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ORIGINAL RESEARCH

Adoption of Waste Heat Recovery Technologies: Reviewing the Relevant Barriers and Recommendations on How to Overcome Them

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Abstract

The wide adoption of heat recovery technologies in industry is hampered by specific "barriers" related to both technical and non-technical issues. This paper attempts to determine these barriers and make recommendations on how to address them. First, a literature review of related material is presented. Among numerous barriers, the main ones identified 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, (x) risk of the system negative impact on the company operations, and (xi) policy and regulations restrictions. Then, based on the above, a structured questionnaire on barriers to the adoption of waste heat recovery (WHR) technologies was prepared and issued to a number of industries throughout the European Union. Upon analyzing the questionnaire, an assessment of the importance and negative impact of each of the above-mentioned barriers is made. Subsequently, 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 new and old WHR technologies.

Keywords Waste heat recovery · WHR technologies · WHR Europe · EU industries · WHR barriers · WHR limitations

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1 Introduction

Waste Heat Recovery areas can be classified into four main groups [1]: (i) energy recycling within the process, (ii) waste heat recovery (WHR) for other on-site processes, (iii) electricity generation with combined heat and power installations, and (iv) district heating systems. Each area of such WHR systems is accompanied by associated barriers. Taking advantage of the waste heat and recovering it in any of the above-mentioned forms could be beneficial for the industrial plant, but it is not really a key factor that concerns the manufacturing industries.

The possibilities of WHR and design of optimal reuse options across industrial zones' plants were presented by Stijepovic and Linke [2]. The authors used a systematic approach to target optimization in achieving maximum WHR for the industrial zone. The authors then presented a design optimization with a case study that considered economic objectives. The industrial WHR potential from all European Union (EU) countries was discussed by Panayiotou et al. [3], Bianchi et al. [4], and Panayiotou et al. [5], but was also presented and 'mapped' by Miro et al. [6] and Forman et al. [7] for a more global implementation.

The iron and steel industry, which is identified as the largest heat user, exhibits the highest potential for Low-Grade Heat (LGH) recovery. The aluminum, cement, ceramics chemical, food and drink, glass, and pulp and paper industries are also significant heat users [8]. Waste heat temperatures can be categorized as low (usually, < 100 °C), medium (usually 100–600 °C), and high (usually, > 600 °C). Further information on temperature range of processes and waste heat potential in different types of industries is presented by Panayiotou et al. [3], Bianchi et al. [4], and Panayiotou et al. [5].

The limitations and barriers to the adoption of WHR technologies can be defined in different categories. DECC [9] identified the barriers as (i) commercial, (ii) delivery, and (iii) technical. Additionally, BCS Incorporated [10] introduced and presented key barriers, listed under different limitations, such as (i) costs; (ii) application, heat stream composition, process, and temperature specific constraints; and (iii) inaccessibility and transportability of certain heat sources.

Long payback periods and material constrains are the key limitations on the cost barrier [11]. Moreover, the materials required differ 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." The scale of the heat recovery system favors larger systems, with the authors defining this category as 'economies of scale.' High operation and maintenance costs are required, depending on the system scale that includes corrosion and fouling. The financial constraint, which is the most common obstacle — as in any technology, is no different in the case of WHR [12].

The most important restriction of the systems is the temperature of the heat stream. Low-temperature industrial facilities do not require on-site use, and the technologies related to low-temperature power generation are very costly and less developed. During low-temperature streams, extensive corrosion and fouling is observed due to the fact that solid and liquid components condense, as hot streams cool down in the recovery equipment [10]. At higher temperatures, materials that are able to withstand the high temperature of the heat stream have higher costs, increasing the overall cost of the system and, therefore, extending the payback period of the system. It is observed, however, that, in practice, inexpensive materials are used and therefore the outside air temperature causes the temperature of the heat stream to decrease. This affects the efficiency and the available energy to be used in the system. The available energy is also related to the heat transfer rate, where a temperature difference between the heat source and the heat sink affects the performance; hence, a larger surface area is required.

Heat stream composition also has an effect on the cost of the recovery system, as streams with high chemical activity require costly equipment materials to prevent corrosion. Chemical composition also affects the heat transfer rates, environmental concerns, and product/process control. The last barrier category in the recovery system, discussed by the BCS Inc. Group, is the inaccessibility, transportability, and limited space [10].

Identification of barriers can be achieved either through the use of surveys, interviews and practical assessments, or through reviews and theoretical frameworks, or both. The current paper focuses on identifying barriers to WHR systems in the EU through both the survey and the theoretical framework.

Rhodin and Thollander [13] presented the energy efficiency of the Swedish manufacturing industry, stating that barriers are regional and sector-specific and better not be generalized. The industry companies involved 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 [14] also conducted a survey research involving 800 Greek industries and the most important barrier identified was the lack of financial support and costs (long payback periods). Overall, the common barriers encountered and 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 [15] addressed barriers to the use of LGH by thermal process industries. The authors distinguished barriers as technical and non-technical. The technical barriers consist of (i) long-distance transport of LGH, (ii) corrosion, (iii) efficiency, and (iv) system integration. 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 LGH recovery systems is the noticeable low temperature of the waste heat. These LGH systems exhibit limitations in terms of available technologies and process options for the WHR. A similar analysis to the above can be found in Walsh and Thornley [16] who classified barriers and limitations according to their origin (shown in Table 1). The authors identified and reported, with the help of a strategic mapping exercise, that lack of infrastructure, financial support, capital cost, and location-related problems are the most significant barriers. The authors also perceived the importance of the barrier of the cost of capital, as raised by stakeholders, as opposed to the project's rate of return. Nagesha and Balachandra [17] examined the views of stakeholders on energy efficiency barriers for small-scale Indian industries. The authors highlighted the lack of awareness and information

Table 1 Mapping of barriers; linkages can be found in [16]

Mapping	Barriers
Structural	Lack of pipe infrastructure
	Location
	Paying for infrastructure
	Access to capital
	Risk
	Capital cost
	Production constraints
Market	Lack of return
	Lack of market interest
	Policy incentives
	Cost to process and supply
	Paying for infrastructure
	Access to capital
	Policy inconsistency
Performance	Alternative internal use
	Performance/quality
	Ageing equipment
	Technology risk
	Reliability of supply (long term)
	Capital cost
	Production constraints
Interaction	Corporate strategy
	Suiting end users
	Communication awareness
	Risk
	Access to capital
	Policy inconsistency

as well as the lack of investment capability and noted that financial and economic barriers were of paramount importance.

Thekdi and Nimbalkar [18] concluded that the cost of energy (from fossil fuels) would be the most important parameter in reporting the economic justification for WHR technologies and systems. Furthermore, the authors stated that WHR technologies have size limitations as regards WHR systems of a variety of temperature ranges. Specifically, regarding LGH streams the authors mentioned that there are limitations on cost, system size, and the lack of use within the plant.

Xu et al. [19] addressed LGH stream barriers and reported recommendation on how to overcome issues of lack of global optimization methodology, high cost of capital, and lack of synchronization between waste heat supply and demand in time, space, and energy grade. Langan and O'Toole [20] addressed the key — as they called it — barrier of cost effectiveness for LGH stream, and proposed a new technology to overcome it. Additional WHR technologies and their application can be found in [21]. Vance et al. [22] reported that barriers to the WHR technologies cannot only be seen in the LGH streams, but also in harsh environments (with undesirable chemicals or exhaust gases with temperatures above 650 °C) in industrial processes. The authors presented the potential of WHR in harsh environments as well as the advantages and disadvantages of the WHR systems and concluded that WHR from these streams can lead to excessive maintenance, short equipment life, and safety risks.

Table 1 shows the "mapping" of barriers in different sectors, as discussed in Walsh and Thornley [16]. As can be observed, some barriers (e.g., capital cost) are common in two or more categories. The authors noted that the risk covers a wide range of types and could be subdivided into other sectors. "Linkages" between barriers can be found in detail in [16].

Rohrer [23] informs that the plethora of LGH that could be used for recovery, would have to meet the minimum requirements and would not be beneficial to the system, if it did not comply. The long-distance barrier depends on the variable pipe length, heat supply temperature, pipe diameter, and pipe insulation. Heat losses due to the piping network were experimentally examined by Comakli et al. [24] at the University of Ataturk. The authors observed that by increasing the insulation thickness of the pipes, the heat loss was reduced by 25%. They also noticed that when the supply water temperature increased, the loss of exergy in the hot water distribution system also increased.

The efficiency of the system with the low waste heat provided is also an important aspect, as it can lead to high capital costs per kW generated. Instead of installing a heat recovery system, in cases where installation and recovery costs are very high (and the depreciation does not satisfy the system), it would be more beneficial to waste the low-grade waste heat, as the low temperature of the heat would result in low efficiency for the system and, therefore, the system would not be cost effective. Another technical barrier to the realization of WHR is the implementation of the system and its utilization without any disturbance in the existing plant operations. Maintenance of the LGH recovery system should not affect the plant operations and should not require shutdown of the plant, as this will implement losses in the production of the plant. Additionally, the use of LGH for power generation will not be as beneficial to the plant as opposed to the direct use of the LGH for space heating.

Holman [25] presented and discussed the barriers and limitations to the use of WHR systems in the United States and emphasized the potential for use in the industry. The author also highlighted 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 cost of the exhaust gases cleaning process affects the limitation of the use of the systems, but additionally, during the cleaning process, valuable heat is removed from the system making the system less effective. Another barrier suggested by the author is the available business models. The implementation of a WHR system has two primary risks, namely, (i) the risk of a negative impact of the system on the operations of the company and (ii) the risk of the failure anticipated return. New business models focus on eliminating risks with viable waste heat resources. The availability of financial agreements is also reported to be a barrier.

More recently, the USA Department of Energy [26], in their Quadrennial Technology Review on the Assessment of Energy Technologies, presented a summary of the limitations and barriers to different equipment used with high temperatures and medium temperatures. Limitations were reported for high-temperature range WHR technologies, such as metallic recuperators, ceramic recuperators, recuperative burners, stationary regenerators, rotary regenerators, regenerative burners, and heat recovery steam generators — boilers. Limitations were also reported for medium-temperature range WHR technologies, such as metallic recuperators, recuperative burners, rotary regenerators, shell, and tube heat exchanger for heating liquid (water).

The barriers were further analyzed and categorized by the US Department of Energy [26] in relation to the type of heat available in the industry. Suggestions, in some cases, were given as to how to overcome these technology specific barriers, depending on the waste heat type.

In addition, there are other general barriers [10] that do not relate to the recovery technology used, such as the limitation of available physical space. This limitation cannot be directly solved as the more compact equipment comes at a higher cost. Another barrier is the discontinued operation of the furnace, which interacts with the heat exchangers, as 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 were presented by Brueckner et al. [12], following the work of Pehnt et al. [27], with related suggestions given. Solutions were proposed for financial and administrative, information, production, and technological barriers. The authors suggested the use of a heat pump when the available heat stream has low temperature, and to cascade the use when the temperature is high. In terms of technological barriers, the ease of transportation of heat can help overcome the absence of a nearby heat sink and export the heat to third parties. A very simple solution of using redundant boilers to overcome the boiler reliability barrier is described, but this is in conflict with financial barriers. In terms of financial barriers, waste heat contracting and the use of service providers could be a solution to focus for the core business. Finally, to overcome the lack of information and available data on WHR successful projects for business and research institutes, information campaigns and technology-specific training courses to selected groups could help the WHR systems flourish.

More research and development were suggested by BSC Incorporated [10], in order to further implement the WHR technologies for the impact reduction of the chemical composition of exhaust gases. The authors suggested the following: (i) development of low-cost heat exchangers made of advanced materials that are resistive to harsh environments and can be cleaned and maintained in an easy and cost-effective manner, (ii) development of low-cost gas cleanup systems that can operate at higher temperatures, and (iii) introduction of new concepts of industrial processes that do not introduce chemical contaminants into exhaust streams.

Finally, a major limitation of the industry is the lack of available data [28] on failed or success stories with previous experiences in heat recovery systems.

Publishing these experiences can help the industry assess the economic and technical risk factors. The lack of publicly available data is also emphasized by Hongyou et al. [29].

The sequel of the current paper is organized as follows. First, based on the literature review above, but also on discussions with individuals and companies from the Horizon 2020 project I-ThERM consortium (see http://www.itherm-project.eu/), Sect. 2 presents a summary of the main barriers to the adoption of WHR technologies and ideas on how to address them. Then, a structured questionnaire on barriers, prepared on the basis of the findings of Sect. 2 and issued to a number of EU companies, is presented and analyzed in Sect. 3. Based on the above, a thorough discussion on strategies and recommendations on how to overcome the barriers is reported in Sect. 4. We conclude with Sect. 5.

2 Summing-Up the Barriers

As already seen in Sect. 1, the wide adoption of WHR technologies in industry is hampered by specific barriers, related to technical or non-technical issues. I-ThERM is a Horizon 2020 project, which has as its main objectives the identification and quantification of the WHR potential by industrial processes in the EU, the investigation and evaluation of barriers to the wide adoption of WHR technologies and ways to overcome these barriers, and the development of WHR technologies and equipment that can be readily selected and applied in industry. Hence, based on the available literature and discussions within the I-ThERM consortium, the major relevant 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, and (xi) policy and regulations restrictions. These findings form the basis of the questionnaire issued to EU companies.

Before proceeding with the analysis of the questionnaire, it is useful to summarize the barriers and the relevant suggestions on how to address them, which exist in the literature (see [12, 16, 26, 27]). Table 2 and Table 3 show the barriers (not exhaustive list) with respect to indicative WHR technology and Waste Heat type, respectively. Finally, Table 4 shows the classification of barriers and proposed solutions given.

3 Questionnaire Design and Results

Related to the findings of the previous section, a questionnaire was prepared for EU industries. The questionnaire was about identifying barriers to the wider adoption of WHR technologies and recommendations on how to overcome them. The extent of the questionnaire was kept as short as possible (8 questions) in order to facilitate the completion by each industry representative. Following a pilot survey in Cyprus, the

Table 2 Barriers with respect to WHR technology

Technology	Limitations/barriers
Ceramic recuperator	High initial and relatively high maintenance costs; limitations with respect to building large size units; system life expectancy limitations because of thermal cycling and leaking likelihood from high-pressure side
Heat recovery steam generators/boilers	High initial cost compared to other options, such as recuperators; limitations as to having large size systems (usually > 25 MM Btu/h); limitations with respect to gases used (only clean/particulate free exhaust gases); limitations on viability (only for plants with need for steam use)
Metallic recuperator	Limitation as to the exhaust gas temperature (up to 870 °C); economically not justifiable for temperatures of < 535 °C; economically justifiable heat recovery efficiency of 40–60%; high maintenance costs when using gases with particulates, combustible material or condensable vapors; limitations as to maintaining/cleaning the heat transfer surfaces; problems with fouling and corrosion of the heat transfer surfaces; limitations as to the life expectancy when the mass flow and the fluids temperature of are cyclic or vary
Recuperative burners	Limitation as to the exhaust gas temperature (up to 870 °C); limitations as to the heat recovery efficiency (< 30%); limitations in size availability (usually for burners with < 1 MM Btu/h); cannot be applied to processes with exhaust gases containing particles or condensable vapors
Regenerative burners	Cost competitiveness; limitations with respect to footprint (too large for many applications); limitations as to the control (complex controls with dampers that are not fully sealed/complex pressure furnace control); limitations as to the bed when using gases with particulates (requires frequent cleaning of the media and the bed, which is plugged)
Rotary regenerators	Limitations as to the reliability of maintenance and operation for the rotary mechanism; higher pressure drop than in recuperators; high-pressure to low-pressure gases seals; plugging of passages for exhaust gases with particulates
Shell and tube heat exchanger for heating liquid (water)	Problems with fouling of the heat transfer surfaces when gases contain condensable liquids or particulates; problems with corrosion due to condensation of moisture at certain cold spots
Stationary regenerators	Cost justifiable for exhaust gas temperatures of > 1095 °C and size of > 50 MM Btu/h firing rate; performance declines with time; limitations with respect to footprint (too large); problems with leakage from dampers and moving parts; plugging of passages for exhaust gases with particulates; problems with chemical reaction between some exhaust gas constituents and the heat transfer surfaces

final version of the questionnaire consisted of the following sections: (i) Introductory information about the company and (ii) 8 (+ 1, for comments) questions about energy use, excess heat and its use, barriers preventing heat recovery, and importance of heat recovery.

Table 3 Barriers with respect to Waste Heat type

Type	Limitations/barriers
By-product gases or vapors and process gases with combustibles in gaseous or vapor form	Lack of availability of economically justified vapor concentrators for recovery and reuse of the organic-combustible components, which would prevent the need for heating a large amount of dilution air and for a resulting large-size equipment (the concentrated fluids could be used as fuel in heating systems — ovens); lack of availability of compact heat recovery systems, which would reduce the size of the heat exchangers (large regenerators)
By-products or waste disposed from thermal processes (Chemical, latent and sensible, heat contained in the materials is not recovered prior to the latter disposal.)	High cost of recycling or cleaning up the residues and treating gases or other materials produced during the recovery or treatment process; not a justified economic collection system for hot material; not justified economics of material processing for the recovery of recyclable or useful materials, or combustibles for the use of chemical heat; possible hazardous materials require special treatment; variability of the quantity of recoverable materials
Clean heated water disposed from indirect cooling systems such as process/product cooling and steam condensers. (Solids or gaseous contaminants are not contained in such streams.)	Lack of economically justified heat recovery systems that convert LGH into a transportable and usable form of energy (e.g., electricity); lack of opportunities to use LGH within the plant
Extended surfaces or parts used in furnaces or heaters	High cost and low efficiency for advanced surface-mounted energy conversion technologies, such as thermoelectric systems; no practical way to recover and collect this heat, particularly for systems such as rolls used for a furnace
Heated air or flue gases containing high (> 14%) O_2 but no large quantities of moisture or particulates	Limitations as to the heat exchanger size that prevent the use of retrofit, which may because of heat transfer or design issues such as the size and shape of the heat transfer surfaces (e.g., tubes or flat plates); lack of availability of combustion systems for small sizes (< 1 MM Btu/h) for use of low O_2 exhaust gases as combustion air for fired systems
Relatively clean combustion products of high-temperature or hot flue gases	Reduced thermodynamic potential for more efficient heat recovery because of materials limitations (especially metallic) that require gases to dilute; limitations as to the heat transfer to the flue gas side in heat exchanger systems steam or other power generation (i.e., organic Rankine cycle); problems with sealing for heat exchanger designs with metallic and nonmetallic (ceramic) components, because of dissimilar thermal expansions

Table 3 (continued)

Type	Limitations/barriers
Combustion products of high-temperature or hot flue gases with contaminants (such as condensable vapors and particulates)	High cost and lack of availability of materials designed to withstand the corrosive effects of contaminants; lack of design innovation to allow self-cleaning of the heat recovery equipment to reduce the need for maintenance; lack of cleaning systems (like soot blowing) that allow easy and on-line removal of material deposits on heat transfer surfaces; limitation as to the heat transfer to the gas side of the heat exchange equipment
High-temperature surfaces	High cost and low efficiency for advanced surface-mounted energy conversion technologies, such as thermoelectric systems; limitations as to practical ways to recover this heat, particularly for systems such as rotary kilns or moving surfaces (conveyors)
Hot liquids and vapors, cooled after processing (such as fluids heated in chemical, food, mining, paper, and petroleum refining industries)	Lack of economically justified energy conversion systems; lack of opportunities to use LGH within the plant; requiring sufficient temperature "head" so that there are no technical barriers to WHR
Hot solids, cooled after processing in an uncontrolled way	Limitations as to economically justified cooling air collection system; lack of economically justified energy conversion systems; lack of opportunities to use LGH within the plant; limitations as to their use in combustion systems (burners), due to variability in cooling air temperatures and the presence of microscopic particulates
Hot solids, cooled after processing by a water or an air–water mixture (such as ash, hot coke, slag, and heat-treated parts)	Lack of economically justified energy conversion systems; lack of opportunities to use LGH within the plant
Hot liquids (including water) with dissolved gases (such as CO_2, O_2, SO_2), traceable solids, or liquids	Lack of economically justified energy conversion systems; costly and energy intensive water degasification processes (such as hot water steam injection/stripping deaeration, vacuum deaeration, gas transfer membrane); lack of opportunities to use LGH within the plant; problems with high pH values for water use within a plant due to the presence of CO_2, SO_2, and other dissolved gases
Hot water with large quantities of contaminants (such as solids from the process or other sources), but without organic liquids or vapors	Lack of economically justified energy conversion systems; lack of opportunities to use LGH within the plant
Make-up or process air with large quantities of water vapor and combustion products or moisture with small quantities of particulates but without condensable organic vapors	Lack of innovative designs that allow the use of condensing heat exchangers (gas–water) with no corrosive effects of carbonic acid produced from CO_2 in flue products; lack of designs that allow self-cleaning of heat transfer surfaces in units such as recuperators; problems with rapid performance drop and plugging of conventional heat exchanger

Table 3 (continued)

Type	Limitations/barriers
Steam disposed as vented steam or steam leaks	High cost and slow return on investment for the steam collection, the cooling system, the condensate collection, and, in some cases, the cleaning system
Other gaseous streams	Application-specific barriers

Companies in various EU countries, namely, Cyprus, Greece, France, Germany, Italy, Portugal, Romania, Spain, and the UK, were informed about the questionnaire through partners of the I-ThERM consortium, a Horizon 2020 project. 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 reasons for not having a higher response were, we believe, confidentiality issues and time required to complete the questionnaire.

The respondents, categorized by country, were 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. Also, the respondents, categorized by type of industry, were 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 ranged from medium to large (40 to 800 employees).

The results for each of the questions mentioned in the questionnaire are shown below.

(1) Type of annual energy use at the company:

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

It is clear that most companies still use fossil fuels, electricity, and district heating as energy source, but there are a number of those that use other types of sources, such as biofuel. In terms of total consumption, it ranged from about 1 to about 50 GWh/year.

(2) Do you produce excess heat?

Yes	No	Do not know
30	7	9

Table 4 Classification of barriers and suggested solutions

Classification	Barrier	Solution
Technological	No nearby heat sink (external heat transfer to third parties)	Build heating pipes for heat transport
Technological	No information about nearby heat sinks	Waste heat exchange (information portal); look for neighboring businesses in industrial areas
Technological	Time discrepancy in generation of heat/demand	Use heat in a different way such as power generation or feeding the power grid or storage
Technological	Low temperature levels	Use heat pumps
Technological	High temperature levels	Mix in steam; cascade the use
Production	Boiler reliability	Redundant boilers
Financial and administrative	No availability of investment funds	Provide subsidies or loans
Financial and administrative	Priority on the core business	Use of service providers and waste heat contracting
Financial and administrative	High rate of return expectations	Provide information about life cycle costs
Information	No availability of business knowledge and personnel	Perform information campaigns and technology specific training courses for selected target groups
Information	High research costs	Develop investment calculation tools for consulting engineers and facility operators in the workplace

Of the 46 companies, only 30 responded that they produced excess heat, 28 of which considered the possibility of using the excess heat internally and 8 (not necessarily different companies) externally. Given the type of companies participating in this survey, however, it seems that they could all produce excess heat. Extending the outcome here to the large number of EU companies producing excess heat, it can be considered that there are a significant number of companies that either do not know that they produce considerable amounts of excess heat or do not have the time to consider using it.

(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 to questions (3.1) and (4.1) verify the knowledge and use by companies of almost all known methods for the use of the excess heat either internally (easier for application) or externally (requires specific conditions for application), 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 have not considered installing a WHR 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 to question (5) cover almost all ten barriers to the wide adoption of WHR 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 WHR 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 identified in the literature, are confirmed by the replies in question (6). The "Other" technological barriers mentioned were (i) the restricted use of LGH in the plant and (ii) the high cost of installations without any real effect on the price of product.

(7) In your opinion, what is the most important driver for installing a WHR system?

Energy saving	Environmental benefits	Fuel cost reduction
29	6	11

“Energy saving” was the “winning” option in question (7), where obviously all three options are essentially equivalent.

(8) In your opinion, how can the barriers related to WHR systems be overcome?

The 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, and
(v) increasing the installation incentives.

4 Strategies and Recommendations for WHR Measures

Strategies and Recommendations depend on the type and size of company and the dependence of the price of goods produced on energy costs. This means that if the price of goods is high due to the amount of energy used for production, the company will probably pay attention to recommendations. The questionnaire confirmed that the main barriers to the wide adoption of WHR 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, and (x) policy and regulations restrictions.

4.1 Lack of Information; Lack of Technology Knowledge for Implementation (Barriers i, ii)

Clear awareness about the technology and financial aspects of the relevant application is essential for decision making. Lack of awareness leads to misconception perception and implementation that may cause inefficient or negative results. The ultimate goal is to optimize the overall energy efficiency and, thus, maximize the economic and environmental benefits. The required information should cover information on the best available technologies, technologies that are available locally and provide methods for selecting 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 technologies, define payback periods through a cost–benefit analysis, and define policy goals and parameters. Moreover, technical assistance and collaboration with other relevant entities should be established.

4.2 Technology Risks (Barrier iii)

The failure of technology to meet specifications may be due to the lack of adequate technological infrastructure, technological innovation, or strained technical capabilities. The complexity of the technical application and the unrealistic schedules and budgets can also present risks. Lack of a measurement system for risk control risk and inadequate project management and monitoring can also cause implementation failure. The implementation of new systems and technology may present new challenges and new risk factors that need to be addressed differently. Risk means dealing with a problem that has not occurred before, but could cause losses or put in jeopardy the success of the new technology application. An investigation on the matter has shown that the causes of project failures are due to ineffective leadership and communication failures, as well as due to poor technical methods. Issues of organizational suitability (including poor specification of requirements, time and project scope or conflicts of people), skill mix (inappropriate staff and lack of application-specific knowledge), management strategy, and other may interfere and should be avoided.

4.3 High Initial, Running, and Maintenance Costs (Barrier iv)

For the success of an application all assets and their effective management are essential. Assets must be planned and monitored throughout their life cycle, from the development stage to their final disposal. Money value optimization can be achieved by considering all the cost factors associated with the asset during its operation. Life cycle costing involves estimating the cost over a lifetime basis, before choosing to purchase and install an asset from the various alternatives available. The life cycle cost of an asset can be several times the initial cost of purchasing or investing, so it is important for management to appreciate the source and magnitude of lifetime costs and take effective action to control it. The short-term approach to saving money by simply buying assets with lower initial acquisition costs does not lead to wise decisions. It is therefore suggested that for each project the life cycle costing should be done and include the initial, running, and maintenance costs, in order to show the true value of the investment for decision making.

Short payback time will give a strong incentive to highly commercialized producers to install any energy efficiency innovation. Also, cost reduction can be achieved through technological innovation. Finally, demonstration projects or independent feasibility studies can be presented and described as beneficial to companies.

4.4 Lack of Financial Support and Lack of Governmental Incentives; Policy and Regulation Restrictions (Barriers v, x)

The more favorable the business environment is, the more likely it is for businesses to 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 potential solution. Entrepreneurs are encouraged and feel competent to expand when entrepreneurship is valued, when new opportunities arise and when entrepreneurs have sufficient knowledge and skills. The willingness and ability to change traditional techniques can be further improved if potential entrepreneurs do not encounter obstacles during the process, when they are confident that they can easily gain external expertise, if necessary, and have the financial means.

Governments directly and indirectly influence the development of the environment to support entrepreneurship. Many government incentives can help grow entrepreneurship. Options include the provision of public procurement programs, venture capital, and tax-based incentives. Also, the protection of patented ideas and innovations by government agencies as well as public investment in education and research further enhance the implementation of new ideas in business.

Financial assistance can be provided by venture capital and alternative funding sources, low-cost loans, and the readiness of financial institutions to finance especially small entrepreneurs and credit guarantee programs managed by financial institutions.

Policy and regulatory restrictions are also the subject of the techno-economic study. Support should be sought from government agencies, and any measures proposed should be followed.

4.5 Size and Available Space Limitations; Lack of Available Infrastructure (Barriers vi, vii)

Space limitations may occur if a minimum efficient size is implemented to a process. In such a case there is no choice but to redesign the process space and create space for the new implementation. Financial means will be needed and a life cycle cost analysis will show the viability of the new implementation.

In terms of available infrastructure, an appropriate detailed study should be conducted by management to demonstrate its ability to take on new tasks. A study by competent and qualified consultants will suggest measures to overcome inefficiency.

4.6 Production Constraints and Risk of Production Disruptions; Risk of the System Negative Impact on the Company Operations (Barriers viii, ix)

During the implementation of the new task, production constraints and the risk of production disruptions may affect the company's production. This will of course have a temporary negative effect on business production and must be considered in the techno-economical study (life cycle cost analysis) that will be carried out before the start of work. Caution should be exercised in cases where the normal life expectancy of the installed WHR technology installed may differ from the remaining process plant lifetime. The minimization and mitigation of such risks can be achieved through demonstration projects or independent feasibility studies. The cheapest method does not always lead to the best result. An appropriate technical study by competent and qualified consultants should consider any negative impacts and suggest measures.

5 Conclusions

In the current paper the main barriers to the wide adoption of WHR technologies in the EU industry were identified and analyzed. A structured questionnaire on barriers, distributed to companies in EU countries, received 46 valid responses from 11 EU countries, which were analyzed. One can conclude that the considered theory of barriers to the adoption of WHR technologies has been confirmed. Following the recommendations and strategies for WHR measures presented in Sect. 4 above, actions remain to be taken as future goals.

More contacts between researchers and WHR technologies experts with key stakeholders in relevant industries with WHR potential will help to fully shape and finalize research objectives on technologies and barriers. Greater emphasis could be placed on the relatively low importance attached to energy efficiency and therefore on the limited resource committed to energy management compared to other corporate priorities. Encouraging companies to commit additional resources to more sophisticated energy monitoring was suggested by the questionnaire respondents to help energy managers identify and build business cases for appropriate WHR technologies.

The development of new WHR technologies and equipment that can be readily selected and applied in industry is an obvious research objective, and any such technologies can be proposed in the form of case studies. When proposing potential WHR options applicable to specific industries, it is important that technologies match the appropriate industrial processes.

For example, the following four main technologies [30] provide a cross section of different types of technology, which could have significant application potential and include areas where there is detailed technical expertise:

(i) Flat heat pipes (FHP), which can be used to recover heat from industrial processes either by conduction, convection, or radiation from waste heat sources with a variety of heat pipe types using various fluids. The rationale for this option is that FHP can function in different environments and at a variety of temperatures depending on working fluid used.
(ii) Supercritical carbon dioxide cycles (sCO2C), which can be designed with multiple heat exchangers and turbomachinery configurations and can be constructed to achieve high overall efficiency for different temperatures and/or pressures, which can benefit a particular cycle application.
(iii) The trilateral flash cycle (TFC) includes only liquid heating and two-phase vapor expansion. TFC systems can produce higher outputs than simple Rankine cycle systems for power recovery from hot liquid streams at temperature of 100–200 °C.

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Declarations

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