
	Processing of paper for recycling (with and without deinking)	N/A	N/A
	Papermaking and related processes	45–90 (Paper machine)	LT
		>350 (Yankee dryer)	HT
Surface Treatment using Organic Solvents industry	Printing	700–800	HT
	Drying and curing	400–700	HT
	Waste gas treatment from enamelling	500–750	HT
	Manufacturing of Abrasives	35–110 in the drier	LT
		700 for the exhaust air treatment	HT
	Coil coating	150–220	MT
Tanning of Hides and Skins	Drying	60–90	LT
Textiles industry	Dirt removal	1200	HT
	Optimisation of cotton warp-yarn	60–110	LT-MT
	Dyeing	80–100	LT
	Oxidation	750	HT
	Drying	130	MT
	Drying and degassing	100–300	MT

Industry	Processes	Temperature range (°C)	Temperature range (LT, MT, HT)
Waste Incineration industry	Pyrolysis	250–700	MT-HT
	Gasification	500–1600	HT
	Oxidation, Combustion	800–1450	HT
Waste Treatment industry	Thermal Treatment	Vitrification 1300–1500	HT
		Sintering 900–1200	
	Drying	100	LT
	Regeneration of carbon	650–1000	HT
	Incineration	850–1200	HT
	Catalytic combustion	200–600	MT-HT
	Dying of wood particles	200-370 for single pass and triple pass dryers	MT
		500 at rotary dryers	HT
Wood-based Panels production industry	Drying of wood fibres	60–220	MT
	Pressing	100–260	MT
	Lamination	130–200	MT

5.3 Waste heat potential of the EU28

According to Panayiotou et al. (2017), the following percentages of waste heat potential for each industry are shown in Table 5 and according to Forman et al. (2016) the waste heat potential of each temperature range is shown in Table 6.

Table 5.Waste heat potential percentage per industry.

Waste heat potential per industry	
Type of industry	**Waste heat potential**
Iron and Steel	11.40%
Chemical and Petrochemical	11%
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%
Textile and Leather	11.04%
Other	10.38%

Table 6.Waste heat potential percentage for each temperature range.

Waste heat potential	
Low temperature <100°C	12.60%
Medium temperature 100-299°C	6%
High temperature >=300°C	11.40%

The preliminary expected waste heat potential estimated is shown in Table 7 based on the energy consumption shown in Table 3, ignoring, however, the temperature range of the heat wasted in each industry. Thus Table 7 presents a rough estimation of the waste heat potential, but close to the results obtained by Papapetrou et al. (2018) who carried out a more detailed analysis and Panayiotou et al. (2017).

Papapetrou et al. (2018) estimated the waste hear potential for the EU28 and compared their results with the ones presented in the Deliverable D2.1 of I-ThERM. Although in the D2.1 only a rough estimation was presented for data from 2012, the results show a good agreement with the results of Papapetrou et al. (2018).

Table 7. Breakdown of waste heat potential of the EU by Industrial Sector in 2016.

Country	I&S	NFM	C&P	NMM	M&Q	F&T	T&L	PPP	TE	M	W&WP	C	NS	TOT [TWh]
AU	3.2	0.3	1.2	1.3	0.2	0.8	0.1	2.1	0.1	0.8	0.5	0.4	0.2	**11.21**
BE	3.3	0.3	5.5	1.9	0.0	1.5	0.3	0.9	0.3	0.3	0.1	0.1	0.5	**14.91**
BG	0.1	0.1	1.1	0.7	0.2	0.2	0.1	0.3	0.0	0.2	0.0	0.0	0.1	**3.25**
CR	0.0	0.0	0.2	0.4	0.0	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.1	**1.26**
CY	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.26**
CZ	2.5	0.1	1.2	1.4	0.1	0.6	0.2	0.7	0.6	0.9	0.2	0.1	0.5	**9.12**
DK	0.1	0.0	0.3	0.6	0.1	0.6	0.0	0.1	0.0	0.3	0.1	0.1	0.1	**2.47**
EE	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	**0.49**
FI	1.6	0.3	1.3	0.4	0.3	0.4	0.0	7.4	0.1	0.4	0.4	0.3	0.3	**13.21**
FR	7.0	1.2	5.6	4.4	0.5	4.8	0.4	2.9	1.4	2.5	0.4	1.1	3.0	**35.09**
DE	17.3	2.6	19.1	8.6	0.5	5.1	0.6	6.8	3.9	7.0	1.3	0.0	3.2	**76.01**
GR	0.2	1.5	0.2	0.2	0.1	0.4	0.1	0.1	0.0	0.0	0.0	0.1	0.5	**3.51**
HU	0.6	0.1	1.4	0.7	0.0	0.6	0.1	0.3	0.3	0.5	0.1	0.2	0.3	**5.13**
IE	0.0	0.5	0.3	0.6	0.1	0.5	0.0	0.0	0.0	0.4	0.1	0.0	0.2	**2.85**
IT	6.3	0.7	4.5	6.1	0.2	2.8	1.4	2.8	0.5	4.5	0.3	0.2	2.0	**32.49**
LV	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.3	0.0	0.0	**0.66**
LT	0.0	0.0	0.4	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.1	0.0	0.1	**1.13**
LU	0.4	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	**0.85**
MT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.05**
NL	3.2	0.3	8.7	0.8	0.2	2.1	0.1	0.7	0.1	0.7	0.1	0.4	0.5	**17.85**
PL	3.5	0.5	3.2	3.8	0.5	2.0	0.2	2.0	0.5	1.0	0.7	0.1	0.9	**18.89**
PT	0.2	0.0	0.5	1.4	0.1	0.5	0.4	1.7	0.1	0.2	0.1	0.1	0.1	**5.24**
RO	2.3	0.0	1.6	1.3	0.1	0.6	0.2	0.2	0.3	0.5	0.2	0.2	0.2	**7.66**
SK	2.8	0.3	0.5	0.6	0.0	0.1	0.0	0.6	0.2	0.3	0.0	0.0	0.2	**5.67**
SI	0.2	0.2	0.2	0.2	0.0	0.1	0.0	0.2	0.0	0.2	0.0	0.0	0.1	**1.51**
ES	4.3	1.3	3.4	4.3	0.6	2.4	0.5	2.0	0.6	1.3	0.4	0.7	1.1	**22.77**
SE	2.0	0.4	0.8	0.4	0.7	0.4	0.0	7.0	0.3	0.4	0.4	0.1	0.9	**13.85**
GB	3.6	0.6	4.1	3.0	0.0	2.7	0.8	2.6	1.7	2.4	0.1	0.4	7.5	**29.54**
EU28	**64.89**	**11.42**	**65.66**	**44.05**	**4.47**	**29.70**	**5.60**	**41.56**	**11.13**	**24.96**	**5.97**	**4.91**	**22.60**	**336.9**

Based on the methodology followed in Papapetrou et al. (2018) for the estimation of the WHR potential, the estimated potential of the various industries are shown in Figure 6 - Figure 12. The waste heat potential in this section is estimated for the most energy consuming industries, which are the Food and Tobacco (Figure 6), Iron and Steel (Figure 7), Textile and Leather (Figure 8), Non-Ferrous Metals (Figure 9), Wood and Wood Products (Figure 10), Non-Metallic Mineral (Figure 11), and Paper Pulp and Print (Figure 12).

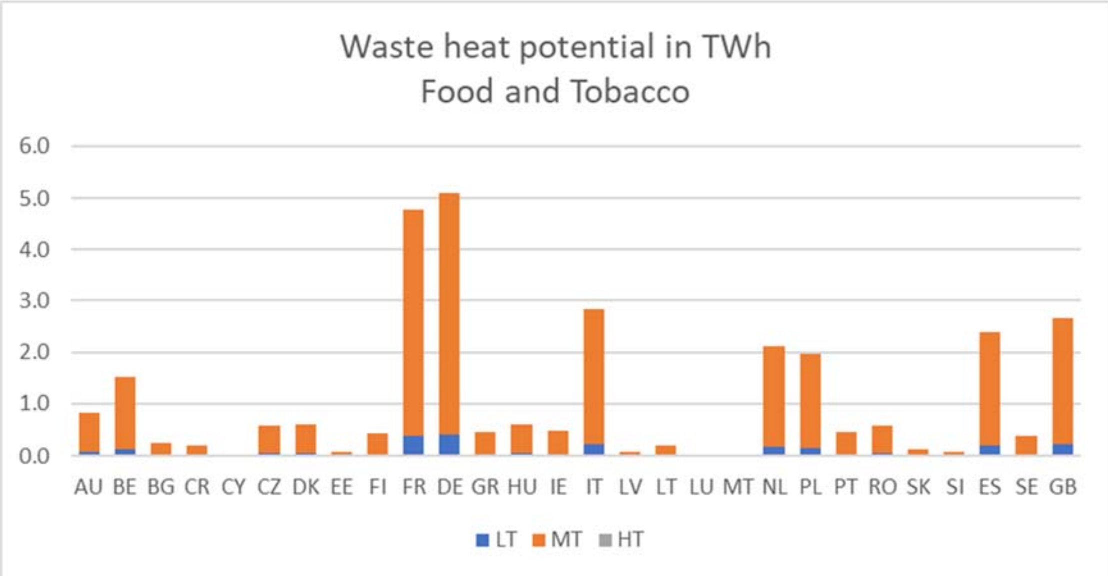

Figure 6. Waste heat potential in each EU country based on the 2016 data per temperature level in Food and Tobacco industry.

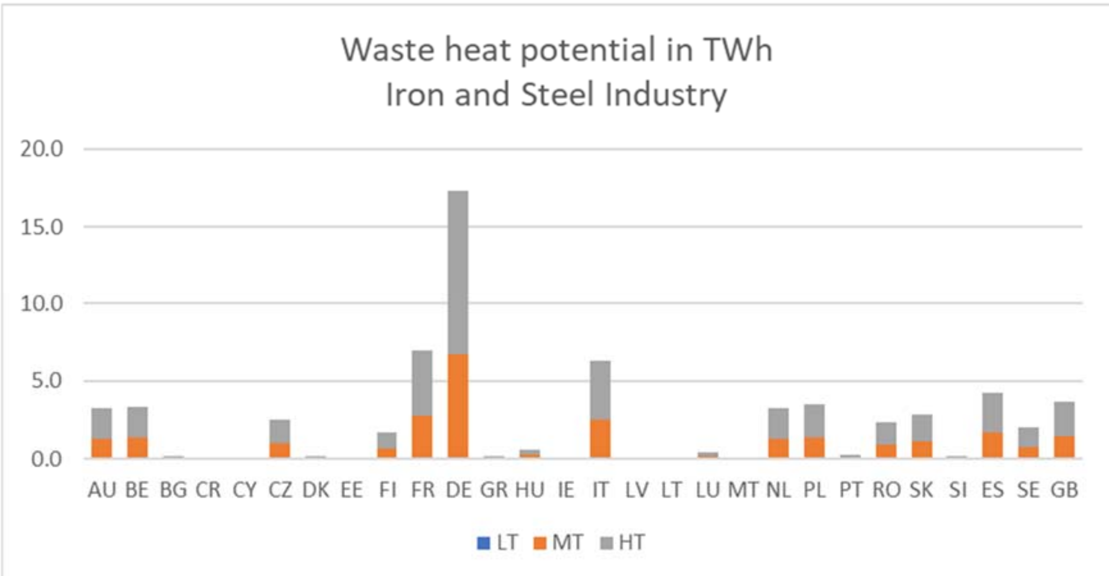

Figure 7. Waste heat potential in each EU country based on the 2016 data per temperature level in Iron and Steel industry.

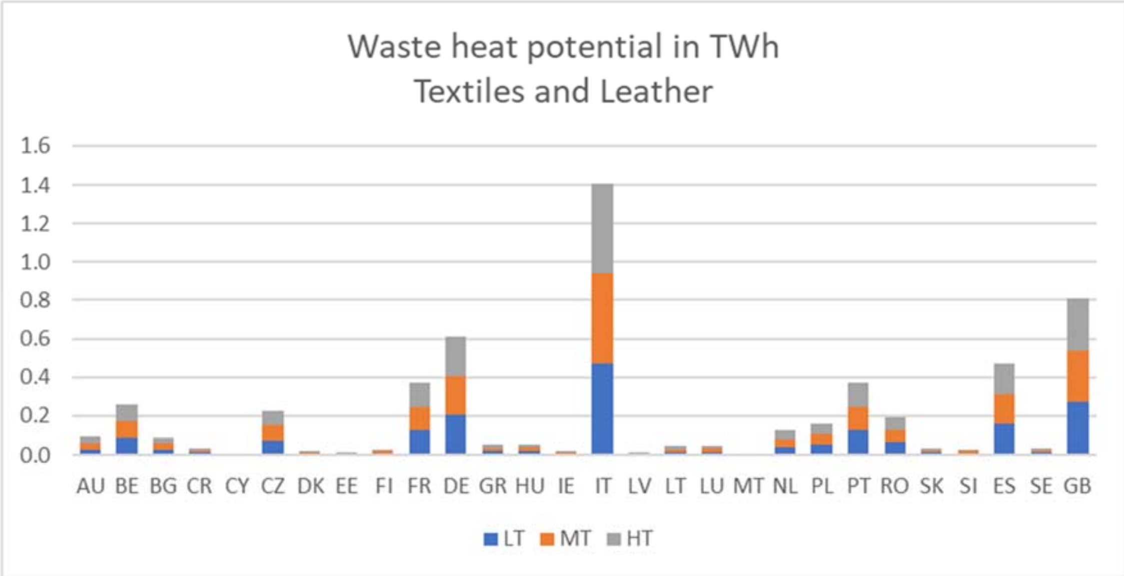

Figure 8. Waste heat potential in each EU country based on the 2016 data per temperature level in Textiles and Leather industry.

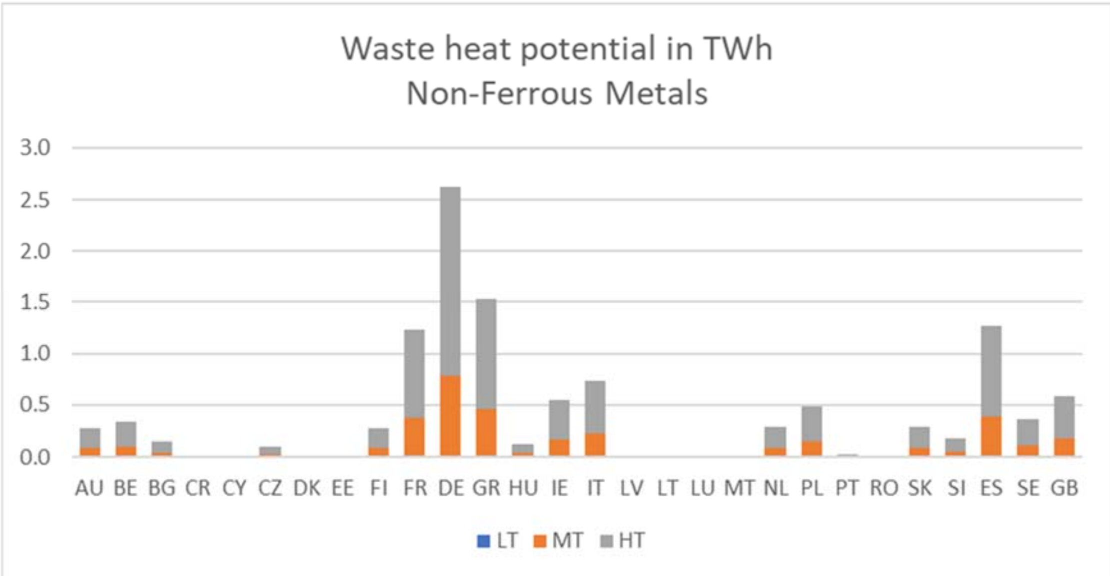

Figure 9. Waste heat potential in each EU country based on the 2016 data per temperature level in Non-Ferrous Metals industry.

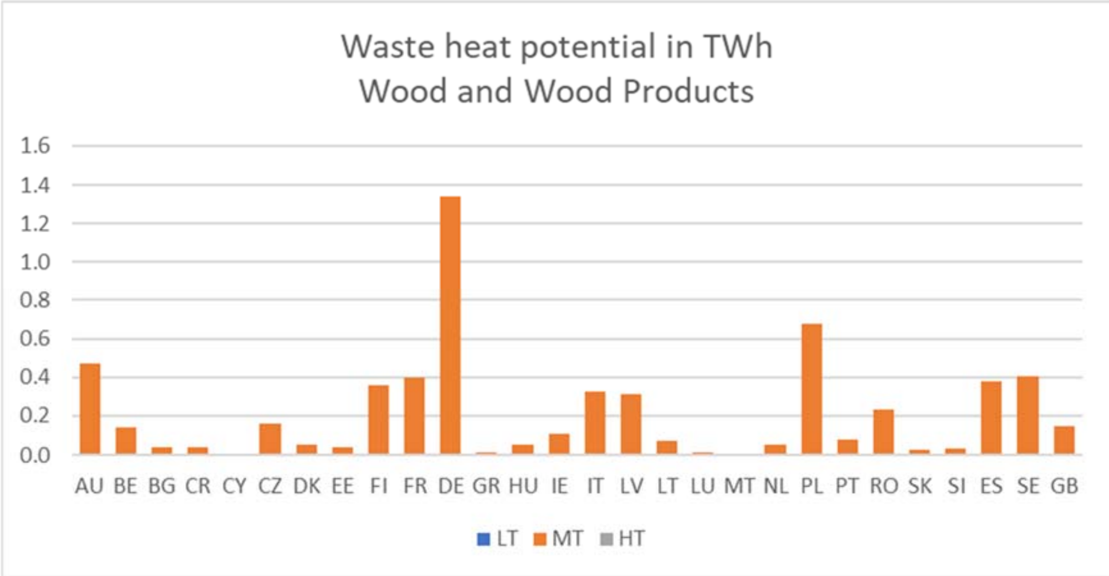

Figure 10. Waste heat potential in each EU country based on the 2016 data per temperature level in Wood and Wood Products industry.

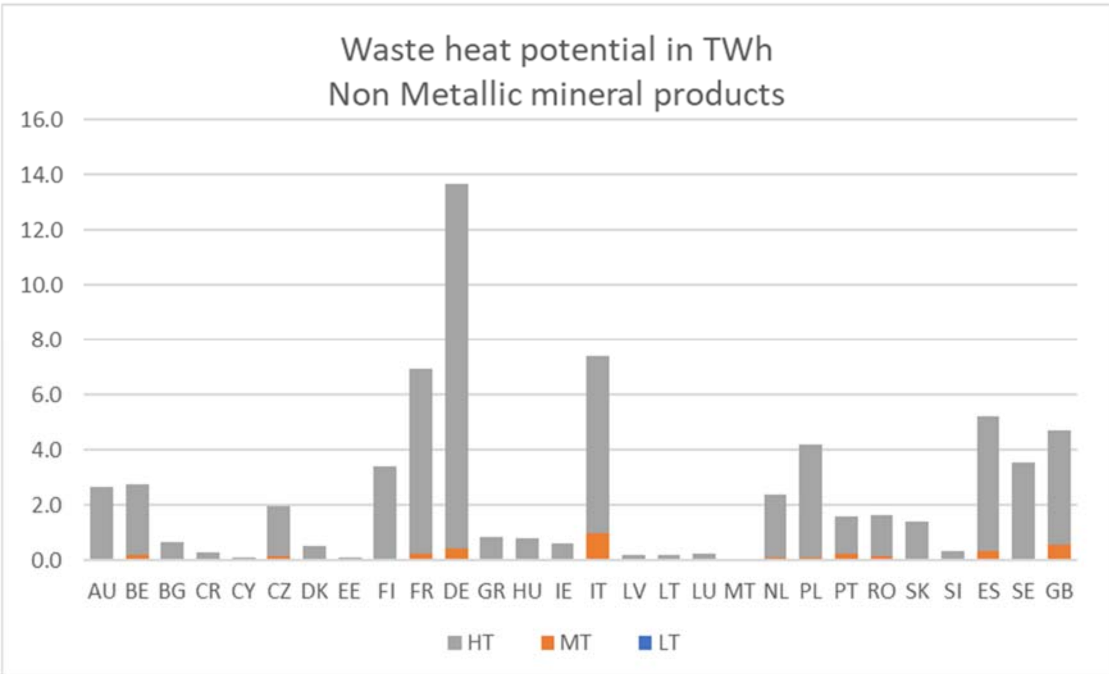

Figure 11. Waste heat potential in each EU country based on the 2016 data per temperature level in Non-Metallic Mineral industry.

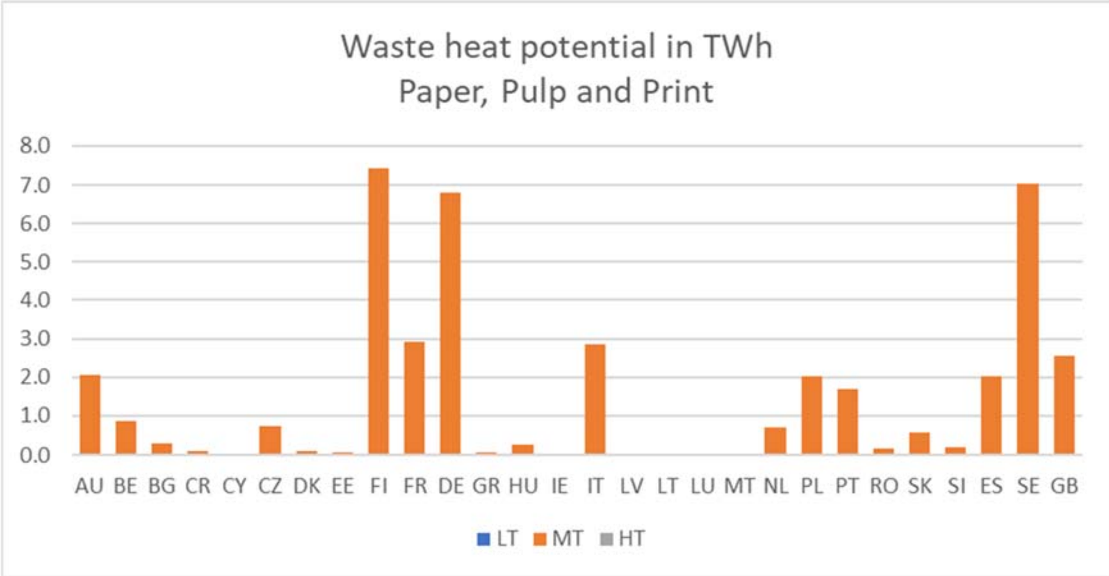

Figure 12. Waste heat potential in each EU country based on the 2016 data per temperature level in Paper, Pulp and Print industry.

6 Potential market of the proposed technologies

In this section, the potential market of the proposed technologies is estimated based on comparison with conventional waste heat recovery systems.

TFC and sCO_2 systems are compared with the ORC market, while for the FHP technology the potential market is estimated by the identification of the industrial processes that the FHP could be used.

In order to identify the potential market of the proposed technologies, the industrial processes where the ITHERM systems can be deployed are considered.

6.1 FHPS

As mentioned earlier in chapter 3 of this report, the Flat Heat Pipe 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 heat pipe 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 heat exchanger system, which condenses the working fluid. Finally, the condensate flows back to the evaporator section under gravity.

Figure 13 shows the positioning of the FHP during a factory test carried out by Jouhara et al. (2017a). As can be seen, the FHP absorb the radiant heat from the hot steel wires.

For the installation of the FHP panels it is required that the industrial processes have radiant heat sources with higher temperatures than the surface temperature of the heat pipes and open spaces close to these processes for the installation of the FHP panels to recover the radiant heat.

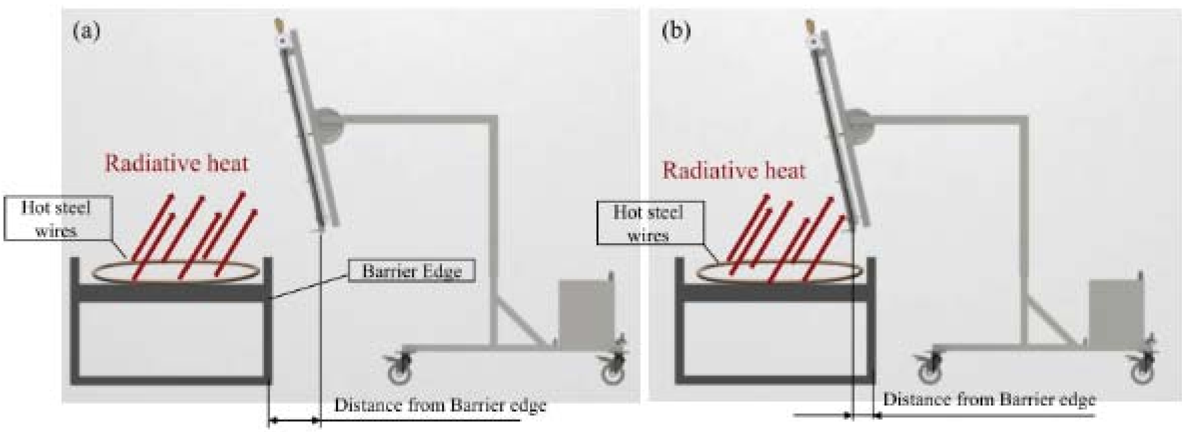

Figure 13. Flat heat pipe (FHP) positioning during the hot wire passing in the manufacturing process.

There are numerous manufacturing processes in the various industries with high temperature processes and wasted heat, but in order to be able to use the FHP system, two main conditions are required:

- The heat is transferred by thermal radiation
- Open space near the radiant source should be available for the installation of the panels

Below, various manufacturing processes with high temperature processes for different industries are shown.

Cement manufacturing

The cement manufacturing process is shown in Figure 14 (CivilDigital, 2018). From the rotary kiln, the hot clinker is cooled using large quantities of air, part of which can serve as combustion air. Coolers are essential for the creation of the clinker minerals which define the performance of the cement. In this process, the combustion air is preheated, thereby minimising overall energy loss from the system. Clinker is usually used on site but can be transported by truck, train or ship to other grinding plants. It is clearly marked that heat from the clinker cooler can be recovered by transferring the hot air back to the preheating tower. There is no open space above any hot process and there is no process which emits radiant heat. Thus, the FHP could not be a good option for the cement industry.

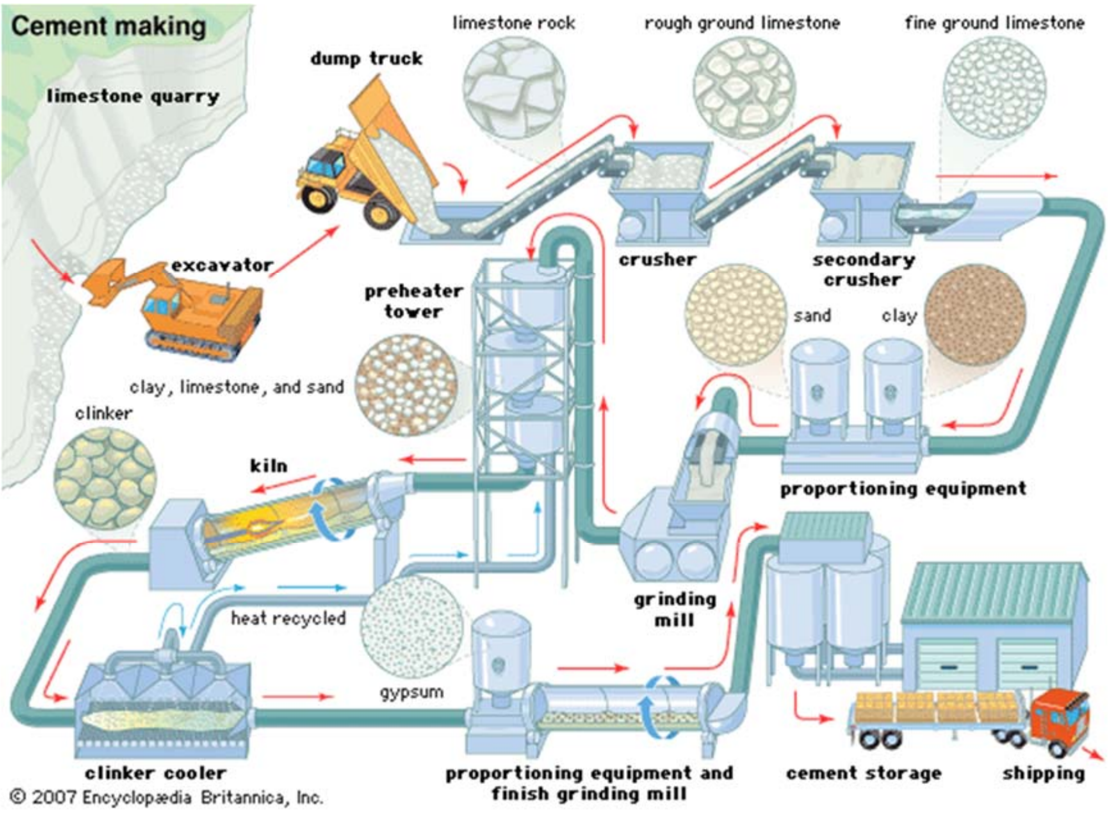

Figure 14. The cement manufacturing process by CivilDigital (2018).

Glass manufacturing

Glass industrial market could be a very good potential market for the FHP systems. It combines high temperature processes and hot material transfer as well in the manufacturing process.

The glass sector covers material production classified into:

- Container glass (60 % of the output in tonnage)
- Flat glass (30% of the output in tonnage)
- Domestic glass, reinforcement fibres (10% of output in tonnage)

In 2017, the EU28 glass production reached a volume of nearly 36 million tonnes. The production breakdown by product is shown in Figure 15.

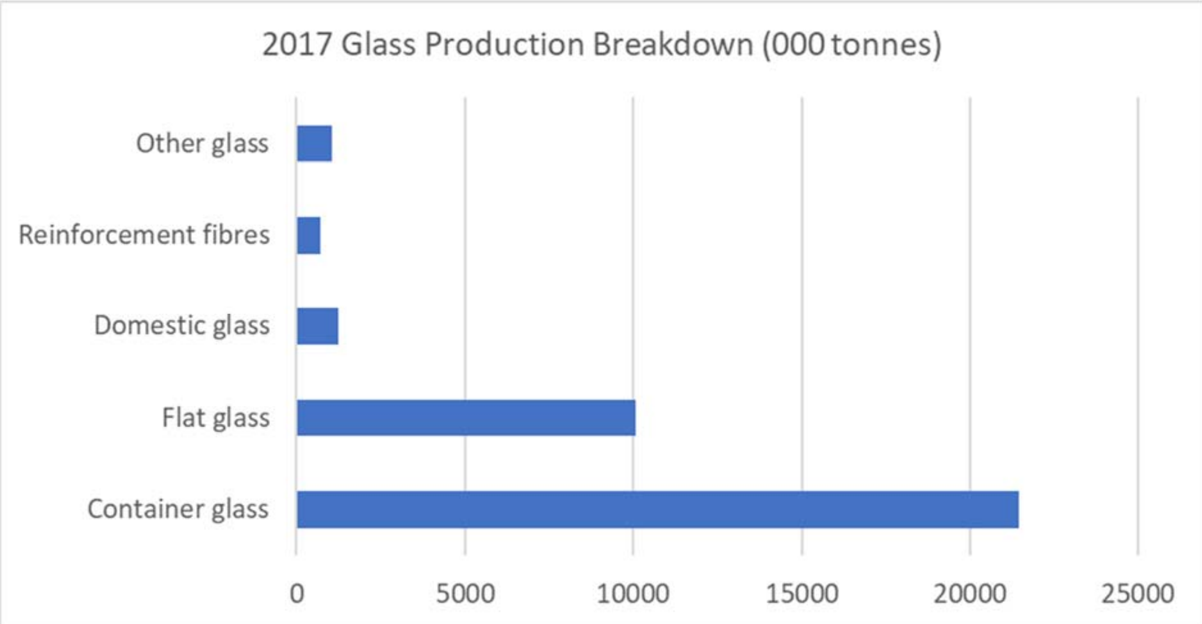

Figure 15. Glass production breakdown in 2017.

Europe is the world's largest glass market, both in terms of production and consumption. The EU glass industry comprises of around 1000 companies and accounts for more than one quarter of the non-metallic mineral sector.

Flat glass production is 30% of the total glass sector in EU with 60 production units. The production of flat glass is dominated by a few large producers, Saint-Gobain around 25% of the EU capacity, AGC 19%, NSG 17%, Sisecam 13%, Guardian 12% and others 14%. 850 tonnes of melted glass are used to produce flat glass products every day.

Container glass on the other hand which is the largest sector of the EU glass industry has 160 manufacturing plants in Europe.

Glass industries are characterised by a multitude of production processes depending on the final product manufactured and its end-applications. However, all these manufacturing processes have a common origin: glass first needs to be melted.

Glass melting requires raw materials which are of two kinds: different types of sand and recycled glass. These raw materials are mixed together, charged in a furnace where there are melted at around 1650°C to form molten glass. The molten glass is then taken out of the furnace to be shaped and cooled down afterwards. For many applications the glass obtained may be further processed to have specific properties such as increased mechanical strength and higher resistance to breakage.

The exact composition of glass may vary to meet specific applications requirements but the most commonly use type of glass, soda-lime glass, is made of silica sand, soda ash, limestone, dolomite and glass cullets (recycled glass). Additional materials such as iron oxide or cobalt can be added to the mix to give a green or blue colour to the glass.

The production process of glass is shown in Figure 16. Although the glass industry would have been a good potential market for the installation of the FHP panels, the manufacturing process of glass both for float and container glass which are the largest sectors, does not allow the installation of the FHP to capture radiant heat at any stage of the process. FHP could have been used only in the annealing process where radiant heat is present but due to the sensitivity of glass this is made in a lehr furnace in controlled conditions.

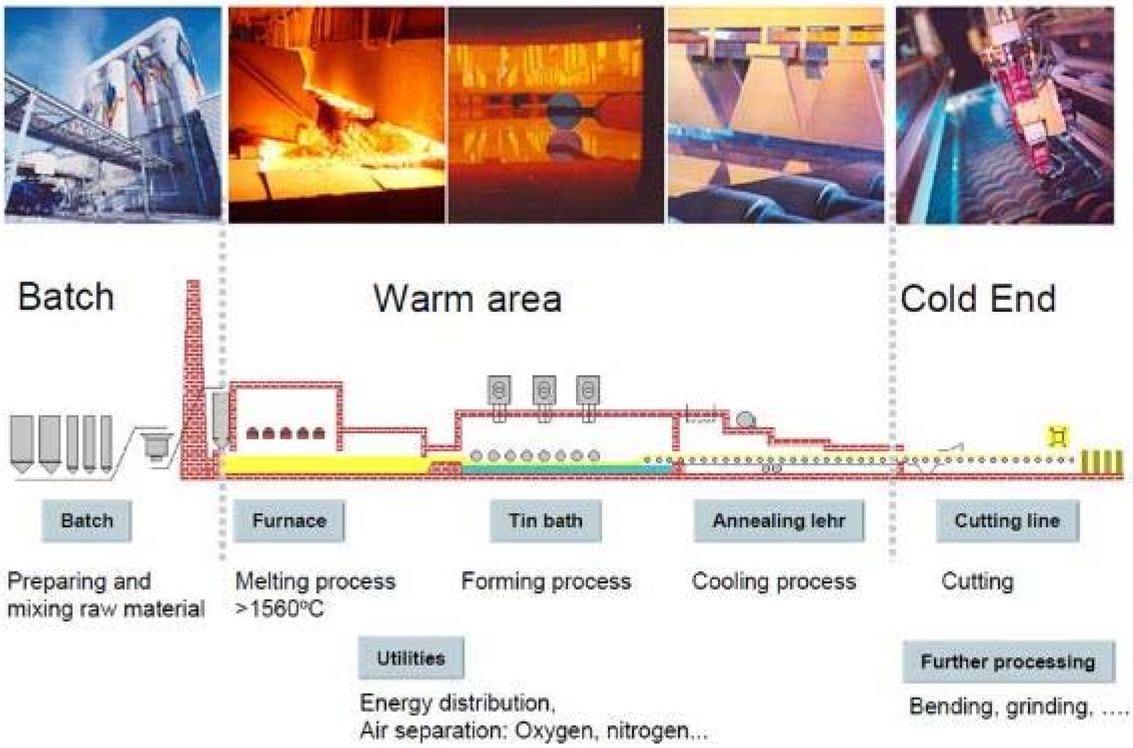

Figure 16. The glass manufacturing process by HEXAD (2016).

Iron and Steel manufacturing

500 steel production sites are split amongst 24 EU countries and around 170 million tonnes of steel is produced every year in Europe (Figure 17).

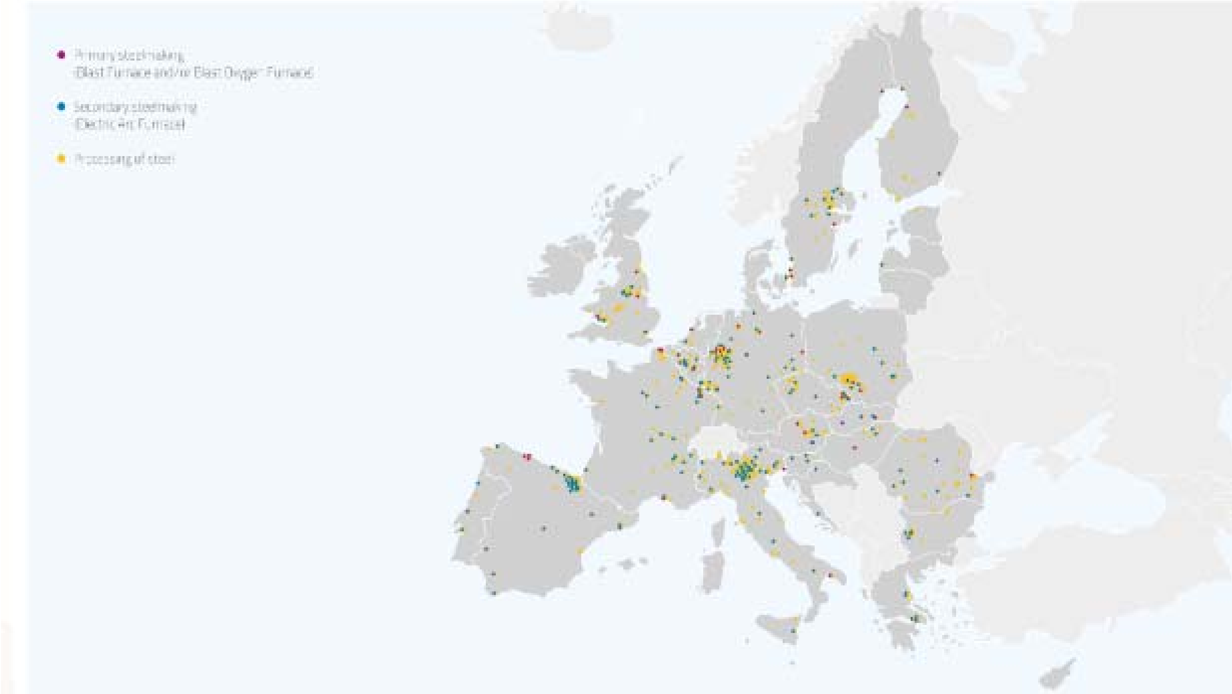

*Figure 17. Steel industry production sites in the EU (*EUROFER, 2018b).

The iron and steel industry produce various widely used materials such as:

1. Train rails
2. Wire rod coils
3. Billets
4. Blooms
5. Slabs

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 manufacturing process of the iron and steel is shown in Figure 18. Wire rod process is also a very common process in the steel industry. The manufacturing process of the wire rope process is shown in Figure 19. FHP can be used to recover radiant heat from the cooling/rolling stage from the wire rob mill where the hot wire rope moves after the casting machine.

At the beginning of the process, the mineral ore is treated by pelletization, sinterization and coking in 1300°C. The mixture of the iron ore, pellet, coke sintered ore and limestone are mixed and unified in a cylindrical blast furnace at 1650°C.

For the conversion of the pig iron to steel, two techniques are followed, called the Basic oxygen furnace and the electric arc furnace, for the treatment of the hot metal and the scrap respectively. After 45 minutes in the BOF and EAF, pig iron is transformed to steel. In order to produce specific properties, the liquid steel passes to the secondary treatment station, the continuous casting. There, the melted steel is formed into slabs, blooms or billets, and further treated in the rolling process to reach the required dimensions.

Each piece is treated by the specific rolling process, either hot rolling or cold rolling mills. For the hot rolling mill, the hot steel slab is reheated to 1330°C and then transferred for further treatment and final shape to the rolling mills which are the wire rod mill, the plate mill, the hot strip mill etc.

The iron and steel products are separated to flat and long products. 62% of the production is for flat products and 38% for long products. The pictures shown in Figure 20 show the steel flat products after the rolling processes and Figure 21 shows the long products after the hot rolling mill as well. Both products emit radiant heat and currently they are being cooled with blowing air, both in the conveyor after the rolling mill and at the laying bed shown in Figure 22.

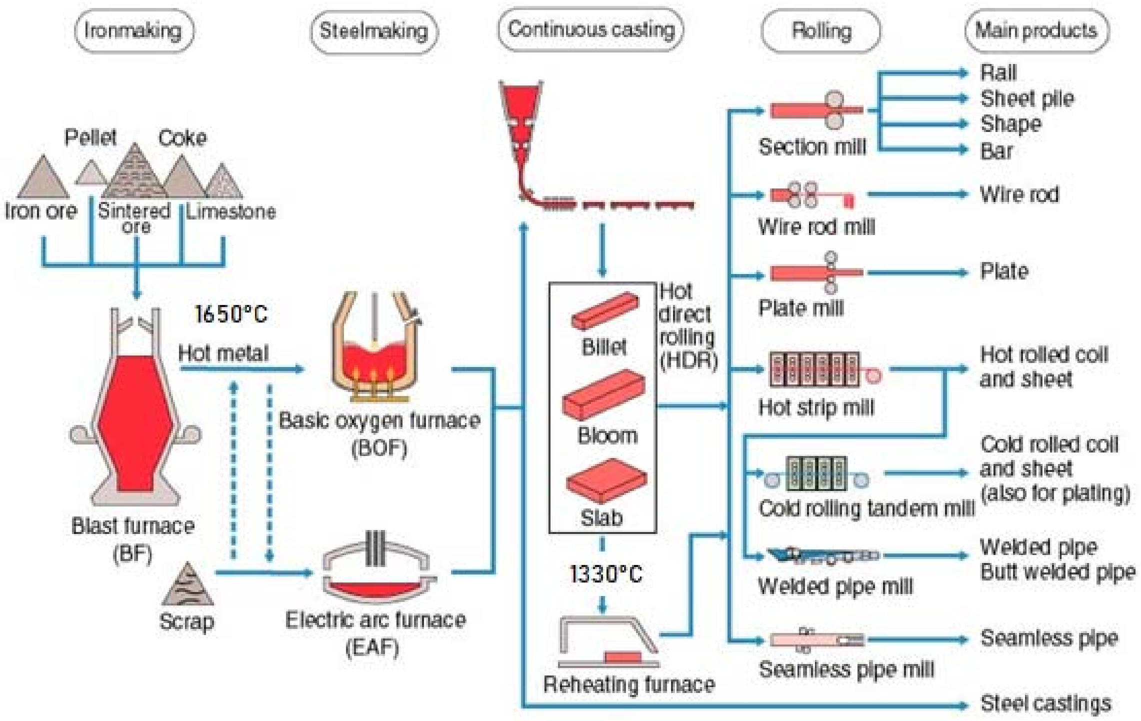

Figure 18. A manufacturing process for Iron and Steel by KAWASAKI STEEL (2003).

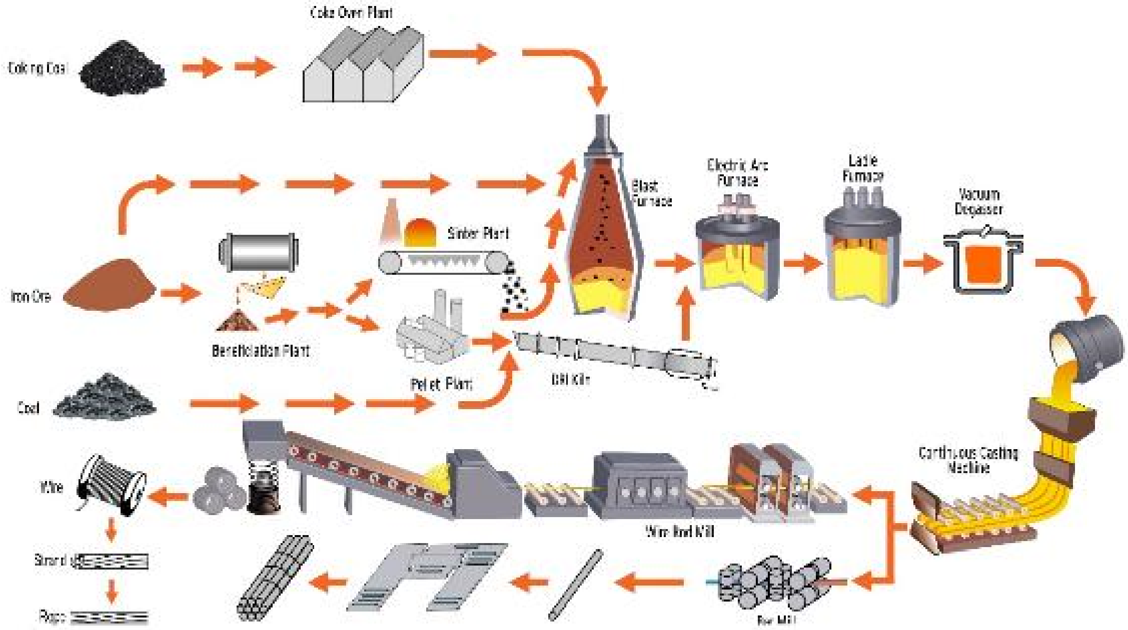

Figure 19. Wire rod process by Usha Martin (2015) *.*

Figure 20. Steel flat product after the rolling process.

Figure 21. Long steel products after the rolling process.

Figure 22. Long steel products in the laying head and cooling bed.

An important market in iron and steel industry in terms of the production market is the manufacturing of train rails (long products). The train rails were made of either cast iron or wrought iron. Cast iron was too brittle and wrought iron was too soft so Steel became and remained the metal of choice for trail rails. Steel is recycled material which can be used from the train rail parts themselves or recycled from food cans and other recycling items. Electromagnets pick up the steel wasted materials and dump it in a bucket truck which transfers the material to the furnace to be heated and melted at 1650°C (Figure 23). To make steel more durable, other metals like carbon and manganese are added in the melted mixture. The alloy then runs through a ceramic tube that shields it from exposure to oxygen which would ruin the metal.

Figure 23. The transfer of the recyclable material to the furnace.

From there the molten metal flows into moulds, which is then extruded into continuous rectangular blocks. Each block is cut into 3.65 m length (Figure 24).

Figure 24. Rectangular blocks formed after the melted metal passed from moulds.

A crane then transfers the blocks into a furnace for reheating. For 5-6 hours blocks are reheated to 1260°C. This allows further shaping. Then the reheated blocks enter a machine calling rolling mill. This elongate each block more than three times its initial length (Figure 25).

Figure 25. The crane transferring the blocks to the reheating furnace and then to the rolling mill for shaping.

Then the long block is cut into 4 pieces which go into another furnace for reheating to prepare them for the next rolling mill which will form them to their final rail shape. T-shape rail is the International Standard (Figure 26).

Figure 26. The long product of steel passing from the rolling mill and the T-shape rollers for its final shape.

For the final shape, each steel rail passes several times through consecutive mills. Then the steel rails are cut into pieces and laid out until they cool at 500°C. Then they sit in a box for 10 hours until they cool to 82°C (Figure 27). When they cool down they pass through two sets of rollers, through the inspection line and finally a saw cuts the rails to whatever size is the order (mainly 25 m).

Figure 27.The laying bed of the hot steel train rails and the final shaping.

Table 8 below shows a list with the most known factories in EU for the production of steel, crude steel, stainless steel and steel casting.

Table 8. List of the most known iron and steel factories in Europe.

Steel plants	Website
Ancofer Waldram	https://www.ancoferwaldram.com/en
Ancon	https://www.ancon.co.uk/
ArcelorMittal	http://m.corporate.arcelormittal.com/
BÖHLER Edelstahl GmbH	https://www.bohler-edelstahl.com/en/
BE Group Oy Ab	http://www.begroup.com/en/BE-Group-Finland/
Bohus	http://web1.bohus.sk/?page_id=125
Brown McFarlane	https://www.brownmac.com/en/
Celsa	http://www.celsa.com/?appIdioma=en
Cogent Power	https://cogent-power.com/
Covis	http://www.covis.it/eng/
CSK Steel	http://www.csk.lv/index.php?id=2&L=2
Diler Holding	http://www.dilerhld.com/default.asp
DSD	https://www.dsd-steel.com/
Euro Mit	http://www.euro-mit-staal.com/cms/
Fiav	https://www.fiav.it/
FOC	http://www.foc.it/en/
Gruppo Lucefin	http://www.lucefin.com/en/
Hi	http://www.hitechsteels.com/
Huta Pokoj SA	https://www.hutapokoj.eu/en
Kind &Co	http://www.kind-co.de/en.html
Levypyora Oy	https://levypyora.fi/en/
Lohmann	http://www.lohmann-stahl.de/1/home/
LTC	http://ltc.it/?lang=en
Megasteel	http://www.megasteel.be/
Metal Goods	http://www.metalgoods.it/en/index.html
Ovako	http://www.ovako.com/
Pipe and Tube Group	https://www.benteler-distribution.com/
Polarputki	https://www.polarputki.fi/en/
Rostfrei Stahl	https://www.rostfrei-stahl.com/en/
SCHMOLZ + BICKENBACH AG	http://www1.schmolz-bickenbach.com/
SeverStal	http://www.severstal.com/eng
Steelgroup	http://steelgroup.com/en/
Terg	http://www.terg.net/
Uddeholm	https://www.uddeholm.com/
UK Steel	https://www.eef.org.uk/

Crude steel	
Salzgitter AG	https://www.salzgitter-ag.com/en/index.html
Spartan UK	https://spartan.metinvestholding.com/en
USS	http://www.usske.sk/en/
Grade steel	
Deutsche Edelstahlwerke GmbH	https://www.dew-stahl.com/en/home/
Erasteel	http://www.erasteel.com/
Outo Kumpu	https://www.outokumpu.com/
Schmidt + Clemens	https://www.schmidt-clemens.com/
Verni Fida S.r.l.	http://www.vernifida.it/index_gb.html
Stainless steel	
Acciai Vender s.r.l	http://www.gruppovender.it/it/acciai-vender/homepage
Acerinox S.A	http://www.acerinox.com/en/index.html
Andus Group	https://www.andusgroup.com/
Core Alloys	http://www.corealloysuk.com/
FaiFtc	http://www.faiftc.it/en
Handtke Wiros	https://www.handtke-wiros.de/about-us.html
Konig	http://www.jc-koenig.de/en/about/partner-and-developer/
Nichelcrom	https://www.nichelcrom.com/en/home/
Outokumpu Steel Company	https://www.outokumpu.com/
Savinox	http://www.savinox.it/
TEC SIM s.r.l.	http://www.tec-sim.com/en/
ThyssenKrupp Acciai Speciali Terni	http://www.acciaiterni.it/en/
Vetchberry Steels	https://www.thyssenkrupp-materials.co.uk/
Voestalpine Edelstahl GmbH	http://www.voestalpine.com/group/en/
Vulkan Inox GmbH	http://www.vulkan-inox.de/
W. Oberste	http://oberste-beulmann.de/en/
William King	http://www.williamking.co.uk/
WS	https://www.werner-schmid.de/en/
Steel casting	
Fonderia Augusta	http://www.fonderia-augusta.com/
I.A.N. Fond Srl	http://www.ianfond.it/index_en.html
LBI	http://www.lbi.fr/spip.php?page=sommaire&lang=en
Nedstaal	https://www.nedstaal.nl/?lang=en
Reiner Brach	http://www.reiner-brach.com/
Slevarna Chomutov, a.s.	http://www.slevarnachomutov.cz/
William Cook	http://www.william-cook.co.uk/

Table 9 below shows the crude steel output of EU in 2017. As can be seen, the major producer is Germany with 26% production from the total EU's crude steel output. In the second and third places with 14.3% and 9.2% is Italy and France.

Table 9.Crude steel output of EU in 2017.

Country	2017 Crude Steel Output ('000 metric tonnes)	% share
Austria	8,135	4.8%
Belgium	7,842	4.6%
Bulgaria	652	0.4%
Croatia	-	0.0%
Czech Republic	4,686	2.8%
Finland	4,003	2.4%
France	15,506	9.2%
Germany	43,910	26.0%
Greece	1,359	0.8%
Hungary	1,901	1.1%
Italy	24,068	14.3%
Luxembourg	2,172	1.3%
Netherlands	6,781	4.0%
Poland	10,289	6.1%
Romania	3,361	2.0%
Slovakia	4,980	2.9%
Slovenia	673	0.4%
Spain	14,434	8.5%
Sweden	4,692	2.8%
United Kingdom	7,492	4.4%
Others	2,056	1.2%
EU28	**168,992**	**100%**

The table below shows the quantity of hot rolled products in EU, by product. 62% of the production is for flat products and 38% for long products as presented by EUROFER (2018).

Table 10. The finished steel production by product in EU 2017.

EU total finished steel production by product	
Products Hot Rolled (2017) ('000 metric tonnes)	**153,857**
Flat products:	**94,809**
Quatro plate	10,953
Hot rolled wide strip	82,073
Other flat products	1,783
Long products:	**59,048**
Wire rod	21,221
Rebars	12,487
Merchant bars	12,930
Heavy sections	9,605
Other long products	2,805

The market share of Europe's flat steel production is shown in the next pie chart (Financial Times, 2018) and in terms of tonnage this is shown in Table 11.

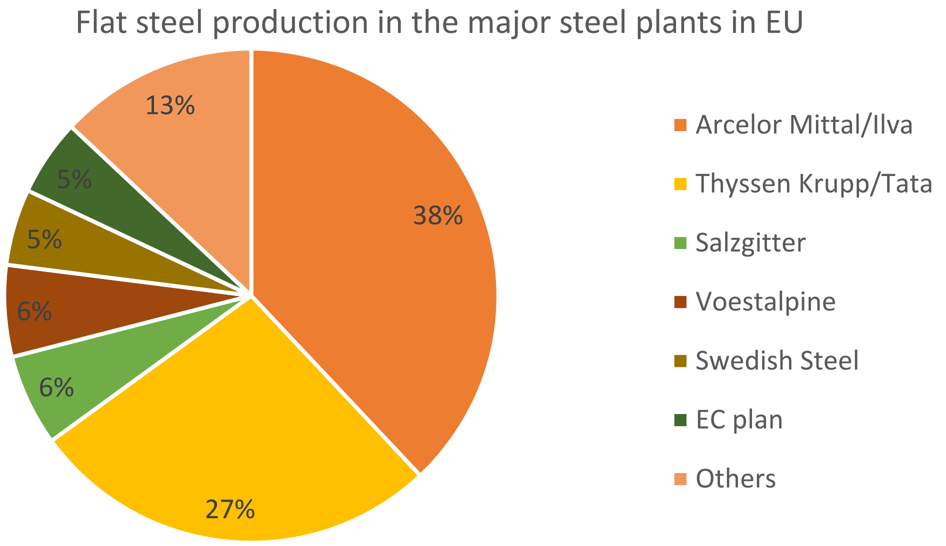

Figure 28. The flat steel production by the largest production companies in EU, 2017.

Table 11. The market of flat steel production in EU 2017.

Flat steel production in the major steel plants in EU	% share	(000's tonnes)
Arcelor Mittal/Ilva	38%	36,027
Thyssen Krupp/Tata	27%	25,598
Salzgitter	6%	5,689
Voestalpine	6%	5,689
Swedish Steel	5%	4,740
EC plan	5%	4,740
Others	13%	12,325
Total	**100%**	**94,809**

The manufacturing process of steel is described earlier in this chapter. Considering now the processes and the market size of the material produced in EU, it is possible to estimate the material that passed through the rolling process or the cooling process or the laying head and cooling beg of the various industrial plants. By knowing the amount of the material passed from these processes where FHP can be used to recover the radiant heat which is lost during these processes, it is possible to estimate the potential of the waste heat which is recoverable.

Flat products as well as long products are formed from the rolling process in different sizes in terms of their cross-sectional area but in specific length depending on the conveyor and the cooling bed. Then, for the formation of the final products, these are cut in specific sizes. Here it is assumed that the products have an average size and from this assumption, the number of products passed from the conveyor and the cooling bed in high temperature are estimated.

Following the radiation heat transfer rate equation below, the theoretical recoverable heat from radiation can be estimated:

$$\dot{Q}_{rad} = \sigma\, A\, ({T_h}^4 - {T_s}^4)$$

Where σ is the Stefan Boltzmann constant (W/m^2K^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, they go through roll strip where they are formed, cut, identifies 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 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 Figure 29.

The following analysis is based on the assumptions below:

- Heat recovery efficiency 75%
- FHP panel surface temperature 100°C
- Product temperature from 1200°C-120°C
- Conveyor width 1.5 m
- Conveyor length 70 m

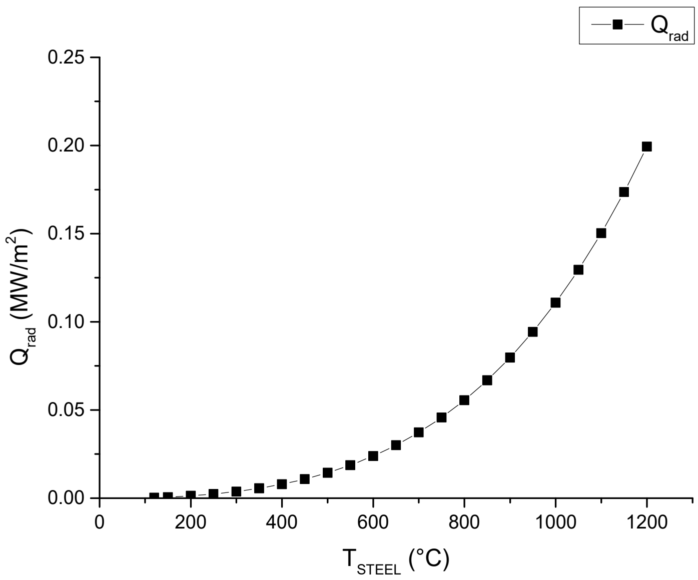

Figure 29. The theoretical radiant heat transfer from the hot slabs in respect to the temperature of the material.

In the case of ArcelorMittal Asturias plant, 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 a prototype. The conveyor length for flat products and long products with open space for FHP to be installed is 60-80 meters. Assuming an average length of 70 m, 1.6 MW of energy can be recovered from each conveyor of length 70 m at the average product temperature from 1200°C - 120°C (Figure 30).

Each plant may have 1-5 lines of conveyors, so the potential heat recovered per plant varies. Avilés steel shop has a length of about 15 m and as there are four 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 two lines, so the potential radiation heat is about 2.2 MW.

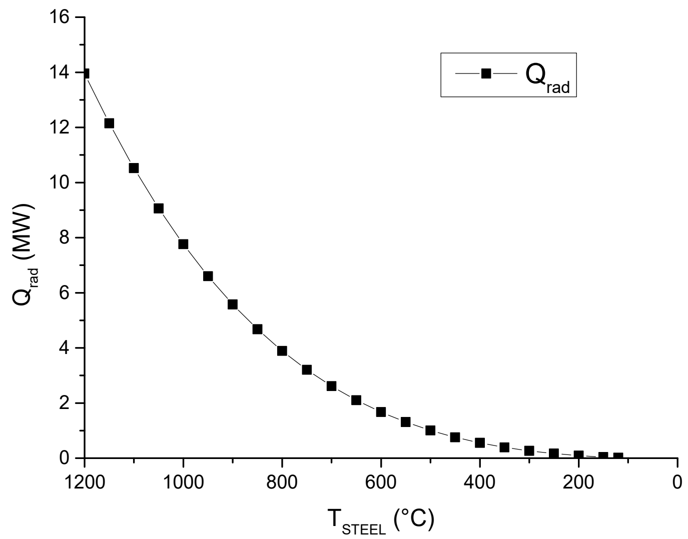

Figure 30. The radiant heat transfer from the hot slabs in respect to the temperature of the material from a conveyor 70 m long.

Knowing that the temperature of the material drops as it moves further from the exit of the rolling mill and assuming the cooling procedure at the conveyor, below an estimation of the technical radiant heat transfer from the hot steel slabs per length of the conveyor and regarding temperature difference between the hot steel and the surface of the FHP panel is shown in Figure 31.

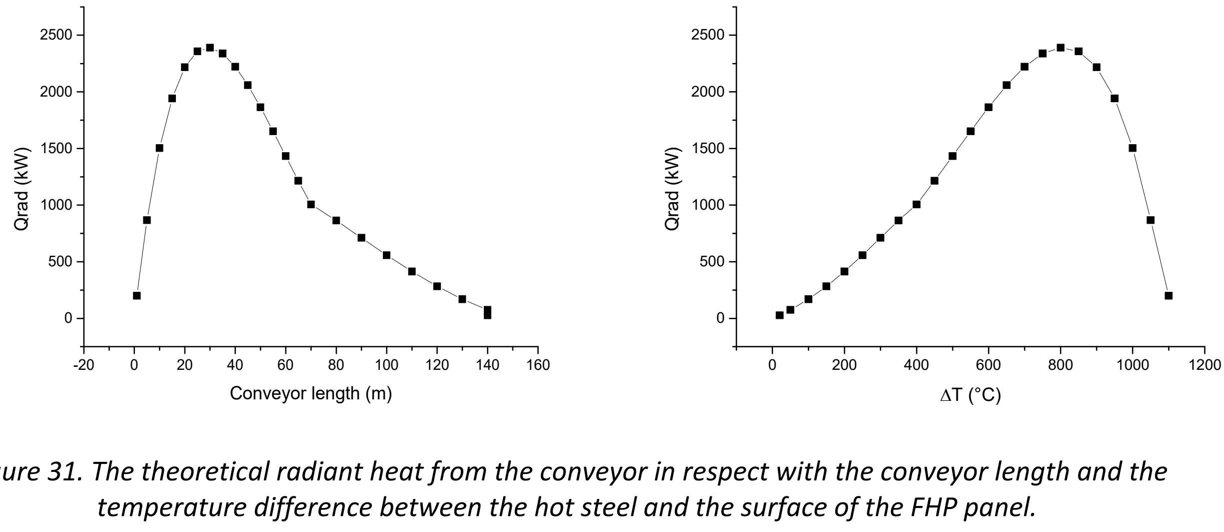

Figure 31. The theoretical radiant heat from the conveyor in respect with the conveyor length and the temperature difference between the hot steel and the surface of the FHP panel.

Using the data presented earlier in Table 9 below the estimated technical amount of recoverable heat potential per country is estimated in *Figure 32* with the following assumptions:

- Each plant may have 1-5 lines of conveyors
- 60% of production is flat products, 40% of production is long products
- Average constant product temperature 660°C
- Heat recovery efficiency 75%
- FHP panel surface temperature 100°C
- Conveyor width 1.5 m
- Conveyor length 70 m

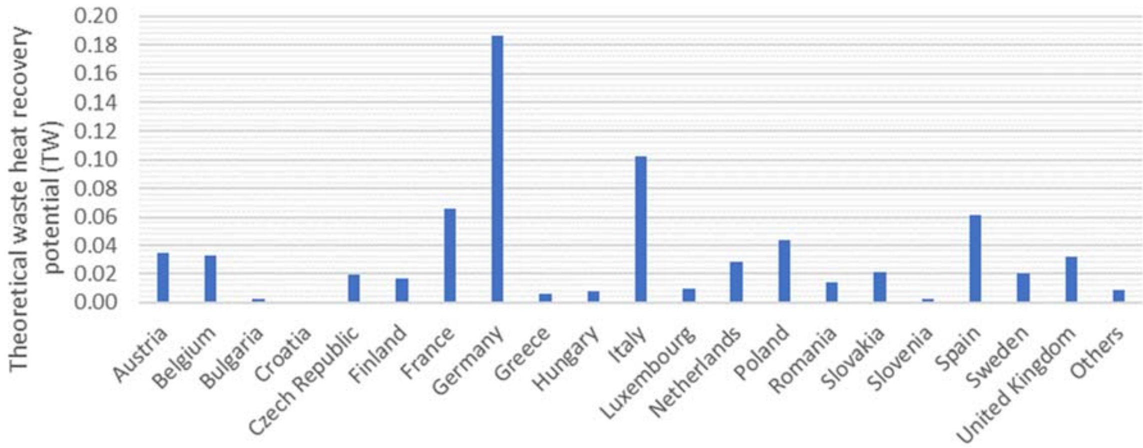

Figure 32. The estimated theoretical WHR of the iron and steel industry by FHP systems, based on the production data from 2017.

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. This requires that all area of the conveyor can be surrounded by FHP panels.

However, this is not the real case since not all the space above the conveyors are open and free for the FHP panels to be installed. Based on the 2017 crude steel production data, and considering that only 10% of this space can be covered by FHP and the waste heat recovery potential is 11.4% as stated earlier in section 5.3, the WHR potential for the iron and steel industry in EU is estimated to be 72 TWh/yr. This is 10.9% higher than the amount estimated in Table 7 and can be explained by the increase of the crude steel production from 2016 and 2017 (World Steel Association, 2018), and the various assumptions made. The estimated WHR for each country is shown in Figure 33, which is fairly comparable with Figure 7.

Considering that 0.596 kg of CO_2 are currently produced for each kilowatt hour 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.

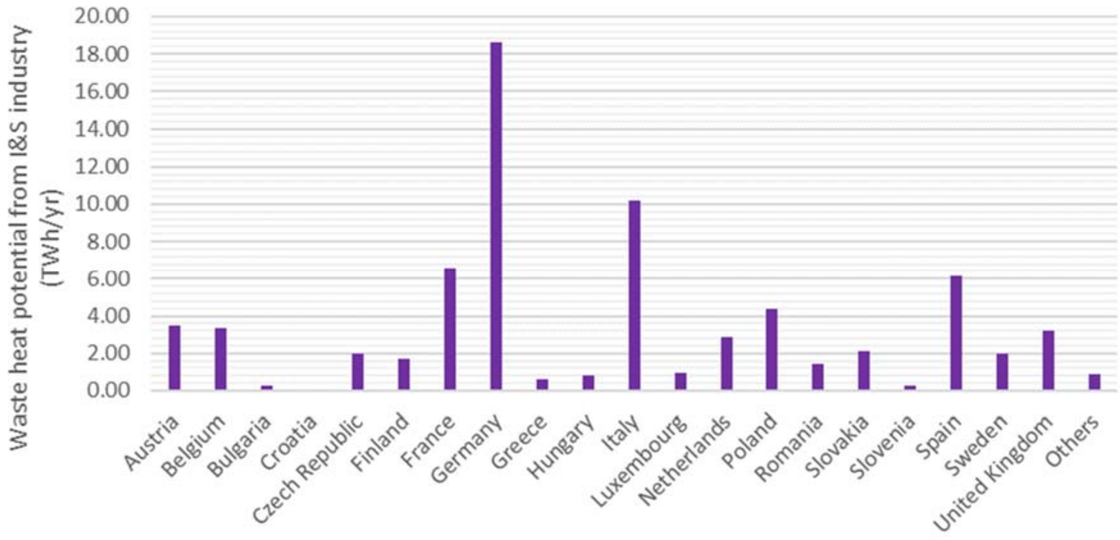

Figure 33. The technical estimated WHR potential from Iron and Steel industry based on 2017 data.

6.2 HPCE

Two solutions exist for recovering the waste heat from boiler flue gases. Conventional economizers preheat boiler make-up or feed water. Condensing economizers recover both latent and sensible heat from the flue gas and are able to raise boiler efficiencies to over 90% (Figure 34).

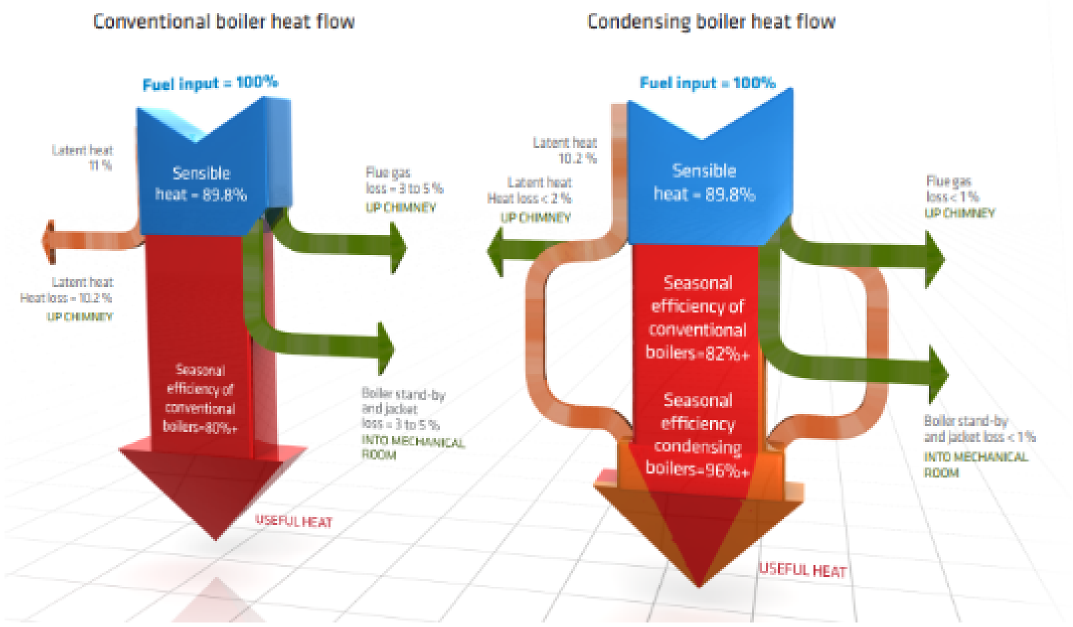

Figure 34.Conventional boiler heat flow vs. condensing boiler heat flow by AIC (2010).

As previously mentioned, boilers equipped with condensing economizers can have an overall efficiency that exceeds 90%. A condensing economizer 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 waste heat recovery.

An indirect contact condensing economizer removes heat from hot flue gases by passing them through one or more shell-and-tube or tubular heat exchangers. This economizer can heat fluids to a temperature of 100°C while achieving exit gas temperatures as low as 25°C. The indirect contact economizer is able to preheat water to a higher outlet or process supply temperature than the direct contact economizer. The condensing economizer must be designed to withstand corrosion from condensed water vapor produced by the combustion of hydrocarbon fuels such as natural gas or light oils. The condensed water vapor is acidic and must be neutralized if it is to be discharged into the sewer system or used as process water.

Another heat recovery option is to use a direct contact condensing economizer, which consists of a vapor-conditioning chamber followed by a counter current spray chamber. In the spray chamber, small droplets of cool liquid come into direct contact with the hot flue gas, providing a non-fouling heat transfer surface. The liquid droplets cool the stack gas, condense and distrain the water vapor. The spray chamber may be equipped with packing to improve contact between the water spray and hot gas. A mist eliminator is required to prevent carryover of small droplets. The direct contact design offers high heat transfer coupled with water recovery capability since heated water can be collected for boiler feed water, space heating, or plant process needs. Recovered water will be acidic and may require treatment prior to use, such as membrane technology, external heat exchangers, or pH control.

Water filtration will also be required for fuel types other than natural gas. The site must have substantial heating requirements for low-temperature process or cold makeup water if a direct contact condensing economizer is to be a viable heat recovery alternative. Because direct contact condensing economizers operate close to atmospheric pressure, altitude and flue gas temperature limit makeup water temperature to 45°C to 60°C.

When considering whether to install a condensing economizer, evaluate changes in system operating parameters. These economizers preheat boiler makeup water and reduce deaerator steam requirements, thereby providing more steam for plant processes. The energy savings potential is decreased if the majority of the deaerator steam is supplied from blowdown heat recovery.

A comparison between condensing heat recovery economizers is shown in Table 12. In case of natural gas is the fuel burned in the boiler, water treatment is required if water of condensation is reused. Special corrosion-resistant materials or coatings may be required on heat exchange surfaces. When light oil is burned, water treatment is required if water of condensation is reused because it is more acidic due to SOx in solution. Special corrosion resistant materials or coatings are required on heat exchange surfaces.

Table 12. Comparison between direct and indirect condensing heat recovery economizers.

Performance Characteristic	Direct Contact	Indirect Contact
Maximum outlet water temperature	60°C	93°C
Minimum flue gas temperature	24°C	24°C
Percent removal of humidity from flue gas	85%	35%
Need for heat exchanger	Depends on Application	No
Recovery of water in flue gas	Yes	Possible

Performance Characteristic	**Direct Contact**	**Indirect Contact**
Footprint per MMBtu/hr of heat recovery	Site specific	Site specific
Permissible fuels burned in boiler - Natural gas - Light oil	 Yes Yes	 Yes Yes

Condensing economizers are constructed from inexpensive, but durable, corrosion-resistant materials. Extensive materials testing has been performed for operation in this service, including for coal combustion. The metallurgy for the tube-side liquid is determined by the liquid chemistry requirements (usually water-based liquid): 304 stainless steel is typical. For gas-side materials, one available technology employs Teflon covered metal tubing and Teflon tube sheets. This technology is often operated across both the acid and water dew points and can accept inlet gas temperatures to 260°C. Typical applications may achieve a cold-end ΔT below 45°C, improve the boiler thermal efficiency by ~ 10 percent, and have a simple payback of 2 to 3 years, based on fuel avoidance. A second technology employs metallic finned tubing, extruded over the water tubing. Aluminium 1000 series fins are preferred, for heat-transfer reasons in natural gas applications, but stainless steel (or other material) fins are used for higher temperatures and/or more corrosive flue gas. This second technology is less expensive and has better heat transfer (per ft^2). Consequently, for the same payback the cold-end approach can be lower, and the water outlet temperature and the boiler efficiency improvement higher. Flue gas condensate from combustion of natural gas typically has a pH of ~ 4.3, and aluminium fins are suitable. For more acidic (or erosive) flue gas conditions, other metallurgy (Incoloy® 825 and Hastelloy®), or a Hersite or equivalent coating, may be used to prevent corrosion damage (Figure 35).

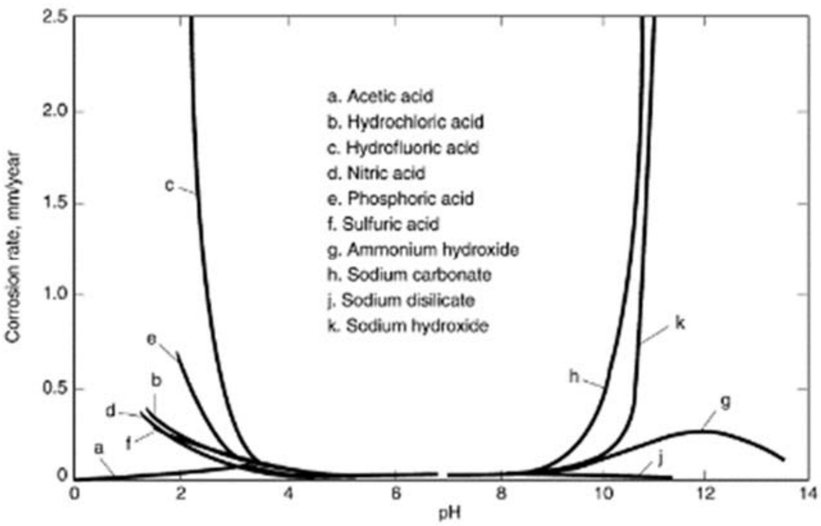

*Figure 35. Effect of corrosion on 110-H14 aluminium alloy by various chemical solutions (*Combustion & Energy Systems Limited, 2007).

Accordingly, the condensing economizer must be designed to withstand corrosion from condensed water vapour produced by the combustion of hydrocarbon fuels such as natural gas or light oils. The condensed water vapour is acidic and must be neutralized if it is to be discharged into the sewer system or used as process water.

The rules for determining the required level of stack protection against corrosion are based on the temperature of the flue gas entering the stack at full load.

- **55°C to 176°C**: At these low temperatures it is recommended that the stack interior be painted or sprayed with a high-solid type non-asphaltic mastic type coating three-sixteenth to a quarter-inch wet thickness. This type of coating will prolong the life of the stack interior from hot sulphuric, hydrochloric, and hydrofluoric acid solutions as well as from vapours present in the flue gas. The application of this mastic is usually made by painters, not by bricklayers. Proper surface preparation includes sand blasting the entire interior stack surface to a near-white condition per code SSPC-SP-10 to ensure that the mastic material will properly adhere.
- **177°C to 204°C**: At these mid-range temperatures, the stack interior does not require an internal coating of mastic protection, but it does require external insulation and lagging to prevent moisture condensation on the outside stack surface.
- **205°C to 454°C:** For gas temperatures in this range, no internal or external protection is required for the prevention of corrosion.
- **455°C and above**: At these elevated temperatures, the internal lining of the stack must be protected with refractory. The refractory material should match the chemistry of the acids within the flue gas. The refractory recipe is usually three parts acid-resistant aggregate and one-part lumnite cement. The refractory is typically pneumatically, or gun applied and is usually 2 inches thick over a reinforcing material such as road-mesh or chicken-wire mesh. The reinforcing mesh is held to the stack interior using stand-offs such as slab spacers, t-slot studs, or studs and nuts.

The I-THERM condensing economizers will be able to be installed in harsh environments since will have high resistance to corrosion and acidic gases. The I-THERM heat pipe condensing economizers (HPCE) have the following design parameters shown in Table 13. Flue gases usually contain SOx, NOx, Cl etc, which upon condensation form corrosive solutions such as H2SO4, HCl etc

Table 13.Thermal design parameters of I-THERM HPCE (Application in Arluy to recover heat from oven exhaust).

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	18.3 kW

However, the condensing economizers proposed in I-THERM project have a major advantage over the conventional condensing economizers and gas boilers. Optimum material coatings and HP fluids are developed for the different temperature ranges as well as approaches to improve primary (exhaust/process) fluid heat transfer coefficient, for the different temperature ranges.

This is the special formed coating of the economizer so as to allow its usage in harsh environments with corrosive exhaust gases. This will eliminate the maintenance requirements for the systems and can increase the prospect of the installation of more condensing economizers for heat recovery (see deliverable 7.3)

As previously mentioned, flue gases usually contain SOx, NOx, Cl etc. These are usually released from various processes of the following industries:

- Iron and steel production (sinter process, palletisation plants, blast furnace, Basic oxygen steelmaking, cake oven plants etc, 900-1350°C)
- Large volume inorganic chemicals (tank furnace process, 430-650° C)
- Glass production (heating furnaces, primary melting, 750-1650°C)
- Production of cement, lime (kiln firing and clinker burning, 1400-2000°C)
- Production of polymers (thermal treatment of water)
- Ferrous metals processing (hot rolling mill, 1050-1300°C)
- Pulp, paper and board production (90-800°C)
- Surface treatment using organic solvents (printing, abrasives, coil coating, 100-700°C)
- Waste incineration (pyrolysis, gasification, 100-700°C)

Temperature range for HPCE by I-THERM is 70-500°C which applies to low to medium temperatures. 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
- Glass

The condensing economizer improves waste heat recovery by cooling the flue gas below its dew point, which is about 60°C for products of combustion of natural gas. The economizer reclaims both sensible heat from the flue gas and latent heat by condensing flue gas water vapour (see Table 14). All hydrocarbon fuels release significant quantities of water vapor as a combustion by product.

Table 14. Boiler Efficiency of Condensing Economizers from U.S. Department of Energy (2012a).

System	**Combustion efficiency at 4% excess O^2 (%)**	**Stack Gas Temperature °C**
Boiler	78-83%	180-290°
- With Feed water Economizer	84-86%	120-150°
- With Feed water and Condensing Economizer	92-95%	25-65°

The available heat in a boiler's exhaust gases is dependent upon the hydrogen content of the fuel, the fuel firing rate, the percent of excess oxygen in the flue gases, and the stack gas temperature.

Consider a natural gas-fired boiler that produces 45359.237 kg/h (100000 lb/hr) of 100-psig saturated steam. At 83% efficiency, the boiler firing rate is about 116 MMBtu/ hr. At its full firing rate, the boiler consumes over 4860 lb of natural gas each hour while exhausting 10938 lb of high temperature water vapor each hour. The water vapor in the flue gas contains over 10.6 MMBtu/hr of latent heat. As shown in Table 15, the total heat actually available for recovery is strongly dependent upon the stack gas temperature at the condensing economizer outlet.

*Table 15. Exhaust gas energy available from a 100000 lb/hr Natural gas fired steam boiler (MMBtu/hr) (*U.S. Department of Energy, 2012).

Flue gas temperature leaving condensing economizer	**25°C**	**35°C**	**50°C**	**65°C**
Sensible heat	6.46	5.75	5.03	4.31
Latent heat	9.51	7.00	2.01	0.0
Total available	15.97	12.75	7.04	4.31

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

$$Q = V \cdot \rho \cdot \Delta h$$

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).

Chart below (Figure 36) from AIC (2010) shows the energy recovery from cooling flue gas for different hot water temperature entering the economizer.

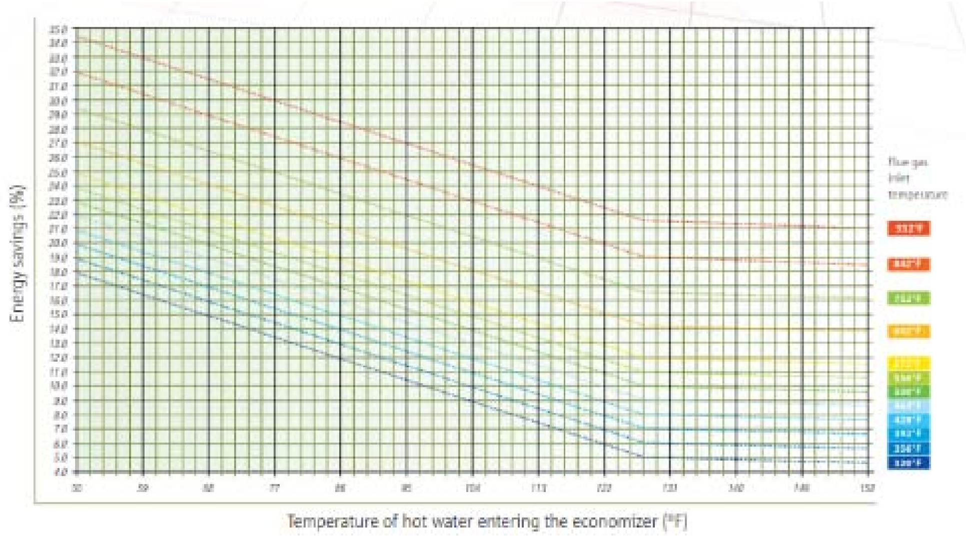

Figure 36. Energy recovery from cooling flue gas for different hot water temperature entering the economizer (AIC, 2010).

Table below shows various manufacturers of economizers in EU.

Table 16. Economizers manufacturers in EU.

Manufacturer	**Country**	**Website**	**Products**
ATTSU TERMICA S.L.	Spain	https://www.attsu.com/en	Heat recovery economizer for boilers
Cass Technava Ltd.	Cyprus	http://www.cass-technava-cy.com/	Boiler economizer
Univer Group	Italy	http://www.univer-group.com/en/	Economizer
ACTE	Belgium	http://www.acte-sa.be/en/solutions-heat-recovery-belgium.html	Heat recovery economizer for boilers

According to Schweitzer (2017), sixty million gas boilers are installed in the EU and represent one of the major space heating technologies. Studies have shown that once users are confronted with a situation where they need to replace their boilers, the majority of them would prefer to invest in a gas boiler again.

The EU market of gas boilers is dominated by "individual wet systems" (using water to transfer heat from the boiler to the space to be heated), which are mainly gas, fuel oil and solid fuel boilers. The rest of the market is district heating (about 10%), collective heating (about 15%) and other systems (mostly individual heaters). There are more than 60 million gas boilers in the EU. Today, the market is mainly for the replacement of existing appliances rather than for new installations.

6.3 TFC

The proposed TFC systems can be compared with the conventional ORC units installed in medium temperature (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 (Paanu and Niemi, 2012). 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 medium temperatures is discussed below.

The I-ThERM contribution is on the optimization of turbine steam expanders already developed by Spirax for low capacity steam power systems to operate efficiently at low heat source temperatures of about 70°C. Another important development beyond the state-of-the art is the thermally driven compression system that will replace the pump in the TFC cycle. This will reduce the parasitic losses of the cycle and will improve overall thermal efficiency. Thus, the proposed TFC units can replace the conventional ORC units working with medium temperature gases.

The conventional ORC units are used in low grade temperature processes (<230^{o}C), in order to convert heat resources, such as solar energy, geothermal energy, biomass, surface seawater and waste heat from a range of thermal processes, into power. Applications include binary geothermal power plants, solar thermal power systems, Solar pond power systems, Solar ORC-RO desalination systems, Duplex-Rankine cooling system,°Cean thermal energy conversion systems and waste heat recovery applications such as power plants, manufacturing processes, cooling of technical equipment, automotive industry, maritime transportations and others (Tchanche et al., 2011).

According to Quoilin et al. (2013) the three main manufacturers of ORC units are Turboden, ORMAT and Maxxtec, based on their references. Table 17 shows the Waste heat recovery units (ORC) installed and are currently under construction within the EU given by Turboden (2018).

Table 17: Turboden - Waste heat recovery units installed and under construction within the EU and the world (reproduced) Turboden (2018).

POWER (MWe)	LOCATION	CUSTOMER	STATUS	Industry*	Temp. range
7	Turkey	CTP Team S.r.l. (Italy) e CTN Makina Mühendislik Insaat Celik Konstrüksiyon Otomasyon (Turkey)	under construction	Air & Gas cleaning equipment (Italy) & Industrial machines manufacturing (Turkey)	
6.2	Turkey	Çalbıyık Grup / Düzcecam	under construction	Cement, Iron & steel	
5	Slovakia	CRH	in operation	Cement	
4	Italy	Ricciarelli S.p.A.	in operation	Packaging & industrial machinery	25 – 40 °C
4	Romania	Holcim SA (LafargeHolcim Group)	in operation	Cement	

POWER (MWe)	LOCATION	CUSTOMER	STATUS	Industry*	Temp. range
3.8	Romania	S.C. Carpatcement Holding S.A. (HeidelbergCement Group)	in operation	Cement	
2.7	Germany	ESF Elbe Stahlwerke Feralpi GmbH	in operation	Steel	26–44 °C
2.5	Japan	Mitsubishi Heavy Industries / Aichi Steel	under construction	Steel	
2.3	Switzerland	Jura-Cement-Fabriken AG (CRH Group)	in operation	Cement	
2.2	Italy	ORI Martin S.p.A.	in operation	Steel	32 – 42 °C
2	Italy	Industria Cementi Giovanni Rossi	under construction	Cement	
2	Morocco	Ciments Du Maroc (HeidelbergCement Group)	in operation	Cement	
10	Italy	Arvedi S.p.A.	in operation	Flat roll steel	29 – 37 °C
1.9	Malaysia	Invest Energy	under construction		
1.8	Italy	Ricciarelli S.p.A.	in operation	Packaging & industrial machinery	
1.7	Germany	undisclosed	under construction		
1.3	Switzerland	Cadcime SA / Holcim Suisse Eclepens – LafargeHolcim group	under construction	Cement	
1.3	Italy	AGC	in operation	Glass	25 - 35 °C
1.2	India	GEA Bischoff GmbH / Saint-Gobain India Pvt.Ltd. - Chennai	under construction	Glass	
1.2	Italy	GEA Process Engineering S.p.A.	under construction	Energy recovery	
1	Italy	Ricciarelli S.p.A.	in operation	Packaging & industrial machinery	
0.8	Austria	Veitsch-Radex GmbH & Co	in operation	Cement, Glass, Steel	
0.7	Italy	Fonderia di Torbole	in operation	Iron coasting	
0.7	Belgium	BiogasTech NV	under construction	Biogas	
0.7	Germany	AGO AG Energie+Anlagen	in operation	Power supply systems	
0.7	Singapore	NatSteel Holdings Pte Ltd	in operation	Steel	
0.7	Italy	Alma CIS/Fater (P&G Group)	in operation	methane networks and systems,	25 - 35 °C
0.6	Germany	Stadtwerke Kempen	in operation		
0.5	Italy	BDF Industries	in operation	Glass, Automation, Energy	
0.5	Italy	Termoindustriale S.p.A.	in operation		

POWER (MWe)	LOCATION	CUSTOMER	STATUS	Industry*	Temp. range
0.5	PORTOGRUARO, ITALY	Cereal Docks	in operation		24 - 34 °C

*based on the information from each company's website

ORMAT's ORC units across the EU are shown in Table 18.

Table 18. ORMAT's ORC units across EU by ORMAT (2018)*.*

Owner	Power (MW)	Location	Industry
Noa (Huelva)	5	Spain	Gas
Almendralejo	3	Italy	Glass
Heidelberg Cement Group	2	Germany	Cement
Soglliano Ambiente	1	Italy	Waste management

Another report from the European Biogas Association lists the leading manufacturers of biogas within the EU, from which 8 of them install ORC systems European Biogass Association (2013). From those manufacturers only one has published references for the installed plants. ORC installed units from this manufacturer are shown in Table 19.

Table 19: ElecrtraTherm ORC units in EU ElectraTherm (2018).

Owner	Location	Year of Installation	Industry
ESCO POND SRL	Italy, Ponderano	2012	Textfile
Ruhe Agrar GmbH	Germany, Hunteburg	2012	Sustainable agriculture, biogas, district heating
etatherm GmbH	Germany, Trechwitz	2012	ORC manufacturing
Güntner GmbH & Co. KG	Germany, Trechwitz	2012	Industrial refrigeration and air-conditioning
WTI wärmetechnische Industrieanlagen GmbH	Austria	N/A	

Table 20 shows the number of ORC units in EU as stated by Tartière and Astolfi (2017).

Table 20: Non-exhaustive list of ORC units installed in EU.

Manufacturer	# ORC units in EU
Adoratec	22
BEP – E-rational	25
Electratherm	5
Enerbasque	1
Enertime	8
Enogia	11 in biogas

Manufacturer	**# ORC units in EU**
Exergy	9
GMK	29
Orcan	8
ORMAT	4
Rank	14
Triogen	37
Turboden	31
Zuccato Energia	20

The global ORC market was overviewed by Tartière and Astolfi. Tartière and Astolfi (2017). Figure 37 shows the different types of industries as well as the share among ORC installed units. As can be seen, the main types of industries (not applications), based on the amount of share, are Gas Turbines (probably electric power generation), Glass, Metals, Cement & Lime.

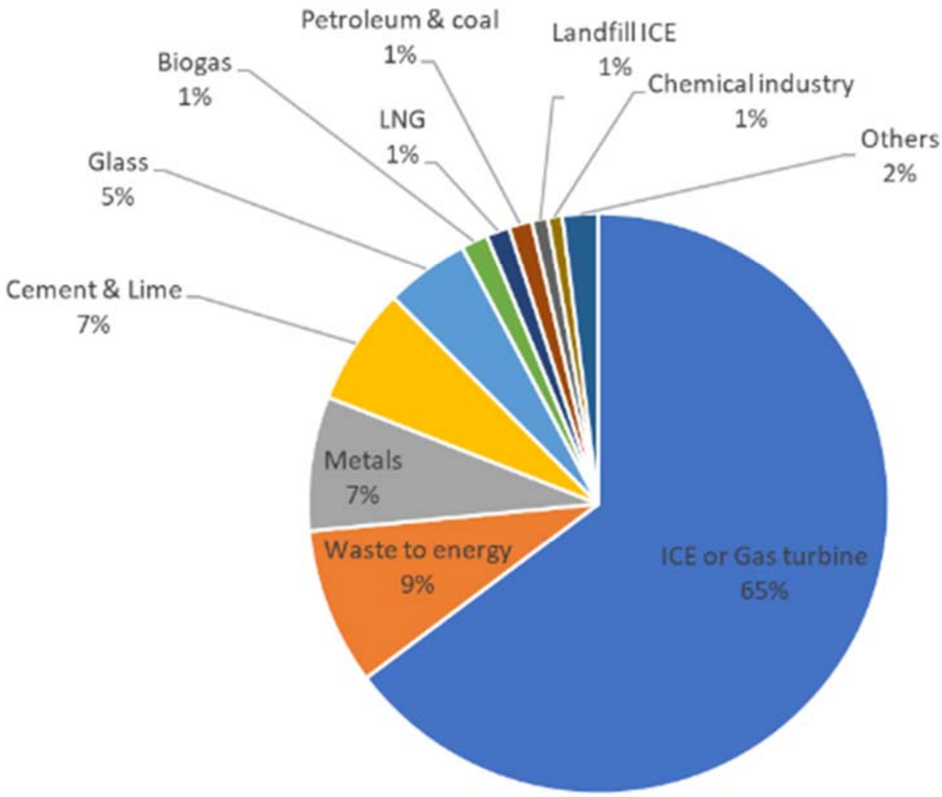

Figure 37. Shares of installed capacity per heat recovery application Tartière and Astolfi (2017).

Table below shows a list of small scale ORC system producers with the respective temperature of the heat source.

Table 21: Non-exhaustive list of small-scale ORC system producers by Tocci et al. (2017).

Company Name	Country	Power (kW)	Expander Type	Heat source T (°C)	Notes
Exergy	IT	100–240,000	Radial	-	Commercial
Enogia	FR	10–20–40–100	Radial	90–160–400	Commercial, turbine coupled with high speed generator
Rainbow	FR	100	Axial	-	Expander 12–15 krpm, efficiency > 80%
Zuccato Energia	IT	30–40–50	Radial	Water T > 94	Commercial, synchronous generator 15 krpm, ceramic bearings
Termo 2 Power	PL	<300	Rotary lobe	-	Prototype, 1.5–3 krpm, self-exciting synchronous generator
Mattei	IT	3	Vane	80–150	-
Rank	SP	50–100	Radial	85–140	2–5 years payback period
EXA	IT	15–150	Piston/screw	70–350	Fluids R 134, R 245fa, Toluene, Induction generator
NewComen	IT	3–120	-	-	-
ConPower	GER	13–75	-	-	Prototype
ZE	UK	95–130	Multi stage radial	-	Permanent magnet generator
ICENOVA	IT	10–30	Eneftech scroll	150	R 245fa, Regenerated cycle
Climeon	SWE	150	Turbine	70–120	-
Exoes	FR	15	Piston swashplate	-	Transport applications
E-rational	BEL	<500	Single screw	105–150	Asynchronous generator

Peris et al. (2015) presents the temperature range of the industrial gases of low to medium temperatures 70°C – 200°C in the table below.

Table 22: Temperatures of industrial gases for low to medium grade (70 – 200°C) ORC by Peris et al. (2015).

Industry	Process	T (°C)
Steel	Coke oven stack gas	190
Glass	Container glass melting Flat glass Fiberglass melting	160–200 /140–160 160–200/300–500 140–160
Food	Flyers Exhaust gases	120–212 164

Tables below show the number of plants installed in the EU for the main industries that use ORC as the main waste heat recovery method. Those industries are Glass (Table 23), Cement (Table 24) and Steel as one may see in the above findings.

Table 23: EU27 flat glass plant distribution and production by Campana et al. (2013).

Country	No. of plants	Product (10^3 t/yr)
Germany	11	1425
France	7	907
Italy	7	98
Belgium	7	907
UK	5	645
Spain	5	645
Poland	3	390
Portugal	1	127
Other	9	1545
Total	**58**	**7500**

Table 24: Cement plants in EU CN cement (2017).

Country	No. of plants
Austria	11
Belgium	9
Croatia	5
Cyprus	3
Czech Republic	6
Denmark	2
Estonia	1
Finland	3
France	48
Germany	50
Greece	8
Hungary	3
Ireland	6
Italy	70
Latvia	1
Lithuania	1
Luxembourg	2
Malta	0
Netherlands	4
Poland	15
Portugal	8
Romania	9
Slovakia	5
Spain	44
Sweden	3
United Kingdom	18
Total	**335**

6.4 sCO_2

The intention in this project is to develop and demonstrate a small modular supercritical sCO_2 power system that can be easily employed for a variety of HT heat recovery to power conversion applications.

The sCO_2 cycle is proposed in this project because of its size, 10 to 100 times smaller than Rankine, its efficiency that exceeds 30% and because of the nice properties of the working fluid, CO_2. It is non-flammable, nontoxic and has a global warming potential of 1.

Likewise, in the TFC systems, the sCO_2 units can be compared with the conventional ORC units installed in high temperature (200°C – 500°C) processes in the industrial sector.

There is no way to estimate the number of sCO_2 units to be installed in EU or the amount of energy that could be recovered by the use of the proposed units, but 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 high temperatures is discussed below.

According to Tartière and Astolfi (2017), 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 plant 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 waste heat recovery applications with products ranging from 10 to 150 kW_{el}. 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. As shown in Table 25 below, the industries with most ORC plants are the Glass, Cement, Steel and Oil & Gas.

Table 25. HREII DEMO Observatory (2013)

Processes	Heat source Temp. (°C)	Industrial Plants	ORC Power estimated (MW)
Flat glass	500	58	79
Cement – Clinker production	350	241	574
Steel from EAF	250	190	438
Steel from rolling mills	400	209	310
Oil & Gass	-	500	1155
Total			**2556**

Another study on the industrial processes and exhaust gases temperature presented by Peris et al. (2015). Previously in Table *22*, the industrial processes with temperature up to 200°C were presented but considering now the installation of sCO_2 systems, the ORC systems for higher temperature are being discussed. Thus Table 26 below shows the industrial processes and relevant gasses temperatures.

Table 26. The temperature of industrial gases from 200-500°C by Peris et al. (2015).

Industry	**Process**	**T (°C)**
Cement	Kiln exhaust gases Kiln cooling gas	200-350/300-450 200-300
Steel	Electric arc furnaces (EAC) Rolling mills Blast furnace stoves Finishing soaking pit	250 300-450 250-300 200-600/300-400
Glass	Flat glass melting	300-500
Chemical	Processing furnaces exhaust Boiler exhaust Refinery gases Gas turbines	340 230 150-300 370-540
Ceramic	Kiln gases	200-300

Cement industry

There are 259 cement plants in EU with 389 kilns with overall capacity of 247.8 million of metric tonnes (Table 27). 11 of these plants have wet process where ORC is not convenient to be installed and for other 19 plants there is no information on the technology used. Thus 229 plants have the potential to install ORC systems in EU or they already have.

Table 27. EU cement plants location and capacity, by Campana et al. (2013).

Country	**No. of plants**	**Nominal Capacity (Mt/year)**
Spain	38	48.3
Italy	59	38.6
Germany	33	28.8
France	31	21.6
Greece	8	14.5
Poland	11	14.0
Portugal	6	10.8
UK	12	10.4
Others	61	60.8
Total EU	**259**	**247.8**

Campana et al. (2013) estimated the potential ORC power for the EU for cement factories after 21 energy audits as shown in Table 28. It is estimated that 576 MW of ORC power can be installed in EU cement industry with 1,940,000 tons of CO_2 savings per year and energy recovery of 4592 GWh/year.

Table 28.ORC power estimate for EU cement factories by Campana et al. (2013).

Country	Daily capacity (10^3 t/day)	P_{ORC} (MW)
Italy	111.7	86.7
Germany	69.8	70.3
Spain	116.5	117.3
France	49.6	49.9
UK	25.1	25.3
Belgium	10.7	10.7
Austria	10.4	10.5
Czech Republic	12.7	12.8
Others	189.3	192.5
Total EU	**595.9**	**575.9**

Steel industry

As can be seen in Table 29, in the steel industry, there are 190 EAF with capacity of 101.7 Mt/year and 11 of them are idle, and a total of 362 rolling mills exist in EU steel industry with capacity 252 Mt/year.

Table 29. Number of EAF and rolling mills in EU steel industry by Campana et al. (2013).

Country	No. of EAF	No. of rolling mills
Italy	40	63
Spain	29	42
Germany	27	52
France	20	38
UK	8	31
Poland	9	19
Belgium	7	9
Romania	6	12
Greece	5	6
Czech Republic	9	12
Others	30	78
Total	**190**	**362**

After the energy audit carried out by Campana et al. (2013), the installable ORC gross power in EU's EAFs and rolling mills are presented in Table 30.

Table 30. ORC gross power potential for the EU steel industries by Campana et al. (2013).

Country	ORC Power in EAF (MW)	ORC Power in rolling mills (MW)	Total ORC power in EU steel industry
Italy	92.9	21.7	114.6
Spain	74.0	82.2	156.2
Germany	85.8	25.6	111.3
France	43.1	30.1	73.2
UK	27.7	19.7	47.4
Belgium	25.7	28.7	54.5
Austria	4.2	12.2	16.5
Czech Republic	0.8	9.2	10.0
Others	83.3	81.0	164.3
Total	**437.5**	**310.5**	**748.0**

It is estimated that the installation of ORC units estimated above will result in 5984 GWh/year energy recovery and emissions savings of 2,162,000 tons of CO_2 per year.

Glass industry

Regarding the glass plants in EU, there are 58 flat glass plants in EU with production of 7,500,000 tones of glass every year (Table 31). From the analysis of Campana et al. (2013), it is concluded that 58 plants of ORC can be installed with total power of 78.5 MW.

Table 31.EU flat glass plants distribution and production by Campana et al. (2013).

Country	No. of plants	Product (10^3 t/year)
Germany	11	1425
France	7	907
Italy	7	908
Belgium	7	907
UK	5	645
Spain	5	645
Poland	3	390
Portugal	1	127
Other	9	1545
Total	**58**	**7500**

7 Conclusions

This deliverable presents a research work based on waste heat recovery technologies. In the first part of the report, the conventional WHR technologies are described and then the proposed WHR systems are presented. The proposed I-ThERM systems have better performance than the conventional systems and thus less emissions.

Later on this report, an analysis of the energy consumption of the industrial sector of the EU28 is presented together with a preliminary assessment of the waste heat potential. The breakdown of the energy consumption for 13 industrial sectors is estimated to be 3217.85 TWh in 2016. From an extensive analysis carried out to identify the various thermal processes of the different industrial sectors, a table is presented summarizing the processes together with the temperature range of their exhaust gases and the temperature range classification according to the WHR classifications.

After the preliminary assessment, the potential market of the most intensive industrial sectors is identified. For the FHP, iron and steel is the biggest potential market while for the CE the potential market is the whole market with condensing boilers or exhaust gases either acidic or not. Regarding HPCE, potentially they can be used in the Cement industry, large Volume Inorganic Chemicals, Food, Drink and Milk Industry, chemicals & plastics and glass. For the TFC and sCO_2 systems, there is a big market which currently is served by the ORC units.

The waste heat potential in the EU has been estimated to be 300–350 TWh/year. This is an important amount of energy saving compared to the 3217.85 TWh energy consumption of 2016, and CO_2 emissions saving as well.

The potential market of the proposed technologies is discussed in terms of the market of the conventional technologies which can be replaced by the proposed ones. The TFC and sCO_2 systems are compared with the ORC market while the HPCE market is compared to the gas boilers market. For the FHP system, there is no related conventional system to compare the size of the market, so the analysis to identify the size of the market 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 is extracted that 72 TWh/yr of waste radiant heat can be potentially recovered from the iron and steel industry which corresponds to 42.5 million tonnes of CO_2 which can be saved if the requested energy is covered by the recoverable energy.

Regarding the cost of the WHR technologies proposed in I-ThERM, it is expected to have 25% extra cost over the conventional technologies but significant improved performance due to higher efficiency. Subsequently, the payback period will be less and return on investment will be better than the conventional technologies.

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