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Decarbonization of Heat through Low-Temperature Waste Heat Recovery: Proposal of a Tool for the Preliminary Evaluation of Technologies in the Industrial Sector

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Abstract: In an industrial energy scenario increasingly focused on decarbonization and energy cost containment, waste heat is a resource that is no longer negligible. Despite the great abundance of waste heat, its recognized potential, and numerous technologies available for its use, the rate of waste heat recovery (WHR) is still low, especially at low temperatures (<230 °C). Non-technological barriers, such as the lack of knowledge and support tools, strongly limit the diffusion of WHR technologies. The work presented in this paper aims to overcome non-technological gaps by developing a simple and operational tool that can support companies in the preliminary stages of evaluating a WHR application. The methodology followed involved the development of specific data-based models for WHR technology sizing by correlating waste heat input characteristics with dimensional and economic parameters of the technologies evaluated. We considered the most representative technologies in the WHR scenario: organic Rankine cycles for electric power generation, heat pumps for thermal power generation, absorption chillers for cooling generation, and plate heat exchangers for low-temperature heat exchange applications. One of the significant strengths of the tool is that it was developed using real and hard-to-find technologies performance and cost data mainly collected through continuous interactions with WHR technology providers. Moreover, the interaction with the technology providers allowed contextualization and validation of the tool in the field. In addition, the tool was applied to three large companies operating in the Italian industrial sector to test its effectiveness. The tool applications made it possible to propose cost-effective solutions that the companies had not considered before, despite the high level of attention with which they were already approaching energy efficiency improvements. The result obtained demonstrates the applicability and innovativeness of the tool.

Keywords: waste heat recovery; organic Rankine cycle; heat pumps; energy efficiency; industrial sustainability; carbon neutrality; decarbonization

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1. Introduction

The European Union (EU) aims to be carbon neutral by 2050. This objective, including the intermediate target to cut greenhouse gas emissions by at least 55% by 2030, is challenging and urgent simultaneously. In addition to increasing renewable energy production, improving energy efficiency and optimizing resources will also play a key role, especially in those sectors that are particularly energy-intensive such as industry [1].

Waste heat is a primary source of recoverable energy loss, offering significant potential for greenhouse gas emissions reduction. Total waste heat emissions account for 23.0–53.0% of global input energy, with a range of theoretical recovery potentials of 6–12% [2]: waste heat recovery (WHR) is considered one of the key factors for achieving carbon neutrality [3].

The industrial sector accounts for approximately one-third of global final energy consumption, on which depends 20% of global CO_2 emissions [4]. According to [5], these significant percentages of emissions are mainly due to processes that require heat, mostly in the form of hot water and steam [6]. It is estimated that approximately 70% of the total energy use in the industrial sector is related to thermal processes, and up to one-third is lost as waste heat [7]. Moreover, most of this heat is available at low temperatures, which makes its reuse more complicated and less attractive [8]. The industrial sector has one of the greatest availabilities of waste heat at low temperatures. According to [9], approximately 66% of the total waste heat in the industry is available at a temperature below 200 °C. On the other hand, the industrial sector is technologically advanced and has all the potential to make the most of this resource [10].

Even for low-temperature heat, defined as heat at temperatures less than 230 °C [11], there are various possibilities for reuse. Recovered heat can be reused directly in other processes that require heat at a lower temperature, it can be reused by increasing its temperature, or it can be converted into other forms of energy such as cooling energy or electricity. Many low-temperature heat recovery technologies have been developed. Nowadays, the market offers various mature technologies such as organic Rankine cycles (ORC), heat pumps (HP), plate heat exchangers (PHE), absorption chillers (AC), and many other technologies under development such as thermoacoustic technology, piezoelectric and pyroelectric generators, ultra-high-temperature heat pumps, and micro-ORC systems [12]. Despite the great potential of this resource due to its wide availability and the presence of numerous technologies for its recovery and reuse, the number of WHR applications in the industrial sector is still low. This aspect is due to the presence of numerous barriers that are accentuated when we consider low temperatures.

While for high-temperature waste heat, most companies present viable recovery potentials [13], low-temperature WHR forces consideration of a more significant number of opportunities, with interventions individually less economically important and challenging to implement. The barriers to low-temperature heat recovery are of various kinds: technical, informational, economic, and organizational. Of these, the lack of knowledge and the absence of support tools limit the diffusion of WHR technologies [14]. Companies find the most significant difficulties primarily in the preliminary stages, leading to the implementation of a heat recovery technology: from identifying waste heat to selecting implementable technologies, and especially, evaluating the costs and benefits of their implementation.

This paper aims to overcome this gap by developing an easy-to-use tool to support companies in evaluating low and very low-temperature heat recovery applications. The tool allows for obtaining a preliminary analysis of the potential of heat recovery of the most representative technologies in the industrial scenario and an estimate of the achievable performances. The proposed tool focuses on developing models based on real data selecting the most representative technology in the WHR scenario: ORC for electric power generation, HP for thermal power generation, AC for cooling generation, and PHE for low-temperature heat exchange applications.

The work presented in this article is part of a three-year project carried out by the research group of the Tor Vergata University of Rome and other Italian universities and coordinated by the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA), aimed at increasing the diffusion of WHR applications in the industrial scenario by preventing non-technological barriers. The tool proposed in this article represents a key element of a larger research project. The research team's goal was to create a tool that is perfectly placed in the industrial context and can be integrated with the energy efficiency tools commonly used by companies. For example, this tool can represent a valid support for a company in conducting an energy audit according to the principles introduced by the Energy Efficiency European Directive 2012/27/EU or in the search for efficiency measures in an ISO 50001 Energy Management System. To this end, the development of this tool saw numerous interactions between the research team and essential industry stakeholders: 20 interviews were conducted with heat recovery technology providers and similar national and international projects. The tool was also tested on three large companies operating in the Italian industrial sector.

The paper is structured as follows: Section 1.1, i.e., Background, presents a comprehensive overview of existing methodologies and approaches for evaluating WHR applications; Section 2, i.e., Methodology, describes the activities carried out to develop the WHR preliminary evaluation tool. Section 3 describes the results obtained from the application of the tool in the three case studies considered, discusses the main issues encountered in applying the tool, and compares the result obtained. Finally, Section 4 highlights the paper's objectives, the significant results obtained, and the next steps of the research.

Figure 1 shows a schematic representation of the approach followed in this work.

Figure 1. Research flowchart.

1.1. Background

WHR technologies can be classified according to the intended use of the recovered waste heat: it can be used directly (at the same or lower temperature level), it can be converted into another form of energy (electrical or cooling energy), or used at a higher temperature [15].

We can identify four categories of heat recovery:

1. **Waste heat to heat**: contains technologies through which recovered waste heat is used to produce thermal energy at a higher temperature level (e.g., heat pumps, mechanical steam compression);
2. **Waste heat to cold**: contains the technologies through which recovered waste heat is used to produce cooling energy (e.g., absorption and adsorption chillers);
3. **Waste heat to power**: contains the technologies through which recovered waste heat is converted into electricity (e.g., organic Rankine cycles, Kalina cycles);
4. **Heat exchange**: contains the technologies through which the recovered waste heat is used directly at the same or lower temperature (e.g., plate heat exchanger, thermal energy storage systems).

Among these categories, ORCs for electric power generation, heat pumps for thermal power generation, absorption chillers for cooling power generation, and plate heat exchangers for directly reusing waste heat are the most popular and mature technologies for low-temperature heat recovery [14,15]. The relevance of the technology to industry, the technological maturity, and the availability of data and information are the motivations that led the authors to investigate these four representative technologies in detail.

Several methodologies for sizing heat recovery technologies exist in the literature, but they are often not easy to use due to their high level of complexity. These approaches are usually dedicated to individual technologies, not providing a comprehensive view of the industrial waste heat recovery scenario.

The following paragraphs describe the primary methodologies and tools in the literature for sizing heat recovery technologies. The purpose is to get a clear overview of the most used approaches and analyze their strengths and limitations.

In [16], the optimization of ORC plants is solved using a two-level approach that includes fluid selection, the determination of operating conditions, and equipment sizing, while in [17], sizing is optimized using an algorithm, the objective function of which is set to meet the electrical power requirement. The paper [18] presents a multi-objective optimization method comparing different solutions (e.g., different working fluids) to obtain the best exergy and environmental performance of the ORC configurations. In [19], an ORC design and optimization methodology based on the "Design to Resource" method is used, which considers all necessary design variables and optimizes thermodynamic efficiency and economic feasibility. In [20], the proposed methodology integrates the techno-economic optimization of the Rankine cycle and the optimization of the layout and sizing of the heat exchanger network. This method allows for complete techno-economic optimization of the entire system; however, the resulting problem is a complex nonlinear mixed-integer system, which can only be solved with an ad hoc algorithm. Finally, the paper [21] proposes a complex method that considers practical aspects such as component limitations and costs.

Regarding heat pumps, in [22], the performance and potential of these technologies are examined, and their competitiveness in very low-temperature ranges (45–60 °C) is demonstrated. Pátek, J et al. presented a new heat pump prototype equipped with a modified scroll compressor and internal heat exchanger [23]. In addition, this paper provides a reference for the study of heat pump heat recovery from low-quality waste heat streams from industrial processes.

The work presented by [24] proposes a numerical model of the system in which the absorption chillers' generation process is simulated. In [23], on the other hand, a set of five equations describing the vapor–liquid properties of the ammonia–water system was developed from experimental data, which allows for the study of absorption cycles without resorting to iterative evaluations. In [24], a schematic approach is proposed that just the inlet and outlet conditions of the chiller components perform the closed-box study of the entire system. Lastly, in [25], a model of a water and lithium bromide absorption refrigeration system is developed, and then the process is simulated with specific software.

There are numerous works involving heat exchangers. In [26], a new sizing method is proposed that also considers the type of exchanger and the most suitable materials for each specific heat flow in the optimization phase. Other methodologies, such as those proposed in [27,28], rely instead on established sizing methodologies based on the characterization of the heat exchange process. Other studies also propose cost estimation methodologies for a heat exchanger design [29–31].

A general point can be made for the approaches presented above. These methods certainly offer viable solutions for individual recovery technologies and have the strength of allowing detailed sizing to be offered. On the other hand, they may not represent a concrete and practical solution for the end-users to whom this work is dedicated.

In addition, the scientific literature presents other methodologies more aligned with what is proposed in this paper. For example, the proposal of [32], later reviewed in [33], aims to define a general process for identifying subsequent combinations of sources and users. The problem with these methodologies is that they are overly general and do not consider the different technologies available for thermal recovery.

Similarly, the paper [34] proposes an approach that does not provide an accurate structured methodology but introduces a feasibility analysis of the various technologies based essentially on the applicable temperature ranges.

More aligned with the aim of this article is the approach proposed by [35], which provides general guidance and steps to be followed to obtain a first attempt at sizing the thermal recovery system. In contrast, only some recovery technologies, such as ORCs and ACs are considered.

It is essential to point out the presence on the web of tools made by companies that produce heat recovery technologies, which allow their selection simply and intuitively. "The Heat Pump Check" [36], "Heat Pump eCalculator" [37], and "Energy Cost Calculator for Commercial Heat Pumps" [38] are tools that start from a small quantity of data (e.g., waste heat source and sink characteristics) allow to identify the most suitable heat pump from among those in the tool database and then evaluate its technical characteristics and economic parameters. Similarly, for heat exchangers, tools such as "HEXpert" from [39], "Plate Heat Exchanger Configurator" from [40], and "Dimensioning" from [41] allow sizing of a heat exchange solution and comparing different options.

Although such tools are highly reliable, the limitation of these tools is that they are not integrated into a single system, making it difficult to use them together and compare results. In addition, those built by specific technology providers are limited to showing only the technologies produced, thus not allowing for a comprehensive view of what the market offers.

In conclusion, although there are already several methodologies and tools in the literature for evaluating WHR solutions in the industrial sector, a comprehensive and well-structured criterion that can offer solid support for companies is still absent.

The gap identified must be overcome; this paper proposes the development of a preliminary assessment tool that, using a few input data, can provide a clear and comprehensive overview of the applicable thermal recovery technologies for the specific case study while also providing technical and economic information to assess their real applicability.

The proposed tool is therefore intended to complement others in the literature, allowing a quick screening of heat recovery opportunities. The goal is to provide a preliminary feasibility analysis and sizing of the leading WHR technologies available on the market while also providing an initial economic evaluation based on real data. These inputs can be crucial for companies by focusing on the most interesting opportunities to be developed in detail. Compared with other existing tools and methodologies, our proposal has the following strengths: operability and usability, including different types of technologies in one tool, and the technology assessment is based on data from different sources and technology providers.

The research team's goal is that this tool can be seamlessly integrated with the other energy efficiency tools commonly used by companies. For example, thanks to the type of data required, it can be a valuable support for a company in the search for efficiency opportunities when conducting an energy audit according to Directive 2012/27/EU as part of an energy management system

2. Methodology

This section describes all the steps that led to the development of the tool for preliminary evaluation of WHR technologies: from the methodology's definition to the development of individual technologies models.

2.1. Preliminary Evaluation Methodology

The first step in establishing a structured method concerns identifying and defining the steps involved in the preliminary evaluation of a heat recovery technology. The approach is divided into four steps:

1. **Data collection and analysis**: the first step in the preliminary assessment involves data collection and analysis aimed at identifying the waste heat flows available and the plant's energy needs (electrical, thermal, and cooling needs). Knowing the needs makes it possible to select technologies compatible with the waste heat characteristics and investigate those that can be implemented at the industrial site. For each energy flow, it is necessary to collect information about thermodynamic characteristics, temporal distribution (to assess possible matching between availability and demand), and the type of fluids involved (information necessary in addition to the estimation of all other quantities such as specific heat and density, but also possible toxicity, flammability or corrosivity). Other valuable data to be collected are geographic location (for determining environmental parameters), opening hours and days (to estimate actual hours of operation); data on current energy generation or supply to estimate any savings produced by thermal recovery (costs of energy carriers, performance parameters of major systems such as boilers and chillers); and additional useful information such as structural constraints (layout, limited space).
2. **Technical evaluation:** the previously collected data are subjected to initial analysis to select possible implementable technologies. Through the use of specific models, the different technically implementable technologies are identified, and a preliminary sizing is provided;
3. **Economic evaluation:** knowing the technical characteristics for the technologies considered, through specific cost functions, an initial estimate of the required initial investment is provided;

4. **Analysis of results:** for all the solutions analyzed, following the technical and economic evaluation, the plant size is estimated, and the electrical, thermal, and cooling energy that can be generated with each of the available thermal waste streams is calculated. Having estimated the size of the plant, the initial investment, and the energy that can be generated, it will be possible to proceed to the calculation of economic indicators of the investment, such as, for example, the payback period (PBP) useful to identify the best solution among those investigated.

Table 1 summarizes the primary information to be collected, while Figure 2 shows a flow chart of the proposed methodology.

Table 1. Data to be collected.

Waste heat	Type of fluid Availability (hour/year) Flow rate Temperature Pressure
Thermal energy demand	Type of fluid Demand (hour/year) Flow rate Required temperature Initial temperature Pressure Flow production (e.g., production efficiency, carrier cost)
Cooling energy demand	Type of fluid Demand hour/year) Flow rate Required temperature Initial temperature Pressure Flow production (e.g., production efficiency, carrier cost)
Electricity demand	Electricity demand (kWh/year) Self-generated electricity (kWh/year) Cost of electricity

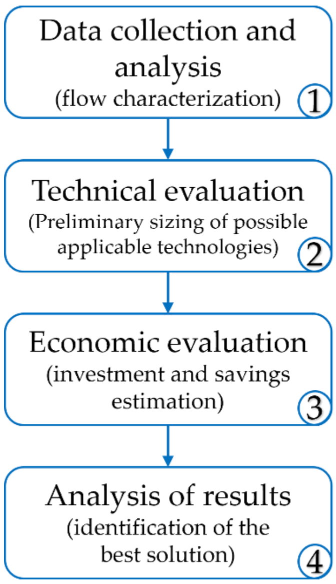

Figure 2. Steps of the methodology.

It should be emphasized that the outcome of a preliminary assessment is not meant to be exhaustive. The optimal solution cannot be chosen without detailed sizing of the specific technology. The preliminary assessment tool aims to investigate possible implementable technologies by providing initial sizing and evaluation parameters that will direct the user to investigate the most attractive solutions. In addition, the proposed methodology uses the PBP as the primary evaluation parameter because it is particularly significant in the industrial scenario. However, depending on the company, other selection criteria may be used, such as the value of the initial investment (significant in small companies with low economic means), the profitability of the investment, or environmental parameters such as maximum reduction of pollutant emissions.

For the technical and economic evaluation stages, ad hoc models were developed for the most representative heat recovery technologies described in the following parameters.

2.2. Most Representative Technologies Models

The preliminary assessment tool considers the most representative technologies for low-temperature heat recovery in the industrial sector. For each of the WHR categories mentioned above, we selected the technology that was found to be the most significant: ORCs for electric power generation, heat pumps for thermal power generation, absorption chillers for cooling power generation, and plate heat exchangers for heat exchange category. Figure 3 shows a schematic representation of the four WHR macro categories and their most representative technologies.

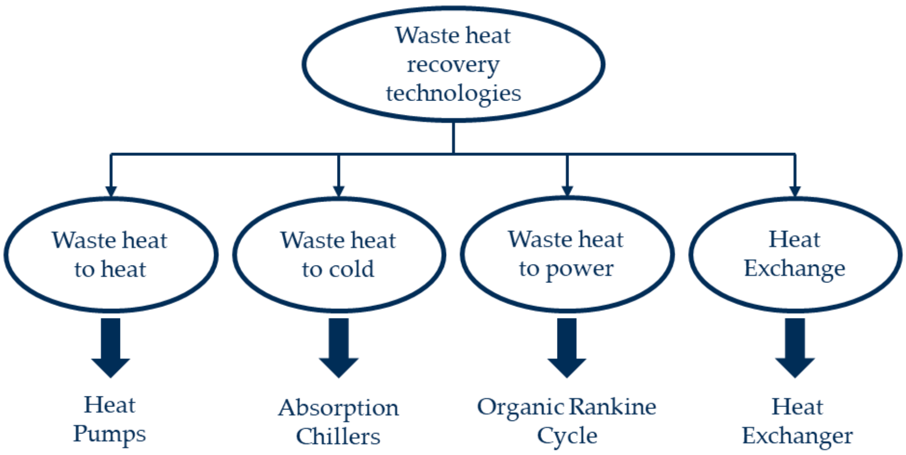

Figure 3. Technologies selected for the four categories of waste heat recovery.

Specific models were developed for each of these technologies to provide the most relevant technical and economic characteristics, starting from information on the recoverable heat flow.

The development of these models follows a standard procedure that can be divided into four steps:

1. Technical data and module specifications of individual technologies available on the market are collected, and their key parameters are recorded to characterize their operation (e.g., minimum allowable waste heat temperature, heat input power, and output power, efficiency). Where available, economic information is collected (investment cost, operation, and maintenance costs, specific cost);
2. Among the variables collected, the relationships between the characteristics of the incoming heat flow and the dimensional parameters are investigated (e.g., the relationship between input thermal power and output thermal power of an ORC);
3. Depending on the type of technology, the relationships needed to calculate the energy generated and the corresponding achievable energy savings are defined;
4. Using the data collected and the results of the literature review and technology providers, relationships were defined to estimate the initial investment required

based on plant size (€/kW). These relationships are necessary for calculating decision support parameters, such as PBP.

The tool evaluates all four WHR technologies considered for each waste heat stream. For each technology, if applicable, the tool provides all the necessary technical and economic parameters to the users to select the technology best suited to their decision criterion (e.g., installed power, investment, and payback period).

The following paragraphs are dedicated to a detailed description of model development for the four technologies considered and a description of their operation.

2.3. Waste Heat to Power: ORC Model

The preliminary evaluation model for ORC technology is based on technical data collected by analyzing 40 ORC modules for generating electricity from low-temperature thermal sources made by various national and international manufacturers. For each module, where available, we collected information regarding the manufacturer, model, thermal input power (P_{th}), electrical output power (P_e), temperature range of the input carrier fluid, temperature of the output carrier fluid, processed flow rate, type of carrier fluid, type of working fluid, and efficiency.

From the analysis of the collected data, we found a significant linear relationship between the electrical power generated and the thermal input power. Figure 4 shows the linear regression analysis conducted, the equation, and the correlation coefficient obtained.

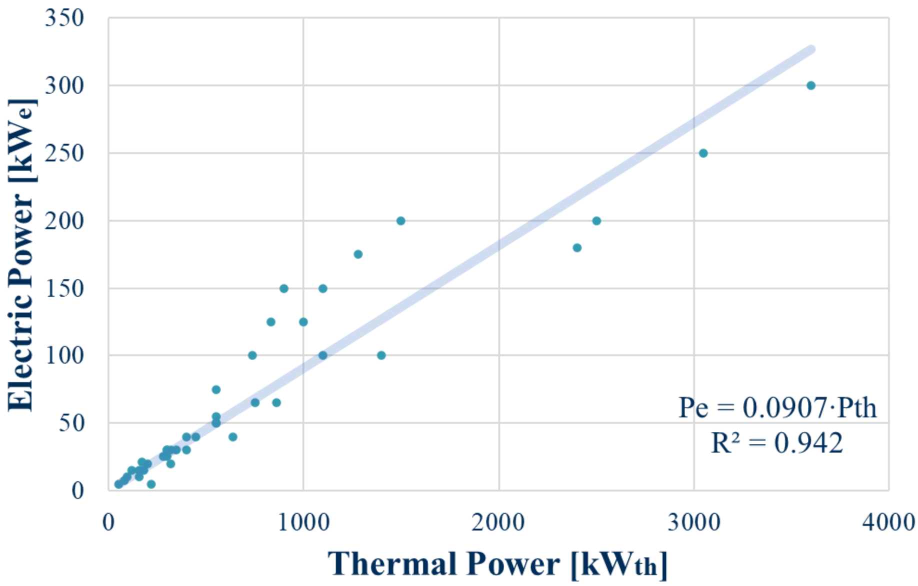

Figure 4. The trend of the electric power produced by the ORC as a function of the thermal input power.

The relation found is characterized by a high value of the correlation coefficient (R^2 = 0.942) and good statistical significance with a p-value of 1.0×10^{-25}, significantly lower than the commonly considered acceptable value of 0.05, corresponding to a statistical significance level of 95%. The thermal input power of the considered modules varies between 55 and 3600 kW_{th}, while the electrical output power varies between 2.5 and 300 kW_{el} per module. Therefore, these ranges represent the validity ranges of this relationship. However, this relationship can also be considered valid for higher powers in the order of MWe due to the validations with technology providers. Table 2 shows the summary output of the regression analysis conducted: correlation coefficient, sample numerosity, linear equation, and statistical significance (p-value).

Table 2. Regression statistics.

Summary Output	
Multiple R	0.971
R Square	0.942
Observations	40
Equation	$P_e = 0.0907\ P_{th}$
p-value	$<1.1 \times 10^{-25}$

This relationship, although considered reliable, has been subject to correction due to the findings of early experimentation of this module and continued contact with technology suppliers. Although size influences the efficiency of an ORC cycle, it turns out to be significantly affected mainly by the temperature of the carrier fluid entering the evaporator. Several efficiency classes can be identified:

- For inlet carrier fluid temperatures between 70 and 150 °C, efficiency values are between 5–12%;
- For inlet carrier fluid temperatures up to 200 °C, the efficiency values are between 10–18%;
- For inlet carrier fluid temperatures up to 300 °C, the efficiency values are between 16–25%;

Therefore, it was deemed appropriate to apply a correction to the identified relationship by introducing correction factors to change the efficiency as a function of waste heat temperature. Specifically, the relationship is valid for temperatures between 70 and 150 °C, while a 25% increase in efficiency is considered for temperatures between 150 and 200 °C, and a 50% increase for temperatures between 200 and 250 °C.

Electrical power can be determined from the characteristics of the waste heat flow. The thermal power input to the ORC module can be estimated from knowledge of the characteristics of the waste fluid, such as flow rate, specific heat, and temperature difference between the inlet and outlet of the heat flow (assuming an appropriate ΔT at the ORC module evaporator).

After calculating the electrical power, it is possible to estimate the annual electrical energy that can be generated, considering the actual hours of operation through the information previously collected. The product between this and the cost of electricity will provide the gross annual savings.

For the evaluation of the initial investment required for installing an ORC system, data collection was carried out regarding the investment cost as a function of size. These data come mainly from interviews with technology providers. Analysis of these data identified an exponential-type relationship between electrical power and specific installation cost:

$$Specific\ cost\left[\frac{€}{kWh}\right] = 7488.7 \cdot P_e^{-0.169} \quad (1)$$

This cost refers to the overall cost of the plant and not the cost of the ORC module alone. Figure 5 shows the sample distribution and the exponential equation obtained.

In addition, according to [42], it was possible to consider an operation and maintenance cost of 10 EUR per MWh of electricity generated. It is now possible to proceed with the calculation of the PBP as the ratio of the initial investment required to the annual savings achievable. This procedure is carried out for each of the available waste heat sources. In addition, based on the validations made, two correction factors were considered, both set at a value of 0.9. They related to the increase in the initial investment related to ORC, to consider other costs such as, for example, those of design or related to extra components; and the reduction in annual savings, to take into account possible misalignments between supply and demand (since the hours of operation, when provided, often represent a purely indicative value).

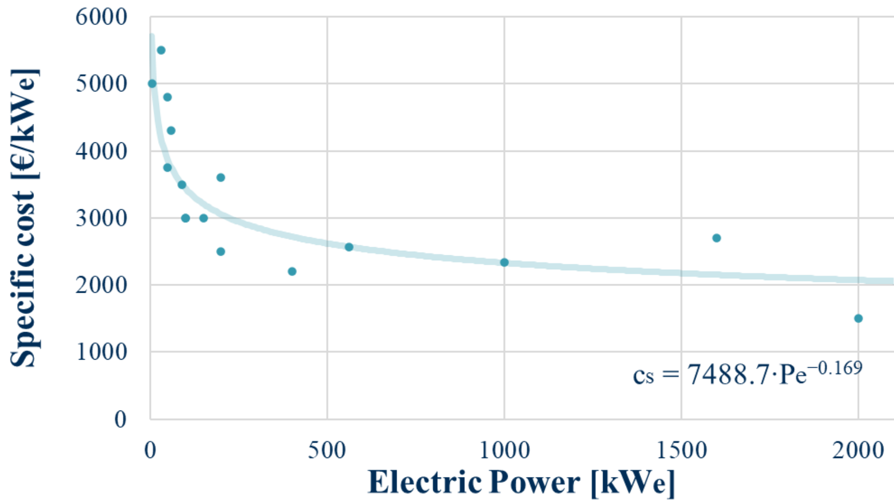

Figure 5. The specific cost of an ORC module as a function of the nominal electric power.

In conclusion, the model is easy to use: once characterized the incoming heat flow, the electrical output power is determined using the relationship identified and, consequently, the cost associated with this technology.

2.4. Waste Heat to Heat: Heat Pump Model

For developing the preliminary evaluation model for heat pump technology, data and specifications were collected from 25 commercially available heat pumps with a total of 49 operating points. For each operating point, where available, information was collected on: manufacturer, model, heat input power ($P_{th,in}$), evaporation temperature (T_{ev}), cold source temperature (T_{cold}), condensation temperature (T_{cond}), hot source temperature (T_{hot}), heat pump temperature difference (ΔT_{lift}), heat output power ($P_{th,out}$), processed flow rate, carrier fluid type, working fluid type, and coefficient of performance (COP). We found a significant linear relationship between heat pump temperature difference (ΔT_{lift}) and COP. This relationship links input parameters with performance parameters needed to size the technology. Figure 6 shows the results of the linear regression analysis, the equation, and the correlation coefficient obtained.

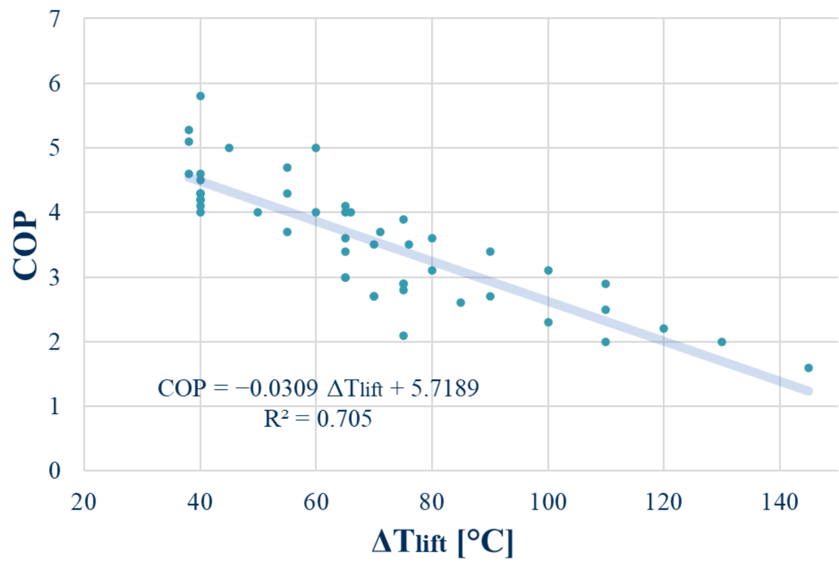

Figure 6. Relation between ΔT_{lift} and COP.

The correlation coefficient (R^2 = 0.705) and statistical significance (p-value = 4.74 $\times$ 10^{-14}) are satisfactory. The limits of applicability of the identified relationship, for the operating points considered, the ΔTlift varies between 38 and 145 °C while the COP varies between 1.6 and 5.8 (with a thermal output power of individual modules varying between 41 and 15,000 kW_{th}). Table 3 shows the summary output of the regression analysis conducted: correlation coefficient, sample numerosity, linear equation, and statistical significance (p-value).

Table 3. Regression statistics.

Summary Output	
Multiple R	0.840
R Square	0.705
Observations	49
Equation	COP = $-0.0309\ \Delta T_{lift} + 5.7189$
p-value	4.74×10^{-14}

The ΔT_{lift} parameter of a heat pump (equal to T_{cond}–T_{ev}) is not commonly known a priori. In agreement with recurring values in the bibliography, ΔT_{lift} can be estimated as the difference between the temperature of the hot source and the temperature of the cold source (waste heat), increased by 15 °C.

At this point, estimating the COP from the linear relationship (Table 3) by calculating the required heat output from the previously collected data, it is possible to determine the electrical power that must be supplied to the heat pump as the ratio of heat output to COP. From the knowledge of these parameters, it is then possible to make an overall balance of the system and estimate the amount of heat flow needed as input, as the difference between thermal power output and electrical power input. By comparing the heat demanded and the waste heat available, it is possible to determine the heat demand percentage that can be satisfied.

The next step involves estimating achievable savings. In the case of initial heat flow generation by a gas boiler, it will be necessary to consider an appropriate boiler efficiency value, usually between 0.85 and 0.95. In addition, it will be necessary to know the price of gas and electricity. For all parameters unknown a priori, a first-attempt value will be given, which can be changed if more detailed data are available.

In cases where unconventional technologies are adopted for the initial heat flow generation, a more accurate assessment of feasibility and achievable savings is deemed necessary.

We now turn to the estimation of the investment cost. The data found in the literature do not appear to be sufficient to construct a statistically significant relationship between specific costs (EUR/kW_{th}) and the investment required. The values found, mainly from online catalogs, applications, and studies in the literature, report specific costs varying between 150 EUR and 500EUR/kW_{th} [43,44]. Interviews with technology providers operating in the heat pump market made it possible to obtain more accurate evaluations: the specific cost ranges between 200 and 300 EUR/kW_{th} for the heat pump component alone to values above 500 EUR/kWh for the whole system.

By the results obtained, it was chosen to assume a specific cost of 500 EUR/kW_{th} for output powers below 200 kW_{th} and 400 EUR/kW_{th} for higher powers.

It is possible to calculate the required investment and the associated PBP from the knowledge of the specific cost of the heat pump system.

This assessment is made for each possible combination of waste heat flow and thermal energy demand.

As in the previous case, we defined two correction factors set at a value of 0.9. In particular, the increase in the initial investment-related heat pumps to take into account other costs such as design costs or extra components, and the reduction in annual savings to take into account both operation and maintenance costs and possible mismatches between supply and demand (since the hours of operation, when provided, represent a purely indicative value).

2.5. Waste Heat to Cold: Absorption Chiller Model

As in the previous cases, technical data of currently commercially available absorption refrigeration cycles were collected for 40 units. For each unit, where available, we collected information about: the manufacturer, model, input power (P_{th}), output cooling capacity ($P_{c,out}$), input temperature (T_{in}), output cold fluid temperature (T_{out}), processed flow rate, carrier fluid type, working fluid type, and COP.

A significant linear relationship was found between cold fluid outlet temperature (T_{out}) and COP performance coefficient. Figure 7 shows the linear regression analysis conducted, the equation, and the correlation coefficient obtained.

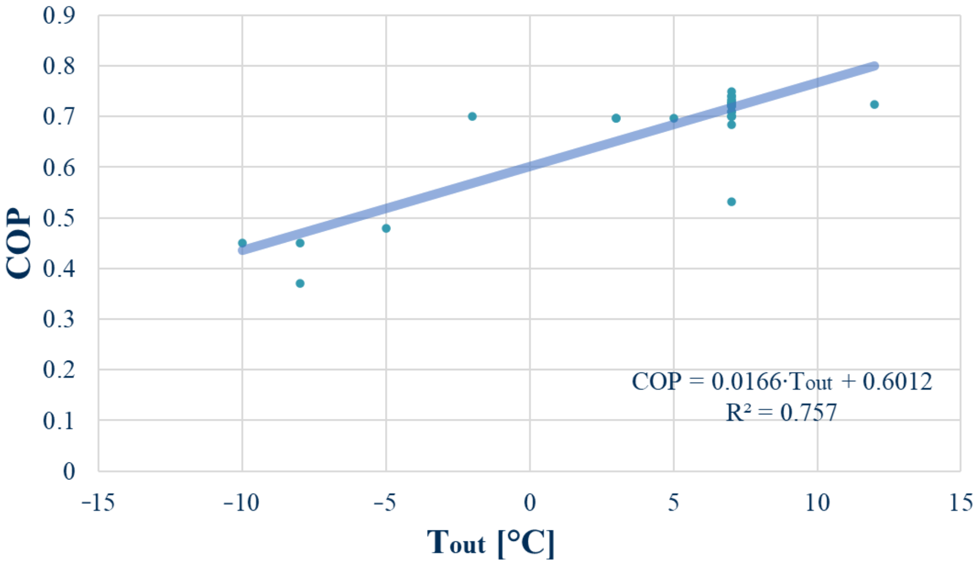

Figure 7. Relation between T_{out} and COP.

Both the correlation coefficient (R^2 = 0.757) and statistical significance (*p*-value = 3.72×10^{-14}) are satisfactory. Regarding the limits of applicability of the identified relationship, for the operating points considered, the T_{out} varies between −10 and 12 °C while the COP varies between 0.37 and 0.75 (with output cooling capacity of individual modules varying between 17 and 2100 kW). Table 4 shows the summary output of the regression analysis conducted: correlation coefficient, sample numerosity, linear equation, and statistical significance (*p*-value).

Table 4. Regression statistics.

Summary Output	
Multiple R	0.870
R Square	0.757
Observations	43
Equation	COP = 0.0166 T_{out} + 0.6012
p-value	3.72×10^{-14}

If the solution is technically implementable, cooling temperature (T_{out}) can be used to calculate COP according to the linear relationship shown in Table 4.

Following the technical data and the literature search results, waste heat temperatures between 80 and 120 °C and T_{out} between −10 °C and 12 °C are permissible. T_{out} outside the range of values used for model construction results in extrapolations of the identified relationship with obtaining COP values distant from reality.

It is possible to calculate the required cooling capacity from the knowledge of flow rate, specific heat, and temperature difference between the inlet and outlet of the cold fluid (data previously collected and generally readily available). Through the COP, the required heat capacity input to the absorber is determined. A minimum ΔT between hot fluid inlet and outlet of 15 °C (first attempt value provided, which can be changed in the module) is considered.

By comparing the required thermal power with the available thermal power, the ability of the waste heat to satisfy, totally or partially, the cooling energy requirement is determined.

Next comes the estimation of potential savings. Here it is necessary to know the current generation system used in the company. In the most common case in which compression refrigerators are used, it is possible to assume (if not known) the COP of the present systems that is generally between 3 and 4. Through knowledge of the operation hours and the energy cost, it is possible to determine the achievable savings as the difference between the pre and post-intervention costs. It must be verified that the cooling energy produced through the absorber does not exceed the requirement; alternatively, the absorber would be oversized.

In the case of initial flow generation through other unconventional technologies, a more accurate assessment will be needed.

As for the investment cost estimation, the low number of data did not allow the construction of a statistically significant relationship between specific cost (EUR/kW) and plant size parameters. In addition, the different sources analyzed report highly variable cost values between 200 EUR/kW and 700 EUR/kW [45–47]. This variability is attributable to the different operating and logistical conditions and the inclusion or non-inclusion of other plant components (evaporative tower, water treatment unit, piping, and service).

Given these considerations, and thanks to the findings of the first round of interviews with technology suppliers, it was chosen to divide the specific cost of the whole system for absorption chiller plants into four cost ranges:

- 900 EUR/kW for cooling power output up to 100 kW
- 500 EUR/kW for cooling output power between 100–200 kW
- 350 EUR/kW for cooling output power between 200–1000 kW
- 250 EUR/kW for cooling output power higher than 1000 kW.

Once the investment is determined, the PBP can be calculated as the initial investment and annual savings ratio. This evaluation is carried out for all possible source–user combinations.

As with the previous ones, the model implemented involves using two additional correction factors, both set at the first-attempt value of 0.9. These factors concern the increase in the initial investment related to absorption refrigerators to account for other costs such as design costs or extra components and the reduction in annual savings to account for both operation and maintenance costs and possible misalignments between supply and demand.

2.6. Heat Exchange: Plate Heat Exchanger

The preliminary sizing module for heat exchangers was developed by considering a specific type: the plate heat exchanger. Plate heat exchangers' typical temperature and pressure application range is generally limited. Depending on the type of gasket used, the maximum temperature and pressure ranges in which plate heat exchangers can be safely used are 200–250 °C and 25–30 bar, respectively. However, these characteristics appear to be perfectly aligned with the boundaries of this work focused on heat recovery at low and very low temperatures.

As for performance, this depends on numerous parameters and operational choices that characterize the specific type of operation. In general, the level of heat exchange efficiency for this type of exchanger is very high and can range from 95% up to more than 99%, with achievable temperature differences of even 1 °C.

Going into the details of the developed model, the preliminary sizing of the heat exchangers saw a slightly different procedure from what was developed for the other technologies considered.

The performance of a heat exchanger is identified by reference to several parameters that characterize the type of service. These parameters are usually thermal length, flow rates, pressure drops, fouling coefficients, seals, maintenance requirements, type of fluids involved, and materials used.

Because of these many factors, it was not considered appropriate to attempt to reconstruct a relationship that would link the output power with the few available input data on waste heat; instead, it was necessary to go into the details of the heat exchange relationships.

For each waste heat flow identified, the model compares the incoming waste heat flow characteristics and the heat sink requirements (energy needs to be met). This comparison determines the type of heat exchange process: no applicable process, heating up to the required temperature, or preheating up to the maximum temperature achievable.

The input data required are:

- For the waste flow (hot fluid), it is necessary to know the flow rate ($\dot{m}_{hot}$), the specific heat ($c_{p,\ hot}$), and the temperature at which the flow is available ($T_{in,\ hot}$);
- For the fluid to be heated (cold fluid), it is necessary to know the flow rate ($\dot{m}_{cold}$), the specific heat ($c_{p,\ cold}$), and inlet and outlet temperatures ($T_{in,\ cold}$, $T_{out,cold}$);
- Time availability and type of the two fluids.

The first assessment concerns the comparison of inlet temperatures between the two fluids:

$$T_{in,\ hot} > T_{in,\ cold} \tag{2}$$

The possibility of meeting the required heat demand with the rejection stream is limited by having a hot fluid inlet temperature higher than the cold fluid. After verifying this simple condition, we can proceed by investigating the possibility of complete heating or partial preheating of the considered flow. Then, the second condition to be evaluated is the comparison between the inlet temperature of the waste fluid (hot fluid) and the outlet temperature of the cold fluid (demand):

$$T_{in,\ hot} > T_{out,\ cold} \tag{3}$$

This condition is the prerequisite for the required demand to be fully satisfied; if not met, the only option is to preheat to the maximum temperature attainable.

In both cases, the next step is the evaluation of the thermal powers exchanged by the two flows and verifying the outlet temperature to which the hot flow would be brought as a result of heat exchange.

Table 5 shows a summary of the cases provided by the model with the different conditions, associated functions, and derived variables necessary for subsequent sizing.

Q_{hot} and Q_{cold} are, respectively, the heat in input to the heat exchanger (waste heat) and the heat transferred to the fluid to be heated, η_{he} is the efficiency of the heat exchanger, ΔT_{min} is the minimum attainable temperature difference in the plate heat exchanger, while $T_{out,hot}$ is the outlet temperature of the waste heat flow.

Generally, plate heat exchangers can work with minimal temperature differences, as low as 1 °C. In this model, we made a precautionary choice to set the ΔT_{min} at 3 °C.

From here on in the formulas, we will refer, whatever conditions are met (Case 1, Case 2, or Case 3), to the variables only as: $T_{in,hot}$, $T_{out,hot}$, $T_{in,\ cold}$, $T_{out,cold}$, Q_{hot}, Q_{cold}.

Having then determined the feasible process and its associated temperatures and heat outputs, one can proceed with the actual preliminary sizing of the heat exchanger.

Table 5. Summary of evaluations of the heat exchange process.

Cases	Conditions	Calculation Procedure	Output Variables
Case 0	$T_{in,\ hot} < T_{in,\ cold}$	No heat exchange process is feasible	None
Case 1	$T_{in,\ hot} > T_{out,\ cold}$ Complete heating up to $T_{out,\ cold}$	Calculation of the required heat output, $Q_{cold} = \dot{m}_{cold} \cdot c_{p,cold} \cdot (T_{out,\ cold} - T_{in,\ cold})$ Calculation of heat required from waste heat, $Q_{hot} = Q_{cold} / \eta_{he}$ Calculation of hot fluid output temperature, $T_{out,\ hot} = T_{in,\ hot} - \frac{Q_{hot}}{\dot{m}_{hot} \cdot c_{p,hot}}$	$T_{in,\ hot}$, $T_{out,\ hot}$ $T_{in,\ cold}$, $T_{out,\ cold}$ Q_{hot} Q_{cold}
Case 2	$T_{in,\ hot} > T_{in,\ cold}$ and $T_{in,\ hot} < T_{out,\ cold}$ Preheating up to $(T_{out,\ cold})_{preheating}$	Calculation of the maximum temperature that the cold fluid can reach, $(T_{out,\ cold})_{preheating} = T_{in,\ hot} - \Delta T_{min}$; Calculation of the required heat output, $(Q_{cold})_{preheating} = \dot{m}_{cold} \cdot c_{p,cold} \cdot \left[(T_{out,\ cold})_{preheating} - T_{in,cold}\right]$; Calculation of heat required from waste heat, $(Q_{hot})_{preheating} = (Q_{cold})_{preheating} / \eta_{he}$; Calculation of hot fluid output temperature, $(T_{out,\ hot})_{preheating} = T_{in,\ hot} - \frac{(Q_{hot})_{preheating}}{\dot{m}_{hot} \cdot c_{p,hot}}$.	$T_{in,\ hot}$, $(T_{out,hot})_{preheating}$ $T_{in,\ cold}$, $(T_{out,cold})_{preheating}$ $(Q_{hot})_{preheating}$ $(Q_{cold})_{preheating}$
Case 3	$T_{in,\ hot} > T_{out,\ cold}$ and $T_{out,\ hot} < T_{in,\ cold}$ o $T_{in,\ hot} > T_{in,\ cold}$ and $T_{in,\ hot} < T_{out,\ cold}$ and $(T_{out,\ out})_{preheating} < T_{in,\ cold}$ Preheating up to $(T_{out,\ cold})_{max}$	Setting the minimum temperature that the hot fluid can reach, $(T_{out,\ hot})_{min} = T_{in,cold} + \Delta T_{min}$; Calculation of the maximum heat output available from waste heat, $(Q_{hot})_{max} = \dot{m}_{hot} \cdot c_{p,hot} \cdot [T_{in,\ hot} - (T_{out,hot})_{min}]$; Calculation of the heat output made available by the heat exchanger, $(Q_{cold})_{max} = (Q_{hot})_{max} \cdot \eta_{he}$; Calculation of the maximum outlet temperature achievable by the cold fluid, $(T_{out,\ cold})_{max} = T_{in,cold} + \frac{(Q_{cold})_{max}}{\dot{m}_{cold} \cdot c_{p,cold}}$.	$T_{in,\ hot}$, $(T_{out,hot})_{min}$ $T_{in,\ cold}$, $(T_{out,cold})_{max}$ $(Q_{hot})_{max}$ $(Q_{cold})_{max}$

The exchange surface area, one of the main drivers for determining the cost of a heat exchanger, can be determined using the well-known sizing equation for a generic heat exchanger [48]:

$$S = \frac{Q}{K \cdot LMTD}, \tag{4}$$

where the terms that appear represent:

- S, heat exchange surface (m^2);
- Q, power (kW);
- K, global heat transfer coefficient (kW/m^2 °C);
- $LMTD$, log mean temperature difference.

With $LMTD$, that can be calculated using the following formula [48]:

$$LMTD = \frac{(\Delta T_{hot} - \Delta T_{cold})}{ln\left(\frac{\Delta T_{hot}}{\Delta T_{cold}}\right)} \tag{5}$$

where $\cdot T_{hot} = T_{in,hot} - T_{out,\ cold}$ e $\cdot T_{cold} = T_{out,hot} - T_{in,\ cold}$.

Regarding the overall heat transfer coefficient (K), reference was made to indicative values: [49] reports a reference range of K for several pairs of fluid types (e.g., water-water, steam-water, compressed air-water, ethyl alcohol-water). The values in [49] refer to cases with typical pressure drops, i.e., between 0.3 and 0.6 bar, and with typical values of fouling coefficients. Note how for other fouling factors, K can also be considerably lower.

In this work, for each pair of fluid types, the supplied range, defined for losses of 0.3 and 0.6 bar, respectively, was averaged and considered valid in this pressure drop range.

Pressure losses are inversely proportional to the size of the plate heat exchanger. In cases where it is acceptable to increase the allowable pressure drop (with higher pumping costs), the heat exchanger will be smaller and consequently less expensive.

In addition, as generally expected in heat exchanger design, to consider the loss in heat transfer efficiency due to the fouling of the transmission surfaces, an oversizing coefficient is provided in the module to be applied to the calculated area. Specifically, oversizing between 50 and 100 percent was considered typical.

Having defined the heat transfer surface area, one can move on to the economic evaluation by estimating the investment cost, achievable savings, and thus the payback time of the investment.

For investment cost estimation, numerous works aimed at defining cost functions for heat exchangers have been analyzed [26,29–31,34]. Most of these reports use only the exchange area (S) as an input variable through which an accurate estimate of component costs can be obtained.

For the realization of this preliminary evaluation model, it was decided to use the relationship proposed by [26], developed specifically for the exchangers made of stainless steel, following the following relationship:

$$C[€] = 8880 \times (10.76 \cdot S)^{0.42} \quad (6)$$

As for the savings estimation, this is done by calculating the pre-intervention costs avoided thanks to the proposed intervention. In particular, a natural gas boiler, a solution widely used in industry, was chosen in the model as the standard technology for meeting pre-intervention needs. In the case of the initial generation of the flow through other unconventional technologies, a more accurate assessment will be needed to calculate the savings.

Note the initial investment required and the achievable annual savings; it is possible to calculate the PBP obtained by relating the initial investment to the calculated annual savings.

This procedure is carried out for each possible combination of waste heat flow and demand heat flow.

Just as with the other models, correction factors were considered. Plant complications can increase the economic investment depending on the specific case. In order to be further cautious with the investment estimate, an additional correction factor was chosen to increase the value of the cost obtained from the equation as a percentage. A reference correction factor set at a first attempt value of 10 percent was included in the model. The user can modify this value to account for special situations, such as in the case of the need to use special materials or considerable distance between heat source and user, or in situations requiring special sizing.

In addition, as done for the other technologies, a correction coefficient was again used to reduce the savings achievable by the proposed intervention. A correction coefficient of 0.9 has been set, and, as in the previous case, this can be modified by the user to take into account specific operating conditions that involve an increase in management difficulty, higher pumping costs due to high-pressure drops, or the need for frequent maintenance work due to the use of encrusting or corrosive fluids.

2.7. Final Considerations

The development of the models previously described was an iterative process carried out by the research team in continuous discussion with other project partners, national and international research projects, and, especially, WHR technology providers. During the research project, 20 interviews were conducted. In particular, the support of the technology suppliers was a crucial factor: their input allowed us to consolidate data collection, validate the identified technical relationships and, above all, obtain updated economics ideally in line with what the heat recovery technology market offers. These economic parameters, helpful in estimating the required investment, would otherwise have been complicated to find in the literature or by consulting online catalogs.

These interactions consolidate the results obtained, allowing the tool's first tests by comparing model outputs with actual proposed solutions.

The last step for the realization of the preliminary evaluation tool saw the implementation of the models on an Excel file intended for use by the external user. The choice of Excel is mainly due to the desire to obtain an easy-to-use tool for companies.

The Excel file consists of several worksheets:

1. "Data Input": represents the main interface, in which preliminary evaluation information about waste heat flows and energy needs will be entered;
2. "ORC evaluation": preparatory to the preliminary evaluation of ORC technology;
3. "Heat Pump evaluation": preparatory to the preliminary evaluation of heat pump technology;
4. "Absorption chiller evaluation": preparatory to the preliminary evaluation of absorption chiller technology;
5. "Plate heat exchanger evaluation": preparatory to the preliminary evaluation of plate heat exchanger technology;
6. "Other Information": a section available to the user to enter additional information deemed helpful in evaluating efficiency measures.

Once the input data (waste heat and energy demands) have been entered, the tool will automatically evaluate the four technologies considered for each source–well combination.

For technical parameters such as ΔT, the efficiency of generation systems, heat exchange efficiency, and energy costs, a first attempt value will be provided based on the findings of the literature analysis. However, there is always the possibility to adjust these values in the case of an experienced user if detailed information is available.

3. Results and Discussion

The preliminary assessment tool was applied to three large companies operating in the Italian industrial sector to validate and test the tool in the field and obtain valuable feedback for its improvement. A call for interest was launched to intercept companies willing to experiment with the tools developed within the research project to select case studies. Among the selection criteria, belonging to the industrial sector and energy consumption intensity were considered crucial. The three selected companies already had a high focus on WHR and thus proved helpful in applying the tool.

3.1. Validation through Case Studies

3.1.1. Case Study 1: Large Company in the Food Industry

The first case study concerns a leading food multiproduct company in Italy. By the high consumption of thermal energy used in most of the production processes characteristic of the industrial plant, the company was intensely interested in the issue of heat recovery and the search for efficiency measures.

The plant is equipped with a 6.8 MWe cogenerator plant that manages to produce most of the electricity required (only approximately five percent of the annual electricity consumed is purchased from the grid). The plant is equipped with a recovery steam generator to produce process steam. Due to the high heat demand, the plant fully utilizes the heat made available by the cogenerator, including lower enthalpy heat flows from the engine cooling circuits, high-temperature water (HT) at 80 °C, and low-temperature water (LT) at 50 °C.

The company is equipped with a thermal power plant with two boilers of 6 MWt each to supplement the plant's thermal needs and several refrigerators (electric chillers and direct expansion refrigerators) located around the plant necessary for the production of glycol water at temperatures of −2 and −8 °C.

The plant's thermal energy consumption is more attributable to the demand for process steam at a pressure of 10 bar used mainly for cooking processes. What is also important is the consumption of HT and LT hot water, mainly used for pasteurization, seasoning, and cleaning. Also significant is the need for refrigeration energy, mainly used for deep-freezing processes, the refrigeration of warehouses for storing raw materials, semi-finished and finished products, and seasoning processes.

In cooperation with the company, we identified a waste heat that has not yet been recovered and can potentially be valorized. This stream refers to the waste heat made available from the desuperheating phase of the ammonia refrigeration plant that supplies cold to approximately 200 rooms in the plant. Desuperheating is carried out through two ammonia–water plate heat exchangers that raise the ammonia temperature from 85 °C to approximately 65 °C. This available heat flow in hot water at 70 °C is not used.

The pasteurization process of a near department operating for a high number of hours/year was identified as a possible destination. The pasteurization process requires the temperature constant at 83 °C for the entire cycle. Losses from the vents are considerable; at present, steam is used to maintain the temperature of the pasteurization process.

It is also essential to analyze the correspondence, both in terms of quantity and availability, between waste heat and requirements to make an initial qualitative assessment of technically implementable heat recovery technologies, taking into consideration the four WHR types provided by the preliminary assessment model (waste heat recovery for electricity production, refrigeration energy, and thermal energy at higher temperatures or heat exchange).

Considering waste heat temperature (between 60 °C and 70 °C depending on operating conditions), it is not possible to use waste heat for electricity production by ORC and refrigeration energy production by using absorption refrigerators. Given these considerations and the plant's high thermal energy requirements, possible alternatives involve reusing waste heat for thermal energy production at a higher temperature using a heat pump or preheating make-up water to be sent to the pasteurizer itself.

The correspondence between waste heat availability and thermal demand is always guaranteed: waste heat is always available (8760 h/year), while the pasteurization process can be estimated at 4800 h/year.

Table 6 summarizes all the information about the waste heat and the identified thermal energy requirements. This information is used as input to the preliminary assessment model.

Table 6. Waste heat source and sink for case study 1.

Waste Heat	Waste heat source	Ammonia desuperheating
	Type of fluid	Water
	Availability (hours/year)	8760 h/year
	Flow rate	5.26 kg/s
	Pressure	<5 bar
	Temperature	65 °C
Thermal Energy Demand	Process	Pastorizzazione
	Type of fluid	Water
	Demand (hours/year)	4800 h/year
	Flow rate	0.2 kg/s
	Pressure	<5 bar
	Required temperature (Tout)	83 °C
	Initial temperature (Tin)	25° C

For the application of the preliminary assessment model, the procedure outlined in the previous section was followed. Tables 7 and 8 show the results of the tool application for the HP and PHE, respectively. For both technologies, the tables show the performance parameters, the installed power, and the economic parameters (investment, saving, and PBP).

For the preliminary evaluation of the heat pump and heat exchanger, all modifiable parameters provided by the model were left at the suggested first attempt values since no changes were deemed necessary given the absence of particular conditions.

Table 7. Heat pump preliminary evaluation.

Heat Pump	
T_{out} (°C)	83
ΔT_{lift}	33
COP	4.70
Output Thermal Power (kW_{th})	48.56
Electric Power (kW_e)	10.33
Input Thermal Power (kW_{th})	38.22
Coverage of needs	100%
Thermal Energy (MWh_{th}/year)	233.95
Electric Energy Needed (MWh_e/year)	49.60
Annual Saving (EUR/year)	12,980.10
Investment (EUR)	26,976
PBP (years)	2.08

Table 8. Plate heat exchanger preliminary evaluation.

Plate Heat Exchanger	
T_{out} (°C)	62
LMTD (°C)	13.93
S (m^2)	0.734
Output Thermal Power (kW_{th})	31.96
Coverage of needs	64.7%
Thermal Energy (MWh_{th}/year)	151.44
Annual Saving (EUR/year)	11,477.57
Investment (EUR)	21,618.08
PBP (years)	2.51

An electricity cost of 0.15 EUR/kWh and a methane cost of 84 EUR/MWh were chosen for both evaluations. For the calculation of achievable energy savings, the efficiency of the previous generation system of 0.90 was used. An oversizing coefficient of 50% was selected for the PHE.

Both proposed interventions show favorable technical and economic parameters. In both cases, the investment's PBP is less than the value of 3 years, which many companies use as the main indicator to assess the feasibility of an energy efficiency intervention. Moreover, the two proposed interventions do not require significant initial investments (27 kEUR for the HP and 22 kEUR for the HE). It should be noted that the use of the HP results in the integral satisfaction of the thermal energy demand considered; in the case of the PHE, this demand is only partially satisfied, making it necessary to use the previous generation system to supplement the remaining share.

These results are sensitive to changes in parameters such as the cost of energy. For example, assuming a methane gas cost of 40 EUR/MWh (before the increase in fuel price in 2021) would result in a PBP of more than five years.

In conclusion, the two evaluated interventions are promising, so it is recommended to investigate both proposals further and evaluate them following the evaluation criteria that the company will reduce most appropriately (e.g., PBP, net present value, CO_2 emission reduction).

It is worth noting that any achievable incentives that would further reduce the PBP of the investment are not considered in the preliminary evaluation.

The Sankey diagrams in Figures 8 and 9 show graphical representations of the two proposed efficiency measures. The size of the flows is proportional to the amount of energy. At the same time, the different colorations differentiate the types of flows (electricity, thermal energy, cooling energy, and natural gas) and the different temperatures at which the flows are available. Both figures show how the portion of heat recovered accounts for a low percentage of the total available waste heat that could potentially be used to meet other needs.

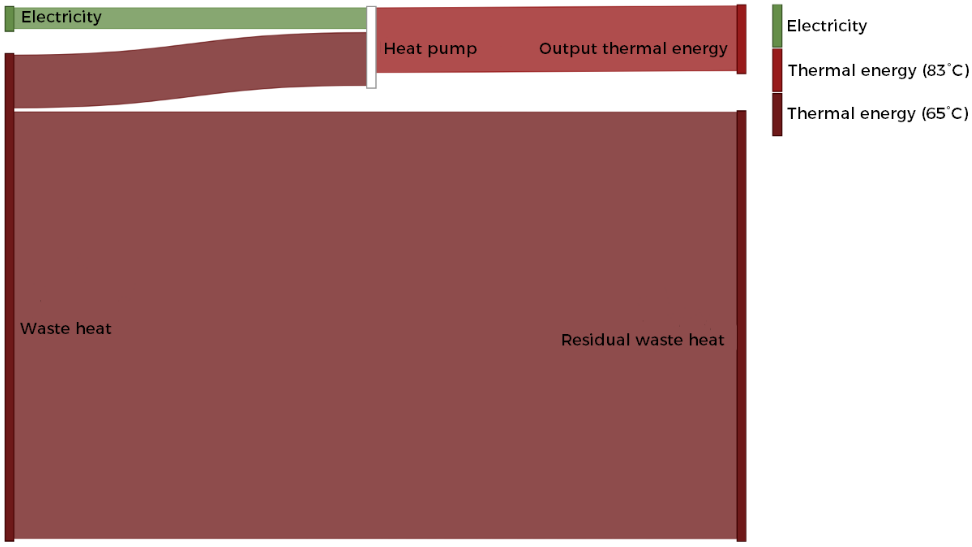

Figure 8. Heat pump Sankey diagram.

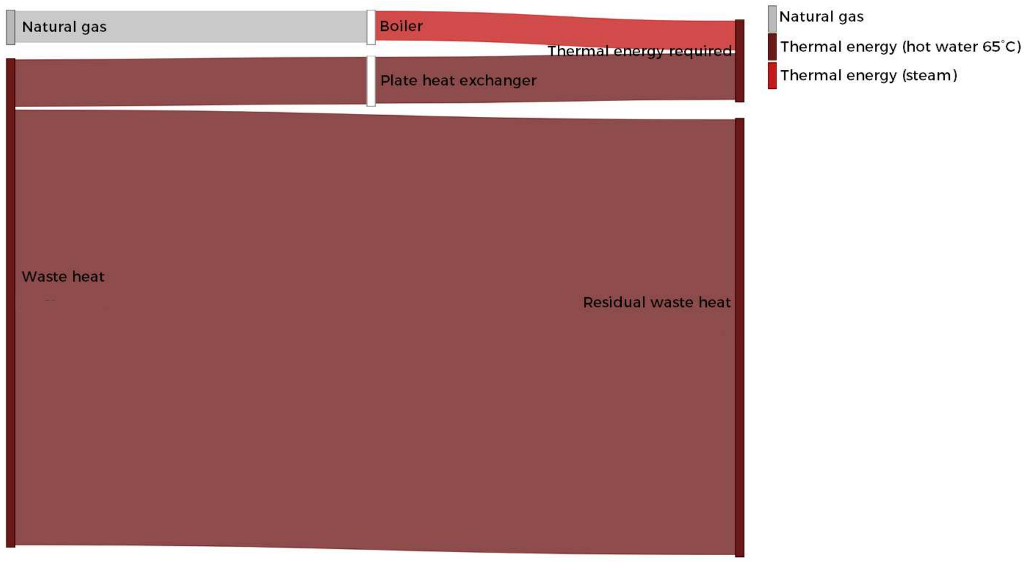

Figure 9. Plate heat exchanger Sankey diagram.

3.1.2. Case Study 2: Large Company in the Paper and Paper Products Processing Industry

The company in question is a leading Italian multiproduct manufacturer of intimate personal care products. The company is characterized by high energy consumption. Although it is not a large user of thermal and cooling energy for production processes, it has shown a strong interest in the issue of heat recovery, motivated by the continuous search for improvement of its energy performance, including from the perspective of energy management system for which the company is certified according to the ISO 50001:2018 standard.

The company's structure under review is organized into three production lots where the numerous production lines are concentrated. A large part of energy consumption is represented by technical service, which includes the auxiliary services supporting the production lines, such as the compressed air plant and other facilities.

The plant is equipped with a plant for the self-generation of electricity consisting of an 8 MW_e engine that mainly uses vegetable biomass (palm oil) for its operation and, to a lesser extent, biodiesel for startup and shutdown. Some of the heat generated is recovered by a first heat exchanger to produce 45 °C hot water and used in the air handling units. Through a heat exchanger, heat from engine exhaust fumes is used to enable the operation of the secondary ORC engine. An additional exchanger enables the production of high-temperature hot water at 90 °C used together with that produced by boilers mainly for heating purposes. The remaining heat is dissipated at the stack with a temperature reduced from 560 °C to approximately 120 °C.

The national power grid also supplies the plant to allow the sale of the energy produced and not used or the purchase of the missing energy, and by methane, which is used at the canteen, solvent disposal, and heating (in support of the cogenerator).

In collaboration with the company, an unrecovered waste stream has been identified. This flow refers to the waste heat made available by one of the circuits that recovers heat from the cogeneration system. The high-temperature circuit produces hot water at a temperature of approximately 90 °C and is used both in the winter months for pre- and post-heating of the AHUs (air handling units) and in the summer months to keep the palm oil tanks at temperature (which would otherwise solidify) and to ensure proper summer de-humidification. Such recovery, by the plant's low thermal demand, is not optimized, especially during summer.

The plant fully self-produces electricity (except for cogenerator shutdowns), and, given the limited thermal demand, the only viable alternative appears to be to use this heat to meet cooling energy needs through an absorption refrigerator.

The plant currently uses electric chillers. Since no chilled water meter was available, hourly electrical absorption data of the chillers for 2021 were used to estimate the cooling energy needs. During the summer months of June, July, August, and September, the average electrical absorption was 605.3 kW_e with an average COP of 2.5.

Table 9 summarizes all the information collected about the identified waste heat and cooling energy requirements. This information will be used as input to the preliminary assessment model.

Table 9. Waste heat source and sink for case study 2.

Waste Heat	Waste heat source	Cogenerator cooling
	Type of fluid	Water
	Availability (hours/year)	7500 h/year
	Flow rate	11.11 kg/s
	Pressure	<5 bar
	Temperature	90 °C
Cooling Energy Demand	Process	Air conditioning
	Type of fluid	Cooling water
	Demand (hours/year)	2500 h/year
	Flow rate	28.91 kg/s
	Pressure	<5 bar
	Required temperature (Tout)	7 °C
	Initial temperature (Tin)	12 °C

Using the input data described above (Table 9), Table 10 shows the results obtained from applying the model for absorption refrigerator technology.

An electricity cost of 0.16 EUR/kWh_e and a COP of the previous generation system of 2.5 was used to calculate the achievable energy savings, following the data provided by the company. Except for the waste heat temperature jump set at 20 °C, all other selectable parameters were left at the values of the first attempt as no changes were deemed necessary given the absence of particular conditions.

The proposed intervention has favorable economic parameters. The payback time of the investment turns out to be two years against a nonnegligible initial investment of approximately 234 kEUR with an estimated annual savings of 87.9 kEUR/year. Moreover, by performing a sensitivity analysis of the PBP by varying the cost of electricity from 0.10 to 0.20 EUR/kWh$_e$, the PBP remains contained between 2.13 years and 4.25 years.

Table 10. Absorption chiller preliminary evaluation.

Absorption Chiller	
Tout (°C)	7
COP	0.646
Maximum Output Cooling Power (kW)	600.6
Cooling Power needed (kW)	1512.5
Coverage of needs	40%
Cooling Energy (MWh/year)	1501.5
Annual Saving (EUR/year)	87,885.1
Investment (EUR)	233,569.5
PBP (years)	2.66

The excellent results can only suggest a deepening of the identified efficiency intervention for the company.

Figure 10 shows the proposed efficiency intervention's graphical representation via the Sankey diagram: approximately 30%waste heat is recovered to produce cooling energy by reducing the electrical demand of chillers.

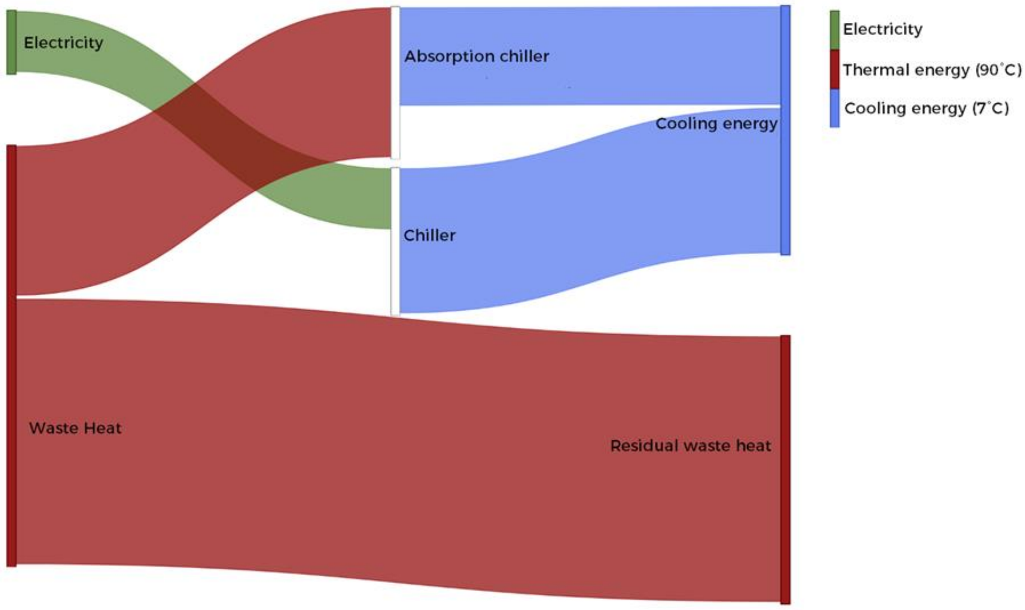

Figure 10. Absorption chiller Sankey diagram.

3.1.3. Case Study 3: Large Company in the Rubber and Plastic Products Processing Industry

The company is a leader in the rubber processing industry and, under its high thermal energy consumption, especially in the form of steam used in the production process, was immediately interested in the issue of heat recovery.

The plant, which is the subject of the study, is not currently equipped with systems for the self-generation of energy and purchases all the necessary electricity from the grid.

The thermal energy needs of the plant are almost entirely due to the demand for process steam. Steam is produced in a thermal power plant consisting of two natural gas-fired diathermic oil boilers with a thermal output of 7 MW$_{th}$ each. The average efficiency of the thermal power plant is approximately 93%. There is also a condensate collection tank from the plant inside the thermal power plant. The plant's production utilities require steam at three pressure levels: 9, 12, and 15 bar under saturated steam conditions. The recovered condensates are partly used, through appropriate heat exchangers, to produce domestic hot water and space heating.

The cooling energy required by the plant is supplied through the use of electric chillers located in the various areas of the plant for a total of approximately 2000 kW installed. The primary demand for cooling energy is due to chilled water production for the curing process. The remaining thermal energy demand is due to the refrigeration of the conditioned chambers where temperature-controlled raw materials are stored. The required chilled water temperature for all utilities is 7 °C with an inlet at 12 °C.

In collaboration with the company, we identified a waste heat flow that could potentially be valorized. This flow refers to steam condensate downstream of the production process, which does not appear to be fully recovered. In collaboration with the company, we evaluated the possibility of recovering the condensate in the form of a single stream: assuming that the condensate is fully recovered, the intervention would make available a flow rate of approximately 0.6 kg/s of superheated water at a temperature of approximately 175 °C and a pressure of 1050 kPa.

It is also essential to analyze the correspondence, both in terms of quantity and availability, between waste heat and requirements.

Since the temperatures required by the thermal consumers are very high (>180 °C), it does not appear possible to use waste heat to meet part of the thermal needs of the plant.

Instead, in the case study considered, logistical constraints prevent the use of waste heat for a colling generation. Additional considerations can be made in evaluating the application of absorption chillers. However, the characteristics of waste heat, given its low flow rate (0.6 kg/s), high temperature (175 °C), and high pressure (1050 kPa), do not allow direct use of waste heat for the technologies currently being considered for modeling. However, it would be possible to envisage a superheated water–hot water heat exchanger with the subsequent use of hot water to feed the absorber. This would certainly imply an extra cost for the heat exchanger but would allow the use of a classical absorber with a low investment cost. These considerations imply the assumption of additional parameters that require a more detailed evaluation.

Given these considerations, the only available alternative involves reusing waste heat for power generation through an ORC plant.

Regarding the match between waste heat availability and electricity demand, this is always guaranteed and can be estimated at 8000 h/year (the plant operates 24 h a day for approximately 340 days a year). Moreover, given the relatively low flow rate of potentially recoverable condensates, their recovery will ensure only the marginal satisfaction of electricity requirements.

Table 11 summarizes the information needed to apply the model for the preliminary assessment of ORC technology.

Table 11. Waste heat source and sink for case study 3.

Waste Heat	Waste heat source	Unrecovered condensates
	Type of fluid	Superheated water
	Availability (hours/year)	8000 h/year
	Flow rate	0.6 kg/s
	Pressure	1050 kPa
	Temperature	≈170 °C
Electricity	Electricity demand (kWh/year)	>10 GWh/year
	Self-generated electricity (kWh/year)	Not present
	Cost of electricity	0.185 EUR/kWh

The procedure outlined in the previous section was followed for applying the preliminary evaluation model. The results of applying the preliminary evaluation model for ORC technology are shown in Table 12. In addition to the data shown in Table 11, an evaporator outlet temperature of 140 °C (corresponding to a ΔT between the inlet and the outlet of the waste fluid of 30 °C) was assumed.

Table 12. ORC preliminary evaluation.

ORC	
Input Thermal Power (kW_{th}):	75.35
Electric Power (kW_e):	8.54
Electric Energy (MWh_e/year):	74.83
O&M costs (EUR/year)	748.33
Annual Saving (EUR/year):	11,711.36
Investment (EUR)	49,466.87
PBP (years)	4.22

The initial investment turns out to be relatively high because of the low power and thus high specific cost (approximately 6000 EUR/kWe). The PBP is also acceptable if it is higher than three years. In addition, given the still relatively high working fluid outlet temperature (estimated at approximately 140 °C), additional cascade heat recovery could be considered. In conclusion, although the PBP is high, the intervention is promising, and the company is advised to evaluate it further.

It is worth noting that this preliminary assessment does not consider any available incentives that would further reduce the PBP.

Figure 11 shows the proposed ORC plant's graphical representation via Sankey diagrams.

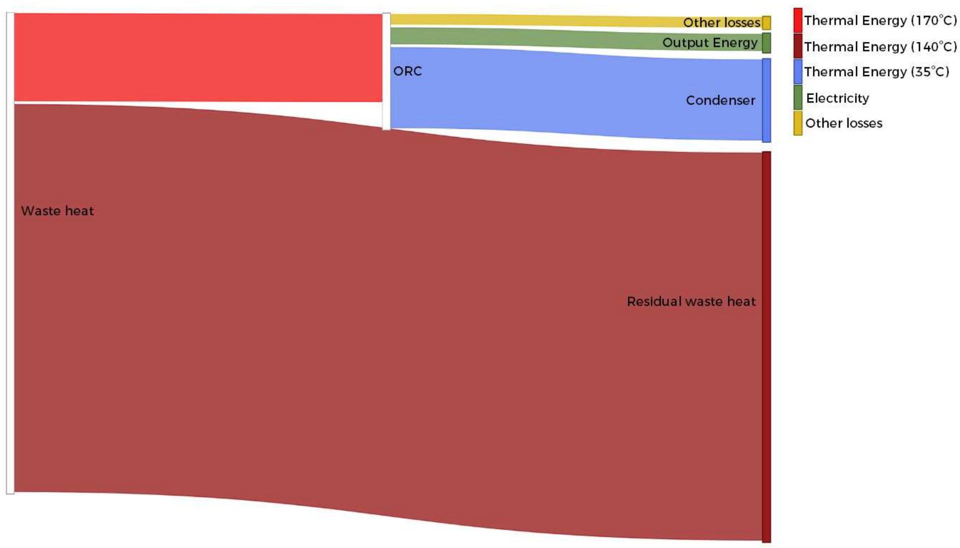

Figure 11. ORC Sankey diagram.

By analyzing Sankey's diagram, it is possible to see the still high potential of waste heat that can be further exploited.

3.2. Discussion

Thanks to the collaboration of companies operating in the Italian industrial scenario, it was possible to carry out the necessary operations to test and validate the proposed tool.

A common approach was followed for the three cases: starting with the presentation of the research project, where possible, organizing a plant site visit, and then moving on to data collection preparatory to the application of the models.

The data collection phase is undoubtedly the most time-consuming; however, this did not generate problems during applications, as all companies had most of the necessary data. This aspect is of paramount importance, deriving a design of tools that could be successfully applied using data and a level of detail that companies typically have.

Table 13 summarizes the results of the interventions evaluated in the analyzed case studies.

Table 13. Summary of results obtained through the application of the preliminary assessment tool for the case studies analyzed.

Case Study	Waste Heat	Use	Technology Proposed	Output Power	Investment	PBP
Large company in the food industry	Ammonia refrigeration system	Pasteurization process	Heat pump	48.6 kW_{th}	27.0 kEUR	2.08 y
		Preheating water for the pasteurization process	Plate heat exchanger	31.6 kW_{th}	21.6 kEUR	2.51 y
Large company in the paper and paper products processing industry	Heat recovery from cogenerator	Air conditioning	Absorption chiller	600.6 kW_c	233.6 kEUR	2.66 y
Large company in the rubber and plastic products processing industry	Steam condensates	Power generation	ORC	8.5 kW_e	49.5 kEUR	4.22 y

All the results obtained were considered attractive by both the research team and the companies involved; therefore, the values obtained suggest further study. It should be remembered how the purpose of the applied model is to obtain as realistic a preliminary assessment as possible to identify the most suitable solutions with characteristics that merit a more detailed study.

Following the applications of the case studies, it was not deemed necessary to make significant changes to the tools developed due to the excellent results obtained. This aspect can be attributable to the tool being explicitly designed for application in the industrial context, always considering the amount and type of data needed aligning with the availability of companies. Therefore, the experiments had the primary and fundamental role of validating and contextualizing the tool by demonstrating its appropriateness and usability. Since similar results were not available in the scientific literature, validation of these results was carried out through the formation of a "focus group." Together with the companies and technology providers, the results obtained were reviewed and found to be aligned with similar applications made by technology providers.

It should be emphasized that the applications allowed smoothly to propose attractive solutions, despite the high level of maturity and attention with which the case study companies were already addressing energy efficiency issues. The methodology made it possible to identify flows that were not easy to exploit and to identify suitable technologies operating under conditions that were not particularly favorable. Companies were often unaware of the ability of such technologies to be usable at certain temperatures and, more importantly, of the performance achievable: this demonstrates the innovativeness and the impact of this tool.

4. Conclusions

In this work, we proposed and developed an easy-to-use tool to support companies in evaluating low and very low-temperature heat recovery solutions. The tool allows a preliminary analysis of the potential of heat recovery of the most representative technologies in the industrial scenario and defines an estimate of the achievable performances. The tool considers the most representative technology for each type of WHR: ORC for electric power generation, HP for thermal power generation, AC for cooling power generation, and PHE for low-temperature heat exchange applications. We developed a specific model for each selected technology based on technical and economic characteristics collected during the literature review and consolidated with technology suppliers. The research team's goal was to create a tool that is perfectly placed in the industrial context and can be integrated with the energy efficiency tools commonly used by companies. For example, this tool can represent valid support for a company in conducting an energy audit according to the principles introduced by the Energy Efficiency European Directive 2012/27/EU or in the search for efficiency measures in an Energy Management System.

In this regard, interaction with technology providers was a crucial contribution to the development of the lines of activity of the research group. During the research project, 20 interviews were conducted with technology providers and national and international research projects, which allowed the proposed tool to be contextualized and validated.

In addition, the tool was tested on operating industrial companies. A total of three case studies were addressed: a large company in the food industry, a large company in the paper and paper products processing industry, and a large company in the rubber and plastic products processing industry. It was possible to identify an unrecovered waste heat stream for each company. With a small number of input data, the application of the tool allowed us to evaluate technically implementable and economically attractive WHR technologies (PBP between 2.1 and 4.2 years). This experimentation proved to be very successful: we found cost-effective solutions that the companies had not considered before, despite the high level of attention with which they were already approaching energy efficiency improvements, confirming the tools' effectiveness.

The feedback obtained from technology providers, national and international research projects and possible user companies highlighted the project's success. These interactions made it possible to confirm the alignment of our research topic with the national and international scientific landscape and the recognized usefulness of the tools developed in supporting the dissemination of heat recovery technologies.

The future developments of this work will involve the improvement of the performance of the models and, at the same time, expand it, considering the most promising technologies on the market.

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