Journal of Cleaner Production 312 (2021) 127494

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Evaluation of the theoretical, technical and economic potential of industrial waste heat recovery in the Basque Country

Pello Larrinaga [a,*], Álvaro Campos-Celador [b], Jon Legarreta [a], Gonzalo Diarce [a]

[a] ENEDI Research Group, Dpto. de Ingeniería Energética, Escuela de Ingeniería de Bilbao, University of the Basque Country - UPV/EHU, Rafael Moreno Pitxitxi 2, 48103, Bilbao, Spain

[b] ENEDI Research Group, Dpto. de Ingeniería Energética, Escuela de Ingeniería de Gipuzkoa (sección Eibar), University of the Basque Country - UPV/EHU, Av. Otaola 29, 20600, Eibar, Spain

ARTICLE INFO

Handling editor: Kathleen Aviso

Keywords:
Economic analysis
Energy efficiency
Heat recovery
Industrial waste heat
Key transfer figures

ABSTRACT

Industrial waste heat recovery shows significant potential for increasing energy efficiency in industry. However, to design strategies that exploit this potential, it is necessary to have data about the quantity and characteristics of industrial waste heat flows. This information is not always readily available and many companies do not even have a systematic record of these energy flows. Hence, bottom-up methodologies to estimate that recovery potential by means of key transfer figures are useful tools within this field. In the present article, four different methods are applied to determine the industrial waste heat recovery potential in the Autonomous Community of the Basque Country (northern Spain), an energy-intensive industrial region with large energy dependency from the outside.

Besides, the analysis of the economic viability of the industrial waste heat recovery is essential, because it determines the final adoption of energy efficiency measures. For that aim, the authors develop an easy-to-apply bottom-up methodology to carry out an assessment for the economic potential of the estimated industrial waste heat at different temperature levels. This method is applied to 129 companies, whose potentials are characterized and discussed.

The obtained results show that, for waste heat streams above 400 °C, more than 90% of the studied companies present payback periods below five years. For those industries with waste heat temperatures below 200 °C, the ratio decreases to around 40%, still a noticeable value. The estimations show a significant opportunity to implement solutions to recover this wasted energy, especially in the iron and steel sector and the petrochemical industry. The development of public policies that encourage these measurements would be also beneficial.

1. Introduction

During the last two decades, a great technological development have resulted in the promotion of energy efficiency measures that have contributed to reducing the specific consumption of final energy (Hardt et al., 2017). Nevertheless, there is still room for additional measures to improve the use of energy resources and foster a more sustainable society. Among the fields where those additional measures can be introduced, it is worth mentioning the recovery of industrial residual thermal energy, commonly referred to as Industrial Waste Heat (IWH).

The sources of existing IWH and its applications are varied, numerous, and flexible enough to adapt to a wide range of situations (Agathokleous et al., 2019; U.S. Department of Energy, 2008). The potential end-uses include power production (electricity and/or mechanical) (Loni et al., 2020; Peris et al., 2020), reuse in industrial processes of the very companies that produce it (Song et al., 2016; Stijepovic and Linke, 2011) and heat for domestic applications, mainly space heating and domestic hot water (Brückner et al., 2014; Moser and Lassacher, 2020).

However, IWH recovery depends on various factors that must be considered, such as the amount of residual heat available, the temperature level, the intermittency and temporal distribution, the distance to demand points and the associated cost of auxiliary transport, storage technologies and energy transformation (U.S. Department of Energy, 2008). All these variables affect both the technologies to be used and the economics of the recovery process. Accordingly, a better understanding

---

* Corresponding author.
E-mail address: pello.larrinaga@ehu.eus (P. Larrinaga).

https://doi.org/10.1016/j.jclepro.2021.127494
Received 27 January 2021; Received in revised form 7 May 2021; Accepted 10 May 2021

of the available IWH can contribute to develop local or regional strategies that can increase the recovery of this relevant energy source that is still largely squandered.

Among the mentioned factors, the amount of available heat and its release temperature level can be regarded as the key aspects to assess the IWH recovery potential of any industrial facility. These two factors condition the potential uses of that energy, the required technology and the recovery cost. As a result, it is necessary to assess reliable estimations of both quantity and temperature level of the emitted IWH. However, today there are no systematized assessments of IWH recovery potential at local, regional or national scales that allow the distribution and location of the residual energy sources, or the conditions in which they are available.

The only related regulation (at European Level) is the European Directive 2018/844 on energy efficiency, which is mainly focused on residential buildings. This directive establishes that big industrial companies have to conduct energy audits to “obtain adequate knowledge of the existing energy consumption profile, (…), identifying and quantifying cost-effective energy savings opportunities, and reporting the findings” (European Union, 2018). Nevertheless, those enterprises with fewer than 250 employees and with an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million, are not required to carry out these energy audits. As a consequence, thorough data related to energy consumptions, exhaust flow rates or operating profiles for several companies are not available in official databases, and sometimes they are nor even known by the very enterprises.

For that reason, several researchers have developed bottom-up methods to estimate the IWH of industrial facilities. These methods are based on thorough assessments and surveys that include data collections of industrial facilities, building features, machinery used, processes involved, specific energy consumptions, etc. (Hong et al., 2020). By the analysis of such data, the IWH recovery potential of each industrial facility is estimated. Then, the bottom-up method is defined aggregating these single surveys to a general approach. The obtained results can be highly accurate and they can be applied at local, regional and national level (Bianchi et al., 2019; Sarah Brueckner et al., 2014).

Among these bottom-up methods, there is a growing interest on approaches based on the use of key transfer figures (Hong et al., 2020; Moser and Lassacher, 2020; Pelda et al., 2020). These models use results of larger bottom-up studies to establish key transfer figures that are employed along with the input data. As a result, the inputs required are easy-to-collect data, such as energy consumption, gas emissions and the main industrial activities of the involved industries. This reduces the time consumed for the process and the information required. However, as the different available methods were originally developed for specific locations, they should not be used elsewhere without adapting the key transfer figures to the industrial characteristics of the intended region. This might render differences in the obtained results.

Accordingly, the first objective of this article is to assess the feasibility of bottom-up methods based on key transfer figures to easily determine the IWH availability of a certain region. To do so, four methods from the bibliography will be selected. They determine the IWH potential, technical or theoretical, per company by considering only two simple reference indicators: fuel consumption (diesel and natural gas) and CO_2 emissions. The four methods will be applied to determine the available industrial waste heat potential of the Autonomous Community of the Basque Country, a representative industrial region located in Northern Spain.

These bottom-up methods determine the IWH technical or theoretical recovery potential; however, this information might not be enough to determine the viability of that recovery: it is necessary to analyse it from an economic perspective. Unless knowledge concerning the economic potential of the IWH recovery at local or regional level is available at an appropriate level, the development of future recovery will be at stake. Hence, the second objective of this study is the development of an easy-to-apply methodology to assess the economic feasibility of recovering any identified IWH potential. Since the temperature level of the exhausted waste heat is essential to conduct any reliable economic analysis (Pili et al., 2020; Valencia et al., 2021), the developed approach will evaluate the excess heat at different temperature ranges.

As a final objective, the article attempts to assess the region’s opportunities to reuse the available IWH potential. So as to, the economic approach proposed by the authors to study their economic viability will be applied. For this aim, payback periods (Kosmadakis et al., 2020) will be employed as a main indicator. Within the evaluation, the geographical availability of the IWH, its temperature levels and the results per industrial sector will be assessed. The obtained results can be employed to develop policies and strategies to promote the revalorization of the currently rejected IWH.

2. Material and methods

As a representative case study, the Autonomous Community of the Basque Country (referred to as Basque Country hereinafter) is selected. This is a highly industrialised region located in northern Spain. Its industry accounts for 24.6% of its gross domestic product (2019 data) (Eustat, 2020) and the energy consumption of its industry represents 39% of the total energy consumption (Eustat, 2019). The region is highly energy dependent: only 7.5% of the final energy consumption has a local and renewable origin, while the rest is imported or locally produced by imported fossil fuels (Ente Vasco de la Energía (EVE), 2017). This dependency might be maintained during the following years, since the locally produced renewable energy is expected to entail only 20% of the final energy consumption of the region by 2030 (Ente Vasco de la Energía (EVE), 2017). Consequently, efforts are required on its industrial sector in order to promote energy efficiency and cleaner production processes.

This context is shared by many European regions, where the recovery of industrial waste heat could be an important strategy for a cleaner production in several production processes. Therefore, the herein presented methodology and the obtained results can be used as a qualitative reference for similar regions.

2.1. Methods to estimate industrial waste heat recovery potential

Four methods were selected to calculate the IWH recovery potential (Q_{IWH}), technical or theoretical. They all estimate the results by the application of transferring key figures, f_M, to either the companies’ fuel consumption (natural gas plus oil diesel) or CO_2 emissions. The main characteristics of the four methods are summarised in Table 1. Each method is detailed in the following sections.

The selected methods were originally applied to different regions than that herein intended. Thus, the key transfer figures had to be adapted to the present case study. Nevertheless, the key figures of

Table 1
Summary of the main characteristics of the four used methods.

	Method 1	Method 2	Method 3	Method 4
Study’s original region	Sweden	Germany	EU-27	UK
Company’s input data	Natural gas + diesel oil	Natural gas + diesel oil	CO_2 emissions	Natural gas + diesel oil
Year of the data	<2002	2008	2010	2000/03
Type of potential obtained	Technical	Theoretical	Theoretical	Technical
Industrial clustering classification system	SNI 1992	NACE rev 2	Own	Own
Number of used industrial clusters	23	22	6	7
Discretization per temperature levels	No	No	No	Yes

Methods 1 (Land et al., 2002) and 2 (S. Brueckner, 2015) were already adapted to the specific characteristics of Basque industry in (Miró et al., 2016). Thus, their data will be directly used within this work. Method 3 (Persson et al., 2014) was initially developed to be used in the 27 countries of the European Union, so the figures established for Spain in that work will be used in the Basque Country. Finally, Method 4 (Papapetrou et al., 2018) included a methodology to easily adapt its key transfer figures to other regions and periods of time, which will be done in this work. Moreover, this last approach classifies the industrial waste heat potential by temperature levels.

2.1.1. *Method 1: (Land et al. (2002)*

It was developed by Statistics Sweden in 2002 to evaluate, in that country, the potential use of industrial waste heat in district heating applications through a bottom-up estimation. It deals with the technical potential and only gas streams are considered.

This approach is based on the use of key figures f_{M1} relating to the waste heat per fuel consumption, specifically natural gas ($Q_{natural\ gas}$) and diesel oil ($Q_{diesel\ oil}$), according to Equation (1). The obtained result reflects the technical IWH potential.

$$Q_{IWH,1} = f_{M1} \cdot \left(Q_{natural\ gas} + Q_{diesel\ oil}\right) \quad \text{Eq. 1}$$

These figures were originally referred to 23 clusters or subsectors of the manufacturing industry, defined by the SNI1992 classification (Swedish Standard Industrial Classification). These 23 subsectors were gathered in five groups and, through the study, different key figures were assigned to each group. These key figures established according to SNI 1992 (Statistiska Centralbyrån (SCB), 1992) have been subsequently adapted to NACE Rev. 2 (Eurostat, 2008), by means of available conversion tables. Hence, the IWH recovery potential can be assessed using the NACE classification.

Miró et al. (2016) combined this method with local data and adapted the original key transfer figures to the specific features of the Basque Country, figures that are included in Table 2.

2.1.2. *Method 2: (S. Brueckner, 2015)*

This is a bottom-up estimation method, developed in Germany, based on data compiled at company level in 2008. Unlike Method 1, the assessment covers theoretical IWH recovery potential.

Method 2 is also based on waste heat per fuel consumption ratios as transfer key figures f_{M2}. In Germany, every four years, industrial companies are required to report several figures on their performance. Exhaust gas emissions (volume, temperature and operating hours), fuel consumption values and other parameters are recorded with the aim of assessing the environmental impacts derived from the industrial activity. Using that information, waste heat per fuel consumption ratios were established for 22 different manufacturing subsectors, as defined by the European Standard Classification Code for Economy Statistics - NACE rev. 2, Sector C Manufacturing.

$$Q_{IWH,2} = f_{M2} \cdot \left(Q_{natural\ gas} + Q_{diesel\ oil}\right) \quad \text{Eq. 2}$$

As in Method 1, the key transfer figure applied to each sector f_{M2} is used, together with the annual diesel oil and natural gas consumption of each company, to obtain the theoretical Q_{IWH} (Equation (2)). Miró et al. also adapted the original key transferring of this method to the data and specific characteristics of the Basque Country (Miró et al., 2016). The distribution of the 22 considered NACE industrial sectors in the eight groups established by this method is listed in Table 3.

Table 2
Key figures to define IWH from fuel consumption data in Method 1 in the Basque Country (Miró et al., 2016).

NACE sectors	f_{m1}
10, 11, 12	0.067
13, 14, 15, 16, 18	0
17	0.031
19, 20, 21, 22, 23, 25, 26, 27, 28, 29, 30, 31, 32	0.096
24	0.2

Even though they look alike, there are differences between methods 1 and 2. On the one hand, the studied industrial subsectors are combined differently: in Method 2, the subsectors are classified in eight groups, three more than in Method 1, which entails a more homogenous assignation of the waste heat per fuel consumption ratios. In fact, the maximum number of subsectors in the same group in Method 2 is five, while in Method 1 it is possible to find 13 subsectors in the same group. On the other hand, in Method 1, six subsectors have a key figure of 0%, which does not occur in Method 2.

2.1.3. *Method 3: (Persson et al. (2014)*

This method was developed in 2010 and designed to be applied in all EU27 countries. It estimates the theoretical industrial waste heat recovery potential using carbon dioxide emissions as the main data input. To develop this approach, Persson et al. used the European Pollutant Release and Transfer Register (E-PRTR), where carbon dioxide emissions per company, as well as other types of emissions, are registered.

As in methods 1 and 2, IWH is estimated by relating primary energy input volumes by means of recovery efficiencies assigned to each industrial sector. Nevertheless, these primary energy volumes are also estimated through characteristic CO_2 emissions per fuel consumption factors per main activity sector. Hence, *CO_2 emissions* are the main input data. Combining these two factors, the carbon dioxide emission factor and recovery efficiency, into transfer key figures f_{M3}, the IWH recovery potential can be determined (Equation (3)).

$$Q_{IWH,3} = f_{M3} \cdot CO_{2\ emissions} \quad \text{Eq. 3}$$

While methods 1 and 2 used standard industrial classifications, Persson et al. established their own system, grouping the studied companies in six significant energy-intensive industrial sectors: chemical and petrochemical, food and beverage, iron and steel, non-ferrous metals, non-metallic minerals, and paper, pulp and printing.

Since the original study was focused on the EU27 countries, no regional adjustments are required for the key transfer figures. Previous studies (Miró et al., 2016) already assumed the value of both factors for Spain as suitable for the Basque Country. The recovery efficiencies, carbon dioxide emission factors and the resulting f_{M3} per sector for Spain are listed in Table 4.

2.1.4. *Method 4: (Papapetrou et al. (2018)*

Method 4 was developed in 2018 to determine the technical IWH recovery potential in all the countries of the European Union. The starting point of the method was a study carried out for the UK industry. Data from 425 companies from 2000 to 2003 were used to obtain their transfer key figures, which determine the fraction of the consumed heat that is technically possible to be reused or recovered. Then, considering the heat consumption per industrial sector, extracted from the Eurostat database (European Comission, 2020), the IWH recovery potential for EU countries is calculated.

Table 3
Key figures to define industrial waste heat from fuel consumption data in Method 2 in the Basque Country (Miró et al., 2016).

NACE sectors	f_{m2}
10, 11, 12	0.108
13, 14, 15	0.282
16, 22, 23, 31, 32	0.139
17, 18	0.08
20, 21	0.088
24	0.186
25, 26, 27, 28	0.221
29, 30	0.18

Table 4
Recovery efficiencies and carbon dioxide emissions factor by sector proposed by Persson et al. for Spain (Persson et al., 2014).

Main activity sector category	Recovery efficiency	CO_2 emission factor [$kgCO_2$/MWh]	Combined f_{M3} [MWh/$kgCO_2$]
Chemical and petrochemical	0.25	225	0.0011111
Iron and steel	0.25	279.72	0.0008938
Non-ferrous metals	0.25	231.48	0.00108
Non-metallic minerals	0.25	246.96	0.0010123
Paper, pulp and printing	0.25	272.2	0.0009019
Food and beverage	0.10	263.16	0.0003799

The method is divided into two parts; firstly, as in the previous three methods, the technical recovery potential is calculated by means of key transfer figures (f_{M4}); secondly, the temperature levels of the potential heat are determined. This allows us to know the actual utility and/or viability of the studied industrial waste heat, a key element to develop IWH recovery strategies. It is important to notice that this approach uses the same non-standard industrial classification as Method 3, but it incorporates an extra group to gather all the activities that could not be included in the other six categories (Papapetrou et al., 2018).

The key transfer figure values proposed by (Papapetrou et al., 2018) were determined for each category using data from the United Kingdom in the years 2000–2003; they are listed in Table 5.

These key transfer figures can be adjusted to the particularities of each country or region in the European Union (Papapetrou et al., 2018). This is performed by multiplying them by a factor that indicates the sector's relative energy intensity (*EI*) of each country compared to the UK (see Equation (4)). In the present work, the factors were adapted to Spain, as there is no specific information for the Basque Country.

$$f_{M4,(Spain,\ Sector)2003} = f_{M4,(UK,Sector)2003}\left(\frac{EI_{(Spain,\ sector)}}{EI_{(UK,\ sector)}}\right)_{2003} \qquad \text{Eq. 4}$$

Then, key transfer figures are again adjusted to update the calculated values for Spain from the period 2000–2003 to 2016 (most recent year with *EI* available data). To do so, the ratio of the energy intensity values in 2016 per industrial sector to the energy intensity values of the period 2000/03 is calculated by means of Equation (5).

$$f_{M4,(Spain,\ Sector)2016} = f_{M4,(Spain,\ Sector)2003}\left(\frac{EI_{(Spain,\ sector)2016}}{EI_{(Spain,\ sector)2003}}\right) \qquad \text{Eq. 5}$$

The energy intensity figures used by Papapetrou et al. were extracted from the *Odyssee-Mure database* (Odyssee-Mure Database, 2017). However, herein information included within two Eurostat databases is used: *Complete Energy Balances (nrg_bal_c)* (Eurostat, 2019) and *National Accounts Aggregates by Industry (nama_10_a64)* (Eurostat, 2020). The obtained key transfer figures for Spain in 2016 are presented in Table 6.

Finally, the industrial waste heat per company is obtained by multiplying the diesel oil and natural gas consumption by the company's corresponding key transfer figure (Equation (6)).

Table 5
Key transfer figures in the UK for the period 2002/03 determined by Papapetrou et al. (2018).

Main activity sector category	f_{M4} for UK in 2000/03
Chemical and petrochemical	0.0781
Iron and steel	0.133
Non-ferrous metals	0.09
Non-metallic minerals	0.113
Paper, pulp and printing	0.073
Food and beverage	0.062
Others	0.016

Table 6
Method 4 key transfer figures for Spain in 2016.

Main activity sector category	f_{M4} for Spain in 2016
Chemical and petrochemical	0.025355
Iron and steel	0.2241
Non-ferrous metals	0.300788
Non-metallic minerals	0.216890
Paper, pulp and printing	0.110005
Food and beverage	0.066272
Others	0.012638

$$Q_{IWH,4} = f_{M4,(Spain,\ Sector)2016}\cdot\left(Q_{natural\ gas} + Q_{diesel\ oil}\right) \qquad \text{Eq. 6}$$

Regading the temperature levels of the calculated IWH, we directly used the results and conclusions of (Papapetrou et al., 2018), where the IWH temperature breakdown per sector at European level was included. That distribution is represented in Table 7 by percentages per sector.

By means of these percentages (*f*), the IWH per temperature level in each company is estimated (Equation (7)).

$$Q_{IWH,4\ (Temperature,\ Company)} = Q_{IWH,4\ (Comapny,Sector)}\cdot f_{(Temperature,Sector)} \qquad \text{Eq. 7}$$

2.2. Method to estimate the recovery economic potential

Apart from the technical and physical constraints, economy adds another relevant restriction to the development of IWH recovery strategies (Ates and Ozcan, 2020; Fitó et al., 2020; Peris et al., 2020). In this work, an economic assessment approach has been developed in order to estimate the economic feasibility of the IWH recovery.

From a macro approach, it is not possible to obtain deterministic values; only a minimum level of profitability can be defined. Hence, it is intended to assess the viability of the investment through the analysis of the payback period necessary to recover the investment considering the worst-case scenario; in other words, the economic viability will be equal to or greater than the determined value. With that aim, a bottom-up analysis has been performed, based on unfavourable conditions for the heat recovery process. The following assumptions have been adopted in order to be as conservative as possible:

1 The company produces heat with 100% efficiency using natural gas and/or diesel oil as fuel.
2 IWH recovery is carried out by means of a counter current heat exchanger.
3 The ratio between fluids heat capacities, *C*, is equal to one, which ensures the minimum effectiveness according to Fig. 1.
4 A Number of Transfer Units (*NTU*) value of 2 is taken for the design of the heat exchanger. This is a common criterion in heat exchanger selection, as the marginal benefit of increasing the NTU value is

Table 7
Temperature distribution of the determined IWH per sector.

	Percentage [%] of the IWH calculated per sector					
Main activity sector category	100/200 °C	200/300°	300/400°	400/500°	500/1000°	>1000°
Chemical and petrochemical	30	–	–	70	–	–
Iron and steel	–	31	8.9	–	46.4	13.7
Non-ferrous metals	100	–	–	–	–	–
Non-metallic minerals	64.4	–	6.8	–	28.8	–
Paper, pulp and printing	100	–	–	–	–	–
Food and beverage	100	–	–	–	–	–
Others	100	–	–	–	–	–

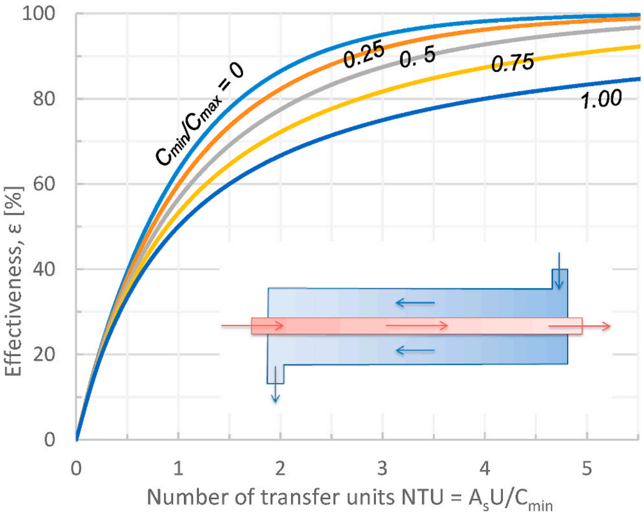

Fig. 1. Effectiveness relations for countercurrent heat exchangers (Kays and London, 1998).

reduced for higher values. This offers an effectiveness, ε, of 65% for a capacity ratio, C, equal to 1 (Kays and London, 1998) (see Fig. 1).

5- An overall heat transfer coefficient (U value) of 10 W/(m^2·K) is taken, which corresponds to the lower boundary for a gas-to-gas heat exchanger type, according to (Çengel, 1998).

Considering these assumptions, it is possible to obtain the size of the heat exchanger, expressed in terms of heat exchange surface area (*AHEX*). The actual recovered IWH power can be expressed (Equation (8)) as a function of the overall heat transfer coefficient (U value), the heat exchange surface (*AHEX*) and the mean logarithmic temperature difference (ΔTlm).

$$\left(\dot{Q}_{IWH}\right)_{recovered} = U\cdot A_{HEX}\cdot \Delta T_{lm} \qquad \text{Eq. 8}$$

The recovered IWH recovery power is a fraction of the IWH available recovery potential, the effectiveness (ε) being the ratio that relates the actual IWH power to this value, as is shown in Equation (9).

$$\left(\dot{Q}_{IWH}\right)_{recovered} = \varepsilon\cdot\left(\dot{Q}_{IWH}\right)_{available} \qquad \text{Eq. 9}$$

As the conservative assumption of $C = 1$ was taken as a reference framework for this analysis, the following simplification can be made by means of Equation (10). *TIWH* represents the temperature of the waste heat stream, while *TMIN* is the minimum temperature that the exhaust flows would reach during the heat exchange.

$$\Delta T_{lm} = \frac{1}{2}\left(T_{IWH} - T_{MIN}\right) \qquad \text{Eq. 10}$$

Therefore, the heat exchange surface can be presented as follows in Equation (11):

$$A_{HEX} = \frac{2\cdot\varepsilon\cdot\left(\dot{Q}_{IWH}\right)_{available}}{U\cdot\left(T_{IWH} - T_{MIN}\right)} \qquad \text{Eq. 11}$$

This equation determines the required heat exchange area (*AHEX*) as a function of the already set parameters, with the exception of the power of the IWH recovery potential (*QIWH*). This could be easily obtained from the IWH recovery potential (*QIWH*) if the annual operating hours were known, but these data are not available in the used databases. In order to overcome this inconvenience, the operating hours (*nhours*) are set as an additional parameter, allowing a parametric analysis to be carried out as a function of this new parameter. Therefore, Equation 11 gives rise to Equation 12.

$$A_{HEX} = \frac{2\cdot\varepsilon\cdot\left(Q_{IWH}\right)_{available}}{U\cdot\left(T_{IWH} - T_{MIN}\right)\cdot n_{hours}} \qquad \text{Eq. 12}$$

As stated, the heat exchange area can be used to get the cost of the heat exchanger. In this case, the shell-and-tube technology has been selected, whose investment cost (*cHEX*) can be determined by the cost estimation model proposed by (Razmjoo and Sajjad Keshavarzian, 2015) (Equations (13) and (14)).

$$c_{HEX} = 995.08\cdot A_{HEX}{}^{-0.246}\left[\frac{€}{m^2}\right] \qquad \text{Eq. 13}$$

$$I = c_{HEX}\cdot A_{HEX}\ [€] \qquad \text{Eq. 14}$$

Then, the investment cost, *I*, for the recuperation technology can be estimated as a function of the IWH recovery potential, the temperature of that calculated waste heat (*TIWH*) and the annual number of operating hours. It is also necessary to define the minimum temperature (*TMIN*) that the exhaust flows would reach during the heat exchange, in order to avoid the presence of corrosive condensates. For this study, it has been assumed that the exhaust flows are cooled down to a minimum temperature of 130 °C.

Considering all these aspects, this relationship between the recovery potential power and the cost of the required heat recuperator is graphically depicted by Fig. 2 for different exhaust flow temperatures.

To perform the economic feasibility analysis, the simple payback is selected as the indicator. It is obtained directly from the relation between the cost investment and the savings. For this aim, it is considered that the entire amount of the recovered energy could be consumed in-situ and it would replace thermal energy produced from natural gas with an efficiency of 100%. A specific cost of 29 €/MWh is considered for the natural gas, according to Eurostat *(nrg_pc_203)* (Eurostat, 2020).

This economic feasibility assessment is only applied within this work to Method 4, as it requires the temperature of the exhaust flow as input. In order to differentiate between feasible and unfeasible solutions, a threshold of 5 years is set for the payback, according to (Rathgeber et al., 2015). This economic approach can be easily replicated in other industrial areas, as the main input is the technical IWH recovery potential, which must be previously calculated.

3. Results and discussion

3.1. Data collection

To carry out an energy study at a macro level, it is essential to create an easy-to-handle database that serves as a calculation tool. In the present work, an own database including data on energy consumption (diesel oil and natural gas), CO$_2$ emissions, activity description, NACE

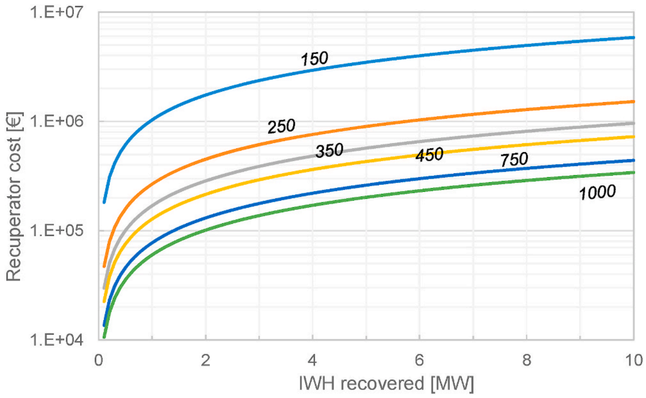

Fig. 2. Estimated heat recuperator cost vs. recovered heat power at different IWH temperatures.

code and location and coordinates of the Basque companies was produced. Data were gathered from the following online public databases:

- CEVEX - Catalogue of Industries and Exporting Companies in the Basque Country (Basque Government. Department of Economic Development and Infrastructure, 2020). Information about the identity of over 5000 Basque companies, their location, activity and products, and their export activity.
- PRTR - Pollutant Release and Transfer Register (Spanish Government. Ministry for Ecological Transition and Demographic Challenge, 2020). Data on pollutant releases to air, water and land, as well as energy consumptions. The information is available by industrial facility and in an aggregated way by industrial activity (NACE code).
- Empresite - Spanish Companies Directory (El Economista, 2020). It includes location, type of activity (NACE code) and billing of several Spanish companies.

The selection of the companies included in the study was done considering the subsectors proposed by each estimation method, as companies are classified in the PRTR database according to their NACE codes. Among the companies included in these sectors, the authors conducted a second selection considering the nature of their manufacturing processes, keeping those companies that generate heat in any step of the production chain. In total, 193 companies are included in the database, whose geographical distribution in the three provinces of the Basque Country is shown in Fig. 3.

The distribution of the companies in the clustering groups proposed by Methods 3 and 4 is represented in Table 8.

3.2. Industrial waste heat recovery potential

The IWH recovery potentials resulting from the application of the four methods are summarised in Table 9.

As it can be observed, a different number of companies was considered for each method. This is because, among the 193 companies considered, only 129 provide their fuel consumption in the consulted databases (natural gas plus diesel oil), while just 161 provide their CO_2 emissions. As a result, the third method cannot be directly compared to the rest, due to the different number of companies that provided the required inputs. Therefore, in order to conduct a direct comparison between the four methods, they have been applied to those 126 companies that made available both natural gas and diesel oil consumption (inputs for Methods 1, 2 and 4) and the CO_2 emissions (Method 3). The IWH recovery potential values for all the methods are summarised in Fig. 4 and Table 10.

Table 8
Number of companies per significant industrial activity, percentages in brackets.

Main activity sector category	Number of companies
Chemical and petrochemical	39 (20)
Iron and steel	83 (43)
Non-ferrous metals	50 (26)
Non-metallic minerals	11 (5)
Paper, pulp and printing	3 (2)
Food and beverage	0 (0)
Others	7 (4)

Table 9
Input data and potential IWH calculated by each method.

	Method 1	Method 2	Method 3	Method 4
Companies studied	129	129	163	129
Input data	$Q_{natural\ gas} + Q_{diesel\ oil}$ 51436.28 GWh/year	$Q_{natural\ gas} + Q_{diesel\ oil}$ 51436.28 GWh/year	CO_2 emissions 13013.33 kt CO_2/year	$Q_{natural\ gas} + Q_{diesel\ oil}$ 51436.28 GWh/year
Potential type	Technical	Theoretical	Theoretical	Technical
IWH [GWh/year]	6632.9	9805.2	11884.7	8115.1

Methods 1 and 4 are those offering a lower potential, as they refer to the technical potential. Methods 2 and 3 provide theoretical potential and therefore result in higher values. The different results, which present an expectable scattering, would represent a possible energy saving of between 13% and 19.2% of the energy consumed for thermal processes, represented by the diesel oil and natural gas consumption. If only the technical potential is considered, this energy saving would vary between 13 and 16.1%, a relevant percentage considering the total amount of consumed energy in the industrial sector.

Following the methodology proposed by (Papapetrou et al., 2018),

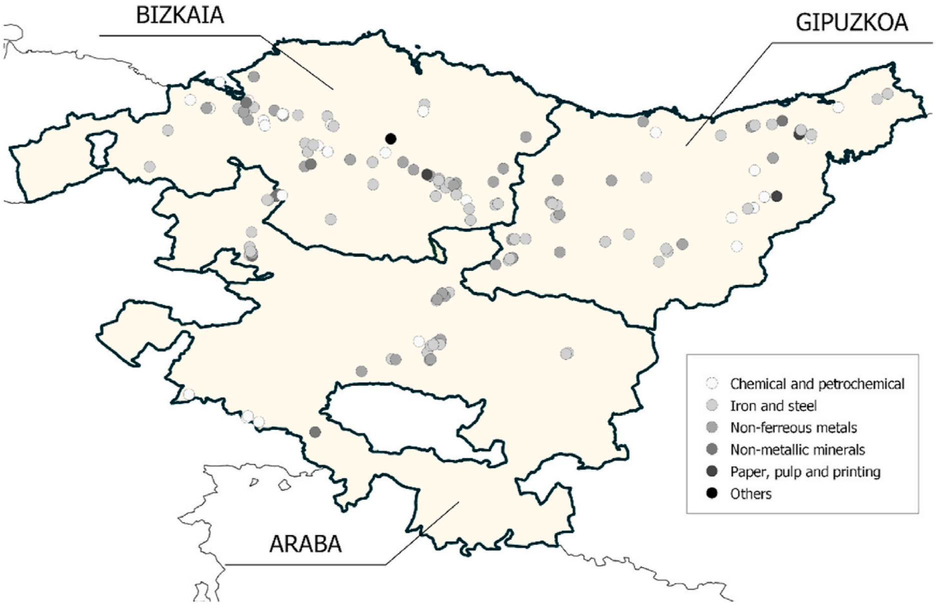

Fig. 3. Distribution of the 193 studied companies in the three Basque Provinces.

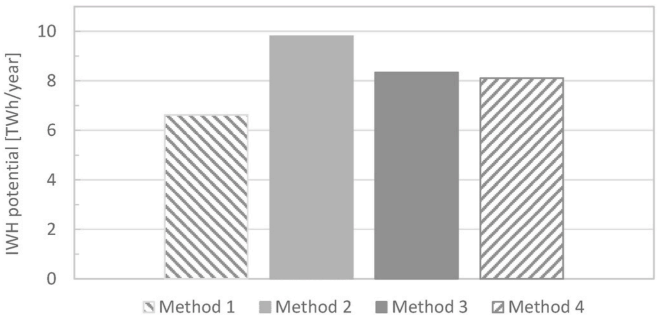

Fig. 4. Estimated IWH recovery potential for the 126 companies that offer both input data, calculated by each method. Striped columns for technical potential, plain for theoretical.

Table 10
Potential IWH calculated by each method for the 126 companies that offer both input data.

	Method 1	Method 2	Method 3	Method 4
Input data	$Q_{natural\ gas} + Q_{oil}$ 50308.7 GWh/year	$Q_{natural\ gas} + Q_{oil}$ 50308.7 GWh/year	CO_2 emissions 7810.783 kt CO_2/year	$Q_{natural\ gas} + Q_{oil}$ 50308.7 GWh/year
Potential type	Technical	Theoretical	Theoretical	Technical
IWH [GWh/year]	6525.1	9648.9	8341.1	8099.7
% recovered [a]	13%	19.2%	16.6%	16.1%

[a] Fraction recovered from the diesel oil and natural gas consumption.

the total IWH recovery potential offered by Method 4 for the Basque Country, 8099.7 GWh/year, can be broken down as represented in the pie chart included in Fig. 5 (remind that this is the only considered method that allows distribution by temperature ranges). In the chart, two pieces of information are provided: the percentage of the estimated technical recovery potential generated at each temperature level and the number of companies that present waste heat per temperature range.

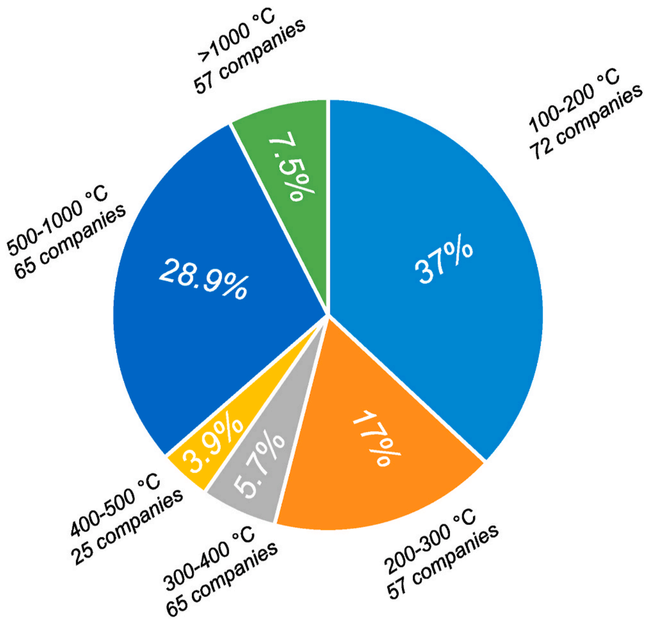

Fig. 5. Basque Country IWH recovery potential distribution by temperature ranges, obtained by Method 4, and number of companies that generate IWH flows at those ranges.

A considerable part of the recoverable heat would be in the range of temperatures from 100 to 200 °C. Concretely, 37% of the estimated technical potential, 3000 GWh/year, would be low quality waste heat that is usually rejected without consideration. According to the estimation, 72 out of the 129 companies studied in Method 4 would generate waste heat at this temperature range.

This can be considered (U.S. Department of Energy, 2008) low quality waste heat; however, several options are nowadays available to reuse this energy. Heat pumps to increase the temperature of the effluent (Kosmadakis, 2019). Rankine cycles with organic fluid (ORC) for electrical production (Mateu-Royo et al., 2019; Wei et al., 2019). Thermal storage (fixed or transportable) (Merlin et al., 2016; White and Sayma, 2020) or even the supply to a nearby district heating network connected (Pelda et al., 2020), could be suitable options for its valorisation.

Besides, 17% of the calculated IWH, 1380 GWh/year in 57 companies, would be distributed between 200 and 300 °C, a range that is considered as medium level for recovery purposes (U.S. Department of Energy, 2008). Finally, it is important to notice that 2954 GWh/year, 36.4% of the obtained total potential, would be technically available at temperatures above 500 °C, an optimum temperature level for recovering that released heat, especially for those processes that require high enthalpy leaps. Moreover, this temperature breakdown can be defined for each company, information that might lead to the development of specific energy recovery projects.

By mapping the studied industries using their coordinates, it is possible to observe the distribution and intensity of the calculated potential by zones. This is useful for knowing in which areas there is a large IWH concentration in order to design recovery strategies or policies. Fig. 6 represents by green circles the intensity of the technical potential IWH per company calculated by Method 4; the higher the potential, the bigger the circle. The figure also illustrates the borders of the inner administrative regions (provinces) of the Basque Country. Bizkaia is located at the upper left corner, Gipuzkoa at the upper right corner and Araba remains at the lower part of the map.

The visual assessment certifies that Bizkaia is the Basque province with the greatest potential. This is explained by the fact that Bizkaia has more energy intensive industry than the other two provinces, where the industry network has other characteristics: in Gipuzkoa there are many companies related to the manufacturing of machine tools and the automotive auxiliary industry, sectors where no relevant IWH has been identified; in the case of Araba, the lowest populated province, IWH sources are concentrated in specific industrial states.

Moreover, there is a relevant concentration of companies in the inland area of Bizkaia, which would represent a great focus of exploitation, as many of them are very close to each other and even in the same industrial estate. These IWH foci could be harnessed without requiring individual facilities for each company, thereafter using the gathered heat in other posterior, industrial or residential, applications (Moser and Lassacher, 2020). In this line, it may be interesting to check which municipalities have important concentrations of potential industrial waste heat, as is done in Fig. 7.

Municipalities highlighted in dark colours concentrate most of the companies due to the existence of important industrial parks and technology parks; so, the possibility of implementing joint technologies for these areas to harness all that IWH might be considered. The analysis of this information would lead to the identification of those municipalities or areas where the concentration of potential recoverable heat could lead to the development of local energy efficiency strategies, something that is possible in politically de-centralized regions as the Basque Country.

3.3. Economic recovery potential

The economic potential obtained with the results provided by Method 4 is presented in Fig. 8. There, the simple payback per company

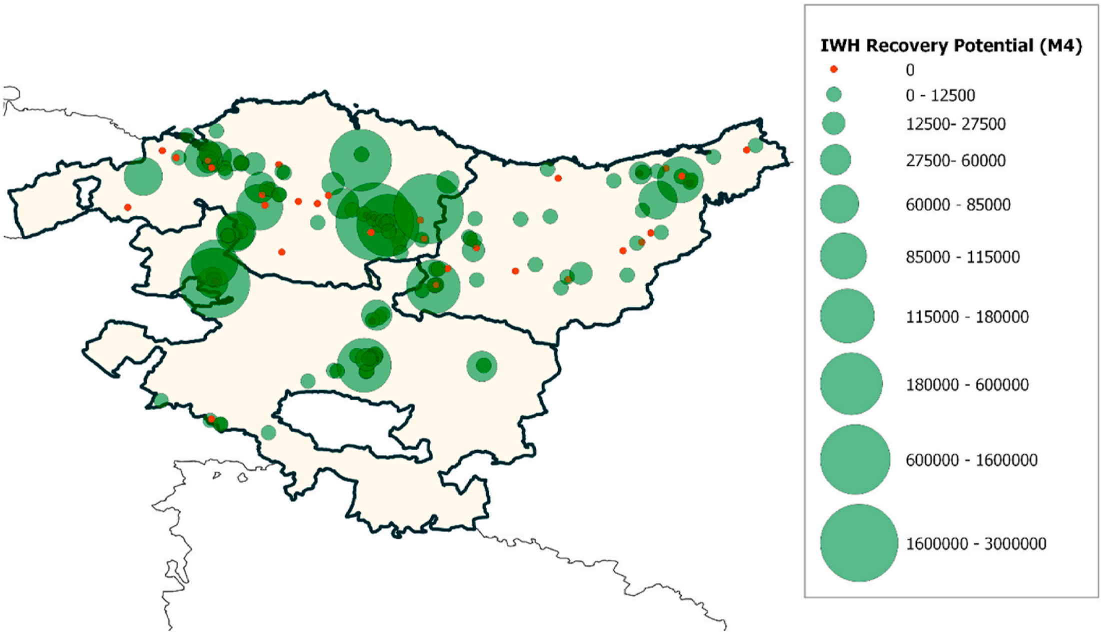

Fig. 6. Mapped results of Method 4, locating all the companies of the Basque Country.

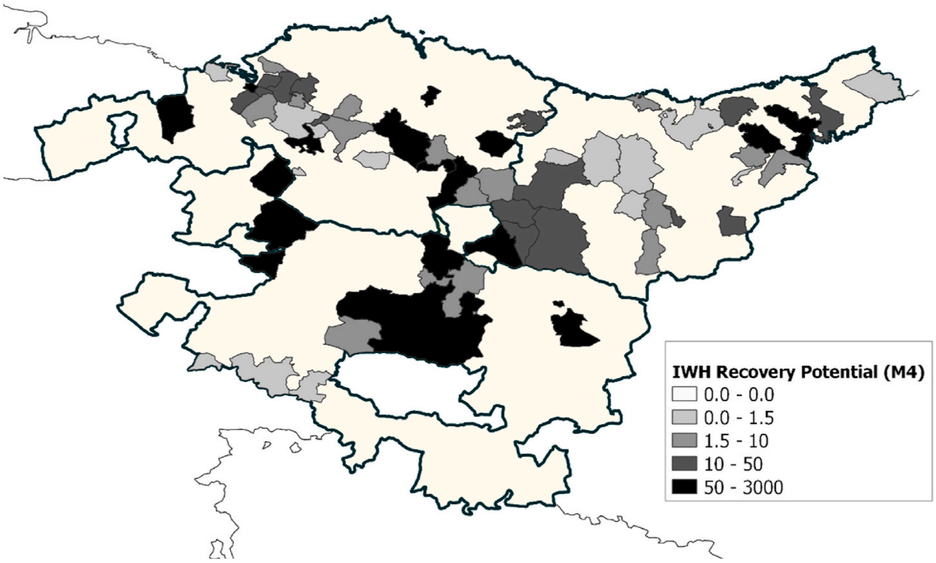

Fig. 7. Results of Method 4 by municipality, the IWH recovery potential intensity is highlighted by colours.

for all temperature ranges is presented. This is calculated by the sum of the simple payback per each temperature range present in the estimated IWH. Three scenarios are assumed: 1000, 4000 and 8000 operating hours per year (Kaygusuz, 2021), *i.e.,* three different working time regimes, from intermittent processes to almost continuous production. The companies were arranged from lower to higher payback value and the 5-year threshold is depicted for the simple payback, which allows us to distinguish between feasible and unfeasible recovery approaches (Rathgeber et al., 2015).

As expected, the number of operating hours is an influencing parameter to establish the economic feasibility of the waste heat recovery. For a certain amount of IWH, the higher the number of operating hours, the lower the average thermal exchange power requires, which decreases the needed heat exchange surface (Eq. (12)). As observed in Fig. 8, for 1000 operating hours per year, 18 out of 129 companies (14%) have a payback period lower than 5 years. However, this figure increases to 72 (56%) and 95 (74%) companies when the IWH is generated in 4000 and 8000 h, respectively. As a result, as the IWH recovery is more interesting in continuous or large batch mode processes (Anastasovski et al., 2020), only the results for 4000 and 8000 h will be assessed in subsequent analyses. These are focused on the economic potential of the heat recovery per range of temperature and the figures obtained per industrial sector.

Firstly, the economic results are evaluated considering the waste heat flow temperatures. The higher the temperature level, the higher the percentage of companies that obtain a payback lower than 5 years. The results are shown in Fig. 9 and summarised in Table 11. The line crossings between different temperature levels in the graphs is explained, taking into consideration the specific amount of thermal power at different temperature levels by companies of different size. In Table 11, for each temperature level, the overall number of companies with a payback below 5 years from the total that generate IWH fluxes at

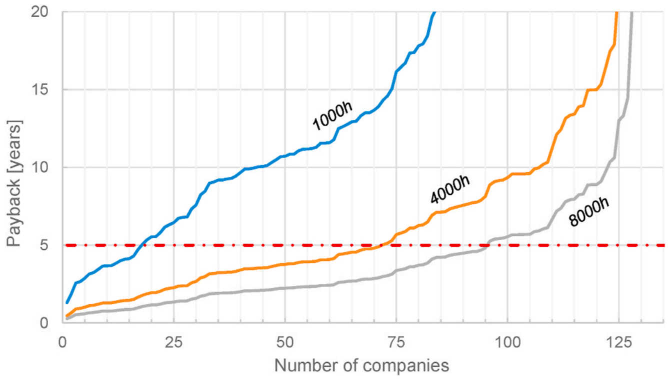

Fig. 8. Influence of the temporal distribution of the industrial waste heat in the estimated payback periods.

the studied temperature level is presented.

For temperatures above 500 °C, the IWH recovery is feasible for the vast majority of the cases; 98% of the companies for 4000 operating hours per year and all of them for 8000 h per year. In fact, when working with waste heat temperatures above 400 °C, there are no significant differences between both numbers of operating hours per year. However, below that figure, the percentage of companies that present viable payback periods is noticeably lower when the same waste heat is released over 4000 working hours.

Additionally, when IWH temperatures are below 200 °C, there is little difference in the economic feasibility, regardless of having 4000 or 8000 operating hours. This reinforces the need to develop effective options to exploit this, on the other hand, abundant source of low quality waste heat (37% of the estimated total technical IWH recovery potential). Additionally, it is convenient to underline that this estimation is carried out for several unfavourable conditions and some of the cases that this economic assessment qualifies as non-viable might present better results if a thorough analysis was to be conducted.

Secondly, the results have been analysed according to the sector categories used by Method 4 (shown in Fig. 10). Again, the graphs included in Figs. 10 and 11 are related to an IWH generation for 4000 and 8000 operating hours, respectively.

Considering the number of companies involved per sector (represented in the title of each graph), the temperature ranges and the payback periods estimated, it could be stated that the "iron and steel" category would be the most interesting industrial sector to develop recovery projects or strategies. In that sector (57 companies out of 129) all the estimated IWH potential is above 200 °C and, additionally, most of the companies present viable investments, especially when the production is distributed in 8000 h. At that operating level, more than 88% of the companies would present payback periods below 5 years in the four temperature ranges. For excess heat streams below 400 °C, longer return periods are registered when the operating level is 4000 h. Specifically 73% of the 57 companies would register admissible return periods in the 300–400 °C range for 8000 working hours and only 45% if the waste heat is released between 200 and 300 °C in 4000 h.

The analysis of the chemical and petrochemical sector, where 25 companies of this study are involved, is also relevant. On the one hand, the economic viability presents satisfactory results in the 400–500 °C range for both annual operating hours: 87% of the sector companies render return periods below 5 years for 4000 working hours and this percentage raises to 92% if 8000 h are considered. On the other hand, the economic potential is almost null for temperatures below 200 °C: less than 5% of the companies would obtain admissible paybacks for both working schedules.

Finally, in the sector of non-ferrous metals, with 34 companies analysed, there is only IWH in the 100–200 °C range, which presents lower economic perspectives than other studied sectors. Only 13% of the companies present payback periods below 5 years for 4000 operating hours per year, while that criteria is filled by 55% of the companies when the number of operating hours is 8000 h. These results encourage further research on economically feasible techniques to reuse this abundant low-grade waste heat.

4. Conclusions

This work has characterized and evaluated the recoverable industrial waste heat potential in the Basque Country, by means of four easy-to-apply bottom-up estimation methods. The region is of special interest due to its representativeness due to the presence of several facilities related to energy-intensive industrial sectors.

The obtained technical potential for IWH recovery is significant. It encompasses 13%–16% of the companies' energy consumption. The geographical distribution of the IWH sources is much higher in the province of Bizkaia, followed by Gipuzkoa and Araba.

Differentiated by temperatures, the largest amount of technically recoverable IWH, 37% is emitted below 200 °C. This significant amount of low quality waste heat could be recovered by means of heat pumps (temperature upgrading) or ORC cycles. In addition, 36% of the residual heat is generated above 500 °C. This emitted energy still possess a substantial quality and, thus, efforts should be performed to reuse it.

Table 11
Number of companies with viable investments at different IWH temperatures, percentages in brackets.

Temperature range	number of companies with PB periods <5 years	
	$n_{hours} = 4000$	$n_{hours} = 8000$
100–200 °C	9/72 (13%)	28/72 (39%)
200–300 °C	26/57 (45%)	50/57 (88%)
300–400 °C	48/65 (74%)	63/65 (97%)
400–500 °C	22/25 (88%)	23/25 (92%)
500–1000 °C	64/65 (98%)	65/65 (100%)
>1000 °C	56/57 (98%)	57/57 (100%)

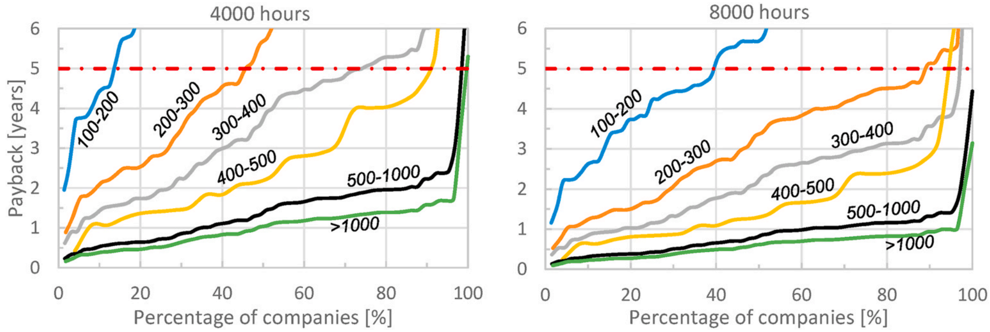

Fig. 9. Evolution of payback periods for the different temperature ranges for IWH released in 4000 (left) and 8000 h (right).

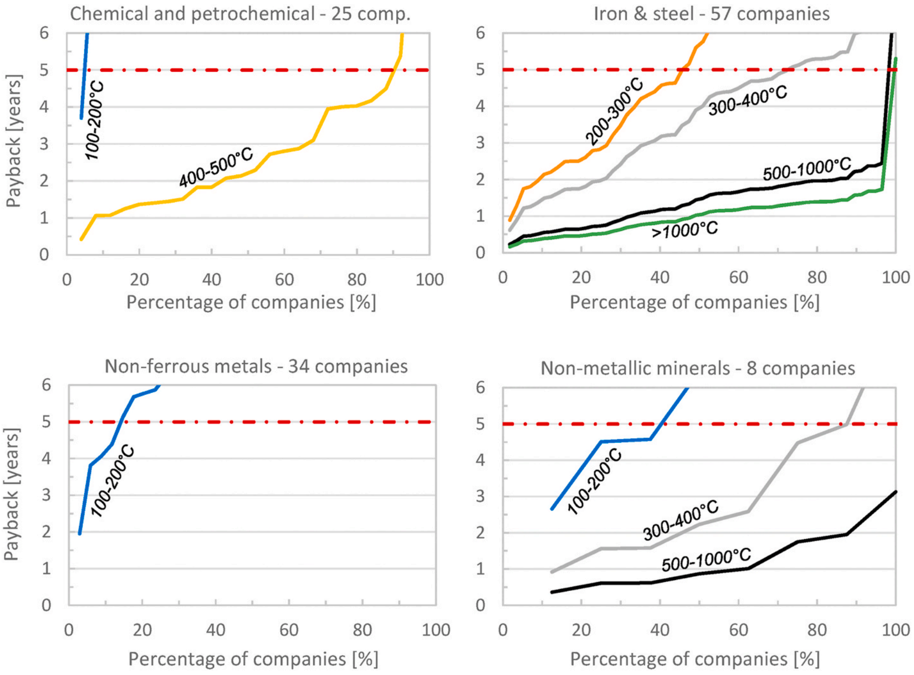

Fig. 10. Payback periods for the different temperature ranges for IWH released in different sector categories. Results for 4000 h.

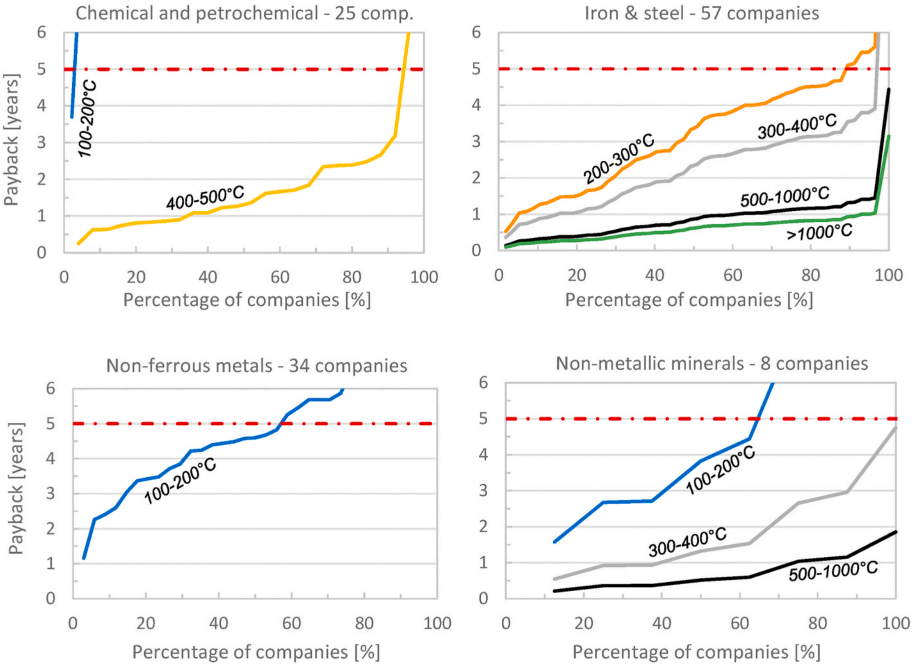

Fig. 11. Payback periods for the different temperature ranges for IWH released in different sector categories. Results for 8000 h.

For most companies with a continuous production regime (8000 operating hours per year), return periods of less than 5 years are obtained in the recovery of waste heat fluxes above 200 °C. Special mention must be made of the iron and steel and petrochemical sectors, which present positive economic perspectives for IWH recovery projects. These results should encourage the implementation of measures for the valorisation of the IWH that is currently expelled into the environment.

Regarding the used methodology, the four methods employed rendered similar results in terms of IWH recovery quantities. This is a remarkable aspect, considering that they were originally developed for different regions and time periods. However, they only provide estimated data. Actual projects would require a more exhaustive assessment including detailed information of productive processes, characteristics of waste streams, their flow rates and temperatures. Future works will entail the validation of the proposed methodology through the collaboration with local enterprises at different industrial sectors.

CRediT author statement

Pello Larrinaga: Conceptualization, Writing - Original draft preparation, Formal analysis, Data Curation, Supervision. Álvaro Campos-Celador: Visualization, Methodology, Resources. Jon Legarreta: Data Curation, Resources. Gonzalo Diarce: Writing - Review & Editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the Spanish Ministry of Science and Innovation (MICINN) for funding through the Sweet-TES research project (RTI 2018-099557-B-C22).

References

Agathokleous, R., Bianchi, G., Panayiotou, G., Aresti, L., Argyrou, M.C., Georgiou, G.S., Tassou, S.A., Jouhara, H., Kalogirou, S.A., Florides, G.A., Christodoulides, P., 2019. Waste Heat Recovery in the EU industry and proposed new technologies. Energy Procedia 161, 489–496. https://doi.org/10.1016/j.egypro.2019.02.064.

Anastasovski, A., Rasković, P., Guzović, Z., 2020. A review of heat integration approaches for organic rankine cycle with waste heat in production processes. Energy Convers. Manag. 221, 113175. https://doi.org/10.1016/j.enconman.2020.113175.

Ates, F., Ozcan, H., 2020. Turkey's industrial waste heat recovery potential with power and hydrogen conversion technologies: a techno-economic analysis. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2020.11.059.

Basque Government. Department of Economic Development and Infrastructure, 2020. Catalogue of industries and exporting companies in the Basque country. http://www.industria.ejgv.euskadi.net/x76aAppWar/buscador/buscadorSimple?locale=es.

Bianchi, G., Panayiotou, G.P., Aresti, L., Kalogirou, S.A., Florides, G.A., Tsamos, K., Tassou, S.A., Christodoulides, P., 2019. Estimating the waste heat recovery in the European Union Industry. Energy, Ecology and Environment 4 (5), 211–221. https://doi.org/10.1007/s40974-019-00132-7. Scopus.

Brückner, S., Schäfers, H., Peters, I., Lävemann, E., 2014. Using industrial and commercial waste heat for residential heat supply: a case study from Hamburg, Germany. Sustainable Cities and Society 13, 139–142. https://doi.org/10.1016/j.scs.2014.04.004.

Brueckner, S., 2015. Industrielle Abwärme in Deutschland-Bestimmung von gesichertem Aufkommen und wirtschaftlicher Nutzbarkeit. Technische Universität München (TUM).

Brueckner, Sarah, Miró, L., Cabeza, L.F., Pehnt, M., Laevemann, E., 2014. Methods to estimate the industrial waste heat potential of regions – a categorization and literature review. Renew. Sustain. Energy Rev. 38, 164–171. https://doi.org/10.1016/j.rser.2014.04.078.

Çengel, Y.A., 1998. Heat Transfer: A Practical Approach. WBC McGraw-Hill.

El Economista, 2020. Empresite. Spanish companies directory. https://empresite.eleconomista.es/.

Ente Vasco de la Energía, 2017. Estrategia Energética de Euskadi 2030.

European Comission, 2020. Eurostat database. https://ec.europa.eu/eurostat/data/database.

European Union, 2018. Directive (EU) 2018/of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. Official Journal of the European Union 156, 75–91.

Eurostat, 2008. NACE Rev. 2. Office for Official Publications of the European Communities.

Eurostat, 2019. Energy Statisticsâ€"Complete energy balances. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_bal_c&lang=en.

Eurostat, 2020a. Gas prices for non-household consumers: Bi-annual data (from 2007 onwards). NRG_PC_203.

Eurostat, 2020b. National accounts aggregates by industry (up to NACE A*64). https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_a64&lang=en.

Eustat, 2019. Consumo final de energía de la C.A. de Euskadi por sectores (Ktep). 2000/2019. https://www.eustat.eus/elementos/ele0000300/Consumo_final_de_energia_de_la_CA_de_Euskadi_por_sectores/tbl0000396_c.html.

Eustat, 2020. Producto interior bruto de la C.A. de Euskadi por componentes de la oferta y demanda, según trimestres. https://www.eustat.eus/elementos/tbl0003222_c.html.

Fitó, J., Ramousse, J., Hodencq, S., Wurtz, F., 2020. Energy, exergy, economic and exergoeconomic (4E) multicriteria analysis of an industrial waste heat valorization system through district heating. Sustainable Energy Technologies and Assessments 42, 100894. https://doi.org/10.1016/j.seta.2020.100894.

Hardt, L., Barrett, J., Brockway, P., Foxon, T.J., Heun, M.K., Owen, A., Taylor, P.G., 2017. Outsourcing or efficiency? Investigating the decline in final energy consumption in the UK productive sectors. Energy Procedia 142, 2409–2414. https://doi.org/10.1016/j.egypro.2017.12.175.

Hong, G.-B., Pan, T.-C., Chan, D.Y.-L., Liu, I.-H., 2020. Bottom-up analysis of industrial waste heat potential in Taiwan. Energy 198, 117393. https://doi.org/10.1016/j.energy.2020.117393.

Kaygusuz, K., 2021. 9. Energy efficiency and renewable energy sources for industrial sector. In: Borge-Diez, D., Rosales-Asensio, E. (Eds.), Energy Services Fundamentals and Financing. Academic Press, pp. 213–238. https://doi.org/10.1016/B978-0-12-820592-1.00009-9.

Kays, W.M., London, A.L., 1998. Compact Heat Exchangers. Krieger Publishing Company.

Kosmadakis, G., 2019. Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries. Appl. Therm. Eng. 156, 287–298. https://doi.org/10.1016/j.applthermaleng.2019.04.082.

Kosmadakis, G., Arpagaus, C., Neofytou, P., Bertsch, S., 2020. Techno-economic analysis of high-temperature heat pumps with low-global warming potential refrigerants for upgrading waste heat up to 150 °C. Energy Convers. Manag. 226, 113488. https://doi.org/10.1016/j.enconman.2020.113488.

Land, A.L., Feldhusen, H., Tvaerme, A., Cronholm, L.A., Sundloef, C., 2002. Industriell Spillvärme – Processer Och Potentialer.

Loni, R., Najafi, G., Bellos, E., Rajaee, F., Said, Z., Mazlan, M., 2020. A review of industrial waste heat recovery system for power generation with Organic Rankine Cycle: recent challenges and future outlook. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2020.125070, 125070.

Mateu-Royo, C., Mota-Babiloni, A., Navarro-Esbrí, J., Peris, B., Molés, F., Amat-Albuixech, M., 2019. Multi-objective optimization of a novel reversible High-Temperature Heat Pump-Organic Rankine Cycle (HTHP-ORC) for industrial low-grade waste heat recovery. Energy Convers. Manag. 197, 111908. https://doi.org/10.1016/j.enconman.2019.111908.

Merlin, K., Soto, J., Delaunay, D., Traonvouez, L., 2016. Industrial waste heat recovery using an enhanced conductivity latent heat thermal energy storage. Appl. Energy 183, 491–503. https://doi.org/10.1016/j.apenergy.2016.09.007.

Miró, L., Brueckner, S., McKenna, R., Cabeza, L.F., 2016. Methodologies to estimate industrial waste heat potential by transferring key figures: a case study for Spain. Appl. Energy 169, 866–873. https://doi.org/10.1016/j.apenergy.2016.02.089.

Moser, S., Lassacher, S., 2020. External use of industrial waste heat. An analysis of existing implementations in Austria. J. Clean. Prod. 264, 121531. https://doi.org/10.1016/j.jclepro.2020.121531.

Odyssee-Mure Database, 2017. http://www.indicators.odyssee-mure.eu/energyefficiency- database.html.

Papapetrou, M., Kosmadakis, G., Cipollina, A., La Commare, U., Micale, G., 2018. Industrial waste heat: estimation of the technically available resource in the EU per industrial sector, temperature level and country. Appl. Therm. Eng. 138, 207–216. https://doi.org/10.1016/j.applthermaleng.2018.04.043.

Pelda, J., Stelter, F., Holler, S., 2020. Potential of integrating industrial waste heat and solar thermal energy into district heating networks in Germany. Energy 203, 117812. https://doi.org/10.1016/j.energy.2020.117812.

Peris, B., Navarro-Esbrí, J., Mateu-Royo, C., Mota-Babiloni, A., Molés, F., Gutiérrez-Trashorras, A.J., Amat-Albuixech, M., 2020. Thermo-economic optimization of small-scale Organic Rankine Cycle: a case study for low-grade industrial waste heat recovery. Energy 213, 118898. https://doi.org/10.1016/j.energy.2020.118898.

Persson, U., Möller, B., Werner, S., 2014. Heat Roadmap Europe: identifying strategic heat synergy regions. Energy Pol. 74, 663–681. https://doi.org/10.1016/j.enpol.2014.07.015.

Pili, R., García Martínez, L., Wieland, C., Spliethoff, H., 2020. Techno-economic potential of waste heat recovery from German energy-intensive industry with Organic Rankine Cycle technology. Renew. Sustain. Energy Rev. 134, 110324. https://doi.org/10.1016/j.rser.2020.110324.

Rathgeber, C., Lävemann, E., Hauer, A., 2015. Economic top–down evaluation of the costs of energy storages—a simple economic truth in two equations. Journal of Energy Storage 2, 43–46. https://doi.org/10.1016/j.est.2015.06.001.

Razmjoo, P., Sajjad Keshavarzian, P.D., 2015. Fuel saving due to pinch analysis and heat recovery in a petrochemical company. In: Proceedings of ECOS-2015. 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.

Song, R., Feng, X., Wang, Y., 2016. Feasible heat recovery of interplant heat integration between two plants via an intermediate medium analyzed by Interplant Shifted Composite Curves. Appl. Therm. Eng. 94, 90–98. https://doi.org/10.1016/j.applthermaleng.2015.10.125.

Spanish Government, 2020. Ministry for ecological transition and demographic Challenge. In: PRTR Spain. Pollutant Release and Transfer Register. http://www.en.prtr-es.es/.

Statistiska Centralbyrån (Scb), 1992. SNI 92: Standard För Svensk Näringsgrensindelning 1992. Statistiska centralbyrån.

Stijepovic, M.Z., Linke, P., 2011. Optimal waste heat recovery and reuse in industrial zones. Energy 36 (7), 4019–4031. https://doi.org/10.1016/j.energy.2011.04.048.

U.S. Department of Energy, 2008. Waste Heat Recovery: Technology and Opportunities. U.S. Industry.

Valencia, G., Fontalvo, A., Duarte Forero, J., 2021. Optimization of waste heat recovery in internal combustion engine using a dual-loop organic Rankine cycle: thermo-economic and environmental footprint analysis. Appl. Therm. Eng. 182, 116109. https://doi.org/10.1016/j.applthermaleng.2020.116109.

Wei, F., Senchuang, G., Zhonghe, H., 2019. Economic analysis of Organic Rankine Cycle (ORC) and Organic Rankine Cycle with internal heat exchanger (IORC) based on industrial waste heat source constraint. Energy Procedia 158, 2403–2408. https://doi.org/10.1016/j.egypro.2019.01.291.

White, M.T., Sayma, A.I., 2020. A new method to identify the optimal temperature of latent-heat thermal-energy storage systems for power generation from waste heat. Int. J. Heat Mass Tran. 149, 119111. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119111.