Design and development of a database to identify and evaluate waste heat recovery opportunities

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Abstract: The continuous search for energy efficiency in the industrial sector, driven by the need to reduce polluting atmospheric emissions and the increase of fuel prices, has made waste heat recovery systems one of the most promising research areas in the last decade. Heat recovery at low temperatures (below 230 °C) is mainly investigated for industrial applications. Despite a large amount of waste heat available at this temperature, the introduction of heat recovery technologies is limited by the lack of proper knowledge about different existing solutions and their application in similar contexts. Therefore, to overcome these limitations, this paper describes the development of a database to provide a comprehensive view of all relevant projects and technologies available for waste heat recovery. The work here presented is the result of the first year of a three-year research project, whose final aim is to provide innovative tools to support companies in identifying, analyzing and evaluating thermal recovery opportunities. Through a systematic literature review, the most used technologies and methodologies in low-temperature heat recovery have been identified. From these results, a preliminary version of the database has been defined, containing the classification criteria and the most useful information to be retained in order to characterize both technologies and projects. This database will represent a key element to develop a comprehensive methodology, that starting with the evaluation of energy flows in the organization, will then allow the identification of heat recovery opportunities applicable in the specific case. In the next years, in collaboration with the Italian National Agency for New Technologies, Energy and Sustainable Economic Development, the proposed tool will be consolidated with the involvement of the important stakeholders.

Keywords: Waste heat recovery; Low-grade waste heat; Energy efficiency; Industrial sustainability.

1. Introduction

A multitude of waste energy flows characterize industrial processes at different temperatures. The waste heat recovery processes consist of capturing heat from these energy flows, to use it directly, raise it to a required temperature level, use it for cooling or convert it into electricity (Panayiotou et al., 2017). 70% of the total energy consumption in the industrial sector derives from thermal processes and up to a third of this energy is typically dispersed (Agathokleous et al., 2019). In Italy, the waste heat potential for the industrial sector is estimated at 27 TWh/year (GSE, Gestore dei Servizi Energetici, 2016). In this regard, industrial waste heat recovery systems appear as one of the most promising research areas, driven by the aim of reducing energy needs and therefore fuel consumption, with consequent improvements in energy costs and environmental impact (Jouhara et al., 2018).

A wide range of methods and equipment is available for thermal recovery of waste heat from industrial processes. There are different ways to classify recovery approaches and technologies; one of these consists of using the temperature at which the waste heat source is available for recovery. As reported in Table 1, applications can be divided into five categories: very high, high, medium, low and very low temperatures (Thekdi and Nimbalkar, 2015).

Table 1: Classifications by temperature range (Thekdi and Nimbalkar, 2015)

Range	Temperature [°C]
Ultra-low temperature	<120°C
Low temperature	120°C–230°C
Medium temperature	230°C–650°C
High temperature	650°C–870°C
Ultra-high temperature	>870°C

The focus of this research is dedicated to thermal recovery at low and very low temperatures (temperatures below 230°C) since most of the waste heat is available for recovery at temperatures between 100 and 200°C (Papapetrou et al., 2018), which shows the enormous potential of these technologies. However, their introduction and application are limited by numerous barriers, mainly due to the lack of proper knowledge about different existing solutions and to technical and economic difficulties, since low conversion efficiencies, typical of low temperatures, are generally characterized by relatively long payback times (Simeone et al., 2016). Furthermore, we are often faced with a not simple alignment between the source of residual heat and the demand to be satisfied (Xu et al., 2019).

To give an example, the recovery of the residual heat of compressed air is one of the best improvement actions in terms of energy-saving rate for a compressed air system, but it is characterized by a relatively long payback period (PBP) (Benedetti et al., 2018).

For ultra-low temperature heat recovery, there are several possible solutions: versatile technologies such as heat pumps to increase the temperature level of the source or the conversion of waste heat into electricity are particularly effective and promising (Van De Bor et al., 2015), (Hammond and Norman, 2014).

The work presented in this paper is the result of the first year of a three-year activity, which has as its primary objective the development of innovative tools to support companies in identifying, analyzing and evaluating thermal recovery opportunities. The main activity has been the structuring of a database capable of containing opportunities and technologies for the thermal recovery of waste heat from industrial processes. In this first year, the aim of the research is the preliminary development of tools that will be validated and refined over the three years.

This paper is structured as follows. Section 2 describes the context analysis carried out through a systematic literature review to identify the most used technologies and methodologies in low-temperature heat recovery. Section 3 describes the activities carried out for the preliminary development of the technology database, while Section 4 discusses the main critical issues encountered and contextualizes the work presented in this paper within the broader research project. Finally, in Section 5, the next steps of the research are discussed.

The reference sector for the research project is the industrial sector while, as regards geographic boundaries, the application context of the developed tools is the Italian industrial context.

2. Literature review

In order to implement useful tools to guide companies in the evaluation and optimization of waste heat recovery processes, it was first necessary to define a detailed state of the art regarding the potential opportunities and technologies available today in the industrial sector. The contents of existing projects and similar databases were analyzed, to extract useful information about the structure, characteristics, and requirements of the database to be created.

In the first part of this literature review, several European projects have been identified. Although referring only to a part of the theme of heat recovery (e.g. projects related to different efficiency opportunities or specific to some technologies or industrial sectors), they have provided valuable contents for the development of this research project.

The "EINSTEIN" and "Greenfoods" projects are both European IEE (Intelligent Energy Europe) projects developed with the objective of increasing efficiency in the use of energy, mainly thermal, in the industrial field, carried out through an optimization of the processes, aimed at reducing energy needs, and a research of opportunities for heat recovery. The industrial facilities to which the projects were addressed are mainly represented by small and medium-sized enterprises (the Greenfoods project was focused on the food and beverage sector), where energy audit costs, specific skills in the sector and a limited budget for energy-saving projects can represent important barriers to the introduction of efficient technologies (Brunner et al., 2010), (Fluch et al., 2017).

The main results of the two projects are represented by guides and software tools capable of providing support for companies and auditors in the various steps of an energy audit: preparation of the visit, acquisition of data, design and energy and economic evaluation of possible solutions. These tools allow an easy, quick and complete assessment of energy efficiency measures for the companies operating in the industrial sector.

The EU-MERCI provided particularly useful inputs to the presented work project, a European project that is part of the Horizon 2020 funding program (The EU-MERCI project, n.d.). The most significant output of the project is represented by the development of a database containing energy efficiency. Although the EU-MERCI project was not focused exclusively on the thermal recovery of waste heat but investigated several kinds of energy efficiency projects, the analysis of the structure of its database was significantly useful. Specifically, the definition of the identified fields and the queries made available to the user for database consultation constituted a valuable starting point for the realization of this work.

Besides, an in-depth investigation of the significant scientific literature of the sector was carried out to identify the recovery technologies available and the recovery projects already implemented. The information was collected for the primary purpose of providing input to the definition of the database structure and supplied for its population.

The analysis of the literature was carried out using the SCOPUS online database (www.scopus.com).

Elaborated from (Durugbo et al., 2013), the approach used consists of three main steps:

• Selection: the input keywords are formulated, and the articles are found;

• Evaluation: this is a first screening of the articles based on the analysis of the abstracts, the non-inherent articles are removed, and the content of the articles deemed associated is deepened;

• Classification: the articles are divided into categories based on their content.

Figure 1 shows a schematic representation of the presented methodology.

For this literature review, no geographical boundaries were considered for the search for articles and, to obtain an appropriate number of articles that can be analyzed, the research is limited to a period between the years 2000 and 2019 and to use the combination of keywords "heat recovery", "low temperature" and "industrial" (in article title, abstract and keywords).

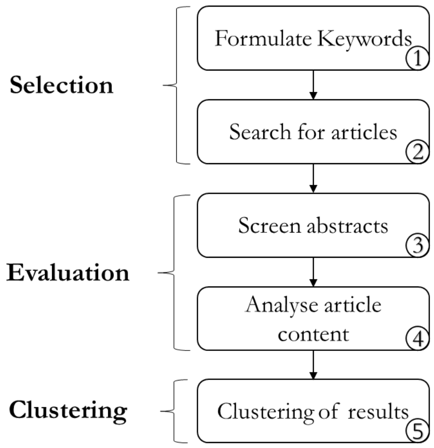

Figure 1: Review methodology

This research, done in December 2019, produced a total of 547, Figure 2 shows the number of documents for each year of publication. It is interesting to note that the issue of low-temperature heat recovery is clearly described by an actively growing interest in the last decade.

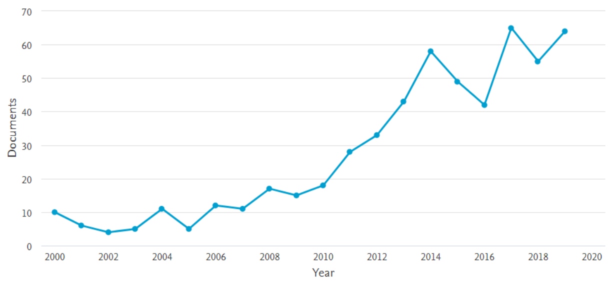

Figure 2: Number of documents per year of publication

Limiting the results to the English language (506 results) and considering, as document type, Article (291), Conference paper (163), Conference review (19) and Review (17) the research produces 490 results subdivided by source type in 307 Journal, 144 Conference proceedings, 29 Book series and 10 Trade journal.

The first screening was done by the authors matching the documents detected with the boundaries of the project, in particular, waste heat recovery applications/technologies at low and very low temperatures (temperatures below 230°C) and the relevance to the industrial sector. This activity identified 333 articles within the boundaries of the research project, which were therefore analyzed and divided into categories.

2.1 Review results

Suggested by (Brückner et al., 2015), a useful way to classify waste heat recovery technologies can be carried out according to its intended use. The categories identified with a brief description of them and the number of documents detected for each are shown in Table 2. In Figure 3, through a pie chart, the percentage population of the defined categories is represented.

The results of the research showed that the most represented categories were heat recovery for electricity production and heat recovery for heat production. In particular, the Organic Rankine Cycles (ORC) to produce electricity and the different types of heat pumps to provide thermal energy have been the most represented technologies (with 72 and 41 results, respectively).

Table 2: Categories

Categories	Description	Number
Waste Heat to Power	Applications in which the heat recovered is used for conversion to electricity.	116
Waste Heat to Heat	Applications, where the heat recovered, is used to produce thermal energy	51
Other Approaches	Not usual methods and applications of heat recovery.	36
Energy Storage	Applications where the recovered heat is destined for storage (thermal energy storage).	32
Heat Exchange	Components, design, materials and fluids for heat exchange.	28
Review	Analysis of literature on technologies, methods, materials and exchange fluids.	25
District Heating	Large-scale heat recovery applications.	21
Hybrid Solution	Applications where the recovered heat is used for the combined production of different energy carriers (electricity, hot, cold).	13
Waste Heat to Cold	Applications, where the heat recovered, is used to produce cooling energy.	11

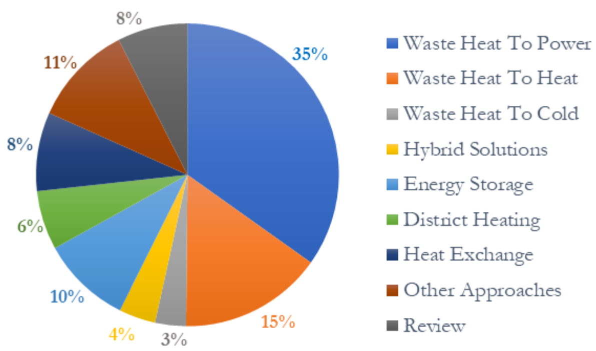

Figure 3: Review results

3. The Database

The presented literature analysis has allowed identifying what could be an appropriate database structure to be implemented. The database must be a tool to support the company in the search for waste heat recovery opportunities. Therefore, we need to create a system that can be as complete as possible, but at the same time simple in use and consultation. The database developed is a tool that will be integrated into a more extensive software system. Through the database, the user, by entering specifically requested input data (section 3.3) can consult the potential technologies that can be implemented for the specific case under consideration. These possible solutions can then be further investigated thanks to decision support elements developed within the project (introduced in section 5).

In this phase of the project, the database is in a preliminary state. It will be validated and perfected over the next two years of research, to increase and evaluate the state of maturity of the technology (e.g. by the Technology Readiness Level metric).

3.1 Database's fields

The approach adopted was to define a structure capable of containing projects of different nature from the most varied sources available, such as literature articles, findings from similar projects and databases already integrated, technologies available from suppliers, theoretical systems, field surveys not available in the literature. Categories relating to three main areas have been identified: general information, technical information and financial information.

Among the general information, there is information relating to the source from which the survey originates, to guarantee easy retrieval; the description of the project; information relating to the state of implementation of the project and the company that adopts it.

The technical information contains specifications regarding the type of heat recovery. It is necessary to characterize the heat source and the flow to which it will be transferred to evaluate the feasibility of heat recovery of the residual heat. Therefore it is required to have information about the quality of the heat to be recovered (temperature), the quantity of heat available; type of fluids involved; availability (Johnson et al., 2008). Besides, information about the used technology is provided.

The last category includes economic parameters: achievable savings, necessary investment and the investment payback time (PBP). These parameters were included as they are fundamental for the company in choosing the type of project, like the technical parameters. However, it should be noted that these economic indices are not exclusively related to technology but will also depend on operating conditions.

Table 3 shows a description of the fields included in the preliminary version of the database.

Table 3: Database's field

Field	Description
ID	Numeric code to identify the measure in the database.
Source	Type of source from which the recovery project or technology was obtained (e.g. literature, similar projects/databases, technology suppliers, etc.).
Source reference	Identifying information of the source to ensure its retrieval (e.g. "doi", URL, etc.).
State of maturity	It represents the state of maturity of the project (eg. implemented, not implemented)
Year	If the measure is implemented, it shows the year of implementation.
Country	It shows the country in which the measure is implemented.
Size	It defines the size of the company that has put in place the heat recovery project: Small < 50 employees; Medium from 51 to 250 employees; Large > 250 employees;
Sector	Standard code (ATECO) used to identify the sector in which a company operates.
Description	Full textual description of the adopted measure
Process	The process from which the heat is recovered
Heat source type	Source from which the heat is recovered (ex. hot water, exhaust gas).
Source temperature	The temperature of the source from which the heat is recovered.
Source flow rate	The mass flow rate of the source from which the heat is recovered.
Availability	Heat source availability.
Recovery type	Indicates the destination of the recovered heat (e.g. heat production, cold production, electricity production, etc.).
Technology	Representative technology of heat recovery (e.g. heat pump, heat exchanger, ORC, etc.)
Output carrier	Energy carrier (s) available as an output to the recovery project (e.g. hot water, hot air, cold water, electricity, etc.).
Dimension	Size required by the equipment for the heat recovery project.
Primary energy saving	The total annual savings achievable or achieved thanks to the implementation of the project are reported.
Calculation method	Specifies which input has been used for the calculation of saving items (invoices, standard methodologies, meters, estimates, etc.).
Investment	it represents the cost of implementation of the project
Pay Back Period	it is the period after which the investment is completely paid back.
Subsidy	it is a field that specifies if the measure has received any subsidies.
Assumptions	Assumptions adopted for the calculation of the previous parameters (e.g. cost of electricity and gas etc.).

3.2 Database population

In this first phase of the study, an Excel worksheet was used for the creation of the database, with the possibility of developing a dedicated IT support at a later stage of the project. Based on the results of the literature analysis, the first population of the database was then conducted to verify the adequacy of its structure. This preliminary population was addressed from a methodological point of view, with the aim of inserting surveys from the different types of sources, to test the versatility of the proposed structure. In particular, findings from:

1. Scientific literature;
2. Existing similar projects;
3. Technology suppliers;
4. Field surveys.

The population of the database will be completed in the following two years, to extend the number of findings and systematize the process, introducing compilation rules and techniques to facilitate the "consistency" of the data and their analysis. The introduction of rules, such as the normalization of categories, has shown that it can make a significant contribution in similar applications (The EU-MERCI project, n.d.).

3.3 Database consultation

The last phase of the database construction was dedicated to the interaction between the database and the user, with the analysis and identification of the queries. The criterion chosen to select the most appropriate queries was to encourage the use and the understanding of the developed tool. For the identification of the basic queries, we started from the knowledge of what must necessarily be the information available to the user to allow a preliminary evaluation of a possible heat recovery intervention.

The selected queries include both technical and financial aspects. Table 4 shows the chosen queries with a description of them.

Each of the available queries consists of a closed field, through which the user can choose from predefined options, and for each query, it will be possible to select multiple preferences. The queries will be divided into mandatory fields and optional fields which need not be selected. In this first version of the database, the only compulsory query identified is the source temperature, as it is essential and discriminating information in the evaluation and choice of the most appropriate technology for a potential opportunity for thermal recovery of waste heat.

To give an example, the user can search through the database for heat recovery technologies divided into different temperature ranges: ≤50°C; 50°C<T≤100°C; 100°C<T≤150°C; 150°C<T≤200°C; 200°C <T≤230°C.

Table 4: Queries

Query	Description
Source temperature	Indicates the temperature at which the heat destined for recovery is available (for defined selectable temperature ranges).
Source type	Type of carrier available for heat recovery.
Recovery destination	Indicates the output of interest from the heat recovery project (e.g. heat production, cold production, electricity production, etc.).
Sector	Standard code (ATECO) used to identify the sector in which a company operates.
State of maturity	Type of project/technology to consult (e.g. implemented project, technology suppliers, theoretical application, etc.)
Investment	The initial investment is necessary for the implementation of the project (for defined selectable ranges).
Pay Back Period	Expected Pay Back Period.

4. Discussion

During this work, the database population has been the most relevant difficulties encountered. The critical point of this preliminary population was the pursuit of its completeness, due both to the type of sources used, mostly coming from bibliographic research and to the chosen structure with a large number of fields to fill in. The quantity and quality of information available are highly dependent on the type of source and, from many of these, was not easy to obtain the whole population of all fields. However, it was preferred to maintain a more complex structure of the database since, if available, all the information described above can contribute significantly to the assessment of the feasibility of a heat recovery intervention.

For each category, at least in this preliminary phase, compilation options such as "information not available" or "not applicable" can be selected from the options. Furthermore, for some fields of the database, multiple choices are available, because it is common that a single project can involve various waste fluids, different technologies or uses of heat. Also, the database contains fields that can be filled in with free text and others to be completed with options of your choice. In the future version, to facilitate the population and consultation of the database, the compilation with free text will be minimized.

The final definition of the categories of the database will be completed in parallel with the progress in its population. As necessary for the definition of the categories, the same consideration can be made for the selection of the queries. The purpose of the queries is to request data from a database. At the moment, the queries have been defined through the results of bibliographic research; then, a consistent evaluation period will be necessary for their development. In this regard, as envisaged in the following two years of the research project, the involvement of interested parties, that will provide feedback on the effectiveness and usability of the tool, will be essential.

The future development of this project is to design a comprehensive methodology capable of supporting companies in the overall analysis of the feasibility of a heat recovery intervention. The method starts with the evaluation of energy flows in the organization, will then allow the identification of heat recovery opportunities applicable in the specific case.

The presented database will represent a key element to develop such a methodology. Once the necessary information has been identified, the user through the use of queries the database can request data from the database to identify potential thermal recovery technologies that can be implemented for the particular case under consideration. These technologies will then be analyzed in detail in the subsequent phases of the methodology

Inspired by (Simeone et al., 2016), this methodology provides five main steps:

1. Waste heat characterization: a collection of information, the significant variables and all the data needed to conduct the subsequent analysis of energy flows and the assessment of the possible solutions for heat recovery;

2. Quantitative and qualitative analysis of waste heat: report of the energy flows involved following the good practices detected during the bibliographic research activity, in particular, the generalization of the exergy analysis deduced from the methodology proposed by (Woolley et al., 2018);

3. Technologies identification: using the database of available technologies and recovery opportunities, possible solutions are identified, based on the key parameters defined in phase 1 and a first assessment of the possible destinations of the waste heat;

4. Analysis of the possible solutions: in analogy with the methodology proposed by (Oluleye et al., 2016), through the potential use of dedicated simple mathematical models, the different technologies and solutions for heat recovery identified will be analyzed and evaluated;

5. Decision support: the analyzed solutions will be compared with each other through the use of technical parameters (such as conversion efficiency, efficiency, percentage of exploitation of the waste heat source, primary energy savings, etc.), economic parameters (initial investment, Net Present Value, PBP, etc.) and environmental parameters (CO_2 emissions).

In Figure 4 is shown the flowchart of the proposed methodology.

This methodology, preliminarily available at flowcharts level, will be studied in depth during the following two years of research, particularly in the characterization of models representative of the main types of technologies available for heat recovery (Organic Rankine Cycle, heat pumps, etc.). The development of these models will allow a detailed analysis of the different potentially applicable technologies, allowing a more effective evaluation of the potential and the characteristic parameters of heat recovery.

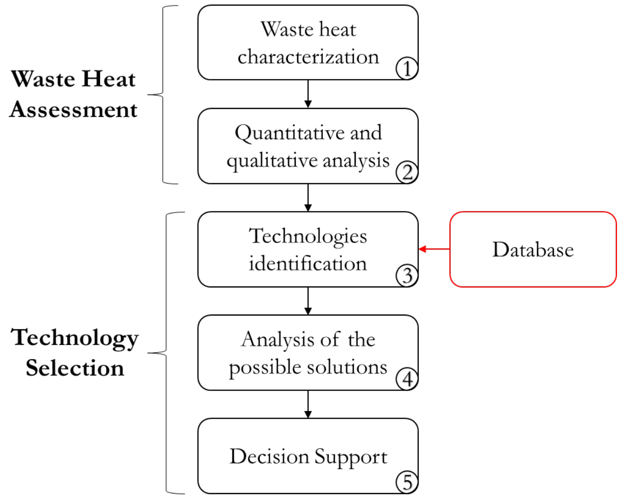

Figure 4: Flow chart of the proposed methodology

5. Conclusion

In this research work, a preliminary version of a database that can provide useful support to companies for the search and selection of heat recovery opportunities has been proposed. In particular, the most representative activities were the selection of the database fields and the identification of the queries for its consultation. Furthermore, in order to verify the structure of the database, a preliminary methodological population was conducted.

In this first phase, it was preferred to maintain a database structure with a large number of fields (twenty-four) which, although it showed problems with regards to completeness in the population, was considered the most suitable, as it contains all the useful information in evaluating a heat recovery opportunity/technology. However, in a subsequent phase of the project, it will be possible and essential to compare with interested parties, such as companies, ESCOs (Energy Service Companies), and technology suppliers. They will be able to give an assessment of the practical usability of the tool and contribute to any necessary changes.

At the same time, we defined the fundamental phases for the development of a methodology that allows evaluating, from a qualitative and quantitative point of view, the energy flows involved in the recovery processes thermal. This methodology, initially proposed at the level of the flowchart, will be studied during the following two-year research period.

The developed tools were subjected to a first theoretical validation using the results of the bibliographic research carried out. However, since these tools are intended for use in the industrial context, an essential experimental validation campaign will be required. In fact, in collaboration with the Italian National Agency for New

Technologies, Energy and Sustainable Economic Development, the next steps of the research will foresee the organization of meetings involving the suppliers of heat recovery technologies operating on the Italian market and companies operating in the industrial sector potential users of the developed tools.

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