Project Title: **Industrial Thermal Energy Recovery conversion and Management**

Project Acronym: **I-ThERM**

Grant Agreement No: **680599**

D2.4 Report on barriers to the adoption of heat recovery technologies and recommendations on how to overcome them

Deliverable	Cyprus University of Technology (CUT)
Contributors Paul Christodoulides (CUT), Georgios Florides (CUT), Gregoris Panayiotou (CUT), Lazaros Aresti (CUT), Soteris Kalogirou (CUT), Elisavet Theophanous (CUT), Giuseppe Bianchi (UBRUN),	

Dissemination Level		
PU	Public, fully open, e.g. web	**x**
CO	Confidential, restricted under conditions set out in Grant Agreement	

Version Control		
1	*Version 1*	*09/04/2019*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 680599

DISCLAIMER

Contents

1. Introduction

The wide adoption of heat recovery technologies in industry is hindered by specific "barriers" related to both technical and non-technical issues. An attempt is made in this report to determine these barriers and make recommendations on how to address them. Firstly, a literature review of related material is presented. Then, based on the review and discussions with people from the I-ThERM consortium as well as personnel of companies in related industry sectors in the EU28, a structured questionnaire on barriers to the adoption of heat recovery technologies was prepared (see Appendix). Major barriers have been identified as: (i) lack of information, (ii) lack of technology knowledge, (iii) technology risks, (iv) high initial and running and maintenance costs, (v) lack of financial support and lack of governmental incentives, (vi) size and available space limitations, (vii) lack of available infrastructure, (viii) production constraints and risk of production disruptions, (x) risk of the system negative impact on the company operations, (xi) policy and regulations restrictions.

The questionnaire was issued to a number of industries across the EU28. In Section 3 an analysis of the questionnaire is performed, where an assessment of the importance and negative impact of each of the above-mentioned barriers is shown. Based on the above, strategies and recommendations on how to overcome the barriers is reported. These recommendations are hoped to be adopted as far as possible in the packaging, installation, commissioning and demonstration of the technologies in the project. The final outcomes will be used as case study material that will be made widely available through publications and the project's website.

2. Literature review

Waste Heat Recovery areas can be classified within four main groups, as described by Crook [1]: (i) Energy recycling within the process, (ii) waste heat recovery for other on-site processes, (iii) electricity generation with combined heat and power installations, and (iv) district heating systems. Every area of such waste heat recovery systems come with concomitant barriers. To take advantage of the waste heat and recover it in any of the above-mentioned forms could be beneficial for the industrial plant, but it is not really a main factor concerning the manufacturing industries.

Waste heat recovery potentials and design optimal reuse options across plants in industrial zones have been presented by Stijepovic and Linke [2]. The authors have used a systematic approach for targeting optimization to achieve maximum waste heat recovery for the industrial zone. Then the authors presented a design optimization with a case study considering economic objectives. The industrial waste heat recovery potential of all EU countries has been discussed in other Reports (deliverables) of I-ThERM as well as by Panayiotou *et al.* [3], but also presented and 'mapped' by Miro *et al.* [4] and Forman *et al.* [5] for a more global implementation.

The iron and steel sector can be identified as the largest user of heat and exhibits the highest potential for recovery of Low Grade Heat (LGH). The chemical, food and drink, pulp and paper, cement, glass, aluminum and ceramics sectors are also significant heat users (McKenna [6]). Waste heat temperatures can be categorized as low (usually <100^{o}C), medium (usually 100–600 ^{o}C) and high (usually >600^{o}C). Further information on temperature ranges of processes and waste heat potential in different types of industries are presented by Panayiotou *et al.* [3].

The limitation and barriers can be defined into different categories and DECC [7] have identified the barriers as (i) commercial, (ii) delivery and (iii) technical. Another document by BCS Incorporated [8] has introduced and presented key barriers listed under different limitations such as (i) costs, (ii) heat stream composition, temperature, process and application specific constraints, and (iii) inaccessibility / transportability of certain heat sources.

Long payback periods and material constrains are the key limitations regarding the cost barrier [9]. Regarding the application use, the materials required defer and in some cases, as stated by the authors, "the overall material costs per unit energy unit recovered increases as larger surface areas are required for more efficient lower temperature heat recover systems." Following on, the scale of the heat recovery system favors the larger systems, with the authors specifying this category as 'the economies of scale'. High operation and maintenance costs are required depending on the system scale that includes corrosion and fouling. The financial constraint – as in every technology – being the most common obstacle, it does not differentiate in the case of waste heat recovery, as mentioned by Brueckner *et al.* [10].

The most important restriction of the systems is the temperature of the heat stream. Industrial facilities with low temperature do not require an on-site use and technologies involving low-temperature power generation are very costly and less developed. During the low temperature streams, an extensive corrosion and fouling is observed due to the fact that the liquid and solid components condense as hot streams cool in the recovery equipment [8]. At higher temperatures, materials that are able to withstand the high temperature of the heat stream have a higher cost, raising the overall system cost and, hence, extending the payback period of the system. It is observed though that, in practice, inexpensive materials are used and therefore the outside air temperature reduces the temperature of the heat stream affecting the efficiency and the available energy to be used in the system. The energy available is also connected to the heat transfer rate where a temperature difference between the heat source and the heat sink affects the performance and hence a larger surface area is required.

Heat stream composition has also an effect in the cost of the recovery system, as streams with high chemical activity require costly equipment materials to avoid corrosion. Chemical composition also affects the heat transfer rates, environmental concerns and product/process control. The last barrier category on the recovery system, discussed by the BCS Inc. Group, is the inaccessibility, transportability and limited space [8].

The identification of the barriers can be achieved either by using surveys, interviews and practical assessments, by reviews and theoretical frameworks, or both. The current task focuses on both the survey and the theoretical framework in order to identify the barriers of the waste heat recovery systems addressed in the EU28.

Rhodin and Thollander [11] have presented the energy efficiency of the Swedish manufacturing industry stating that barriers are depended on regional and sector specific and should not be generalized. The industry companies involved have all noted that ‘production-related issues have higher priority than energy efficiency and the cost of production disruptions was a barrier to energy efficiency’.

Sardianou [12] has also conducted a survey research involving 800 Greek industries and the most important barrier identified was the lack of financial support and the costs (long payback periods). Overall, the common barriers addressed were (i) the risk to the return balance, (ii) the lack of information and (iii) the lack of technology knowledge from the industries.

The Tyndall Center at the University of Manchester [13] addressed the barriers to utilize LGH from thermal process industries. The authors have distinguished barriers as technical and non-technical barriers. The technical barriers consist of (i) the long-distance transport of low grade heat, (ii) the corrosion, (iii) the efficiency and (iv) the integration of the system, whereas the non-technical barriers consist of (i) the context and the relevance, and (ii) the rationale for addressing the non-technical barriers. The low temperature of the low-grade heat system recovery systems is the noticeable low temperature of the waste heat. These LGH systems exhibit limitations as to the technologies available and the process options for the waste heat recovery.

Figure 1 shows the mapping of barriers and linkage at different sectors as discussed in the Manchester report. As can be observed in the figure, some barriers are intersecting two or more categories, with risk being the barrier affecting all categories. The authors noted that risk covers a wide range of types and it could be subdivided into other sectors. The arrows on the figure indicate the linkage between barriers.

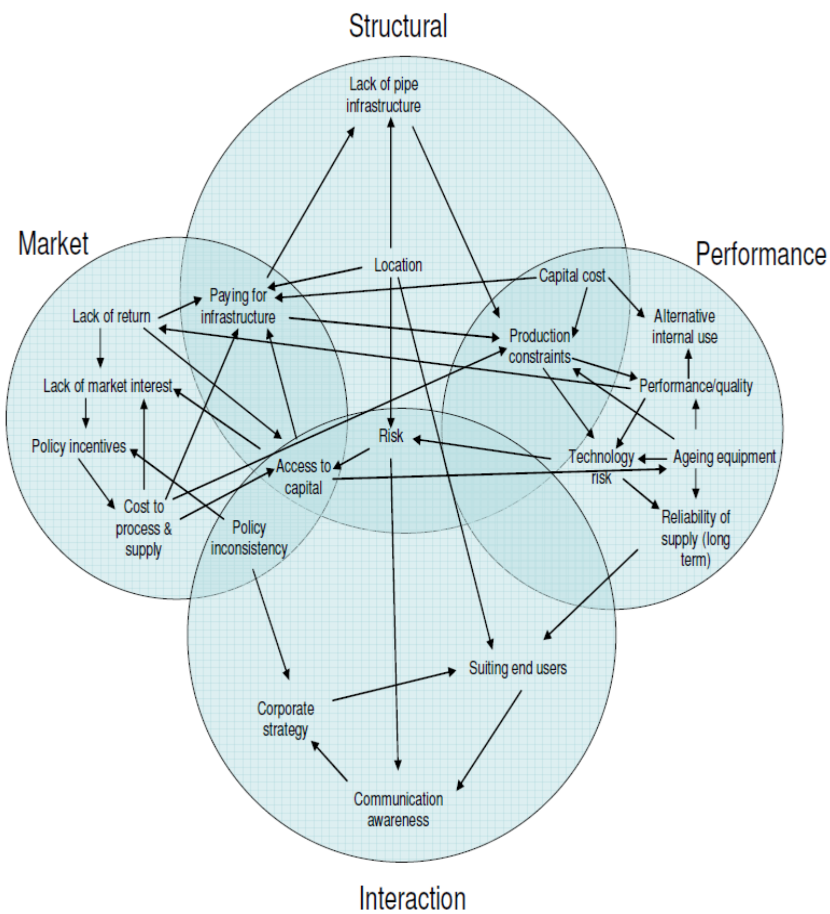

Figure 1. Mapping of barrier linkages [13]

Rohrer [14] informs that the plethora of LGH that could be used for recovery, should satisfy minimum requirements and it would not be advantageous for the system if it does not comply. Long distance barrier depends on the variable of the length of the pipes, temperature of the heat supply, the pipe diameter and pipe insulation. The heat losses due to the piping network have been experimentally examined by Comakli *et al.* [15] at the University of Ataturk. The authors have observed that by increasing the insulation thickness of the pipes, the heat loss decreased by 25%. They have also noticed that when the temperature of the supply water increased, the loss of exergy in the hot water distribution system also increased.

System efficiency with the provided low waste heat is also an important aspect, as it may result in high capital cost per kW generated. Rather than installing a heat recovery system, in cases where the cost of installation and recovery are very high (and depreciation does not satisfy the system), it would be more beneficial for the low-grade waste heat to be wasted since the low temperature of the heat results in a low efficiency for the system and therefore the system would not be cost effective. Another technical barrier in realizing waste heat recovery is the implementation of the system and its utilization without any disturbance within the existing plant operations. The maintenance of the LGH recovery system should not affect the plant operations and should not require the plant to be shut down in order to maintain the system, as this will implement losses in production of the plant. Additionally, the use of LGH for power generation will not be as beneficial for the plant as opposed to the direct use of the LGH for space heating.

Holman [16] has presented and discussed barriers and limitations of employing waste heat recovery systems in the United States and has emphasized the potential of the use in the industry. The author also highlights the quality variability of the waste heat to be used for power generation, such as temperature, flow rate and cleanliness of the waste heat stream. The high costs of the exhaust gases cleanness process impact the limitation on the use of the systems, but additionally during the cleanness process valuable heat is removed from the system making the system less effective. Another barrier suggested by the author is the available business models. Implementing a waste heat recovery system has two primary risks, namely (i) the risk of the system negative impact on the company operations, and (ii) the risk of the failure anticipated return. New business models are focusing on eliminating the risks with viable waste heat resources. Availability of financial agreements are also noted to be a barrier by the author.

More recently the USA Department of Energy [17] in their Quadrennial Technology Review on the Assessment of Energy Technologies, presented the following two tables summarizing limitations and barriers for different equipment used with high temperatures (Table 1) and medium temperatures (Table 2).

Table 1. Limitations of Currently Available Waste Heat Recovery Technologies, High Temperature (>650ºC) Ranges [17]

Equipment	Limitations and Barriers
Metallic recuperators	• Upper temperature limit of 870ºC • Economically justifiable heat recovery efficiency 40%–60% • High maintenance for use with gases containing particulates, condensable vapors, or combustible material • Reduced life expectancy in applications where the mass flow and temperature of the fluids vary or are cyclic • Fouling and corrosion of heat transfer surfaces • Difficulty in maintaining or cleaning the heat transfer surfaces

Equipment	Limitations and Barriers
Ceramic recuperators	• Reduced system life expectancy due to thermal cycling and possibility of leaks from high-pressure side • High Initial cost • Relatively high maintenance • Size limitations – difficult to build large size units
Recuperative burners	• Lower heat recovery efficiency (usually less than 30%) • Temperature limitation – exhaust gas temperature less than 870ºC • Limited size availability (usually for burners with less than 1 MM Btu/hr) • Cannot be applied to processes where exhaust gases contain particles and condensable vapors
Stationary regenerators	• Large footprint • Declining performance over the lifetime • Plugging of exhaust gas passages when the gases contain particulates • Chemical reaction of certain exhaust gas constituents with the heat transfer surfaces • Possibility of leakage through dampers and moving parts • Cost can be justified only for high-temperature (>1095ºC) exhaust gases and larger size (>50 MM Btu/hr firing rate)
Rotary regenerators	• Seals between the high-pressure and low-pressure gases (air) • Plugging of exhaust gas passages when the gases contain particulates • High pressure drop compared to recuperators • Maintenance and operation reliability for rotary mechanism
Regenerative burners	• Large system footprint for many applications • Complicated controls with dampers that cannot be completely sealed • Difficult pressure control for the furnace • Cost competiveness • Plugging of the bed when the gases contain particulates. Require frequent cleaning of the media and the bed.
Heat recovery steam generators - boilers	• Limited to use for large size systems (usually higher than 25 MM Btu/hr) • Limited to use with only clean and particulate free exhaust gases • Only viable for plants with need for steam use • Initial cost is very high compared to other options such as recuperators

Table 2. Limitations of Currently Available Waste Heat Recovery Technologies, Medium Temperature Ranges [17]

Equipment	Limitations and Barriers
Metallic recuperators	• Lack economic justification for exhaust gas temperature below about 535 ºC • Economically justifiable heat recovery efficiency 40%–60% • High maintenance for use with gases containing particulates, condensable vapors, or combustible material • Fouling of heat transfer surfaces • Difficulty in maintaining or cleaning the heat transfer surfaces

Equipment	Limitations and Barriers
Recuperative burners	• Lower heat recovery efficiency (usually less than 30%) • Limited size availability (usually for burners with less than 1 MM Btu/hr) • Cannot be applied to processes where exhaust gases contain particles and condensable vapors
Rotary regenerators	• Seals between the high-pressure and low-pressure gases (air) • Plugging of exhaust gas passages when the gases contain particulates • High pressure drop compared to recuperators • Maintenance and operation reliability for rotary mechanism
Shell and tube heat exchanger for heating liquid (water)	• Fouling of heat transfer surfaces when the gases contain particulates or condensable liquids • Condensation of moisture at selected cold spots and resulting corrosion

The barriers have been further analyzed and categorized by the US Department of Energy [17] in relation to the type of heat available in the industry (see Table 3). Suggestions, in some cases, have been given as to how to overcome these technology specific barriers.

Table 3. Waste heat by type and associated barriers addressed in the US industry [17]

Type of waste heat	Associated barriers
High-temperature combustion products or hot flue gases that are relatively clean	• Reduced thermodynamic potential for the most efficient heat recovery due to materials limitations (particularly metallic) that require gases to be diluted • Heat transfer limits on the flue gas side in steam generation or other power generation (i.e., organic Rankine cycle) heat exchanger systems applications • Seal issues for heat exchanger designs with metallic and nonmetallic (ceramics) components (due to dissimilar thermal expansions)
High-temperature flue gases or combustion products with contaminants such as particulates or condensable vapors	• Availability or cost of materials that are designed to resist the corrosive effects of contaminants • Lack of design innovation that will allow self-cleaning of the heat recovery equipment to reduce maintenance • Lack of cleaning systems (similar to soot blowing) that allow easy and on-line removal of deposits of materials on heat transfer surfaces • Heat transfer limitations on the gas side of heat exchange equipment
Heated air or flue gases containing high (>14%) O2 without large amounts of moisture and particulates	• Limitations on the heat exchanger size that prevent use on retrofit, which may be due to heat transfer limitations or design issues such as size and shape of heat transfer surfaces (e.g., tubes or flat plates) • Lack of availability of combustion systems for small (less than 1 MMBtu/hr) sizes to use low O2 exhaust gases as combustion air for fired systems

Type of waste heat	Associated barriers
Process gases or by-product gases and vapors that contain combustibles in gaseous or vapor form	• Lack of available, economically justifiable vapor concentrators for recovery and reuse of the organic-combustible components, which would avoid the need for heating a large amount of dilution air and the resultant large equipment size. The concentrated fluids can be used as fuel in the heating systems (ovens). • Lack of availability of compact heat recovery systems that will reduce the size of the heat exchangers (large regenerators)
Process or make-up air mixed with combustion products, large amounts of water vapor, or moisture mixed with small amount of particulates but no condensable organic vapors	• Rapid performance drop and plugging of conventional heat exchanger. Unavailability of designs that allow self-cleaning of heat transfer surfaces on units such as recuperators. • Lack of innovative designs that allow use of condensing heat exchangers (gas-water) without having the corrosive effects of carbonic acid produced from CO_2 in flue products
Steam discharged as vented steam or steam leaks	• No major technical barriers. The major barriers are cost and return on investment for the collection of steam, the cooling system, condensate collection and, in some cases, the cleaning system.
Other gaseous streams	• Application-specific barriers
Clean heated water discharged from indirect cooling systems such as process or product cooling or steam condensers. This stream does not contain any solids or gaseous contaminants	• Lack of opportunities to use low-grade heat within the plant. Lack of economically justifiable heat recovery systems that can convert low-grade heat into a transportable and usable form of energy, such as electricity.
Hot water that contains large amounts of contaminants such as solids from the process or other sources, but does not contain organic liquids or vapors mixed with the water	• No major technical barriers for cleaning the water (removing the solids) • Lack of opportunities to use low-grade heat within the plant or economically justifiable energy conversion systems.
Hot water or liquids containing dissolved perceptible solids, dissolved gases (e.g., CO_2, O_2, and SO_2) or liquids	• No major technical barriers for filtering the water (removing the solids) • The presence of SO_2, CO_2, and other dissolved gases presents problems of high PH values for water use within a plant. Typical water degasification processes (vacuum deaeration, gas transfer membrane, hot water steam injection/stripping deaeration, etc.) are energy intensive and costly. • Lack of opportunities to use low-grade heat within the plant or economically justifiable energy conversion systems

Type of waste heat	Associated barriers
Hot solids that are cooled after processing in an uncontrolled manner	• Economically justifiable cooling air collection system • Lack of opportunities to use low-temperature heat within the plant or economically justifiable energy conversion systems. • Variations in cooling air temperatures and the presence of microscopic particulates prevent their use in combustion system (burners)
Hot solids that are cooled after processing using water or airwater mixture. Examples include hot coke, ash, slag, and heat-treated parts	• No major technical barriers for filtering the water (removing the solids) • Lack of opportunities to use low-grade heat within the plant or economically justifiable energy conversion systems
Hot liquids and vapors that are cooled after thermal processing. Examples include fluids heated in petroleum refining or the chemical, food, mining, or paper industries	• No major technical barriers for recovering heat if there is sufficient temperature "head" • Lack of opportunities to use low-grade heat within the plant or economically justifiable energy conversion systems
By-products or waste that is discharged from thermal processes. These materials contain sensible, latent, and chemical heat that is not recovered prior to their disposal.	• Economically justifiable collection system for hot material • Economics of processing the material to recover recyclable or useful materials, or combustibles for use of chemical heat • Materials are often classified as hazardous materials and need special treatment • Cost of recycling or cleaning the residues and treatment of gases or other materials that are produced during the recovery or treatment process • Variations in the amount of recoverable materials
High-temperature surfaces	• No practical way of recovering this heat, especially for systems such as rotary kilns or moving surfaces (i.e. conveyors) • Low efficiency and cost for advanced surface-mounted energy conversion technologies such as thermoelectric systems
Extended surfaces or parts used in furnaces or heaters	• No practical way of recovering and collecting this heat, especially for systems such as rolls used for a furnace • Low efficiency and high cost for advanced surface-mounted energy conversion technologies such as thermoelectric systems

Additionally, other general barriers [8], not concerning the recovery technology used are the limitation of available physical space. This limitation cannot be directly solved as more compact equipment come with a higher cost. Another barrier is the discontinued furnace operation, which interacts with the heat exchangers as the fluctuations can cause damage due to thermal cycling. This limitation is equivalent to the market value of higher performance heat exchangers that can withstand high temperature difference fluctuations.

Now, possible solutions to specific technological, production, financial and administrative barriers have been presented by Brueckner *et al.* [10], following the work of Pehnt *et al.* [18], with relevant suggestions introduced in Table 4. The authors have proposed the use of a heat pump when the available heat stream has low temperature, and to cascade the use when the temperature is high. On the technological barriers, the ease of transportation of heat can help overcome the absence of nearby heat sink and eport the heat to third parties. A very simple solution of using redundant boilers to overcome the boiler reliability barrier is described, but it conflicts with the financial barriers. Concerning the financial barriers, waste heat contracting and the use of service providers could be a solution to focus on the core business. Finally, to overcome the lack of information and the available data on waste heat recovery successful projects for business and research institutes, information campaigns and technology specific training courses to selected groups could help the waste heat recovery systems flourish.

Table 4. Ways of overcoming the Barriers [18]

Barriers	Possible suggested solutions
Technological barriers	
No nearby heat sink - For heat transfer to third parties	Building heating pipes, heat transport
No information about heat sinks nearby	Waste heat exchange (information portal) Look for neighboring businesses such as in industrial areas
Time discrepancy Generation of heat/demand	Using heat in a different way such as power generation or feeding the power grid, storage
Temperature levels - Too low	Using heat pumps
Temperature levels - Too high	Mixing in steam or similar, cascading the use
Production process	
Boiler reliability	Redundant boilers
Financial and administrative barriers	
Availability of investment funds	Subsidies, loans
Priority of the core business	Use of service providers, waste heat contracting
Too high rate of return expectations	Information about life cycle costs
Information	
Lack of business knowledge and personnel	Information campaigns and technology specific training courses for selected target groups
Research costs too high	Development investment calculation tools for consulting engineers and facility operators in the workplace

Further research and development in order to further implement the waste heat recovery technologies has been suggested by BSC Incorporated [8] with the impact reduction of the chemical composition of exhaust gases. The authors suggest the following: (i) development of low-cost heat exchangers with advanced materials that can withstand harsh environments or that can be easily and cost effectively cleaned and maintained, (ii) development of low-cost gas cleanup systems that can operate at elevated temperatures, and (iii) identification of new industrial process concepts that avoid introducing chemical contaminants into exhaust streams.

Finally, an important limitation of the industry is the lack of available data [19] on failed and success stories with previous experiences on heat recovery systems. The publication of those experiences can help the industry estimate the economic and technical risk factors. The lack of publicly available data is also emphasized by Hongyou *et al.* [20].

3. Questionnaire design and results

Based on the findings of the previous section, a questionnaire aimed at EU28 Industries was prepared. The questionnaire is concerned with the identification of the barriers for the wider adoption of heat recovery technologies and recommendations on how to overcome them. The extent of this questionnaire was kept as short as possible (8 questions) in order to make it easy to complete by each industry representative. After a pilot survey in Cyprus, the final version of the questionnaire (see Appendix) consists of the following sections: (i) Introductory information about the company, and (ii) 8 (+ 1, for comments) questions related to energy use, excess heat and its use, barriers preventing heat recovery, importance of heat recovery.

Companies in various EU countries, namely Cyprus, Greece, France, Germany, Italy, Portugal, Romania, Spain and the UK were notified about the questionnaire through partners of the consortium. They had the option to complete the questionnaire online or by hand. The response from companies was particularly slow. Eventually 46 valid questionnaires were completed. The main reason for not having a higher response is, we believe, confidentiality issues and time required to complete the questionnaire.

The respondents are categorized with regard to country as follows: 2 from Belgium, 4 from Cyprus, 3 from Greece, 4 from France, 7 from Germany, 6 from Italy, 3 from the Netherlands, 2 from Portugal, 2 from Romania, 6 from Spain and 7 from the UK.

With regard to type of industry, they can be categorized as follows: 5 from Iron and Steel, 5 from Chemical/Petrochemical, 4 from Non-ferrous metal, 5 from Non-metallic minerals, 7 from Food and Tobacco, 4 from Paper Pulp and Print, 5 from Wood / Wood Products, 5 from Textile and Leather, 4 Thermal energy engineering and 2 Turbomachinery. The size of the companies varied from medium to large (40 to 800 employees).

The results for each of the questions listed on the questionnaire are shown below.

1. Annual energy use at the company: Type:

Biofuel	Fossil fuels	Electricity	District heating	Other
12	42	46	21	4

Clearly, most companies still use fossil fuels, electricity and district heating as energy source, but there is a number of them using other types of sources, like biofuel. Regarding total consumption, it varies from about 1 to about 50 GWh/year.

2. Do you produce excess heat?

Yes	No	Do not know
30	7	9

Out of the 46 companies only 30 replied they produced excess heat, 28 of which examined the possibility of using the excess heat internally and 8 (not necessarily different companies) externally. Taking into consideration the type of companies taking part in this survey, though, it seems that they could all produce excess heat. Projecting the outcome here to the large number of EU companies that produce excess heat, it can be thought that there is a considerable number of companies that they either do not know that they produce considerable amounts of excess heat or are not did not have the time to consider its utilisation.

3. Have you examined the possibility of using the excess heat internally?

Yes	No	Do not know
28	18	-

3.1. If you answered "yes" to question 3, what was (is) the method used (to be used) and the temperature ranges:

Method	Number	Temperature Range (°C)
Economizers	13	70-500
Plate heat exchangers	7	50-400
Regenerative and recuperative burners	3	800-1500
Waste heat boilers	10	70-400
Air preheaters	19	50-400
Heat pipe systems	4	500-1000
Steam generator	13	100-650
Thermodynamic cycles	3	100-500
Heat Pumps	5	40-70
Flat heat pipes	2	500-1000
Condensing economizers	3	70-500
Trilateral Flash Cycle	0	
Supercritical Carbon Dioxide Cycle	0	

3.2. If you answered "yes" to question 3, what was the outcome?

Not profitable	Profitable, but not yet implemented	Implemented
12	7	9

4. Have you examined the possibility of using the excess heat externally?

Yes	No	Do not know
8	23	15

4.1. If you answered "yes" to question 4, what was (is) the method used (to be used) and the temperature ranges:

Method	Number	Temperature Range (°C)
Economizers	0	
Plate heat exchangers	0	
Regenerative and recuperative burners	0	
Waste heat boilers	0	
Air preheaters	2	50-400
Heat pipe systems	6	500-1000
Steam generator	2	100-650
Thermodynamic cycles	0	
Heat Pumps	4	40-70
Flat heat pipes	0	
Condensing economizers	0	
Trilateral Flash Cycle	0	
Supercritical Carbon Dioxide Cycle	0	

4.2. If you answered "yes" to question 4, what was the outcome?

Not profitable	Profitable, but not yet implemented	Implemented
1	5	2

The replies in Questions 3.1 and 4.1 verify the knowledge and the use by companies of almost all well-known methods for using the excess heat either internally (easier to apply) or externally (needs specific conditions to be applied), within all temperature ranges (low, medium, high). Regarding the implementation of the use of the excess heat and its profitability, it seems that many companies find this non-profitable.

5. If you haven't considered installing a waste heat recovery system at all, what is(are) the reason(s)?

Reason	Number
Lack of information (i) / technology knowledge (ii)	20
Technology risk (iii)	10
No requirement for using the recovered heat (x)	12
High initial cost (iv)	18
Running and maintenance costs (iv)	13
Lack of financial support / governmental incentives (v)	18
Size / available space limitations (vi)	10
Lack of available infrastructure (vii)	15
Production constraints (viii)	12
Risk of production disruptions (viii)	13
Risk of the system negative impact on the company operations (ix)	7
Policy/regulations restrictions (x)	2
Other	0

The replies in Question 5 cover nearly all ten barriers to the wide adoption of heat recovery technologies, except the "policy/regulation restrictions". The most "common" barriers seem to be "the lack of information / technology knowledge", the "high initial cost" and "the lack of financial support / government incentives".

6. What are the technological barriers for non-installing a waste heat recovery system? Please choose 1 or more answers.

Barrier	**Number**
High capital cost per KW generated (low system efficiency)	17
Low quality and not constant heat stream	10
High cost material to withstand the heat	7
Stream with high chemical activity	7
Transportability (long distance transport of low grade heat)	9
Disturbance within the existing plant operations	7
Other	2

The usual technological barriers, as found in the literature, are confirmed by the replies in Question 6. The "Other" technological barriers mentioned were restricted use of low grate heat in the plant and expensive installations without any real effect on the price of product.

7. In your opinion, what is the most important driver for installing a waste heat recovery system?

Energy saving	Environmental benefits	Fuel cost reduction
29	6	11

"Energy saving" was the "winning" option in Question 7, were obviously all three options are essentially equivalent.

8. In your opinion, how can the barriers related to waste heat recovery systems be overcome?

Suggestions offered by the respondents are the following:

- (i) research and testing,
- (ii) technological innovation to reduce capital cost,
- (iii) demonstrated case studies,
- (iv) availability of information,
- (v) increasing the installation incentives.

4. Strategies and Recommendations for Heat Recovery Measures

Strategies and Recommendations depend on the type and size of company and dependence of price of produced goods on energy expenses. This means that if the price of goods is high because of the amount of energy used for production, the company will probably pay attention to recommendations. The questionnaire verified that the barriers to the wide adoption of heat recovery technologies are: (i) lack of information, (ii) lack of technology knowledge, (iii) technology risks, (iv) high initial and running and maintenance costs, (v) lack of financial support and lack of governmental incentives, (vi) size and available space limitations, (vii) lack of available infrastructure, (viii) production constraints and risk of production disruptions, (ix) risk of the system negative impact on the company operations, (x) policy and regulations restrictions.

- *Lack of information; lack of technology knowledge for implementation (i; ii)*

Clear awareness regarding the technology and financial aspects of the application in question are necessary for decision making. Lack of awareness leads to faulty perception and implementation that may cause inefficient or negative results. The ultimate goal is to optimize the overall energy efficiency and, in this way, maximize the economic and environmental benefits. The required information must cover information on the best available technologies, technologies that are locally available and provide methods for choosing the most effective technology. To overcome the information barrier, it is suggested to establish an information exchange platform that will establish a research and development group, collect and analyze data from relative scale projects, search and define the best available technology, define pay-back time through a cost benefit analysis and define policy goals and parameters. Moreover, technical assistance and collaboration with other related entities should be established.

- *Technology risks (iii)*

Failure of technology to meet specifications may be due to lack of adequate technology infrastructure, technological newness or strained technical capabilities. Technical application complexity and unrealistic schedules and budgets may also present risks. Lack of a measurement system to control risk and inadequate project management and tracking may also cause failure of application. Implementing new systems and technology may present new challenges and new risk factors that must be handled differently. By risk is meant the confrontation of a problem that has not happened before, but which could cause some loss or threaten the success of the new technology application. An investigation into the matter has shown that the causes of project failures are due to ineffective leadership and failures in communication as well as because of poor technical methods. Issues of organizational fitness (including conflicts of people, time and project scope or poor specification of requirements), skill mix (inappropriate staff and lack of application-specific knowledge), management strategy and others may interfere and must be avoided.

- *High initial, running and maintenance costs (iv)*

For the success of an application all assets and their effective management is essential. Assets must be planned and monitored throughout their entire life cycle, from the development stage through to their final disposal. Optimizing value for money can be achieved by taking into consideration all the cost factors relating to the asset during its operational life. Life cycle costing involves estimation of costs on a whole life basis before making a choice to purchase and install an asset from the various alternatives available. Life cycle cost of an asset can be several times the initial purchase or investment cost, therefore it is important that management should appreciate the source and magnitude of lifetime costs and take effective action to control it. The approach to save money in the short term by buying assets simply with lower initial acquisition cost does not lead to wise decisions. It is therefore suggested that for every project the Life cycle costing should be done and it should include initial, running and maintenance costs, showing the real value of the investment for decision making.

Short pay-back time will give a strong motive to highly commoditized producers to install any energy efficiency innovation. Also, reduction of costs can be achieved through technological innovation. Finally, demonstration projects or independent feasibility studies can be presented and be described as beneficial to companies.

- *Lack of financial support and lack of governmental incentives; policy and regulations restrictions (v; x)*

The more favorable the business environment, the more likely the businesses will develop and grow. No business can start or expand without financial means and support. Finding a way for “tariff” payments or upfront grants can be a possible solution. Businessmen are encouraged and feel competent to expand when entrepreneurship is valued, when new opportunities arise and when the businessmen have sufficient knowledge and skills. The willingness and capability to change traditional techniques may be further improved if potential entrepreneurs do not face obstacles during the process when they are confident that they can obtain outside expertise easily if necessary and have the financial means.

Governments both directly and indirectly affect the development of the environment for backing entrepreneurship. Several governmental incentives can help developing entrepreneurship. Options include provision of venture capital funds, tax-based incentives, and government procurement programs. Also, protection of patented ideas and innovations support by government agencies and public investment in education and research stimulate further the implementation of new ideas in business.

Financial assistance may be offered by venture capital and alternative sources of financing, low-cost loans and willingness of financial institutions to finance especially small entrepreneurs and credit guarantee programs run by financial institutions.

Policy and regulations restrictions are also subjects of the techno-economic study. Support by government agencies should be asked and any suggested measures should be followed.

- *Size and available space limitations; lack of available infrastructure (vi; vii)*

Space limitations may arise in the case that minimum efficient size is implemented in a process. In such a case there is no other option than redesign the process space and make allowance for the new implementation. Financial means will be needed and a life cycle cost analysis will show the viability of the new implementation.

Regarding available infrastructure, a proper detailed study should be undertaken by the management that will show its ability to undertake the new tasks. A study by competent and knowledgeable consultants will suggest measures to overcome the inefficiency.

- *Production constraints and risk of production disruptions; risk of the system negative impact on the company operations (viii; ix)*

During implementation of the new task, production constraints and risk of production disruptions may affect the production of the company. This of course will have a temporary negative effect on the business output and must be considered in the techno-economical study (life cycle cost analysis) that will be undertaken before commencing works. Care should be given for cases where the normal expected lifetime of the heat recovery technology installed may differ from the remaining process plant lifetime. The minimization and the mitigation of any such risks can be achieved through demonstration projects or independent feasibility studies. Not always the cheapest method leads to the better result. A proper technical study by competent and knowledgeable consultants should examine any negative impacts and suggest measures.

5. Concluding Remarks

The main barriers to the wide adoption of heat recovery technologies in EU Industry have been identified and analysed. A structured questionnaire regarding the barriers was distributed to companies in EU countries. Twenty seven valid responses from 9 EU countries were collected and analyzed. One can conclude that the assumed theory regarding the barriers to the adoption of heat recovery technologies, based on literature review, were confirmed.

Following the recommendations and the strategies for WHR measures presented in Section 4 above, there remain actions to be taken as future goals (within the I-ThERM time limits) as follows.

(1) Industry engagement workshop: A workshop with key stakeholders will help fully articulate and finalise the research objectives with regard to barriers. The meeting can include discussion groups to address the key barriers. One issue is the relatively low importance placed on energy efficiency and therefore limited resource committed to managing energy in comparison to other corporate priorities. Encouraging companies to commit additional resource to more sophisticated energy monitoring was thought by the questionnaire participants to help energy managers identify and build business cases for appropriate heat recovery technologies.

(2) To report the outcomes in the form of a report/scientific paper.

(3) To make the final outcomes widely available through the project's website. These outcomes will be adopted as far as possible in the packaging, installation, commissioning and demonstration of the technologies of the project.

(4) Case study(ies): The outcomes may be used as case study material. When proposing potential WHR options applied to particular industries, it is important to match technologies to appropriate industrial processes. The four main technologies that can be examined give a cross-section of different technology types, all of which could have significant potential for application and include areas where there is detailed technical expertise within the consortium. In particular, there can be application of some of the following technologies:

(i) Flat heat pipes (FHP) used to recover heat from industrial processes either with conduction, convection or radiation from waste heat sources with a variety of heat pipe types using various fluids. The rationale of this choice is that FHP can function in different environments and in a variety of temperatures depending on working fluid used.

(iii) Supercritical Carbon Dioxide Cycles (sCO2C) can be designed with multiple configurations of turbomachinery and heat exchanges and can be constructed to achieve high overall efficiency for different temperatures and/or pressures, which may benefit a particular cycle application.

(iv) Trilateral flash cycle (TFC) involves liquid heating only and two-phase expansion of vapor. TFC systems can produce higher outputs than simple Rankine cycle systems in the recovery of power from hot liquid streams in temperature ranges of 100–200°C.

Appendix: Waste heat recovery - Questionnaire

Introductory information

- Company name (*Note: you can remain anonymous*): ______________________
- City/Country: ____
- Main production/activity: _______________________________________
- Number of employees: ____
- Name and title of person completing the questionnaire:

  ____
- E-mail: ____

Excess heat from the facility

Below are a number of questions related to excess heat from your facility.

1. Annual energy use at the company (approximately)?

i. Biofuel (MWh/year): ______

ii. Fossil fuels (MWh/year): ______

iii. Electricity (MWh/year): ______

iv. District heating (MWh/year): ______

v. Other (MWh/year), comment: ______

2. Do you produce excess heat?

i. Yes: ______

ii. No: ______

iii. Do not know: ______

3. Have you examined the possibility of using the excess heat internally?

i. Yes: ______

ii. No: ______

iii. Do not know: ______

3.1 If you answered "yes" to question 3, what was (is) the method used (to be used) and the temperature ranges: ____________________________

3.2 If you answered "yes" to question 3, what was the outcome?

i. Not profitable: ______

ii. Profitable, but not yet implemented: ______

iii. Implemented, comment (How much and for what?): ______

4. Have you examined the possibility of using the excess heat externally?

i. Yes: ______

ii. No: ______

iii. Do not know: ______

4.1 If you answered "yes" to question 4, what was (is) the method used (to be used) and the temperature ranges: ______________________________

4.2 If you answered "yes" to question 4, what was the outcome?

i. Not profitable: ______

ii. Profitable, but not yet implemented: ______

iii. Implemented, comment (How much and for what?): ______

5. If you haven't considered installing a waste heat recovery system at all, what is(are) the reason(s)?

i. Lack of information / technology knowledge ______

ii. Technology risk ______

iii. No requirement for using the recovered heat ______

iv. High initial cost ______

v. Running and maintenance costs ______

vi. Lack of financial support / governmental incentives ______

vii. Size / available space limitations ______

viii. Lack of available infrastructure ______

ix. Production constraints ______

x. Risk of production disruptions ______

xi. Risk of the system negative impact on the company operations ______

xii. Policy/regulations restrictions ______

xiii. Other (please specify) ______

6. What are the technological barriers for non-installing a waste heat recovery system? Please choose 1 or more answers.

i. For ___ºC temperature of the heat stream: (*specify the temperature*)

High capital cost per KW generated (low system efficiency) _______

Low quality and not constant heat stream _______

High cost material to withstand the heat _______

ii. Stream with high chemical activity _______

iii. Transportability (long distance transport of low grade heat) ______

iv. Disturbance within the existing plant operations ______

7. In your opinion, what is the most important driver for installing a waste heat recovery system:

i. Energy saving ______

ii. Environmental benefits ______

iii. Fuel cost reduction ______

8. In your opinion, how can the barriers related to waste heat recovery systems be overcome?

____

____

____

____

____

____

______

9. Other comments:

____

____

__

____

____

__

____

____

__

References

[1] A. Crook, "'Introduction'. In: Profiting from low grade heat. A.W.Crook, (ed). Watt committee on energy report no.26.," The institute of electrical engineers, Herts, United Kingdom, 1994.

[2] J. Holman, "Perspective: Waste Heat to Power — Still Waiting for a Breakthrough," IDC Energy Insights,Renewable Energy Strategies, 2011.

[3] I. BCS, "Waste Heat Recovery: Technology and Opportunities in U.S. Industry," U.S. Department of Energy, Industrial Technologies Program, U.S. , 2008.

[4] U. Manchester, "Addressing the barriers to utilisation of low grade heat from the thermal process industries," Tyndall Centre for Climate Change Research, Manchester, 2010.

[5] P. Rohdin and P. Thollander, "Barriers to and driving forces for energy," *Energy,* pp. 1836-1844, 2006.

[6] E. Sardianou, "Barriers to industrial energy efficiency investments in Greece," *Journal of Cleaner Production,* vol. 16, no. 13, pp. 1416-1423, 2008.

[7] K. Comaklı, Y. B. and C. O., "Evaluation of energy and exergy losses in district heating network," *Applied Thermal Energy,* vol. 24, no. 7, pp. 1009-1017, 2004.

[8] W. Rohrer, "Waste heat recovery," in *The energy management handbook (6th ed),* United States of America, Fairmount Press, 2007.

[9] U.S Department of Energy, "Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing Technology Assessments," Quadrennial Technology Review, 2015.

[10] J. Norman, "Industrial Energy Use and Improvement Potential," Bath University, Bath, 2013.

[11] DECC, "The future of Heating: Meeting the challenge," Department of Energy and Climate Change, London, 2013.

[12] M. Z. Stijepovic and P. Linke, "Optimal waste heat recovery and reuse in industrial zones," *Energy,* vol. 36, no. 7, pp. 4019-4031, 2011.

[13] F. Clemens, K. M. Ibrahim, P. Robert and M. Bernd, "Estimating the global waste heat potential," *Renewable and Sustainable Energy Reviews,* vol. 57, pp. 1568-1579, 2016.

[14] L. Hongyou, P. Lynn and Z. Qi, "Capturing the invisible resource: Analysis of waste heat potential in Chinese industry," *Applied Energy,* vol. 161, pp. 497-511, 2016.

[15] S. Brueckner, L. Miró, L. F. Cabeza, M. Pehnt and E. Laevemann, "Methods to estimate the industrial waste heat potential of regions – A categorization and literature review," *Renewable and Sustainable Energy Reviews,* vol. 38, pp. 164-171, 2014.

[16] M. Pehnt, J. Boedekery, M. Arens, E. Jochem and F. Idrissora, "Die Nutzung industrieller Abwärme-technisch-wirtschaftliche Potenziale und energiepolitische Umsetzung," Wissenschaftliche Begleitforschung zu uebergreifenden technischen, oekologischen, oekonomischen und strategischen Aspekten des nationalen Teils der Klimaschutzinitiative FKZ 03KSW016A und B, Germany, 2010.

[17] L. Miró, S. Brücknerb and L. F. Cabeza, "Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries," *Renewable and Sustainable Energy Reviews,* vol. 51, pp. 847-855, 2015.

[18] C. Forman, M. I. Kolawole, R. Pardemann and B. Meyer, "Estimating the global waste heat potential," *Renewable and Sustainable Energy Reviews,* vol. 57, pp. 1568-1579, 2016.

[19] G. P. Panayiotou, G. Bianchi, G. Georgiou, L. Aresti, M. Argyrou, R. Agathokleous, K. M. Tsamos, S. A. Tassou, G. Florides, S. Kalogirou and P. Christodoulides, "Preliminary assessment of waste heat potential in major European industries," *Energy Procedia,* vol. 123, pp. 335-345, 2017.

[20] U. Department of Energy, "Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing Technology Assessments," Quadrennial Technology Review, 2015.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 680599.

Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 680599.

Disclaimer

The Horizon 2020 project has been made possible by a financial contribution by the European Commission under Horizon 2020 research and innovation programme. The publication as provided reflects only the author's view. Every effort has been made to ensure complete and accurate information concerning this document. However, the author(s) and members of the consortium cannot be held legally responsible for any mistake in printing or faulty instructions. The authors and consortium members reserve the right not to be responsible for the topicality, correctness, completeness or quality of the information provided. Liability claims regarding damage caused by the use of any information provided, including any kind of information that is incomplete or incorrect, will therefore be rejected. The information contained in this document is based on the author's experience and on information received from the project partners.