Methodologies to estimate industrial waste heat potential by transferring key figures: A case study for Spain

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Abstract

In the current European energy context, the use of recovered industrial waste heat provides an attractive opportunity to substitute primary energy consumption by a low-emission and low-cost energy carrier. In the case of industrial waste heat, this potential is currently not only largely untapped, but also unaccounted for. In order to achieve a widespread use of recovered industrial waste heat, assessments with a large scope and high spatial resolution are needed. Three methods published in the period 2002–2010 have been found in the literature, which are potentially transferable to other regions. These three methods are based on either the energy consumption of each manufacturing sector or the individual site CO_2 emissions. The scope of this analysis is, first, to investigate in how far a transfer of the figures to different countries or regions is sensible in comparison to former studies in the literature. In the process, some uncertainties when transferring methods were identified (different definitions of industry, different standard industrial activities classifications or no standard at all, etc.). The second goal is, once the methodology is accepted, to apply it to a case study, in this case the industrial sector in Spain and two of its counties (Catalonia and the Basque Country) for the years 2001, 2009, 2010 and 2013. In this period, and based on the different approaches employed, the Spanish annual industrial waste heat potential ranges from 54.3 to 151.1 PJ, Catalonia from 8.6 to 29.7 PJ, and from 7.2 to 11.9 PJ for the Basque Country. The methods are considered highly transferable but uncertainties inevitably arise in the case that the source and destination industrial sectors are very different.

Keywords

Waste heat, excess heat, manufacturing industry, Spain, waste heat potential

Abbreviation list

IWH	Industrial waste heat
EPA	Environmental Protection Agency
SIC	Standard Industrial Classification
IDAE	Instituto para la Diversificación y Ahorro de la Energia
ICAEN	Institut Català d'Energia
EVE	Ente Vasco de la Energia
SNI	Swedish Standard Industrial Classification
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
Q_{IWH}	Industrial waste heat potential
E_{FUEL}	Fuel consumption per sector
f	waste heat per fuel consumption ratio
E-PRTR	European Pollutant Release and Transfer Register
M1	Method 1
M2	Method 2
M3	Method 3

1 Introduction

Since the industrial sector continues implementing efforts to improve its energy efficiency, recovering industrial waste heat (IWH) provides an attractive opportunity for a low-emission and low-cost energy source. This heat can be recovered and reused in other processes onsite (to preheat incoming water or combustion air, preheating furnace loads, etc.), or transformed into electricity, cold or other type of heat. Many technologies are available for IWH recovery: Brueckner et al. [1] proposed and classified these technologies into active and passive technologies depending on whether the heat is being used directly at the same or at lower temperature level or whether it is transformed to another form of energy or to a higher temperature. Moreover, in that paper an economic analysis taking into account the maximum acceptable investment cost for each technology is estimated and compared with the current investment cost depending on the operating hours of the systems proposed.

Before taking advantage of recovered IWH, its characteristics (amount, thermophysical properties, type of potential, etc.) and its location should be known. Regarding its characteristics, Brueckner et al. [2] proposed differentiating between theoretical, technical and economic potential when assessing IWH potentials and suggests a categorization of the methods to account IWH found in the literature along three dimensions: study scale, data collection, and approach (bottom-up and top-down). Regarding the location of the heat source, Miró et al. [3] reviewed and identified the IWH potential for 33 countries worldwide taking into account scientific and other dissemination sources.

However, site-specific data on annual waste heat volumes rejected from industrial facilities is very rare, which makes the exploitation of this energy source difficult. Existing assessments often do not specify the methodology used, in some cases apparently making expert assumptions that are not scientifically justified [3]. Moreover, in some regions the manufacturing industry is a very secretive economic sector and their energy related parameters are not reported. This situation urges the employment of alternative data parameters to assess excess heat availabilities [4]. One of these alternatives may be the adaptation and transfer of key figures originally developed for another region. Three medium precise IWH assessments have been found in the literature, in which transferrable figures are available (developed by Brueckner et al. [5], Land et al. [6] and Persson et al. [4] respectively) and are applied here to assess the potential in other regions. These three methods combine bottom-up and top-down approaches and are either based on the energy consumption of each manufacturing sector or their CO_2 emissions.

Other studies defining methodologies to estimate the IWH potential have been found in the literature. However, they cannot be transferred due mainly to the mismatch between the classification of the industry in the applied region and in the original study. Latour et al. [8] assessed in 1982 the industrial waste heat from the 10 Environmental Protection Agency (EPA) regions from the US considering 19 selective industrial sectors and the percentage of the annual purchased fuels and electricity discharged as waste heat was presented. Although they classified the industrial sectors according to the Standard Industrial Classification (SIC) valid at that moment, the conversion to the current standard classifications was not possible. In Korea, Chung et al. [9] presents in 2010 the most recent ratios of recovery potential and energy purchased, however the exact definition and boundaries of each industrial sector considered by the authors is not available. Pehnt et al. [10] combined studies from Vienna, Norway and the US and the therein derived key figures to estimate the waste heat potential for Germany in 2010, however some of the key figures were not published, only the final results. In the Ecoheatcool project [11] the heat demand in Europe were investigated by Euroheat&Power, a pan-European district heating association [12]. To evaluate the economically feasible waste heat potential for all 32 European states the energy factors derived from Land et al. (Method 1 [6]) were also used. McKenna et al. [13] estimates the IWH recovery potentials in the UK industry based in the CO_2 emitted in the different industrial sites involved in the European Union Emissions Trading System. McKenna et al. [13] study is more detailed, taking into account specific subsector parameters like the combustion emission fraction, the load factor, etc. which implies a huge effort in collaboration with industrial trade groups which was not possible in the case of Spain. This study was later used by Hammond and Norman [14] to estimate the technical potential of various heat recovery technologies, also in the UK. Finally, Miró et al. [15] updated and transferred McKenna et al. [13] approach to the non-metallic mineral industry in Europe for the period 2007-2012.

Most of the industries worldwide neither record not publish their waste streams. The general aim of this study is to apply and to discuss the suitability of transferring three IWH potential evaluation methods identified in the literature to a different region than the original. The specific objectives are (1) to evaluate if transferring key figures is a suitable methodology to perform a first approach in terms of evaluating the industrial waste heat potential, and (2) once the methodology is accepted, to apply it to a case study, in this case Spain. This region is selected since in that region the potential expected is high (due to a high presence of energy-intensive sectors) and the fact that the Spanish manufacturing industry is a very secretive economic sector and, therefore it is not possible to apply more accurate methods to estimate the IWH potential. The results obtained are compared, when available, to former studies in the investigated regions. Moreover, the suitability of transferring these methods is verified by applying them to Sweden and to the German non-metallic minerals sector, since former IWH potential assessments have been performed in these two cases and comparison and discussion is possible. Once the use of these methods is accepted, a case study is selected, in this case the Spanish manufacturing industry, as well as two of the most industrialized Spanish regions: Catalonia and The Basque Country.

The structure of this article is organized as follows: first of all in this article the three methods selected are presented and their adaptation to be transferrable to the scope of the study is described. Then, the validation of their transference is assessed and, finally, the results obtained for Spain, Catalonia and the Basque Country are shown and widely discussed.

2 Methods

Methods to estimate IWH can be classified by accuracy in three different categories: rough methods, using few statistical data, medium precise estimate, with more detailed literature data and coefficients, and high precision methods, with measured data. In order to estimate the IWH for a region, it is very difficult and time consuming to collect or measure individual site data. That is why high precision methods have not been considered by the authors. Similarly, rough methods are not considered because their high uncertainty. Thus, Three medium precise estimation methods from the literature have been selected as they can be transferred, assuming some uncertainties, to other regions. Two of the methods are based on waste heat per industrial fuel consumption ratios, the other considers individual CO_2 emissions of the industrial sites.

In case of the first two methods (Method 1 and Method 2) based on waste heat per fuel consumption ratios (f), the data needed from the studied region is the fuel consumption per industrial sector. The different sources of fuel consumption used are IDAE [16] and Eurostat [17] for Spain, ICAEN [18] for Catalonia and EVE [19] for the Basque Country. All of them use their own non-standard industrial classifications in order to report the energy consumption. For that, both the fuel consumption and the industrial classification have been adapted to match with the key figures from the original methods. In this process, experts from the institutions which publish these data have contributed. The resulting equation to obtain the sectors ratios and their IWH potential (Q_{IWH}) also takes into account the fuel consumption per sector (E_{fuel}) as it can be seen in Equation 1:

$$f(\%) = \frac{Q_{IWH}}{E_{fuel}} \qquad \text{(Eq. 1)}$$

To apply Method 3, CO_2 emissions per site are needed. Therefore, the European Pollutant Release and Transfer Register (E-PRTR) database [20] is used. The original publication has already published one IWH recovery potential for Spain in 2010 and this is the value used in this study. However, in the case of Catalonia and the Basque country, the authors have applied the original methodology to estimate the potentials.

2.1 Method 1: Land et al. [6]

In 2002, Statistics Sweden developed the key figure relating the waste heat per fuel consumption for companies in each SNI group (Swedish Standard Industrial Classification). They originally used the SNI 1992 sectors 10 to 37. From these sectors only sectors 15 to 37 belong to the manufacturing industry. The 23 sectors from the manufacturing industry considered were divided into 15 groups, each group with a ratio. These figures were originally developed to evaluate the potential use of waste heat in district heating systems (bottom-up estimation). Thus, only companies with more than 3 GWh equivalent of oil use per year that are close to settlements were considered. To be considered as a settlement, the villages had to have at least 200 inhabitants and less than 200 meters between neighboring houses. Therefore, 80 communities were investigated of which ten did not formerly have a district heating system. Within these communities, a total of 994 companies were considered. To develop these figures, data from the government agency SCB (Statistics Sweden [7]) or, when no data was available, empiric values from the Swedish district heating association were used. The investigated potential is a technical potential and only gas streams are considered.

This method is based on waste heat per fuel consumption figures (f_{M1}). Original figures referred to the SNI1992 classification. However, by using available conversion tables, the figures have been transformed into SNI2002 and then to NACE Rev. 2. In this process, NACE subsector 20.14, manufacture of other organic basic chemicals, (which belonged originally to the same group as 10 to 12) has been neglected. The results of combining the ratios from Method 1 to each region considered are shown in Table 1.

Table 1 *Result of combining* waste heat per fuel consumption figures *from Method 1 [6] to Spain (both IDAE and Eurostat) and Catalonia fuel consumption data*

NACE rev. 2 sectors	f_{M1}	
	Spain and Catalonia	**Basque Country**
10,11,12	6.7%	6.7%
13,14,15,16,18,33	0.0%	0.0%
17	3.1%	3.1%
19, 20, 21, 22, 25, 26, 27, 28, 29, 30, 31, 32	12.9%	-
19, 20, 21, 22, 23, 25, 26, 27, 28, 29, 30, 31, 32	-	9.6%
23	3.9%	-
24	20.0%	20.0%

When combining data from this study to the regional data, the industrial sectors have been finally aggregated in six different groups in the case of Spain and Catalonia and in five different groups in the case of the Basque Country. The only difference in the final ratios defined for Spain and Catalonia and for The Basque Country is sector 23 (manufacture of other non-metallic mineral products). The number of industrial sectors in the same group varies from 1 to 13 sectors in a group.

2.2 Method 2: Brueckner et al. [5]

In Brueckner et al. [5], a bottom-up estimation of the theoretic waste heat potential in Germany is presented based on emission declarations for 2008 evaluated on a company level. In Germany, companies from the production sector are required to report their exhaust gas emissions every four years in order to prevent and minimize negative environmental impacts. Among other values, the used fuel type and amount are reported as well as the exhaust gas volume, temperature and operating hours. Exhaust gas values are recorded for each stream separately, but the data concerning fuel type and amount is only available at the company level. Each company is categorized into a manufacturing subsector according to the produced goods. For this, a national version of the European standard classification code for economy statistics NACE rev. 2 is used (Nomenclature statistique des activités économiques dans la Communauté européenne – Sector C Manufacturing Subsectors 10-33 without 19). For each one of the 22 sectors considered, an industrial waste heat to fuel consumption ratios is derived.

Method 2 is also based in waste heat per fuel consumption figures (f_{M2}). When combining ratios from Method 2 to the different original data from Spain, Catalonia and the Basque Country, the following ratios have been obtained (Table 4 2).

Table 2 *Result of combining* waste heat per fuel consumption figures from *Method 2 [5] to Spain (Eurostat)*

NACE rev. 2 sectors	f_{M2}			
	Spain (Eurostat)	**Spain (IDAE)**	**Catalonia (ICAEN)**	**Basque Country (EVE)**
10,11,12	10.8 %	10.8 %	10.8 %	10.8 %
13,14,15	28.2 %	28.2 %	-	28.2 %
13,14,15,16,31	-	-	11.6 %	-
16	9.9 %	-	-	-
16,31	-	10.1 %	-	-
16,22,23,31,32	-	-	-	13.9 %
17	-	-	9.1 %	-
17,18	8.0 %	8.0 %	-	8.0 %
18	-	-	3.2 %	-
20,21	8.8 %	8.8 %	8.8 %	8.8 %
22	-	-	16.5 %	-
22,31,32	13.1 %	-	-	-
22,23,32	-	14.8 %	-	-
23	14.8 %	-	14.8 %	-
24	18.6 %	18.6 %	18.6 %	18.6 %
25,26,27,28	22.1 %	-	-	22.1 %
25,26,27,28,33	-	21.6 %	-	-
25,26,27,28,29,30, 33	-	-	20.2 %	-
29,30	18.0 %	18.0 %	-	18.0 %
32	-	-	8.1 %	-

The original 23 sectors composing the manufacture industry, each one with its own ratio, have been aggregated into 8 different groups in the case of The Basque Country, into 9 different groups in Spain (IDAE) and in 10 different groups in Catalonia and Spain (Eurostat). Differences between both Spanish sources remain in groups 16, 23, 31 and 33. Applying this method, the maximum of sectors combined in the same group are 5.

Regarding to the classification of industrial sectors proposed by both methods, groups 10-12 (food, beverages and tobacco) and 24 (basic metals) are not combined to any other industrial sector. The rest of sectors are combined differently in both methods. Moreover, for sectors 10 to 12 the f ratio has a value of 6.7 % in the Method 1 and 10.8 % in Method 2. For sector 24, similar ratios values are obtained for both approximations (18.6 – 20.0 %). In Method 2 none of the sectors have a IWH ratio of 0 % while in Method 1 sectors 13, 14, 15, 16, 18 and 33 have a f of 0 %. Final values of f (once combined to meet the industrial sector classification) get a range of values of 0-20.0 % when applying Method 1 and 3.2 – 28.2 % when applying Method 2. The maximum of sectors combined in the same group are 5 in Method 2, while in Method 1 there are 13. It is expected that the smaller the number of sectors combined in the same group, the more accurate results can be obtained.

2.3 Method 3: Persson et al. [4]

Persson et al. [4] used the European Pollutant Release and Transfer Register (E-PRTR) where the site carbon dioxide emissions can be found. Given this data and, additionally, characteristic carbon dioxide emission factors reflecting average national fuel mixes per main activity sector, assessments of annual primary energy input volumes to excess heat activities are established. From this, excess heat volumes can be estimated by relating primary energy input volumes to default recovery efficiencies. These recovery efficiencies (Table 3), which is 25 % in the case of the non-metallic mineral industry, represent the maximal levels of excess heat potential. Using this methodology, the potential excess heat for EU27 and for energy and industry sector is estimated. Persson et al. used their own non-standard industrial classification. Originally they divided the industry in the following sectors without a direct relation to any standard classification: chemical and petrochemical, food and beverage, iron and steel, non-ferrous metals, non-metallic minerals, and paper, pulp and printing. For this article, this method is only applied to 2010 data as it is the year in which the original method was developed and the sector emission factor were calculated.

In Table 3, the recovery efficiencies for the manufacturing industrial sectors used by Persson et al. [4] are listed as well as the carbon dioxide emission factor for Spain.

Table 3 Recovery efficiencies by sector proposed by Persson et al. [4] and carbon dioxide emission factor for Spain

Main activity sector category	**Recovery efficiency (%)**	**Carbon dioxide emission factor (gCO_2/MJ)**
Chemical and petrochemical	25	62.5
Iron and steel	25	77.7
Non-ferrous metals	25	64.3
Non-metallic minerals	25	68.6
Paper, pulp and printing	25	77.0
Food and beverage	10	73.1

No adjustments have been done to the original method as the author has provided the results of his study for Spain obtained during the realization of his article. In the case of Catalonia and the Basque Country, the authors have applied the original methodology to the CO_2 emissions collected in the E-PRTR database.

In Table 4, the main characteristics of the three transferable methods presented are summarized. Taking into account all these characteristics their relative accuracy can be determined. Regarding to the year of the data, the closer the year of the original method to the year in which the method should be applied, the better. The same applies to the original region and original industrial classification, i.e. the closer the characteristics of the original region and industry to the applied region, the higher the expected accuracy. Finally, technical potentials reflect better than the theoretical potentials the amount of waste heat which can be finally used. For these reasons Method 2 can be considerate as the most accurate.

Table 4 Main characteristics of the three methods presented

	Method 1	**Method 2**	**Method 3**
Year of the data	<2002	2008	2010
Original region	Sweden	Germany	Countries from EU-27
Input data	Energy (fuel) consumption	Energy (fuel) consumption	CO_2 emissions
Type of potential considered	Technical	Theoretical	Theoretical
Original industrial classification used	SNI 1992	NACE rev. 2	Own (Table 3)
Original industrial sectors evaluated	15-37	10-33 excluding 19	Six sectors
Accuracy of the method	++	+++	++

3 Validation of the method with existing approaches

When transferring methods originally derived from a specific country to another region some uncertainties are expected as it is implied that the industrial sectors are equal in both countries, they use the same or similar processes/technologies with comparable efficiencies, etc. If for example one country has a high degree of automation in a sector while in the other country there is a lot of manual work, it is probable that the waste heat production per used fuel and CO_2 emissions are different. This is also the case if the dominating processes in a sector in two countries differ too much – in one country metal industry might be melting and forging metal while in another it is bending and blanking. It is also very important that the definition of the industrial sectors is very clear in both countries and that the classifications can be transformed into one another. If this results in an aggregation of different sectors, the result of the estimation will get rougher the further the sectors are aggregated. Other uncertainties like the reference year of the data have been minimized by using the same year as the reference study to analyze the potential. All of these parameters tend to limit the applicability of the method to another system and context; the more consistent they between the original and destination system, the more accurate the expected results.

Because of all these uncertainties, the aim of this section is to analyze the feasibility of transferring key figures from one region to another. This feasibility is assessed by comparing the transfer of two Methods proposed to previously published data with the most similar study scope. The cases selected to assess this feasibility are: the IWH recovery potential scale from in Sweden and in the German non-metallic mineral industrial sector.

3.1 Swedish manufacture industry

There are five former studies which evaluate the Swedish IWH recovery potential (Figure 1). Two of the former Swedish studies (Land et al. [6] and Cronholm et al. [21]) focused only on IWH that can be used in district heating systems. Thus, the waste heat sources had to have a certain size and needed to be close to settlements, etc. Therefore, the values obtained are expected to be lower than the others due to their scope. The investigated potential is found to be 34.0 PJ by Land et al. [6] and 21.2-28.4 PJ by Cronholm et al. [21]. These potentials are technical potential and the exact date of the original data is not known.

Two studies based on industrial CO_2 emissions were published, assessing the maximal theoretical potential for 2009 [22] and for 2010 [4] resulting 97.0 and 85.6 PJ, respectively. Persson et al. [4] assessment includes the manufacturing industry while in the Heat Roadmap report [22] the potential includes also the fuel supply in the definition of industry. That is why the value from this two sources are ~~is~~ expected to be higher.

Moreover, Broberg et al. [23] assessed the Swedish potential by scaling up the results obtained via questionnaires to the industry. The data used for this study refers to 2010 and is focused only in the energy-intensive industries: pulp and paper, chemical, steel, and concrete industries.

Finally, the potential obtained when applying Method 2 is highlighted in Figure 1 (46.0 PJ). It can be seen that the potential obtained are from the same magnitude than the rest and, as expected and explained in this section, it is higher than the values obtained by Land et al. [6] and Cronholm et al. [21], and lower than the obtained in Heat Roadmap [23] and by Persson et al. [4] (as highlighted in the grey area in Figure 1) . Therefore the authors consider it feasible to transfer figures from Method 2 (originally from Germany) in order to assess the potential of other countries.

3.2 German non-metallic mineral industry (NACE sector 23)

Transferring the waste heat per fuel consumption figures from Germany to Sweden (section 3.1) showed a promising result in terms of possible transferability. To ensure this transferability, different studies are transferred to the German non-metallic mineral industry. This industrial sector has been chosen because of (1) according to Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide document [24] European cement industries have a similar capacity and 90 % of the kilns use the same manufacturing process, (2) McKenna et al. [13] state its homogenous nature and (3) it is one of the major waste heat producing sectors [3].

The potential in the non-metallic mineral sector obtained by applying Method 1 is compared in Table 5 to three studies performed previously by Brueckner et al. [5], Persson et al. [4], and Miró et al. [18]. In this case, because of the availability of the data, a comparison using different years is possible and Method 1 is applied to the fuel consumption data of the German non-metallic minerals sector.

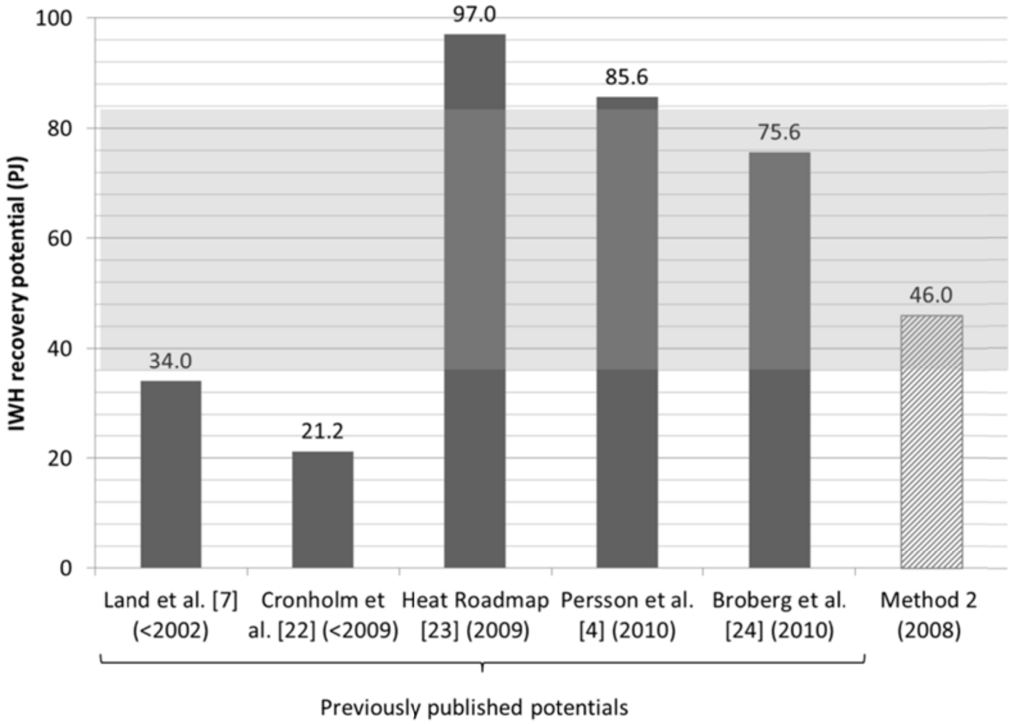

Figure 1. Validation process: comparison of the Swedish industrial waste heat potential by different authors to the obtained transferring Method 2. In grey, feasibility area.

Miró et al. [15] adapted and updated the methodology proposed by McKenna et al. [13] and based on CO_2 emissions, to this sector for all the European countries and for the period 2007-2012. Results for Germany show a potential from 13.6 to 30.6 PJ. Brueckner et al. [5] accounted for 29.76 PJ in the German non-metallic mineral industry in 2008. Results obtained with Method 1 are expected to be lower but quite similar to these last two studies because of their accuracy. The contrary is expected with Persson et al. [4] who calculate a maximal theoretical potential.

Table 5 Validation process: IWH potential in the German non-metallic mineral industry, in PJ

		2008	2009	2010	2011	2012
Method proposed	Method 1 [6]	10.5	9.7	9.8	10.0	9.6
Previously published potentials	Brueckner et al. [5]	29.76	-	-	-	-
	Persson et al. [4]	-	-	102	-	-
	Miró et al. [15]	15.2 -30.4	13.6 - 27.3	14.3 - 28.5	15.3 - 30.6	14.9 - 29.7

When applying Method 1 to the German non-metallic mineral industry, the potential obtained is the lowest one from the four presented in Table 5, as expected. Method 1 follows a quite similar trend as the lower value of Miró et al. [15], and therefore supports the possible transferability. It can be also seen that the results obtained by Brueckner et al. [5] and Miró et al. [15] show a rather good match and consistency while especially the results from Persson et al. [4] greatly differ, as expected.

4 IWH potential estimation. Case study: Spain

In this section, the Spanish IWH recovery potentials using the three methods presented is estimated as well as the potential of Catalonia and the Basque Country. This region was selected because of the high potential expected, due to the presence of energy-intensive sectors and the fact that the Spanish manufacturing industry do not report waste heat related parameters, which makes not possible to get more accurate IWH potential estimations.

In order to minimize the influence of the year in the calculation, the same year of the input data is considered when possible.

4.1 Spanish IWH recovery potentials

Table 6 compares the input data as well as the IWH recovery results calculated for 2010. Input data for Method 1 and 2 refers to the industrial fuel consumption for the manufacturing sector while for Method 3 it refers to the CO_2 emissions of this sector. The IWH recovery in Spain is estimated in the range 60.2 - 151.1 PJ. When applying Method 1 and Method 2 a range is shown in order to consider the two databases available for Spain (IDAE and Eurostat).

Table 6 Comparison of the results obtained for Spain, 2010

	Method 1	**Method 2**	**Method 3**
Input data	560.7 / 569.5 PJ		42,225 $MtCO_2$
IWH recovery potential	60.2 – 64.4 PJ	83.6 – 85.0 PJ	151.1 PJ

Comparing the results from Method 1 and Method 2, Method 2 is expected to provide more exact values due to the lower number of aggregated industrial sectors in the same group (Table 1). Moreover, it is expected and observed that Method 2 results surpass the ones obtained by Method 1 as it considers theoretical potential (Table ~~1~~ 4). When comparing Method 3 to the others, the value estimated is significantly higher, which is expected as the authors from Method 3 calculate maximal potential levels (chapter 2.3).

The most recent potentials which can be calculated are from 2013, in which the Spanish IWH potential is 56.3 – 56.7 PJ using Method 1 and 74.2 - 79.4 using Method 2.

4.2 IWH recovery potentials in the Spanish counties

From the 17 counties of which Spain is composed, Catalonia and the Basque Country are two of the most industrialized and most energy-consuming regions [25]. So their industrial input energy and IWH recovery potential is expected to be significant regarding to the total Spanish potential. First, former assessments found for the Basque Country are presented. In the case of Catalonia no former studies have been found. Then, the comparison between the Basque Country and Catalonia with respect to Spain is shown and discussed.

4.2.1 Basque Country

In the case of the Basque Country, two former studies were published in 1997 from Bonilla et al. [26] and in 1998 from Lopez et al. [27]. Bonilla et al. [26] assessed the IWH potential based on eight waste heat recovery technologies and classified it in seven temperature ranges and in stream types (gas, solid and liquid). The specific industrial sectors considered in the study are not specified. The total IWH theoretical potential is 28.21 PJ considering only gas streams. One year later, Lopez et al. [27] published another assessment for the Basque Country in which nine industrial sectors (integral steel industry, non-integral steel industry, paper, metal transformations, cement, chemical industries, food, drinks and tobacco, glass, and rubber) and residential, public and commercial sectors have been taken into account. They divided the IWH potential, as previously Bonilla did, and the total IWH theoretical potential is 48.17 PJ, considering all streams (gas, solid and liquid). In Table 7, a comparison of both former estimations and the three methods proposed in this article is done. As Bonilla et al. [26] and Lopez et al. [27] studies were published in 1997 and 1998, 1997 is the year considered when applying Method 1 and Method 2. In the case of Method 3, only data from 2010 is available. Regarding the input fuel of the industrial sector considered, the Bonilla et al. [26] value is significantly higher than the one considered by Method 2 (almost a factor of 3); they may have considered the energy production sector and/or the electrical energy. Therefore a higher IWH recovery potential obtained in Bonilla is expected. The number of groups in which the industrial sectors from Method 1 and 2 are divided (Table 1 and Table 2) is lower for Method 1 which means less accurate results. Moreover, it is expected and observed that Method 2 results are higher than Method 1 as it considers theoretical potential (Table 4). Method 3, based on CO_2 emissions, results in a higher IWH estimation value than Method 1 and 2. This trend was already observed when analyzing Spain.

Table 7 Comparison between the results obtained for the Basque Country with former studies

	Bonilla et al. [24]	**Lopez et al. [25]**	**Method 1**	**Method 2**	**Method 3**
Input data	126 PJ from 260 companies	n.a.	48.7 PJ (w/o electricity) [19]	48.7 PJ (w/o electricity) [19]	3,630,709 tCO_2 from 7 companies
Year for input data	<1997	<1998	1997	1997	2010
IWH recovery potential	28.8 PJ (gas streams)	48.72 PJ (gas, liquid and solid streams)	5.4 PJ (gas stream)	6.8 PJ (gas stream)	11.99 PJ (gas stream)

Last time EVE [19] published input energy specified by industrial sectors was in 2001. However, Method 3 is applied to 2010, as it is the year in which the original method was created, and Basque emissions data are obtained from the Spanish PRTR database [28]. The share between the fuel consumption and Method 1 and 2 and the share between the CO_2 emitted and Method 3 are expected and found to be similar as a direct relation of energy consumption and IWH potential is expected [3] (Table 8). Moreover, Figure 2 shows the 2001 IWH potential comparison as well as the relation between the IWH potential and the fuel consumption, which ranges 8-17 %.

Table 8 Comparison between the Basque Country and Spain, 2001 and 2010

		Spain	Basque Country	Share
Input data	Fuel consumption (2001)	796.7 PJ	61.9 PJ	7.8 %
	CO_2 emitted (2010)	42,225,000 tCO_2	3,630,709 tCO_2	8.6 %
IWH potential	Method 1 (2001)	76.4 PJ	7.2 PJ	9.4 %
	Method 2 (2001)	110.7 PJ	9.9 PJ	8.9 %
	Method 3 (2010)	151.1 PJ	11.99 PJ	7.9 %

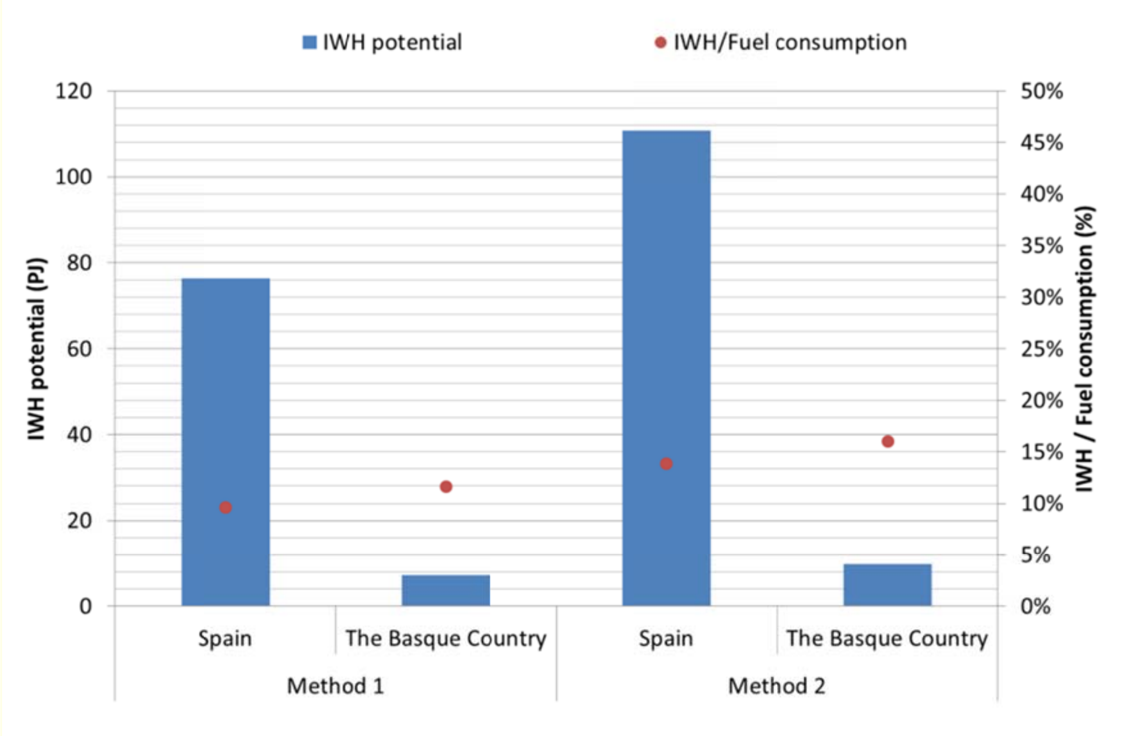

Figure 2. IWH potential comparison for Spain and The Basque Country and IWH per Fuel Consumption percentage, 2001

4.2.2 Catalonia

The analysis of Catalonia and Spain (Table 9) has to be done in 2009 for Method 1 and Method 2 since is the most recent year in which both fuel consumption data is available. Notice that for

Spain, two values for fuel consumption are considered as they come from two different databases. Spanish potential estimated by Method 3 is from 2010, so the methodology is applied to Catalan data from the same year using the same carbon dioxide emission factors from [28]. Method 1 and 2 are proportional to the fuel consumption and Method 3 to the CO_2 emitted. Therefore, a similar share is expected and obtained. Moreover, Figure 3 shows the average IWH potential (period 2009 and 2010) as well as the relation between the IWH potential and the fuel consumption, which ranges 7-14 % in the case of Method 1 and Method 3 (similar to The Basque Country case). This relation increases up to 30 % when applying Method 3.

Table 9 Comparison between Catalonia to Spain

		Spain	**Catalonia**	**Share**
Input data	Fuel consumption (2009)	586.7 – 587.7 PJ	100.3 PJ	17.1 %
	CO_2 emitted (2010)	42,225,000 tCO2	8,120,272 tCO2	19.2 %
IWH potential	Method 1 (2009)	54.3- 56.6 PJ	8.6 PJ	15.1 – 15.8 %
	Method 2 (2009)	79.4 - 80.6 PJ	12.4 PJ	15.4 – 15.6 %
	Method 3 (2010)	151.1 PJ	26.2 PJ	17.3 %

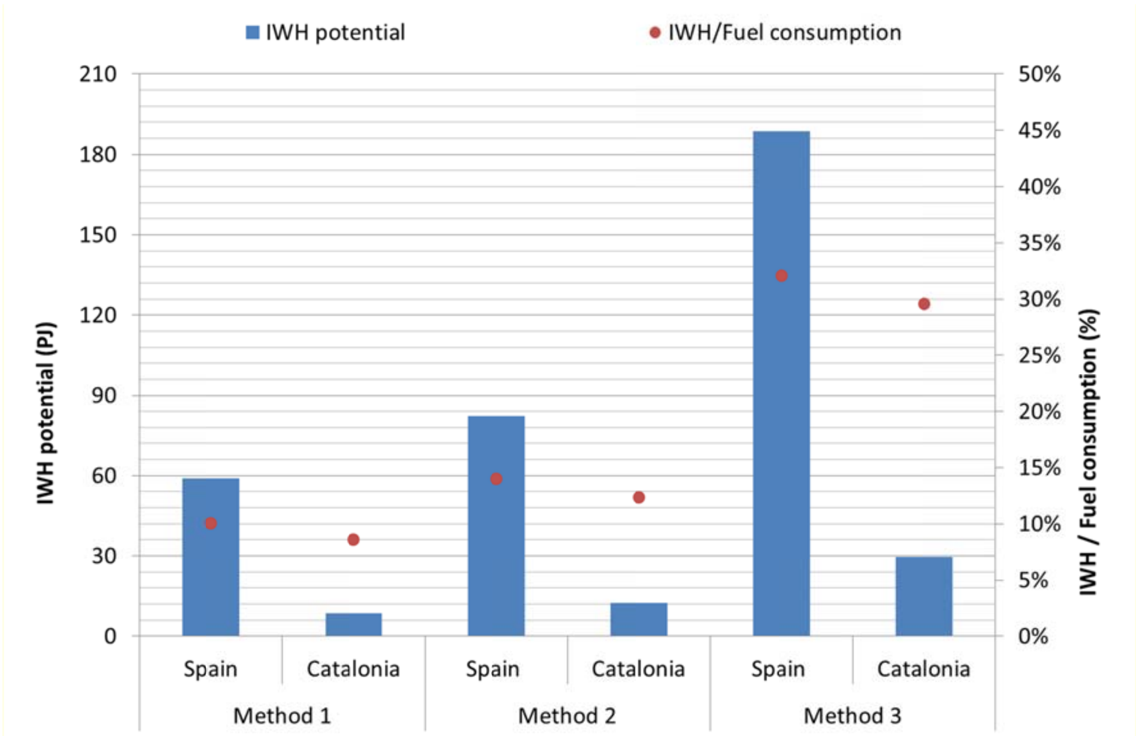

Figure 3. IWH potential comparison for Spain and Catalonia and IWH per Fuel Consumption percentage, average 2009-10

5 Conclusions

Currently there is a lack of industrial waste heat (IWH) recovery assessments with a large scope and high spatial resolution. That fact prevents the deployment or the use of this heat source. Therefore, alternative methods to assess IWH potential must be developed while industrial sites do not publish their waste streams characteristics (which could lead to very accurate analysis).

One of these alternative methods is the transfer of figures from an assessment developed for a specific region to another region. In the literature, three IWH assessments have been found in which transferrable ratios are applied to assess the potential. These three methods are based on the energy consumption of each manufacturing sector or their CO_2 emissions. The objective of this study is to adapt and to discuss the transfer feasibility of these methods, and then to transfer these IWH potential evaluation methods identified in the literature to the Spanish manufacture industry as well as for the Catalan and Basque industry. This region is of special interest because (1) the influence of energy-intensive sectors like the non-metallic mineral sector is important and a high IWH potential is expected, (2) its manufacturing industry is a quite secretive economic sector and do not publish the characteristics of their waste streams. In that case, it is not possible to estimate in a more accurate way the IHW potential of the region.

The new contribution of this paper lies in the assessment of the feasibility of transferring medium precise estimates to other regions as an alternative way to assess the IWH potential with a reasonable uncertainty. For that an application and comparison of several estimation methods to determine industrial waste heat, and the choice of the most accurate method based on a validation for Sweden and Germany. Hence the suitability of this transference is assessed by comparing results to former studies in the investigated regions. This analysis is done to the Swedish industry and to the German non-metallic minerals sector.

In the case study, the three regions are studied in the years 2001, 2009, 2010 and 2013, depending on the available information. In this period, Spanish annual industrial waste heat potential ranges from 54.3 to 151.1 PJ, 8.6 to 29.7 for Catalonia, and 7.2 to 11.9 for the Basque Country. Method 1 and Method 2 show similar potentials while Method 3 results in higher potentials. This behavior was already expected because of the characteristics of each method.

In principle these methods are highly transferable, but the degree to which they can be transferred strongly depends on similarities between the original and target systems. Hence in the transfer of figures, some assumptions lead to uncertainties in the results. For example, it is considered that industrial sectors in the original method area and in the applied area are equal, that they use same or similar processes with comparable efficiencies, etc. Other uncertainties like the reference year of the data have been minimized by using the same year than the reference study to analyze the potential. Thus further work should consist, first, of developing an adjustment of the methods presented to account for the differences in technology/process and industrial structure of the different regions considered and, second, of developing more accurate methods to assess the IWH potential, especially by better considering and adjusting for technological and structural differences between study areas.

Acknowledgements

The authors want to thank the following institutions which helped with the collection of the data used: thank you to Ente Vasco de la Energia (EVE), to Instituto para la Diversificación y Ahorro de la Energia (IDAE), and to Eurostat. They also want to thank specially Urban Persson from Halmstad University (Sweden) for his help and collaboration and to Alvaro Perez de Laborda from EVE. The work is partially funded by the Spanish government (ENE2011-22722 and ULLE10-4E-1305) and by BMWi Federal Ministry for Economic Affairs and Energy in Germany (Project FKZ 0327383B Mobile Sorption Heat Storage). The authors would like to thank the Catalan Government for the quality accreditation given to their research group GREA (2014 SGR 123). This project has received funding from the European Commission Seventh Framework Programme (FP/2007-2013) under Grant agreement NºPIRSES-GA-2013-610692 (INNOSTORAGE) and from the European Union's Horizon 2020 research and innovation programme under grant agreement No 657466 (INPATH-TES). Laia Miró would like to thank the Spanish Government for her research fellowship (BES-2012-051861).

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6 Annex

NACE rev.2 division C: manufacturing

NACE rev. 2 code	Description
10	Manufacture of food products
11	Manufacture of beverages
12	Manufacture of tobacco products
13	Manufacture of textiles
14	Manufacture of wearing apparel
15	Manufacture of leather and related products
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
17	Manufacture of paper and paper products
18	Printing and reproduction of recorded media
19	Manufacture of coke and refined petroleum products
20	Manufacture of chemicals and chemical products
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
22	Manufacture of rubber and plastic products
23	Manufacture of other non-metallic mineral products
24	Manufacture of basic metals
25	Manufacture of fabricated metal products, except machinery and equipment
26	Manufacture of computer, electronic and optical products
27	Manufacture of electrical equipment
28	Manufacture of machinery and equipment n.e.c.
29	Manufacture of motor vehicles, trailers and semi-trailers
30	Manufacture of other transport equipment
31	Manufacture of furniture
32	Other manufacturing
33	Repair and installation of machinery and equipment