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Proposal of a methodology for the preliminary assessment of low temperature heat recovery opportunities for industrial applications

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ABSTRACT

Despite the large availability of low-temperature industrial waste heat, and the maturity of the technologies for its exploitation, the rate of implementation of these interventions in the industrial sector is low, mainly due to the presence of numerous barriers, such as the complexity of identifying the solution on which to focus attention based on the available heat and internal needs. Through the definition of a comprehensive methodology, this work aims to propose an easy-to-use tool that can provide real support to companies in the preliminary assessment of waste heat recovery opportunities.

Keywords: Waste heat recovery, Organic Rankine Cycle, low-temperature waste heat, energy efficiency, industrial sustainability.

1. INTRODUCTION

Waste heat is the principal source of recoverable energy: about 50% of the total energy used is usually dispersed as waste heat, in particular at low temperatures (<300 ° C) [1]. On the other hand, there are multiple technologies available for waste heat recovery: from the production of electricity to the reuse of heat at a higher temperature or to produce cooling energy. For these types of heat recovery technologies such as Organic Rankine Cycles (ORCs), Heat Pumps (HPs) and Absorption Chillers (ACs), are mature and particularly promising [2,3].

Despite the wide availability and the maturity of these technologies, the implementation rate of WHR interventions is low [4]. This situation can be explained by the presence of numerous barriers, mainly due to the lack of proper knowledge.

The work presented in this paper is part of a larger three-year project whose primary objective is the development of innovative tools to increase the spread of Waste Heat Recovery (WHR) interventions in the industrial scenario by preventing non-technological barriers.

1.1 Background

The growing interest in WHR has led to the development of different methodologies for the evaluation and design of technologies involved. Most of them provide a very detailed approach to design and optimize a particular technology [5–7]. Other methodologies, such as that proposed by [4], do not consider the different technologies available for the recovery of waste heat, but only identify the best conditions to carry out the heat exchange.

Although well structured, these approaches are not easy to implement in the industrial context to which we want to refer. Moreover, especially in the field of low and very low temperatures, there is still no comprehensive methodology, which, through a higher-level approach, provides a preliminary evaluation of the thermal recovery of waste heat flows, while considering the different technologies that can be implemented.

Basing on these considerations, this work aims to define a clear and complete methodology that can increase the diffusion of the recovery of waste heat flows and provide proper support for all those companies which, due to their limited size, do not have enough resources to devote to energy management.

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The originality of the proposed methodology lies in the combination of a simplified input with robust data gathering from literature and case studies. This allows to have reliable results with little effort required to the user.

2. MATERIAL AND METHODS

2.1 Methodology

The first step in the development of the methodology passes through the definition of its phases. As shown in Figure 1, the proposed approach is divided into four stages:

1. Data Acquisition: it is necessary to characterize the waste heat flows available (temperature, type of fluid, flow rate, availability), and any electrical, thermal and cooling energy demands;
2. Preliminary evaluation: with the data previously collected, through the use of a model, an initial technical and economic assessment of the possible technologies that can be implemented is carried out;
3. Technology design: the most promising technologies among those investigated are subjected to a detailed analysis;
4. Decision making: the solutions are compared from various point of view, for example economic saving and environmental aspects, then the best solution is identified according to the company needs.

In this work, the focus is placed on the second stage: the preliminary evaluation. This phase is of fundamental importance both because it will provide the inputs to the following steps and because it is the part that we have found to be missing in the literature.

For this first level assessment, we have developed a model described in the following paragraph. The goal is to create a simple tool that can be used directly by companies and that, based on the necessary data collected, provides immediate response regarding the possible convenience of the various interventions.

This model 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 dictated by the Energy Efficiency European Directive 2012/27/EU.

Fig 1 Steps of the methodology

2.2 Model

It is possible to identify three macro typologies of solutions in WHR: use of the waste heat flow for the production of electricity, heat, refrigeration or a combination of these energy forms.

Thanks to the results of the bibliographic research conducted for each of these macro-typologies we have selected some of the most representative technologies: ORC for the generation of electricity, HP for the generation of thermal energy and AC for the production of cooling energy. For each of these technologies, we have developed a specific model that is capable of providing, starting from the information about the recoverable heat flow, the most relevant characteristic technical and economic parameters.

In this paragraph, we describe the procedure used to create the preliminary evaluation model for the ORCs. The approach used is divided into three steps:

1. Technical data of ORC modules available on the market are collected (41 samples were analyzed for ORCs). The fundamental parameters are recorded to characterize the technology in question such as the minimum waste flow temperature allowed, the incoming thermal power, the output electrical power and information about the investment required (I_0);
2. Among the available variables, we need to search for the existence of a relation between the characteristics of the incoming heat flow and an important parameter in the design of the specific technology considered. In the case of the ORC, a significant linear correlation (p-value <0.05) has been identified between thermal input power and electrical output power (Figure 2);
3. We move on to the investment evaluation: with the data collected, it is possible to reconstruct the trend of the specific cost as a function of the electrical power for an ORC module (figure 3).

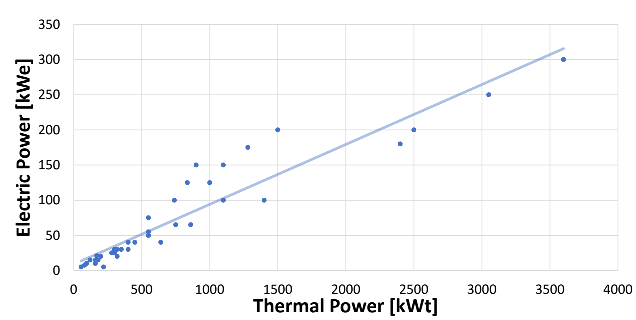

Fig 2 The trend of the electric power produced by the ORC as a function of the thermal power ($r^2 = 0.9074,\ p_{value} = 1.05 \cdot 10^{-20}$)

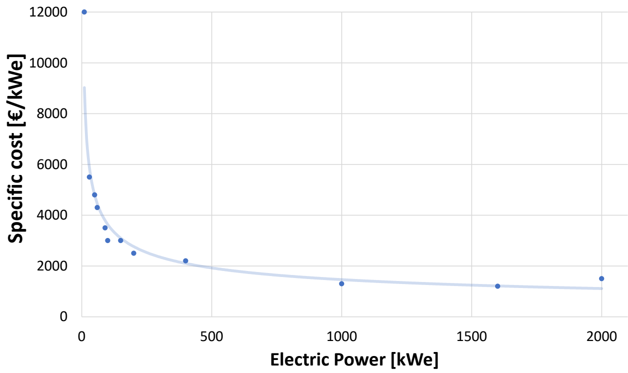

Fig 3 The specific cost of an ORC module as a function of the nominal electric power.

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.

We used the same approach for the other two technologies examined. The main difference concerns the relations identified. For HPs, we have found a significant correlation between the Coefficient Of Performance (COP) and the ΔT_{lift} (the temperature difference in the heat pump) while for ACs between COP and incoming thermal energy.

As for the development of the model, the significance of all identified correlations is satisfactory; despite this, a more significant number of samples would undoubtedly increase the accuracy of the analysis, and it will also allow dividing the relations identified into multiple operating intervals.

2.2.1 Model validation

To validate the model, we selected different applications of the technologies considered from real case studies or specific design models from the literature. The data used in the validation phase are different from those used to create the model.

In particular, for ORCs the parameter chosen to compare the model results and the data from the real application is the electrical power (Pe), the COP for HPs and the required thermal power (Pth) for ACs. We selected these parameters because they are characteristic for the respective technologies, and also because they are often the only available data in the literature.

We defined the value ε value as the relative error between the cited parameters found in the literature and those predicted by the model.

Table 1 shows some of the results obtained for the validation.

Table 1 Results of the model validation

Technology	Comparison parameter	ε	Ref.
ORC	P_{el}	5.7%	[8]
ORC	P_{el}	2.7%	[9]
HP	COP	13%	[10]
HP	COP	11%	[10]
AC	P_{th}	1.2%	[11]
AC	P_{th}	3.0%	[12]

Considering the generality of the model the validation step can be regarded as satisfactory as in all cases, we obtained errors of less than 15%.

3. CASE STUDY AND FIRST RESULTS

An Italian company operating in the food sector has a waste heat flow whose data are shown in table 2.

Table 2 Waste heat to be recovered

Temperature	80 °C
Availability	4900 h/year
Mass flow rate	3.5 kg/s
Fluid	Water

In addition to the electricity demand, there are thermal and cooling energy demands compatible with the recovery opportunities. For the thermal energy requirement, the fluid involved is water at a temperature of 98 °C, while for the refrigeration energy requirement, it is water at 0° C. The temporal correspondence between availability and demand is satisfied for all possible source-sink combinations.

In this application, we do not know the exact quantity of the energy demands to be satisfied. We have assumed that they are sufficiently big to be partially satisfied by the recovered waste heat. Also, to carry out the economic analysis (before and after the recovery of waste heat), for each energy carrier involved, we assumed a price in line with the Italian industrial energy scenario (electricity supplied by the grid and natural gas for the production of thermal energy).

Since there is only one waste heat flow available and three different forms of energy flow required, the evaluation is carried out for each possible combination.

Table 3 shows the results of the model application.

Table 3 Results of the model application

ORC	HP	AC
P_e=21 kW	COP=4.7	P_e=21 kW
E_e=248 MWh_e	E_t=160 MWh_t	E_e=248 MWh_e
I_0=156.5 k€	I_0=20.4 k€	I_0=261.6 k€
PBP=12.2 years	PBP=4.4 years	PBP=3.7 years

For the case study considered, the AC is characterized by the lowest Pay-Back Period (PBP) but requires the most significant investment. Since the model refers to a preliminary assessment, it is impossible not to consider the HP which therefore remains a valid hypothesis that needs, as for the AC, to move on to the subsequent phases and be thus further analyzed. The worst result is obtained for the ORC with an unacceptable PBP value, suggesting a clear rejection of this option. This poor performance is caused by the combination of low temperature and low availability to which this technology is very sensitive.

The proposed method does not use specific sizing criteria, but empirical relationships and this will certainly produce uncertainty in the results. This aspect, even if evaluated, is considered acceptable as this is exclusively a preliminary assessment that will require the subsequent sizing phases. Despite this, the model provides a good result.

4. DISCUSSION AND CONCLUSION

In this work, we proposed a tool to support companies in WHR evaluation, providing a preliminary analysis to identify the potential of heat recovery and define an estimate of the achievable performances. This model has been validated and applied in a case study showing good results.

It should be noted that the limited number of data required by the model leads to numerous assumptions. Still, on the other hand, this represents a strength of the proposed methodology as this is the level of detail of the information often available in the context we want to refer to.

The future developments of this work will foresee the involvement of WHR technology providers to improve the performance of the model and at the same time, expand it considering the most promising technologies on the market.

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