Industrial waste heat: mapping, estimations and recovery by means of TES

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TESI DOCTORAL

Industrial waste heat: mapping, estimations and recovery by means of TES

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Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
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CERTIFICA:

Que la memòria “Industrial waste heat: mapping, estimations and recovery by means of TES” presentada per Laia Miró Toran per optar al grau de Doctor s’ha realitzat sota la seva supervisió.

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Resum

Les tendències actuals en el subministrament i la demanda d'energia són econòmicament, ambientalment i socialment insostenibles. En aquest context energètic, l'ús de la calor residual industrial (CRI) representa una oportunitat atractiva de substituir el consum d'energia primària per una font amb baix nivell d'emissions i baix cost. Tot i el seu prometedor potencial, actualment aquesta calor residual industrial no tan sols no s'utilitza, sinó que la seva disponibilitat és també desconeguda.

De fet, aquesta calor es pot recuperar i reutilitzar en altres processos en el mateix lloc on s'ha generat (per tal de preescalfar entrades d'aigua, d'aire de combustió, de les càrregues de forns, etc.), en una localització diferent en la que s'ha generat mitjançant l'emmagatzematge d'energia tèrmica mòbil o sistemes de calefacció i refrigeració urbana o, finalment, ser transformada en electricitat o calor a una altra temperatura (inclòs fred).

Així doncs, l'objectiu d'aquesta tesi doctoral és el de superar algunes de les barreres tecnològiques i de la informació que dificulten l'ús d'aquesta font d'energia actualment i proporcionar a la literatura i als investigadors més coneixement sobre el tema per tal de promocionar el seu desenvolupament i el seu ús.

Els quatre articles que composen aquesta tesi es centren en tres aspectes diferents. En primer lloc, la identificació del potencial mundial actual de CRI a escala nacional i l'anàlisi de la seva plausibilitat. Una cop es va observar que hi havia una manca considerable d'avaluacions de CRI, el segon aspecte en que es centra la tesi va ser en la generació de noves avaluacions per tal d'estimar el potencial de CRI. Així doncs, es va estimar el potencial de CRI tant a la indústria de la manufactura espanyola, així com en la indústria de minerals no metàl·lics europea. L'últim aspecte que es va tractar en aquesta tesi és la recuperació i reutilització d'aquesta calor. L'emmagatzematge d'energia tèrmica va ser la tecnologia seleccionada per la seva capacitat d'acoblar geogràfica i temporalment les fonts i les demandes de calor. Es va avaluar exhaustivament els casos pràctics on aquesta tecnologia ha estat implementada o ha estat proposada per a una futura implementació.

Resumen

Las tendencias actuales de suministro y de demanda de energía son económicamente, ambientalmente y socialmente insostenibles. En este contexto energético, el uso del calor residual industrial (CRI) representa una oportunidad atractiva de sustituir el consumo de energía primaria por una fuente de bajo nivel de emisiones y de bajo coste. A pesar de su prometedor potencial, este calor residual industrial está actualmente en desuso además de ser su potencial desconocido.

De hecho, este calor se puede recuperar y reutilizar en otros procesos en el mismo lugar donde se ha generado (para precalentar entradas de agua, de aire de combustión, de las cargas de hornos, etc.), en una localización diferente en la que se ha generado mediante el almacenamiento de energía térmica móvil o sistemas de calefacción y refrigeración urbana o, finalmente, ser transformado en electricidad o calor a otra temperatura (incluso frío).

Así pues, el objetivo de esta tesis doctoral es el de superar algunas de las barreras tecnológicas y de la información que existen en la utilización de esta fuente de energía actualmente así como proporcionar a la literatura y a los investigadores un conocimiento más profundo del tema para promocionar su desarrollo y su uso.

Los cuatro artículos que componen esta tesis se centran en tres aspectos diferentes. En primer lugar, la identificación del potencial mundial actual de CRI a escala nacional y el análisis de su plausibilidad. Una vez se observó que había una falta considerable de evaluaciones de CRI plausibles, el segundo aspecto en que se centra la tesis fue en la generación de nuevas evaluaciones de estimación del potencial de CRI. Por lo tanto, se estimó el potencial de CRI tanto en la industria de la manufactura española, como en la industria de minerales no metálicos europea. El último aspecto que se trató en esta tesis es la recuperación y reutilización de este calor. El almacenamiento de energía térmica fue la tecnología seleccionada por su capacidad de acoplar geográfica y temporalmente las fuentes y las demandas de calor. Se evaluó exhaustivamente los casos prácticos donde esta tecnología ha sido implementada o ha sido propuesta para una futura implementación.

Summary

Current trends in energy supply and demand are economically, environmentally and socially unsustainable. In this energy context, the use of recovered waste heat provides an attractive opportunity to substitute primary energy consumption by a low-emission and low-cost energy carrier. Despite its potential, in the specific case of industrial waste heat (IWH), this potential is currently not only largely untapped, but also unaccounted.

In fact, this heat can be recovered and reused in other processes on-site (to preheat incoming water or combustion air, preheating furnace loads, etc.), off-site by means of Mobilised Thermal Energy Storage (M-TES) systems or district heating and cooling networks (DHC) or, last but not least, transformed into electricity, cold or another type of heat.

Thus, the aim of this PhD is to overcome some of the current technological and information barriers and to provide the literature and the researchers with more knowledge of the topic and supporting its widespread development.

Therefore, the four articles that compose this thesis are focused in three different aspects. The first aspect was the identification of current IWH potential worldwide at country scale and the analysis of their feasibility. Once it was observed that there is a significant lack of feasible assessments, the second aspect to focus was the generation of new assessments to estimate the regional IWH potential. Therefore, it was estimated the IWH potential in the Spanish manufacture industry as well as in the European non-metallic mineral industry. The last aspect is the recovery and reuse of this heat. Thermal Energy Storage (TES) was selected because of its ability of geographically and temporary matching heat sources and heat demands. An exhaustive research of current case studies and the analysis of their characteristics and suitability are assessed.

Nomenclature

DOI	Digital Object Identifier
DH	District Heating
DHC	District Heating and Cooling
CHP	Combined Heat and Power
GIS	Geographic Information System
HT	High Temperature
E-PRTR	European Pollutant Release and Transfer Register
EU	Europe
IWH	Industrial Waste Heat
LT	Low temperature
MT	Medium Temperature
M-TES	Mobilized Thermal Energy Storage
NACE	*Nomenclature Statistique des Activités Économiques dans la Communauté Européenne*
PTES	Pit thermal energy storage
SCI	Science
SIC	Standard Industrial Classification
TES	Thermal Energy Storage
UK	United Kingdom
US	United States
UTES	Underground thermal energy storage

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1 Introduction

1.1 Current energy trends

Current trends in energy supply and use are economically and environmentally unsustainable. It is expected that energy-related emissions of carbon dioxide (CO_2) will more than double by 2050 and fossil energy demand will increase concerns over the security of supplies [1]. A change of this trend can contribute to reduce the use of key resources like energy, raw materials, land and water, to make regions less dependent on fossil fuel imports, and to bring health benefits. Therefore, the European Commission Roadmap [2] suggests that, by 2050, the EU should cut its emissions to 80% below 1990 levels. To achieve that, all sectors need to contribute according to their technological and economic potential, especially power generation and distribution and manufacturing industry (Figure 1) which are the sectors with higher influence in total emissions. But even optimized systems will release waste heat which in some cases can still be used in other processes.

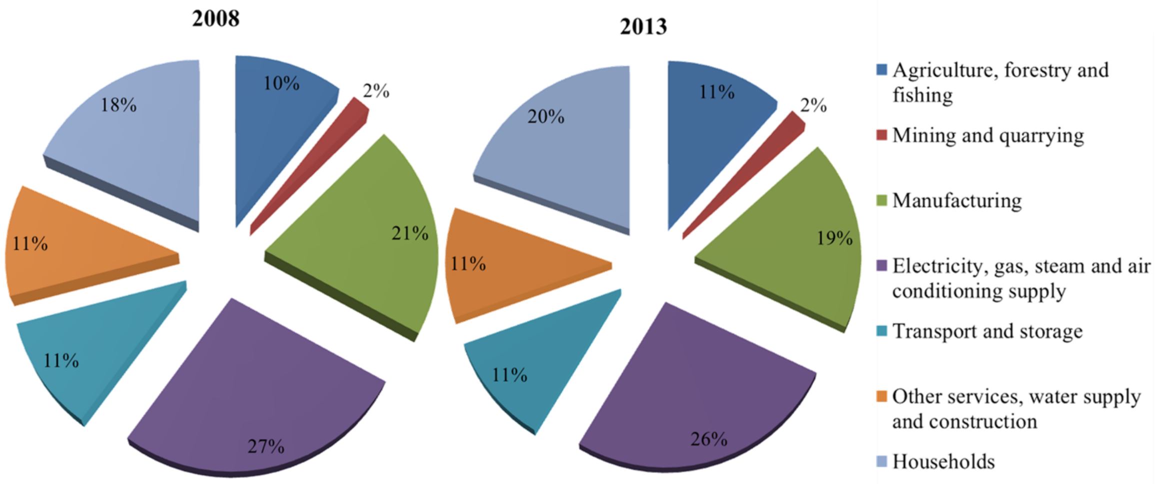


Figure 1. Greenhouse gas emissions by economic activity, EU-28, 2008 and 2013 (% of total emissions in CO_2 equivalents) [3]

1.2 Manufacturing industry

In this thesis the manufacturing industry is defined using the NACE Rev. 2 classification [4]. In this classification all the economic sectors are coded and the manufacturing industry is identified as Section C and includes the physical or chemical transformation of materials, substances, or components into new products. Raw materials are products of agriculture, forestry, fishing, mining or quarrying as well as products of other manufacturing activities. Substantial alteration, renovation or reconstruction of goods is also considered to be manufacturing [4].

Due to its significant amount of energy consumption, manufacturing industry is identified as one of the potential sectors in which emissions can be decreased by, for example, reducing the generation of IWH, recycling it within the heating system itself and recovering it to use outside the plant or to produce electricity. In the energy consumption and the CO_2 emissions from the manufacturing industry in the period 2008-2013 can be seen (Figure 2). Both parameters have a decreasing trend during this period.

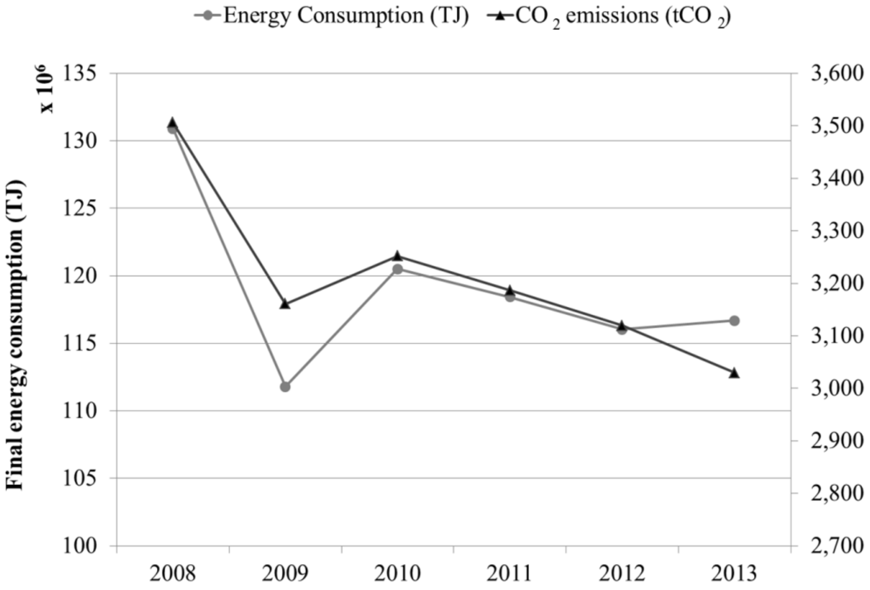


Figure 2. CO_2 emissions and energy consumption of the manufacturing industry in Europe during the period 2008-2013 [4]

This industrial waste heat is normally recycled from five typical energy intensive industrial subsectors: chemical and petrochemical, iron and steel, non-ferrous metals, non-metallic minerals, and pulp and paper production. Figure 3 shows the case of Europe in 2014, where the five most energy consuming manufacturing do not consider non-ferrous metals but food and tobacco. Those sectors represent 72% of all the consumption (Figure 3).

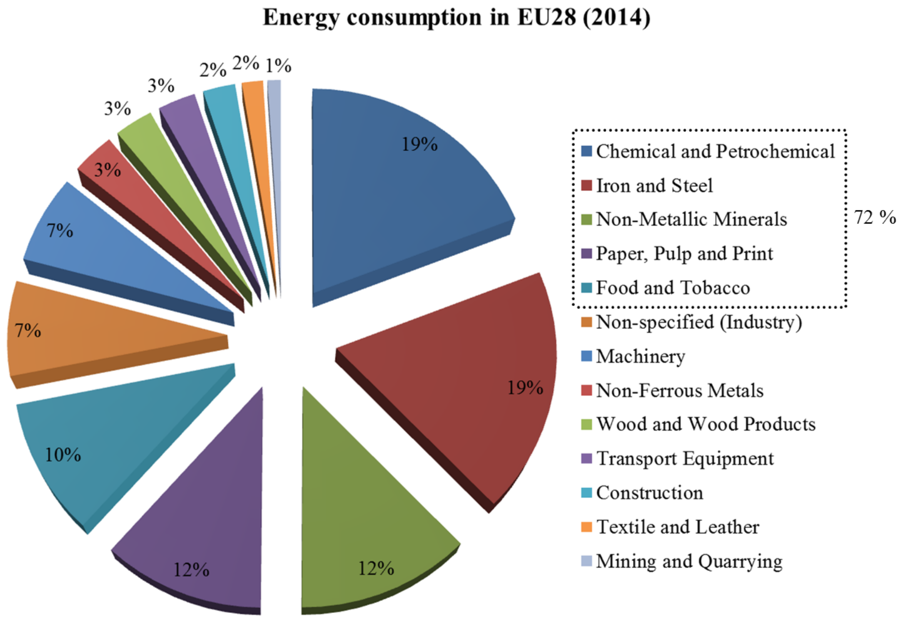


Figure 3. Percentage of energy consumption per sector in Europe (2014) [4]

In general, this heat can be used:

- On-site in an industry for input energy saving (pre-heating processes, thermal comfort, refrigeration, etc.).
- Off-site in another location.
- Off-site bye means of a district heating network system.

However, current recovery and recycling of industrial excess heat is difficult to know since it is not reported in international energy statistics. The only agencies that report these heat streams are national district heating associations gathering own national statistics [5]. Therefore, a study performed by the Heat Roadmap Europe 2050 project [5] developed the first IWH estimation assessment at EU27 scale including the major industrial plants within the energy-intensive sectors (chemical and petrochemical, food and beverage, iron and steel, non-ferrous metals, non-metallic minerals, and paper, pulp and printing) and refineries. The country values they achieved are shown in Table 1 representing a total of 2708 PJ/y in Europe.

Table 1. IWH potential for EU27 in 2010 [5]

Member state	**IWH potential (PJ/y)**	**Member state**	**IWH potential (PJ/y)**
AT	75	IT	315
BE	115	LT	21
BG	22	LU	4
CY	4	LV	1
CZ	64	MT	-
DE	525	NL	160
DK	13	PL	149
EE	3	PT	53
EL	56	RO	75
ES	226	SE	97
FI	82	SI	4
FR	302	SK	51
HU	27	UK	252
IE	13	**EU27**	**2708**

Moreover, they plotted the locations of those IWH sources (Figure 4) and concluded that many of these plants are located near urban areas giving the possibility of transferring the excess heat to heat consumers in district heating systems.

1.3 Industrial waste heat definition

Several definitions exist about this concept. Therefore, in 2015 the participants in the IEA IETS Annex XV (Industrial Excess Heat Recovery – Technologies and Applications) [6] defined some of the concepts found in the literature: *waste heat*, *surplus heat*, *secondary heat*, *low-grade heat*, *black*, *white* or *green excess heat*. However most of the references found in the literature follow neither any classification definition nor any definition at all.

In this thesis, industrial waste heat is defined as the forms of heat (latent and sensible) that escape an industrial system which are not the main purpose of the system [9]. In industrial facilities, sources of waste heat can be single machines or whole systems that release waste heat into the environment, for example, furnaces, waste water from washing, drying or cooling processes, and also refrigeration systems, combustion engines, etc. Waste from those sources can be released either diffusively as radiation or convection at a surface or through a stream like exhaust gas, steam or cooling fluids. Moreover, heat from combined heat power (CHP) plants and power plants is not considered.

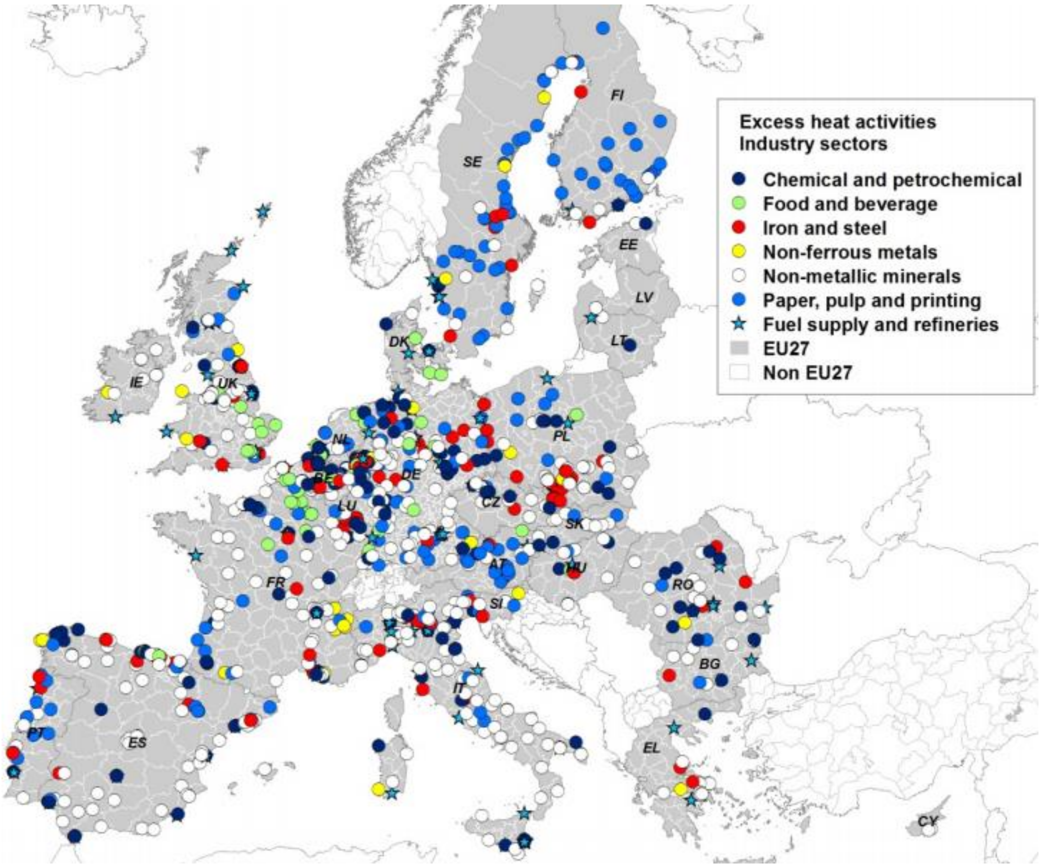


Figure 4. Location of energy intensive industries with considerable volumes of waste heat [5]

Typically, high temperature waste heat has more potential to be reused. Figure 5 shows the distribution of high, medium and low temperature applications in different sectors in Germany for 2005 [9][10]. High temperature waste heat holds a large share of the processes in the metal production and mineral processing sectors while the food and tobacco industry has not any high temperature heat demand.

1.4 Methodologies to assess IWH

In this section, the main parameters to consider when using any methodology to assess IWH are described: the type of potential, the accuracy and the approach and the scope (individual process, site or region).

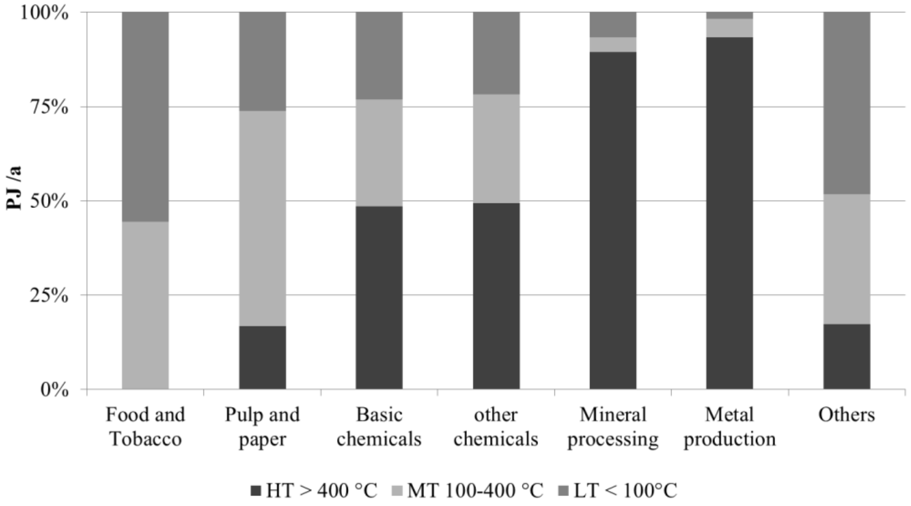


Figure 5. Process heat demand of different sectors by temperature: high (HT), medium (MT) and low (LT) [9]

1.4.1 Type of potential

Before considering different methods to estimate the waste heat potential, it is necessary to distinguish the heat potential type which is considered. Based on the literature [11][12], three different types of potentials should be distinguished: the theoretical or physical potential, the technical potential, and the economically feasible potential (Figure 6). The theoretical potential only takes into account physical constraints. For example, that only waste heat above ambient temperature is considered. Constraints related to whether or not it is possible to extract that heat from the carrier fluid or whether there is any way of using it (the minimum temperature to allow the operation of a system, temperature losses due to heat transfer, etc.) define the technical potential. Therefore, this potential type depends on the technologies used. Finally, the economic (or feasible) potential takes into account financial parameters like energy prices, interest rates and payback periods.

1.4.2 Accuracy and approach of the method

Different points of view have been used to classify waste heat estimation methods. In 2008, Blesl et al. [12] differentiated them by accuracy: a rough method (using few statistical data), a medium precise estimate (with more detailed literature data and coefficients), and a high precision method (with measured data). Two years later, Pehnt et al. [13] distinguished the methods based on efficiency factors, on questionnaires or on measured data. Recently, Brueckner et al. [7] proposed another classification (Figure 7) and used it to classify the current IWH potential estimations in the literature. In this classification, three perspectives were taken into account: the scale of the study, the way the data is acquired, and the approach. Regarding the data acquisition, whether the data is estimated or surveyed is distinguished. Surveyed data could either be measured data or collected via a questionnaire, official reports or online databases. To consider estimated data, efficiency parameters take into account the input energy while waste heat per company size parameters (for example, number of employees, sales, etc.). Surveyed data are usually more precise, but they are also more time consuming to obtain, especially in-situ measurements. Moreover, when companies or sites need to be screened, conflict with confidentiality of process data can be found. In this review, a total of 22 references were reviewed and classified and, according to the authors, more estimations than bottom-up surveys were found. Considering the approach, twice as many cases of bottom-up estimations than of top-down estimations were found. Finally, the authors highlighted the lack of standardization in the industry definition and methodology scope which makes not possible to deeply discuss and compare them.

1.4.3 Scope of the analysis

Depending of the scope of the analysis, different methodologies can be applied. When estimating the potential of a region or an industrial sector, the available approaches used by the researchers are the ones previously classified by Brueckner et al. [7] in Figure 7.

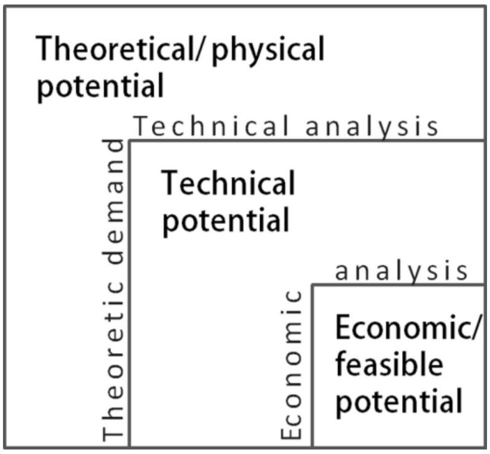


Figure 6. Types of potential [13]

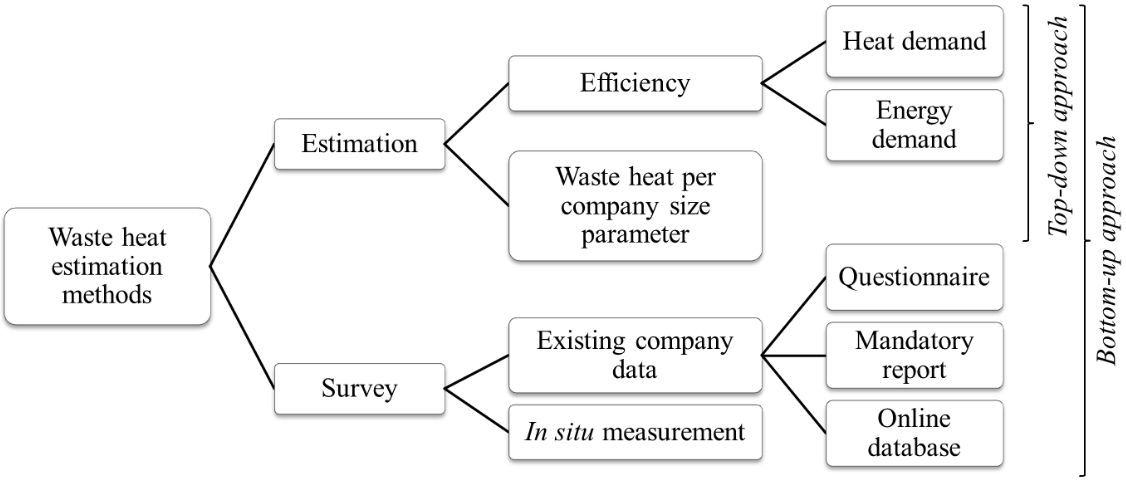


Figure 7. Waste heat estimation methods proposed by Brueckner et al.[7]

However, for specific sites or processes other methodologies can be found: Pinch analysis and exergy analysis. Pinch analysis is a heat integration method based on thermodynamics in which combined hot and cold streams are plotted in a temperature versus heat load graph to identify the amount of heat recovery [8]. On the other hand, exergy analyses allow identifying exergy losses within a system and give thus a tool for identifying the unit operations which lead to big losses [14].

1.5 Technologies

To take advantage of this IWH potential there are different technologies available. Some processes with lower temperature may not be a useful source of industrial waste heat directly, but the heat can be upgraded. Temperature is one of the most important criteria when considering if the process would either produce valuable waste heat or could use waste heat as an energy source [13].

These technologies can be categorized (Figure 8) as passive or active technologies or depending on the subsequent use of the waste heat (direct use, use after upgrading or power generation). Heat exchangers and thermal energy storages (TES) are the two dominant passive technologies. TES are interesting or even necessary in systems with fluctuating or intermittent waste heat streams. These technologies can be used for recycling or reusing waste heat within an industry to heat or preheat other processes. Heat pumps, chillers and heat engines are active technologies. Active applications of waste heat are categorized into two types: to provide heat or cold, or to provide electricity. Technologies to provide heat or cold can be also called heat transformation technologies as they modify the inlet temperature upgrading or downgrading it.

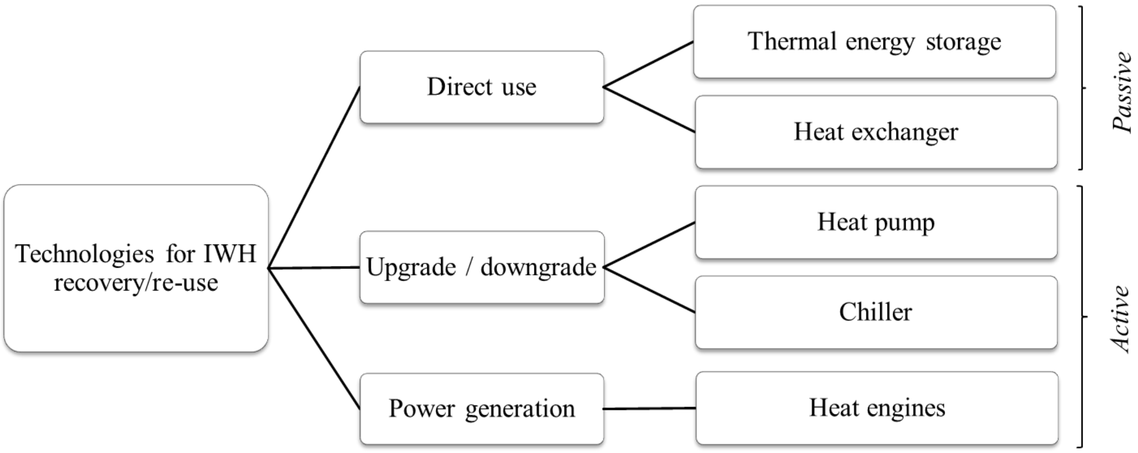


Figure 8. Technologies for IWH recovery/re-use based on [6][11]

The economic feasibility of the heat transformation technologies was assessed by Brueckner et al. [11] by means of the *maximum acceptable cost* approach. This approach considers investment cost, operating cost and operating hours. However, the input parameters are three consumer types (Industry, Real State and Enthusiast) defined by the interest rate, the payback period and the annuity factor. For the present day technology cost, absorption chillers are profitable for Real Estate consumer types and when operated for at least 2500 h per year for Enthusiast consumer types. More than

6500 h per year are needed in order to be profitable for Industry consumers (Figure 9). Besides, absorption heat pumps are profitable starting at 3000 h for Industry consumer types while for the rest even less operating hours are economically feasible. Finally, for Real Estate and Enthusiast consumer types, the maximum acceptable investment cost is already at or above the present day investment cost of the technology, and for Industrial consumer types when exceeding 4000 operating hours per year.

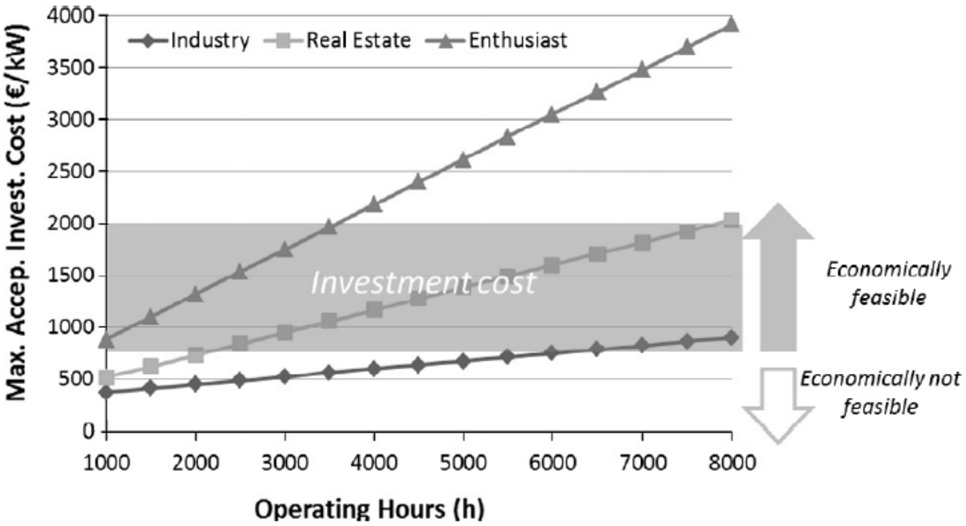


Figure 9. Maximum acceptable investment cost for absorption chillers. In grey, current investment cost considered for the absorption chiller case [11]

Hammond and Norman [15] went one step further and defined the working requirements of the different technologies available and plotted them (Figure 10) relating the temperature of the waste heat source and its amount (in MW_{th}). The authors also highlighted that the potential for heat transport is the same that the on-site re-use. For some temperature sources only a technology is available (heat pumps and on-site heat recovery at low waste heat magnitudes) while other sources can be utilized by different technologies.

1.6 Barriers to use IWH

In order to take advantage of IWH, a significant amount of excess heat (preferably not fragmented) has to be available in the form of high temperature exhaust or by-product gases. In addition, from a variety of processes, these gases contain corrosive materials and particulates (blast furnaces, EAF or basic oxygen processes [16]), making them difficult and expensive to capture and recover as an energy resource. Moreover, financial and regulatory constraints are very common obstacles for new technologies, so they are for waste heat technologies as well. In addition, making profit from their waste heat is not the main business case for manufacturing companies.

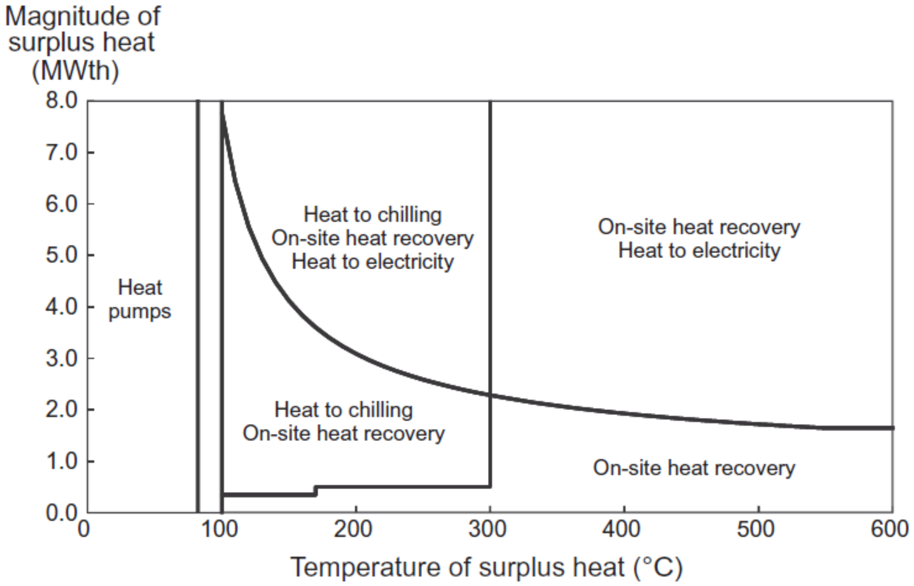
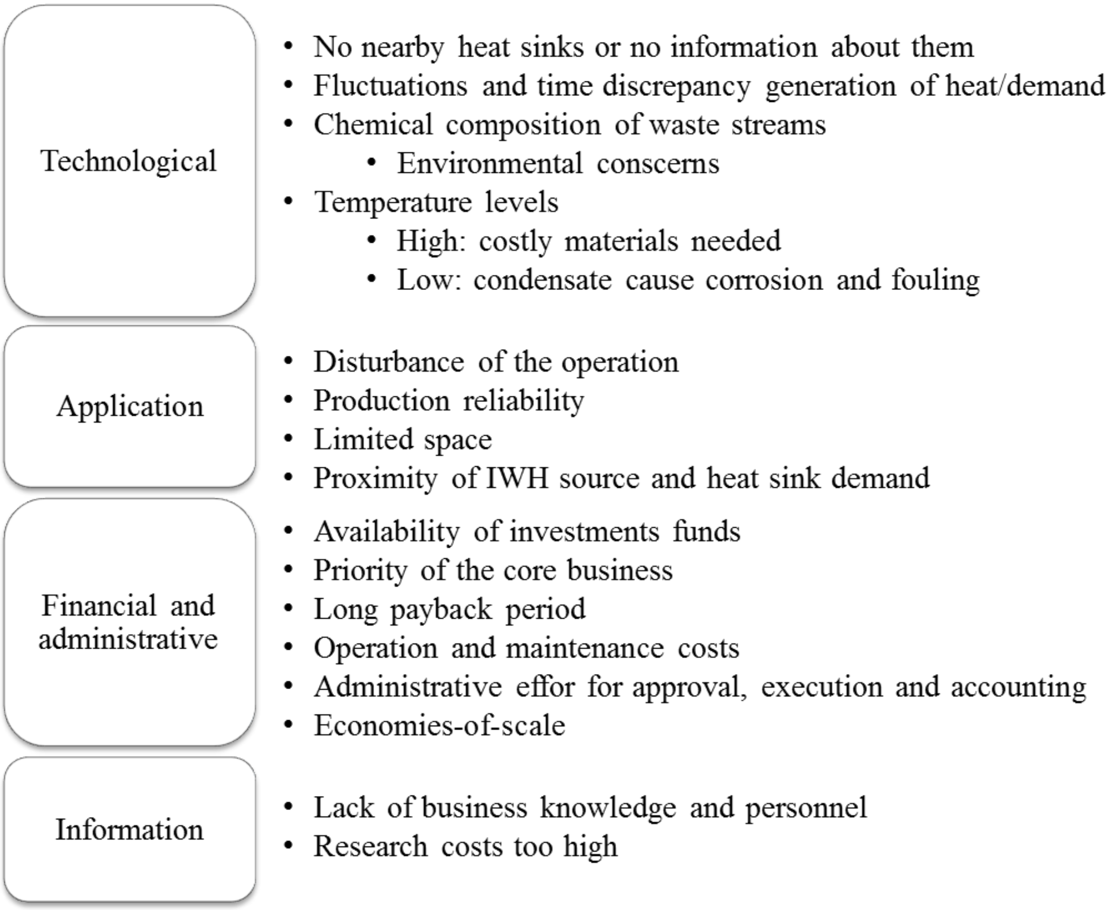


Figure 10. Suitability of the different technologies in relation with the IWH recovery temperature source and its magnitude [15]

As the International Energy Agency [1] points out, there are also significant technical challenges and limitations to excess heat recovery. These technical challenges are sometimes the main barriers to the implementation of industrial excess heat recovery projects. Therefore, a revision of the obstacles to develop the use of IWH identified by experts classified by technical, application, financial and administrative, and information are summarized in Figure 11.

Beside the barriers, one important possible competitor to industrial excess heat is combined heat and power (CHP). The experts from IEA IETS Annex XV [6] compared the climate effects of the different margin power production technologies in the power grid system: fossil-fuel and biomass based systems and IWH. They conclude that less emitting margin technologies will be introduced more in the future and it is likely that excess heat will be one important technology for GHG emissions reduction in future systems [6].



Technological

- No nearby heat sinks or no information about them
- Fluctuations and time discrepancy generation of heat/demand
- Chemical composition of waste streams
    - Environmental conscerns
- Temperature levels
    - High: costly materials needed
    - Low: condensate cause corrosion and fouling

Application

- Disturbance of the operation
- Production reliability
- Limited space
- Proximity of IWH source and heat sink demand

Financial and administrative

- Availability of investments funds
- Priority of the core business
- Long payback period
- Operation and maintenance costs
- Administrative effor for approval, execution and accounting
- Economies-of-scale

Information

- Lack of business knowledge and personnel
- Research costs too high

Figure 11. Barriers to develop the use of IWH, based on [7][16]

2 Objectives

The present thesis aims to overcome some of these technological and information barriers providing the literature with more knowledge of the topic and supporting its widespread development. Even though the potential and the advantages of re-using IWH has been recently highlighted by many international agencies and experts, the topic is in its early stages of development and much research is still needed to achieve a widespread development. Therefore, the main objective of this thesis is to provide a step forward in the IWH potential from the point of view of potential estimation and technologies to recover and re-use this heat.

To fulfil this global objective, several sub-objectives regarding the current availability of IWH regional assessments, the generation of new assessments and the feasibility of using specific technologies to recover and re-use IWH are defined:

- To identify the available regional IWH assessments and to discuss their feasibility.
  It is crucial to first analyse the currently available IWH assessments to identify their feasibility, their strengths and their weaknesses. Moreover, this analysis to be done allows finding the research niches in the topic.

- To identify potential sectors or regions with a lack of IWH potential assessments.
  Spain is identified as potential region of research because of the lack of IWH potential assessments and the influence of the energy-intensive industrial sectors. Moreover, the European potential of the non-metallic mineral industry is also of interest because of the amount and high exhaust temperature of heat streams.

- To identify transferable methodologies available in the literature to generate new IWH potential assessments.
  The lack of IWH assessments and the growing interest for IWH recovery, urges to identify new methodologies to be applied when estimating the IWH potential.

- To analyse the case studies in which TES have been proposed as technology to recover and re-use IWH.

  The possibility of coupling, from a geographic and temporal point of view, the heat source and the heat demand is the main characteristic of TES. Therefore, it is a potential technology to take advantage of IWH sources. Available case studies will be assessed.

3 PhD thesis structure

The PhD thesis consist of four papers: three of them have already been published in SCI journals (Paper 1, Paper 2 and Paper 4) while Paper 3 has been submitted and is currently under revision process.

This thesis is within the frame of the estimation of IWH recovery and it has been structured as it can be seen in Figure 12. Paper 1 presents an overview of the available IWH potential estimations performed at worldwide scale and published in scientific and dissemination articles. From this review it can be concluded that the IWH recovery potential is untapped, which may be due to the lack of assessments of both IWH potential and recovery technologies. Therefore, the thesis aimed to cover those two topics.

On the one hand, two articles were written in order to generate new IWH potential estimations: at Spanish and at European scale. In particular, Paper 2 identified in the literature three methodologies to estimate IWH and the feasibility to transfer those methodologies to other countries was assessed. Once this methodology was validated, it was later applied to Spain. At European scale, Paper 3 assessed the IWH potential of the non-metallic mineral sector which is one of the most energy consuming (energy intensive) manufacturing sectors. In that case, a methodology based on CO_2 emissions was used.

On the other hand, the possible technologies that can be applied to the IWH subsequent use were analysed as well and, among the available ones, Paper 4 focuses on TES. This technology allows collecting the excess heat to be delivered in a later time on in a different location than where it is generated.

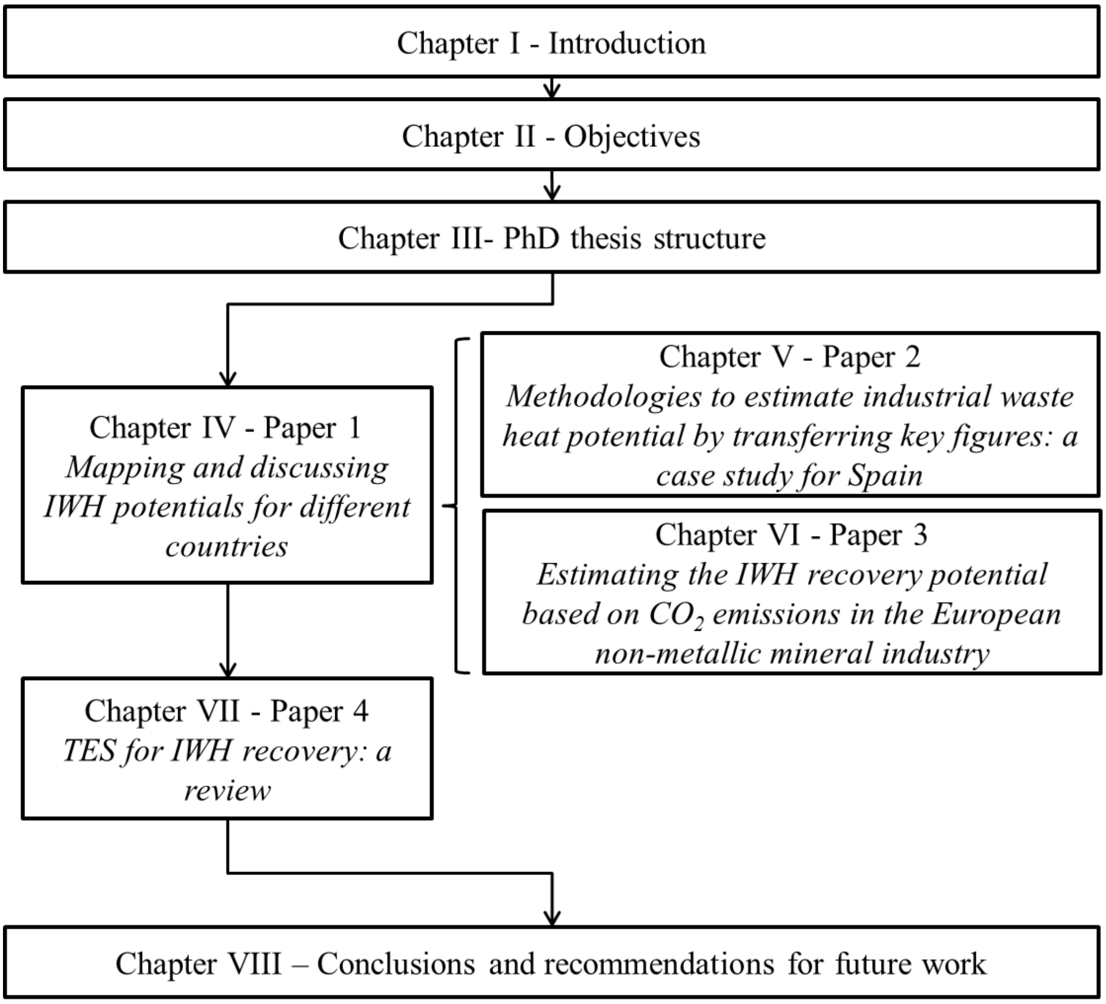


Figure 12. PhD structure

4 Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries

4.1 Introduction

The benefits of using IWH for other applications have been already shown. However, the first necessary step to promote its worldwide use is the quantification of the exact amount of IWH available and its location.

Special attention has been paid to these concepts and, in fact, some previous studies have been published IWH potential estimations. However, these estimations have been mainly done for reduced scopes (an industrial site, a region, etc.). That is the case, for example, of the Energie-Atlas Bayern [17] which is an online platform in which some companies of the Bavarian German state feed their data regarding the exhaust streams or, another example, the Heat Roadmap Europe [5] which estimates the IWH potential in EU-27 taking into account only five industrial manufacturing sectors. Those two studies include, moreover, the exact location of the heat sources.

4.2 Contributions to the state-of-the-art

The main contributions to the state of the art are (1) to collect all the available worldwide IWH potential estimations, (2) to assess their feasibility and, once the revision is done, and (3) to list some recommendations regarding how further IWH potential assessments should be performed. This is presented in the following paper:

- L. Miró, S. Brueckner, L.F. Cabeza. Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries. Renewable and Sustainable Energy Reviews (2015) 847-855.

An introductory comparison of IWH potential assessments at different scales related to their industrial energy consumption was performed for four available case studies:

- Germany and the states of Baden-Württemberg and North Rhine Westphalia.

- France and the department of Dordogne and the administrative region of Nord-Pas-de-Calais.
- Canada and the province of Québec.
- Spain and the autonomous community of The Basque Country.

In this previous case study comparison, it has been found that there is a lack of accurate information regarding the industrial sector for smaller scales than country scales, and, therefore, in this review the study scale selected was the country scale.

A total of 33 IWH country estimations were reviewed in this study (considering US and EU as countries). In some cases (US, EU, Sweden, UK, France, and Germany) more than one value is found per country (Figure 13).

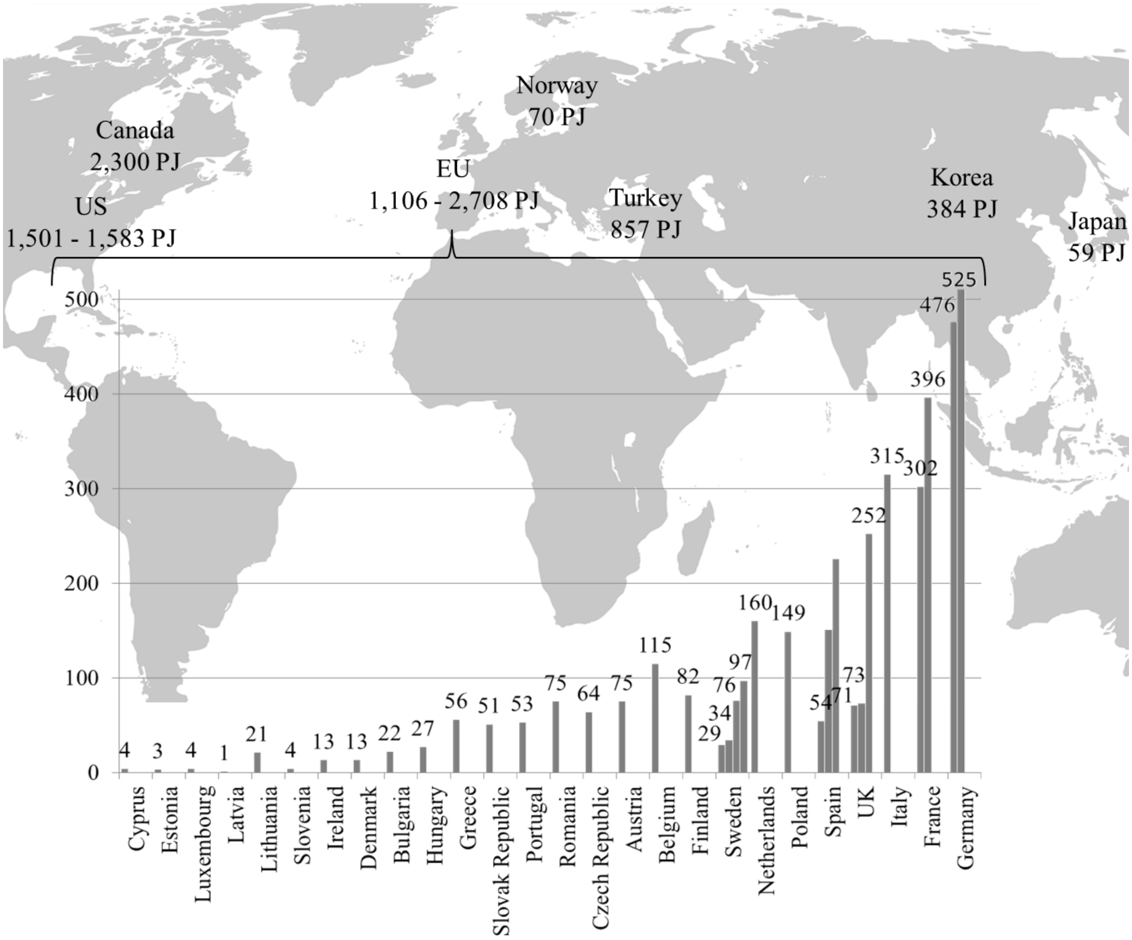


Figure 13. IWH potential estimations worldwide (in PJ/y)

However, due to the lack of homogenization when reporting the data in the literature, a validation process to assess the reliability of the data was performed. This process consisted of comparing the IWH potentials found to some parameters assumed directly proportional. Notice that the reference year for these parameters has been selected, as close as possible, to the publication year of the IWH potential estimations found in the literature.

Those parameters were:

- Energy consumed by the country, in PJ/y. This parameter represents the total energy consumed by the country and it gives a first rough idea of the size of the country.
- Energy consumed by the industry, in PJ/y. Energy consumed by the manufacturing sector in each country.
- Percentage of IWH intensive industries in the country, in %. The intensive industries are here defined as the industrial sectors which are usually the main waste heat producers. The sectors included in this definition are: the non-metallic minerals, non-ferrous metals, paper, pulp and print, chemical and petrochemical and iron and steel.

The analysis is done by plotting these parameters ordered by increasing order. Then, the comparison of each country with the neighbour values and with the general trend allows the detection of non-feasible data. For example, Figure 14 shows the countries ordered by Energy Consumed by the Industry (green line) and their IWH potential (blue bar). In this figure, the IWH potential estimations from Latvia and Lithuania, among others, are far from their neighbour values.

Depending if the values show a direct relation with the parameters selected, this analysis classifies the country potentials in: reliable or non-reliable IWH potentials. Results show that most of the values are considered reliable. However, for 1/6 of the data found, the authors recommend further research to analyse their reliability. When analysing the potentials, a lack of specifications regarding the methodology used, the year of the data, the exact scope, etc. was detected.

This situation urges reliable and well described data to be published, which is essential to promote the use of this untapped energy. That is why the authors made a list of the minimum parameters that should be explained when reporting IWH potential estimations:

- Typology of IWH potential (physical, technical or economical potential).
- Methodology used to account the IWH potential (bottom-up or top-down).
- Temperatures at which the energy content is calculated.
- Year of the data used in the calculations.
- The type of IWH stream (liquid or gas).
- The exact scope of the study (industrial sectors and activities that are considered).

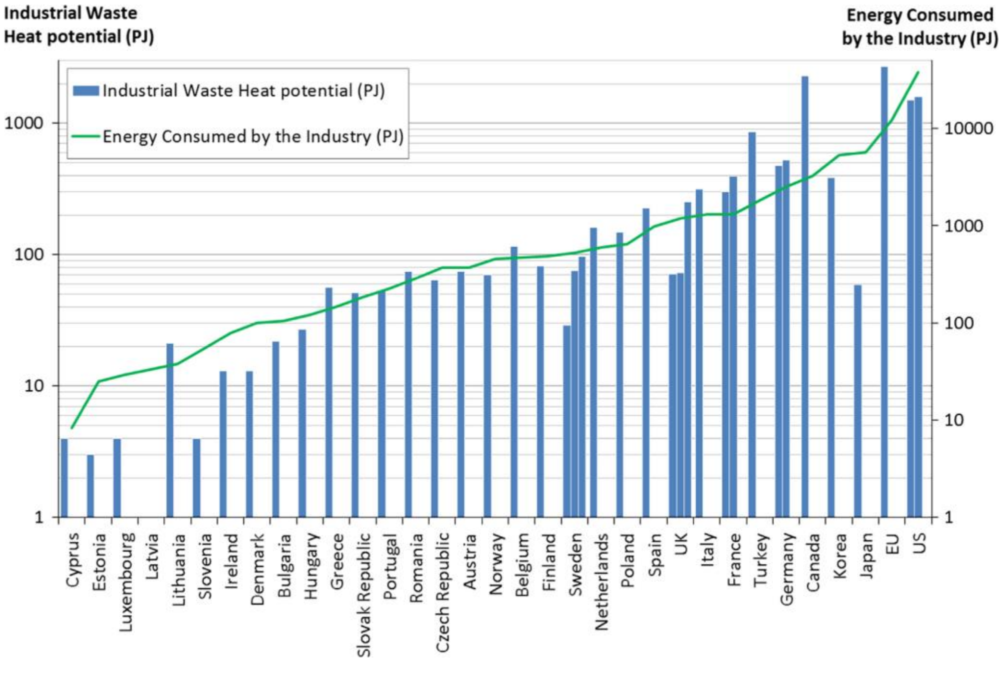
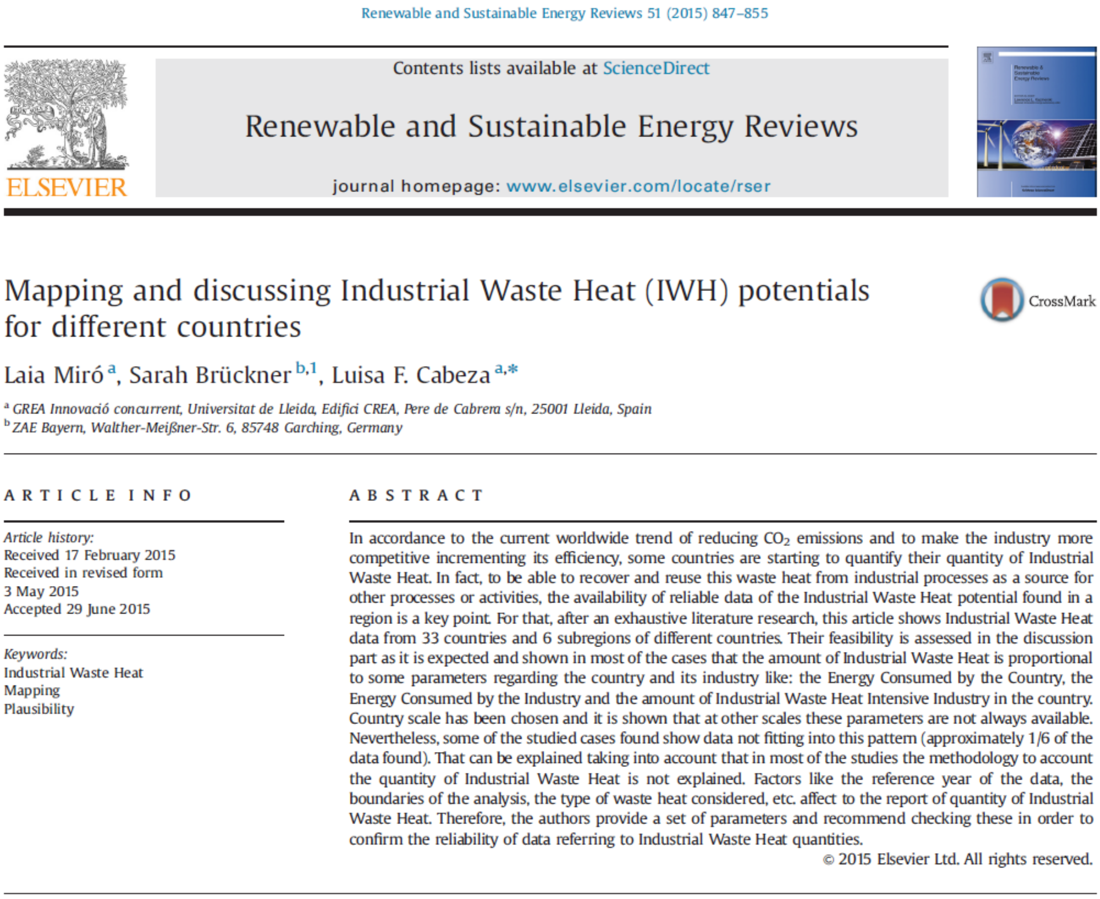


Figure 14. Industrial Waste Heat potential (left axis, in PJ) and Industrial Energy Consumption (right axis, in PJ)

4.3 Contribution of the candidate

The candidate looked for the list of references to review used in the article and leaded the writing. Moreover, the candidate generated all the graphical information support in the article. The submission preparation and the revision process were also leaded by the candidate. The co-authors collaborated mainly in the discussion and language correction of the article.

4.4 Journal paper



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Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries

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ABSTRACT

In accordance to the current worldwide trend of reducing CO_2 emissions and to make the industry more competitive incrementing its efficiency, some countries are starting to quantify their quantity of Industrial Waste Heat. In fact, to be able to recover and reuse this waste heat from industrial processes as a source for other processes or activities, the availability of reliable data of the Industrial Waste Heat potential found in a region is a key point. For that, after an exhaustive literature research, this article shows Industrial Waste Heat data from 33 countries and 6 subregions of different countries. Their feasibility is assessed in the discussion part as it is expected and shown in most of the cases that the amount of Industrial Waste Heat is proportional to some parameters regarding the country and its industry like: the Energy Consumed by the Country, the Energy Consumed by the Industry and the amount of Industrial Waste Heat Intensive Industry in the country. Country scale has been chosen and it is shown that at other scales these parameters are not always available. Nevertheless, some of the studied cases found show data not fitting into this pattern (approximately 1/6 of the data found). That can be explained taking into account that in most of the studies the methodology to account the quantity of Industrial Waste Heat is not explained. Factors like the reference year of the data, the boundaries of the analysis, the type of waste heat considered, etc. affect to the report of quantity of Industrial Waste Heat. Therefore, the authors provide a set of parameters and recommend checking these in order to confirm the reliability of data referring to Industrial Waste Heat quantities.

L. Miró, S. Brueckner, L.F. Cabeza. Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries. Renewable and Sustainable Energy Reviews (2015) 847-855.

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

5.1 Introduction

Focusing in the medium accurate methodologies previously defined by Blest et al. [12], three methods which report key figures characterizing the industrial waste heat of the different industrial manufacturing sectors were found in the literature. Land et al. [18] evaluated the technical potential use of waste heat in district heating systems. Thus, only companies with more than 3 GWh equivalent of oil use per year that are close to settlements were considered. Its limited scope and the technical potential are expected to lead to low IWH potential estimations. Brueckner et al. [19] estimated the theoretic waste heat potential in Germany based on emission declarations for 2008 evaluated on a company level. Among other values, the used fuel type and amount are reported as well as the exhaust gas volume, temperature and operating hours. Last but not least, Persson et al. [20] used the CO_2 emissions from the E-PRTR database, the average national fuel mixes per activity sector and recovery efficiencies to assess IWH potential for subsector at European scale.

Other methodologies to estimate the IWH potential have been found in the literature. However, they cannot be transferred due to the mismatch between the current industrial classifications and the ones used in the original studies. This is the case, for example, of Latour et al. [21] who assessed in the early 80’s the industrial waste heat from some regions in the US considering 19 energy intensive industrial activities. 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. Another example is Chung et al. [22] who presented in 2010 and for Korea the most recent ratios of recovery potential and energy purchased, however the exact scope of each industrial sector considered was not available.

5.2 Contribution to the state-of-the-art

The main contributions to the state of the art are (1) the literature revision of the available methodologies to estimate IWH potential based in key figures, (2) the feasibility analysis of these key figures to be transferred to other regions (different from the original region in which they are generated), and (3) to adapt and apply these key figures to estimate the IWH potential of Spain. This work is presented in the following paper:

- L. Miró, S. Brueckner, R. McKenna, L.F. Cabeza. Methodologies to estimate industrial waste heat potential by transferring key figures: a case study for Spain. Applied Energy 169 (2016) 866-873.

The main objective of this article is to present an alternative approach to estimate the IWH potential for a region. Therefore, three medium accurate methods based on key figures which are potentially transferable to other regions have been identified in the literature.

Method 1 type of potential is technical while for Method 2 and 3 the potential is theoretical. Moreover, in Method 1 and 2 the key figures (f) are based on fuel consumption per sector while Method 3 on CO_2 emissions mass and CO_2 emission factors per sector, as it can be seen in Table 2. Taking into account the characteristics of those three methods, their relative accuracy can be determined. Regarding to the year of the data, the closer the year of the original method and to the year in which the method is applied, the better the data is. The same applies to the original region and original industrial classification. 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.

When transferring methods originally developed from a specific country to another region, some uncertainties are expected derived from, for example, different degree of automatisation, different dominant industrial sectors, different year of the data used for the assessments, etc. Those parameters limit the applicability of this methodology. Therefore, as the second objective, the feasibility of transferring the key figures from one region to another is assessed by comparing the transfer of two methods to previously published data with the most similar study scope: the Swedish manufacturing sector and the German non-metallic mineral industry. As an example, Figure 15 shows how the Swedish manufacturing sector calculated by applying Method 2 is in the feasibility area taking into account the scope and definition of the previously published analysis. Thus, the authors consider it feasible to transfer figures to assess the potential of other countries.

Table 2. Main characteristics of the three methods considered in this article

Characteristics	**Method 1** **[18]**	**Method 2** **[19]**	**Method 3** **[20]**
Original region	Sweden	Germany	EU27
Year of the data	<2002	2008	2010
Approach	Bottom-up	Bottom-up	Bottom-up and Top-down
Type of potential	Technical	Theoretical	
Key figure	$f = \frac{IWH}{Energy\ (fuel) consumption}$		$f = \frac{IWH}{\frac{mass\ of\, CO_2}{emission\ factor}}$
Input data needed	Energy (fuel) consumption		CO_2 emissions mass

The third goal is to apply these methodologies to a case study region. In this case Spain which was selected because the lack of previous accurate IWH assessments and the significant IWH potential expected. On the one side, the Spanish manufacturing sector is not obliged to report waste heat related parameters which makes not possible to get accurate IWH potential estimations. Besides, only a previous European study [20] reports the Spanish IWH potential and two other studies assessed the potential of the Basque Country subregion [23][24]. On the other side, a significant IWH potential was expected in this country due to the presence of energy-intensive sectors [11], like the non-metallic mineral sector which potential was estimated in the period 2007-2012 by Miró et al. [25].

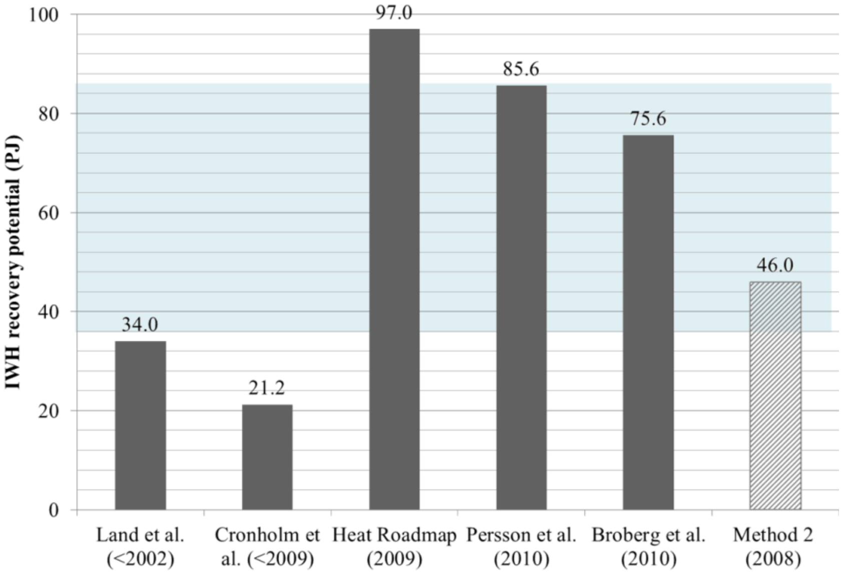


Figure 15. Validation process: comparison of the Swedish IWH potential by different authors to the obtained transferring Method 2. In blue, feasibility area

Moreover, this methodology transfer was applied to two of the most industrialized subregions in Spain: Catalonia and the Basque Country. To do this, a process of adaptation of the key factors is needed due to the fact that none of the regions considered in this article follow the same industrial classification than the original methods. An example of how do the key factors look after this process in the case of Spain can be seen in Table 3.

The IWH potential for these three regions has been assessed using the transfer of these three methods. The potential obtained refer to 2001, 2009 and 2010 depending on the available input information. In these years, and as it can be seen in Table 4, the Spanish annual IWH 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. The transfer of Method 1 and Method 2 shows similar potentials while Method 3 results in higher potentials, which was expected due to their different scope.

5.3 Contribution of the candidate

The calculations derived from applying the methods found in the literature to the different regions selected as well as the data analysis of this article was done by the candidate. Moreover, the writing, preparation for submission and revision process was leaded by the candidate. The co-authors collaborated mainly in the validation, discussion and language correction of the article.

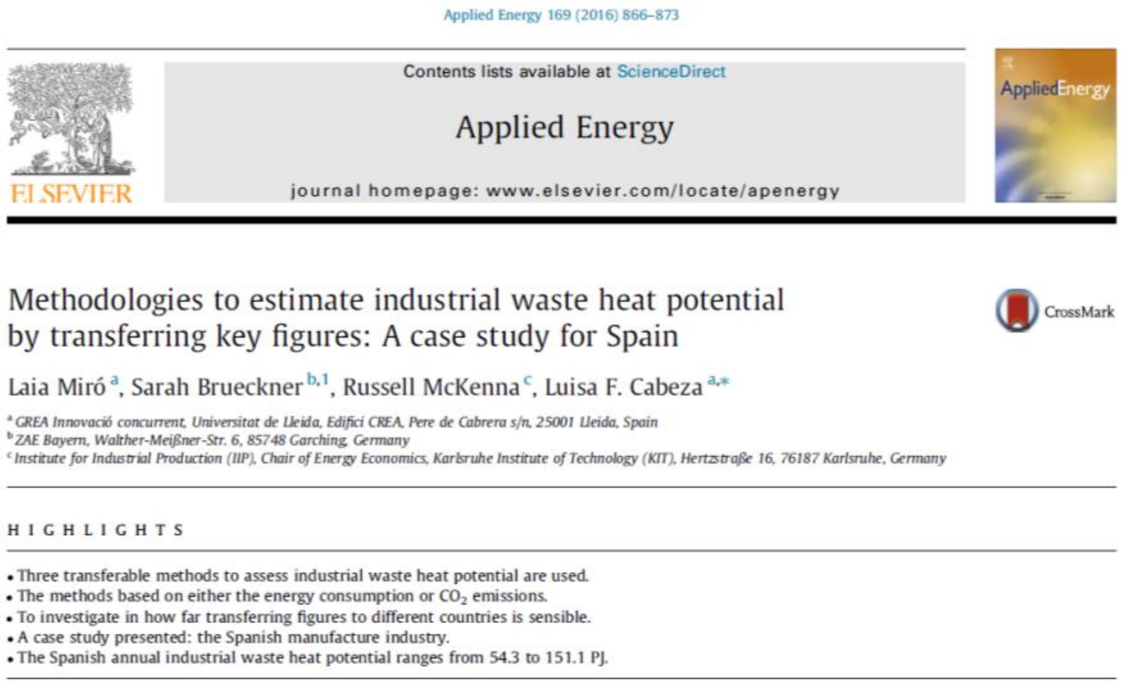
Table 3. Key factors for the Spanish manufacture industry derived from Method 1, Method 2 and Method 3

Industrial sector (according to NACE rev. 2)	f_{M1}	f_{M2}	f_{M3}
10 - Manufacture of food products	6.7	10.8	10.0
11 - Manufacture of beverages	6.7	10.8	10.0
12 - Manufacture of tobacco products	6.7	10.8	-
13 - Manufacture of textiles	0.0	28.2	-
14 - Manufacture of wearing apparel	0.0	28.2	-
15 - Manufacture of leather and related products	0.0	28.2	-
16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	0.0	9.9	-
17 - Manufacture of paper and paper products	3.1	8.0	25.0
18 - Printing and reproduction of recorded media	0.0	8.0	25.0
20 - Manufacture of chemicals and chemical products	12.9	8.8	25.0
21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	12.9	8.8	-
22 - Manufacture of rubber and plastic products	12.9	13.1	-
23 - Manufacture of other non-metallic mineral products	20.0	14.8	25.0
24 - Manufacture of basic metals	20.0	18.6	25.0
25 - Manufacture of fabricated metal products, except machinery and equipment	12.9	22.1	-
26 - Manufacture of computer, electronic and optical products	12.9	22.1	-
27 - Manufacture of electrical equipment	12.9	22.1	-
28 - Manufacture of machinery and equipment n.e.c.	12.9	22.1	-
29 - Manufacture of motor vehicles, trailers and semi-trailers	12.9	18.0	-
30 - Manufacture of other transport equipment	12.9	18.0	-
31 - Manufacture of furniture	12.9	13.1	-
32 - Other manufacturing	12.9	13.1	-
33 - Repair and installation of machinery and equipment	0.0	0.0	-

Table 4. Main results of the key figure transfer to Spain, Catalonia and the Basque Country

		Year	**Spain**	**Catalonia**	**The Basque Country**
Input data	Fuel consumption (PJ)	2001	796.7	-	61.9
		2009	587.2	100.3	-
	CO_2 emissions (tCO_2/y)	2010	42,225,000	8,120,272	3,630,709
IWH potential (PJ)	Method 1	2001	76.4	-	7.2
		2009	55.5	8.6	-
	Method 2	2001	110.7	-	9.9
		2009	80.0	12.4	-
	Method 3	2010	151.1	26.2	12.0

5.4 Journal paper



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

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HIGHLIGHTS

- Three transferable methods to assess industrial waste heat potential are used.
- The methods based on either the energy consumption or CO_2 emissions.
- To investigate in how far transferring figures to different countries is sensible.
- A case study presented: the Spanish manufacture industry.
- The Spanish annual industrial waste heat potential ranges from 54.3 to 151.1 PJ.

L. Miró, S. Brueckner, R. McKenna, L.F. Cabeza. Methodologies to estimate industrial waste heat potential by transferring key figures: A case study for Spain. Applied Energy 169 (2016) 866-873.

DOI:10.1016/j.apenergy.2016.02.089

6 Estimating the Industrial Waste Heat Recovery Potential based on CO_2 Emissions in the European Non-Metallic Mineral Industry

6.1 Introduction

McKenna et al. [26] reported in 2010 an IWH assessment for the UK manufacturing industry. This was done using a bottom-up approach based on the individual site CO_2 emissions (Figure 16). The main data source was the UK National Allocation Plan for the EU Emissions Trading Scheme, supplemented by capacity/output and specific energy consumption data for certain heterogeneous sectors (aluminium, iron and steel and chemicals). In that study, it was estimated that around 60% of industry has been covered in terms of energy use, and 90% of energy-intensive sectors. The methodology proposed is the same for all sectors, except for the heterogeneous sectors which have specific considerations. The first step was to estimate the split between process emissions and combustion emissions for the sector. The next step was to calculate an overall emission factor for the subsector. Based on these emission factors and fuel splits for each sector, total site fuel consumption at a particular site is determined. To calculate the heat load of a site, the combustion efficiency and load factor also need to be considered (Figure 16). In order to reflect the constraints on heat recovery, including the impossibility of recovering all waste heat, a conservative approach was adopted whereby this fraction is set somewhat below published values so the range of heat recovery fractions is set at 10–20%.

6.2 Contribution to the state-of-the-art

The main contribution to the state of the art is to assess the technical IWH recovery potential of the European non-metallic mineral industry for Europe in the period 2007-2012 by adapting and applying a methodology based in the one previously presented by McKenna et al. [26]. This work is presented in the following paper:

- L. Miró, R. McKenna, T. Jaeger, L.F. Cabeza. Estimating the Industrial Waste Heat Recovery Potential based on CO_2 Emissions in the European Non-Metallic Mineral Industry. Submitted to Energy Efficiency, 2016.

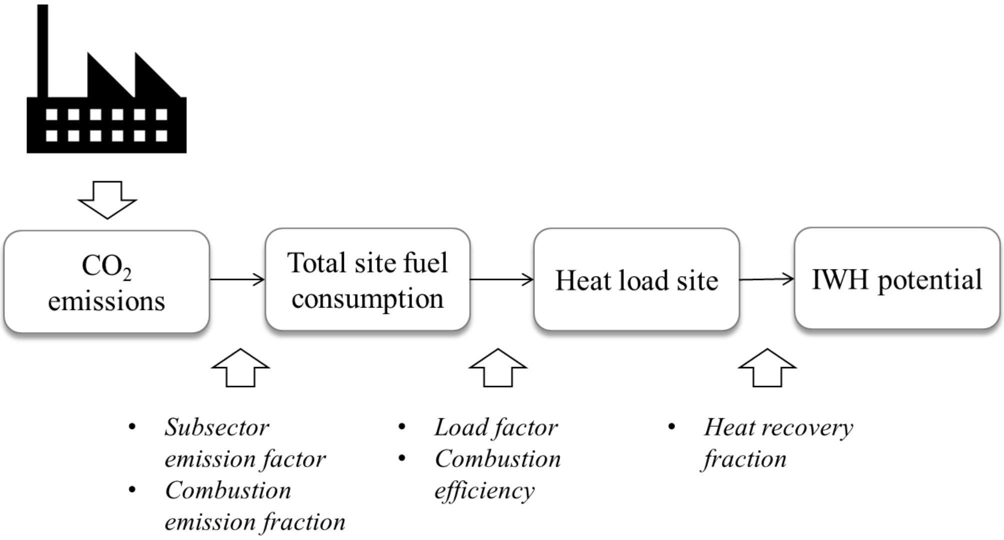


Figure 16. Methodology proposed by McKenna et al. [26]

The methodology presented by McKenna et al. [26] was selected because of its accuracy as it is a bottom-up approach which uses specific data from each industrial activity. However, the methodology has been adapted to fit in the European non-metallic mineral industrial sector. That sector was chosen, on the one hand, because according to McKenna et al. [26] is one of the homogeneous sectors in which the methodology proposed can be applied, on the other hand, because is one of the energy-intensive sector and its IWH potential is expected to be significant [11].

This analysis is of special interest because of the temporal frame in which the potentials are evaluated, the large region of study considered and the approach. Regarding the temporal frame, this study considers a six-year period which allows a temporal trend to be observed, whereas only one-year or average values are available in the literature. Moreover, 28 countries (EU27 and Norway) are considered and the regional specific parameters of the study are adapted. Finally, real site-level data is used in this bottom-up approach assessment which contributes to the accuracy of the results.

However, the scope of this analysis was limited by the data source employed. In particular, the individual site CO_2 emissions were obtained from the European Pollutant Release and Transfer Register (E-PRTR) [27]. Releases and transfers must be reported only if the emissions of a facility are above the production and pollutant thresholds set out in the E-PRTR regulation (Table 5).

Table 5. Subsectors considered in this assessment according to E-PRTR directive [27]

Industrial activity	**Activity capacity threshold**	**CO_2 releases to air threshold (kg/year)**
CEMENT	With a production capacity of 500 tonnes per day	100 million
LIME	With a production capacity of 50 tonnes per day	
CEMENT / LIME		
GLASS	With a melting capacity of 20 tonnes per day	

According to McKenna et al. [26] methodology, the equation which relates all the parameters to calculate the IWH potential is presented in Equation 1:

$$IWH\ potential = RF \cdot \frac{C_T \cdot f_C \cdot \eta_c}{K_T \cdot LF} \qquad \text{Equation 1}$$

where:

K_T is the overall emission factor for the subsector, obtained from the regional energy statistics,
C_T is the total emissions of the site, obtained from the E-PRTR database,
F_C is the combustion emission fraction,
η_C is the efficiency conversion from fuel to heat,
L_F is the load factor, and
R_F is the recovery fraction, which is fixed at 10 and 20%.

The highest IWH potential has been identified in Germany, Italy, France and Spain. Their temporal evolution from 2007 to 2012 is show in Figure 14 as well as the relation with the CO_2 emissions and the production of the industrial activities selected.

A direct relation was expected (and later corroborated) and between the CO_2 emissions and the IWH potential (Equation 1). Moreover, in those figures it can be observed that the trends in production (output) closely match those for CO_2 emissions (except for some years in France).

In general, a decreasing trend in CO_2 emissions and, consequently, IWH potential can be observed in the period analysed. More specifically, German and France show the lowest values in 2009 with a slightly recuperation in 2012 while Italy and Spain show a clear decrease trend. The vertical bars are divided in the different non-metallic mineral activities included in the analysis; in there, the importance of the cement-related activities in the sector can be seen.

The average IWH recovery potential per site in the period 2007-2012 is 0.35 PJ/y for Germany, 0.28 PJ/y for Italy, 0.31 PJ/y for France and 0.31 PJ/y for Spain.

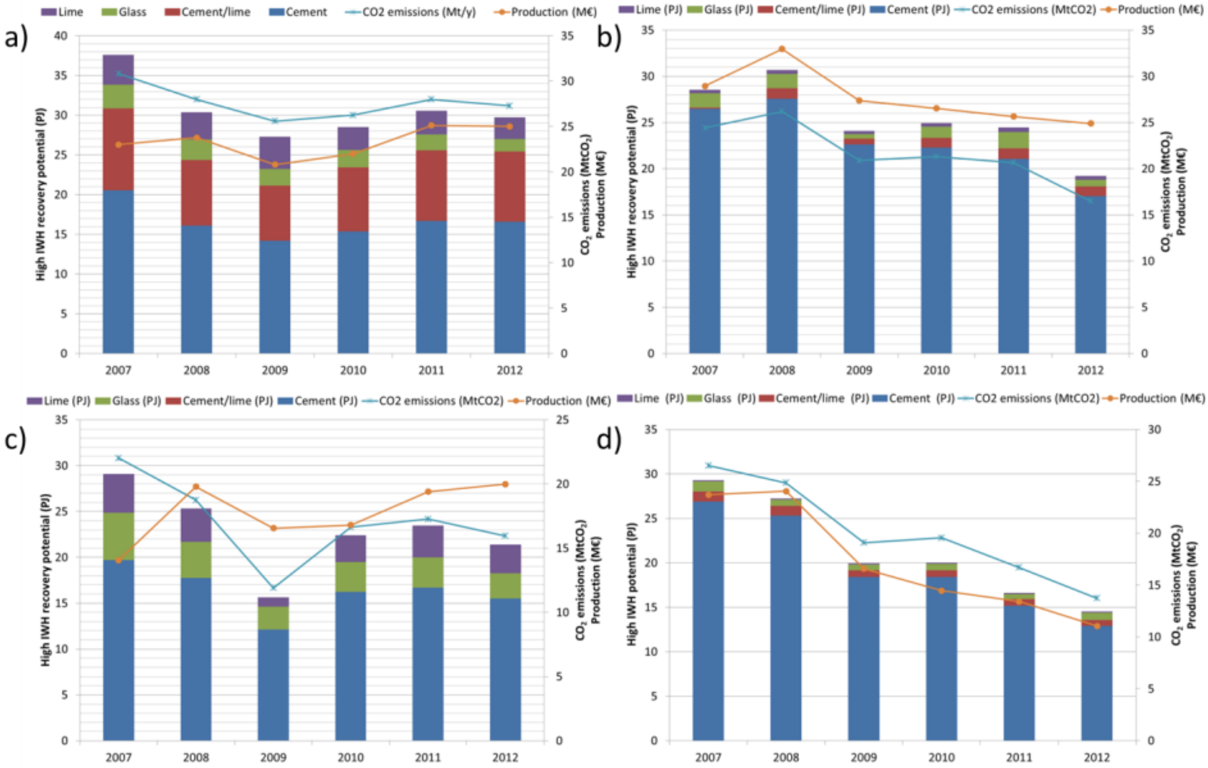


Figure 17. IWH potential (in PJ), CO_2 emissions (in $MtCO_2$) and production (in M€) for Germany, Italy, France and Spain

The exact location of the heat sources allows the deployment of the technologies and strategies to reuse this heat. Hence, Figure 18 shows the location of the 403 facilities included in the analysis: their circle size represents the average IWH recovery potential in PJ and their colour the industrial activity in the period 2007-2012.

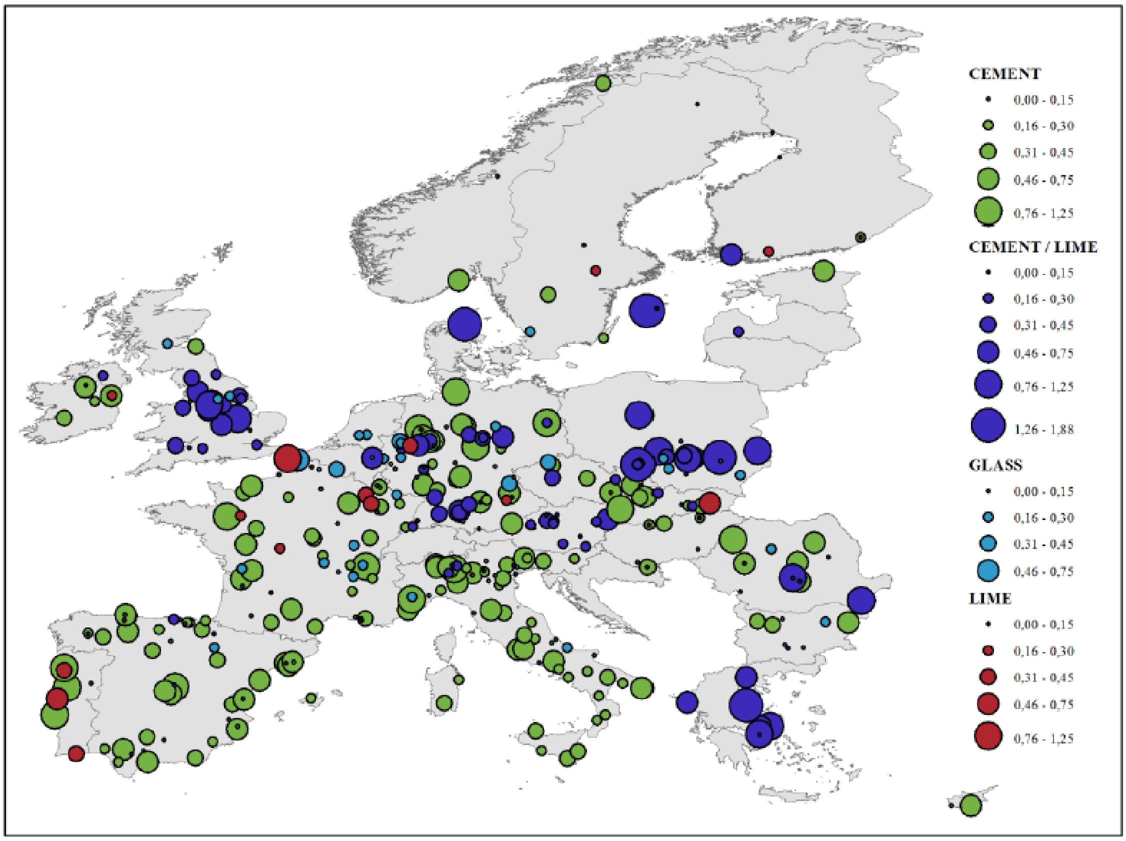


Figure 18. Location and average IWH potential (in PJ) in the period 2007-2012

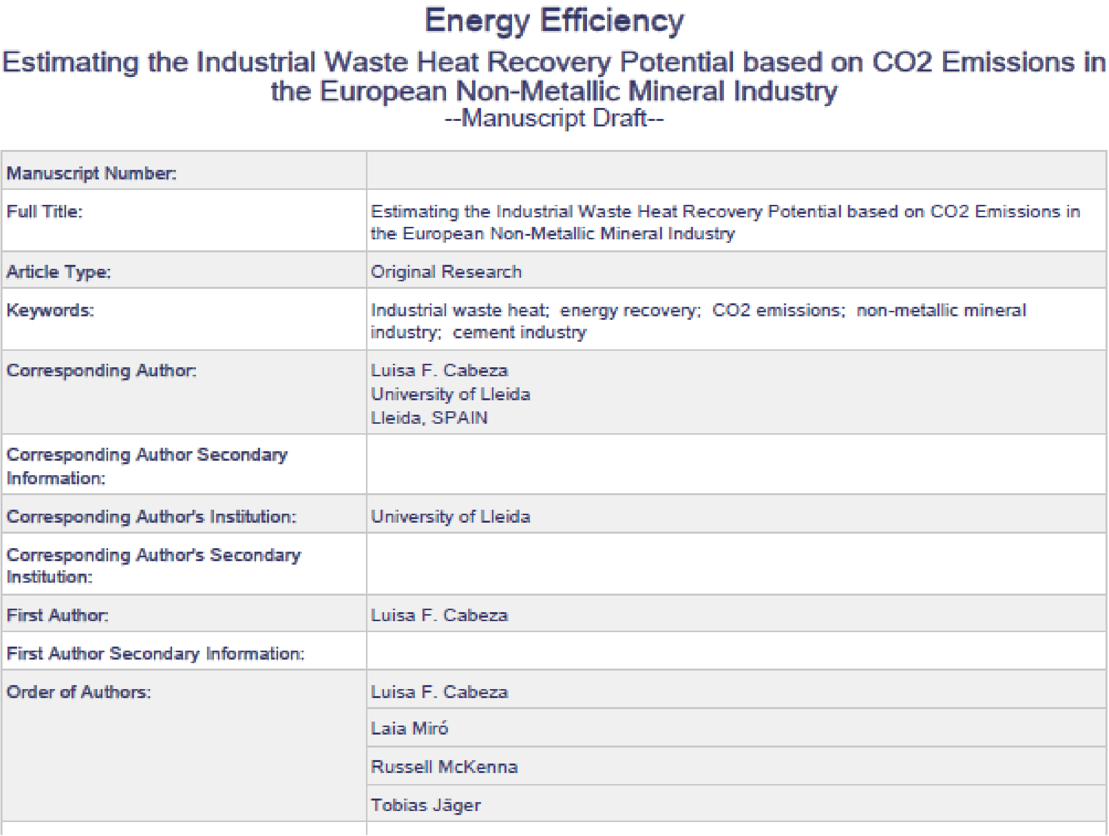
6.3 Contribution of the candidate

The collection of the input data in the E-PRTR database from all the European sites in the non-metallic mineral industry as well as the calculations and the results plotting derived from applying the methodology was done by the candidate.

Moreover, the writing, preparation for submission and revision process was leaded by the candidate.

The co-authors collaborated mainly in the GIS plot, the discussion and the language correction of the manuscript.

6.4 Journal paper



Energy Efficiency

Estimating the Industrial Waste Heat Recovery Potential based on CO2 Emissions in the European Non-Metallic Mineral Industry

--Manuscript Draft--

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7 Thermal Energy Storage (TES) for Industrial Waste Heat (IWH) Recovery: A Review

7.1 Introduction

The importance of the recovery of IWH has been highlighted in the previous articles. However, the following step is to investigate in more detail the IWH sources as well as the possible technology alternatives to reuse this heat.

Numerous technologies are currently available to recover and reuse IWH. According Brueckner et al. [11] these technologies can be categorized as passive technologies, whether the heat is being used directly at the same or at lower temperature level, or as active technologies, whether it is transformed to another form of energy or to a higher temperature level. However, this review focuses only on TES technologies. These technologies have become an important thermal management tool which helps solving the problem of matching the discontinuous IWH supply with the heat sink demand and achieving a better capacity factor (ratio of the actual output over a period of time), allowing the process components to be designed for a lower maximum output, for avoiding start-up and partial load losses, and for reducing investment cost in combination with cost intensive components (such as refrigerators or Organic Rankine cycle engines) [28]. Besides, the International Energy Agency [1] states that TES technologies are well positioned to reduce the amount of heat which is currently wasted due to the temporal and geographic decoupling of heat supply and demand.

Depending on the temporal characteristics of this decoupling (hourly, daily, weekly or seasonally [29]), the exhaust and the application temperature, the storage capacity and estimated storage costs, the different available TES material types (sensible, latent and thermochemical (TCM) storages) need to be considered to choose the most suitable technology. Therefore, the storage period as well as the heat capacity and cost of different TES candidates are presented in Table 6.

Table 6. Typical parameters of TES systems, based on [29]

TES systems	**Storage period (hours, days, seasonal)**	**Capacity (kWh/t)**	**Cost (€/kWh)**
Sensible (hot water)	Days /seasonal	10 - 50	0.1 - 10
PCM	Hours /seasonal	50 - 150	10 - 50
Chemical reactions	Hours /days	120 - 250	8 - 100

7.2 Contribution to the state-of-the-art

The main contribution of this review to the state of the art is to collect, present and characterize the case studies found in the literature in which TES systems have been used to recover and reuse IWH. This is presented in the following paper:

- L. Miró, J. Gasia, L.F. Cabeza. Thermal Energy Storage (TES) for Industrial Waste Heat (IWH) Recovery: A Review. Applied Energy 179 (2016) 284-301.

More than 35 examples of IWH sources in which TES systems have been proposed to recover and reuse this heat have been found in the literature. The main advantage of these systems is that allow storing the heat for a later use including the possibility of use it in a different location. That is why those examples have been first divided depending on the location of the subsequent use of this heat (Figure 19): in the same site in which it is generated (on-site use) or transported by means of Mobilised TES (M-TES) and used to another site (off-site use).

The scope of this review includes all the industrial activities excluding commercial or services activities. Within this scope, the first studies regarding the use of TES in this sector were published in the late 70’s however until 2006 the topic has not been of interest again.

All the case studies found in the literature for both on-site and off-site recovery have been listed and compared in these tables (Table 7 and Table 8) regarding to: the excess heat source characteristics (activity and temperature), the TES material proposed and its storage capacity, the subsequent use (and distance, if applicable) of the waste heat identified and the calculated environmental or economic savings.

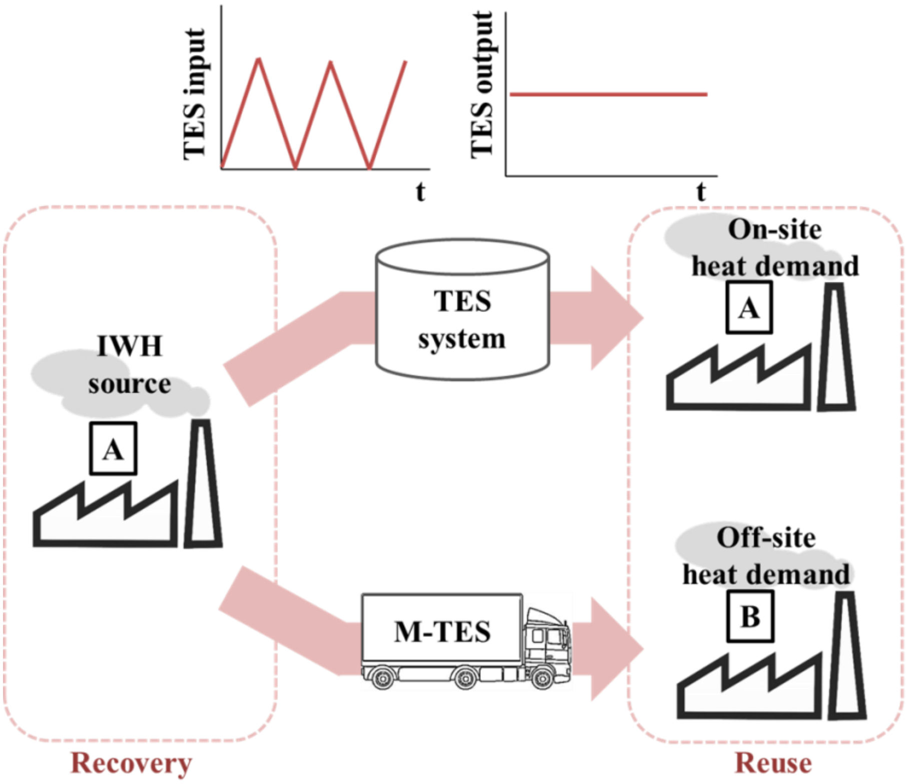


Figure 19. Possible on-site and off-site use of the IWH sources

Table 7. Summary of the TES systems for on-site IWH recovery and reused, found in the literature

IWH Source		**TES system**		**Heat demand**		**Savings**
Source	**Exhaust temperature (°C)**	**TES material**	**Storage capacity (MWh)**	**Heat sink**	**Temperatur (°C)**	
Foundry	n.a.	Water (BTES)	3800	Space heating	40 – 60	1500 tCO_2/y
	300	Packed bed dual-TES media	10	Internal processes, space heating	< 100	n.a.
	n.a.	Aluminium shots	n.a.	Furnace input scrap material	n.a.	On-site reuse of 6.4 % of the IWH
Steelmaking	315 – 1500	Packed bed with refractory brick, slag or scrap steel	n.a.	Steam for power generation	n.a.	0.0227 MW/t of product
	n.a.	Endothermic reactions	n.a.	Steam, hot water	n.a.	n.a.
	>1200	Copper	n.a.	Endothermic reaction	n.a.	n.a.
	<1427	Sodium acetate trihydration salt	n.a.	n.a.	n.a.	n.a.
	430	Molten salts	90 kWh/m^3	Internal processes, steam for power generation	n.a.	60-80 kWh/t of energy consumption and 45 $kgCO_2/t$ of product

	600 – 1500	Steam	n.a	On-site processes and DH	n.a.	22483 tCO_2/y
Metal casting	1200 – 1600	Molten slag	n.a	n.a	n.a	n.a
Cement plant	177 – 816	Rock beds and draw salts	n.a.	Steam for power generation	n.a.	$6.8 \cdot 10^6$ MWh of energy consumption
Concrete plant	n.a.	Eutectic mixture of KNO_3 and $NaNO_3$ with graphite	n.a.	Saturated steam	120 – 250	n.a.
	n.a.	Reinforced concrete slabs and paraffin	1.25	Internal processes	n.a.	45% in energy consumption and 15000 t CO_2/y
Organic sulfactants plant	110 – 160	(1) Metal encapsulated PCM (2)-(3) Concrete	(1) 1.28 (2) 0.17 (3) 0.40	Preheat internal processes	n.a.	Steam supply (1) 56%, (2) 50% and (3) 70%
Yeast and ethyl alcohol plant	25 – 40	Water	n.a.	Onsite heating, cooling	n.a.	Heating and cooling demand of 2-3 %
Paper and pulp processing facility	n.a.	Water	n.a.	Steam	n.a.	Fuel consumption $1.2 \cdot 10^9$l/y
Food factory	65	Water	n.a.	Water preheating	n.a.	Energy consumption 5-6 %
Chocolate industry	n.a.	Water	n.a.	Hot water network	n.a.	n.a.

n.a. non available

Table 8. Summary of the M-TES systems for off-site IWH recovery and reused, found in the literature

IWH Source		**M-TES systems**			**Heat demand**		**Savings**
Source	**Exhaust temperature (ºC)**	**TES material**	**TES material amount**	**Storage capacity (MWh)**	**Heat sink**	**Distance (km)**	
Steelmaking	n.a.	PCM Zeolite	n.a.	n.a.	Utility plant	30	n.a.
Aluminium factory Incineration	n.a.	(1) Sodium acetate trihydrate (2) Zeolite	15 t	(1) 2.4 (2) 3.4	Industrial drying, air conditioning and swimming pools	(1) 10 (2) 7	Energy costs drop to 15 €/MWh
n.a.	n.a.	Erythritol	n.a.	n.a.	n.a.	10 – 50	n.a.
n.a.	n.a.	Erythritol	n.a.	n.a.	DH network	48	n.a.
Sludge incinerator	70 – 350	PCM 1 (melting at 58 ºC) PCM 2 (melting at 118 ºC)	n.a.	2	Civic gymnasium	2.5	Energy consumption: 68-95%, CO_2 emissions: 71-93 %
n.a.	200	Erythritol	17.5 t	1.5	Hot and cold water	20	Energy consumption: 88-92.3 %, CO_2 emissions: 73.4-79.8 %
Steelwork	250	NaOH	17.5 t	2.3	Chemical plant	10	Energy consumption: 91.4 % CO_2 emissions: 82.5 %

Steelwork	250	Na_2CO_3/NaOH	17.5 t	1.9	Chemical plant	10	Energy consumption: 90.5 %, CO_2 emissions: 81.4 %
n.a.	n.a.	Erythritol	n.a.	224	DH network	48	n.a.
CHP plant	n.a.	Erythritol	n.a.	$9.15 \cdot 10^{-3}$	DH network	20	n.a.
Electrical heater	n.a.	Erythritol	74 kg	$14 \cdot 10^{-3}$	n.a.	n.a.	n.a.
n.a.	n.a.	Erythritol	80 kg	2	n.a.	n.a.	n.a.
n.a.	n.a.	Sodium acetate trihydrate	16.6 t	2.3	n.a.	6	616 kg CO_2/cycle
Incineration plant	n.a.	Zeolite	14 t	n.a.	Industrial drying process	7	n.a.

n.a. non available

Regarding the on-site recovery and reuse of the IWH, the industrial activities which apply TES to recover excess heat identified are: some manufacturing industrial sectors (basic metal, non-metallic mineral, chemical, pulp and paper and food production), vehicle engines, power plants and incineration plants. As expected, the activities in which researchers proposed the use of TES systems coincide with the most energy-consuming sectors (those sectors the IWH produced is higher). However, the studies found in the literature do not report enough information for a deeper analysis and comparison. Even though not all cases report the location of the IWH source, most of the analyses were developed in Europe and USA. The basic metal subsector is the one which has most potential and has attracted most attention in the scientific community. This may be due to the high exhaust temperatures of the activities (Table 2) which allow a wide variety of subsequent uses of this heat. In this subsector, the two main IWH sources identified in this sector are foundries and steelworks which use different TES material types depending on the subsequent use. For power generation molten salts, metals and ceramic materials were proposed. In the case of on-site processes and space heating purposes, lower temperature TES materials like water are used. Besides, in the cement and concrete production plants from the non-metallic mineral subsector the specific heat sources were identified (clinker cooler and kiln system exhaust gas), and, depending on the exhaust temperature the different types of TES materials (molten salts and ceramic materials) were proposed for power generation and on-site production processes. Fewer cases were identified for the rest of the manufacturing sector. In the case of the chemical activities only numerical studies were published in which different TES materials were used for on-site processes and climate control. Regarding both pulp and paper and food industrial activities, only numerical case studies using water as TES material were identified. Since the exhaust temperature for these sectors is as high as in the previous mentioned subsectors, the feasible subsequent uses are the pre-heating of other water flows in the process.

On the other hand, the off-site systems consist of the transport of heat by means of truck, train or boat, which is also named M-TES. It has been observed that on-site recovery systems are by far more frequent in the literature than off-site systems. In fact, the off-site recovery and reuse of IWH by means of M-TES has been addressed so far in numerical studies and almost no public information has been found of real prototypes. The heat sources in which M-TES were proposed to be applied are incineration plants, CHP and basic metal production. All cases were developed in Germany, Sweden and Japan. PCM and TCM were the two types of TES material proposed and erythritol (PCM) is proposed in almost half of the studies. Due to the possibility of geographically transporting waste heat, potential subsequent uses of this heat can be in applications like industrial processes, DH networks or climate control. Moreover, reported distances between heat source and heat sink range from 2 to 50 km. The obstacles which were found by the researchers when developing this technology are the limitations of working with big amounts of TES materials (for example, heat transfer problems) and that its economic suitability depends of factors like the price of fuels, which are not easy to predict.

The lack of studies found in the literature may be due to different factors: the maturity level of TES systems, the industry production processes and their financial barriers, and the commercial confidentiality in these sectors. Regarding to the technology maturity, and according to the IEA Energy Storage Roadmap [1], only residential hot water heaters with storage, UTES, cold water storage and PTES (pit thermal energy storage) are the thermal storage technologies in commercialisation maturity level. The rest are still in early or middle stage of development and will require further attention before their potential can be fully realised. Therefore, both trend and maturity can be seen in Figure 20 in which the case studies found in the literature are plotted depending on the year in which they are published, the industrial activity they belong and the maturity (which is related to the scale of the study). In general, a clear lack of pilot plant and real scale studies can be seen and all of them are very recent, which indicates a trend and a possible research niche. Moreover, first cases published regarding this topic were done in the 80’s and focused in the manufacturing industry. However, until almost 20 years later the topic has not been studied again, which coincides with the period when the environmental awareness has gained more relevance because of the environmental policies worldwide. Finally, the interest in transporting IWH by means of M-TES has increased in the last decade as a result of the widespread use and commercialisation of TES materials and systems.

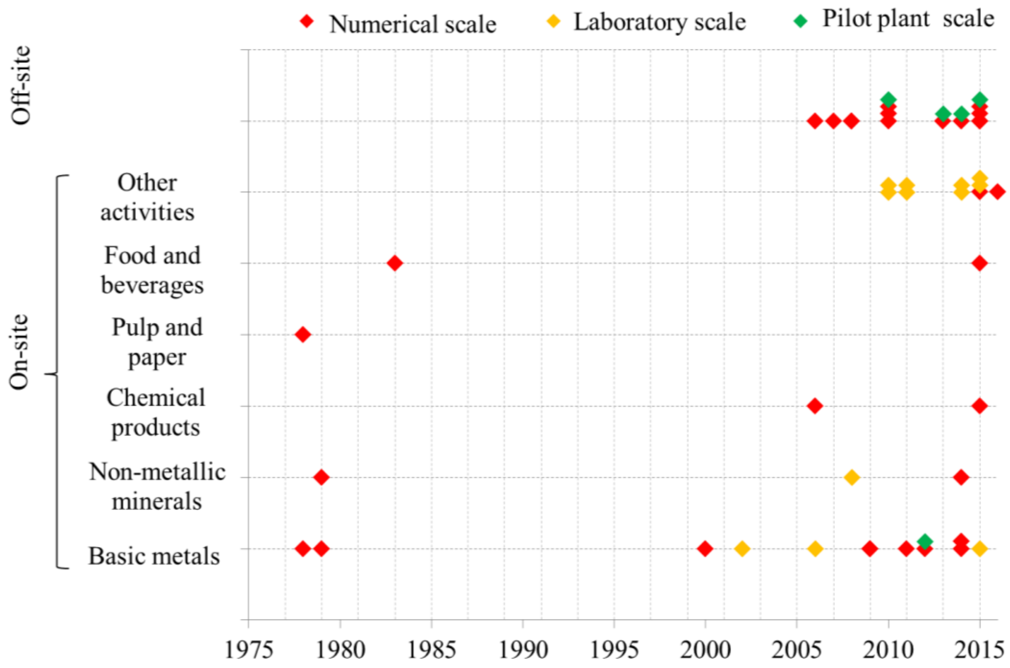
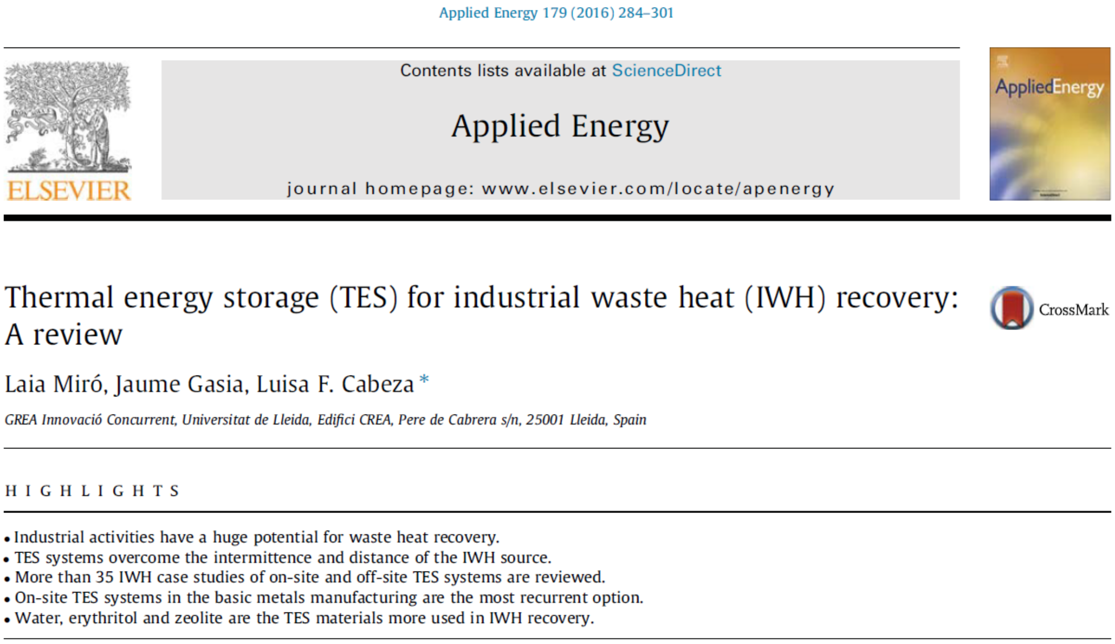


Figure 20. Maturity and trends of the TES systems reviewed

7.3 Contribution of the candidate

The candidate looked for the list of references to review used in the article, decided the structure and leaded the writing. Moreover, the candidate generated all the graphical information support in the article.

7.4 Journal paper



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Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review

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HIGHLIGHTS

- Industrial activities have a huge potential for waste heat recovery.
- TES systems overcome the intermittence and distance of the IWH source.
- More than 35 IWH case studies of on-site and off-site TES systems are reviewed.
- On-site TES systems in the basic metals manufacturing are the most recurrent option.
- Water, erythritol and zeolite are the TES materials more used in IWH recovery.

L. Miró, J. Gasia, L.F. Cabeza. Thermal Energy Storage (TES) for Industrial Waste Heat (IWH) Recovery: A Review. Applied Energy 179 (2016) 284-301.

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8 Conclusions and recommendations for future work

8.1 Conclusions of the thesis

This thesis has increased the knowledge in the field of recovering and reusing IWH. The importance of taking advantage of this alternative heat source has been recently highlighted by many international agencies and experts. However, there is a lack of information regarding the amount of available IWH mainly due to the fact that waste heat generation sites are not obliged to measure neither to report these streams.

Therefore, four articles are presented focusing on the current situation and availability of the worldwide regional assessments, on the generation of new regional and sectorial estimations and on the use of specific technologies to recover and reuse this heat.

Regarding the state of the art, the available regional IWH assessments are identified and plotted in a worldwide map, which allows identifying both the regions with available assessments as well as the regions with a lack of estimations and the feasibility of the values reported. The IWH estimation data from a total of 33 countries worldwide are collected. In order to assess the feasibility of the data, the authors propose a methodology based on relating the IWH potential with the actual country and industrial energy consumption. It was found that:

- 1/6 of the data found is considered not feasible. Within this context, special attention when dealing with the data from Canada, Lithuania, Sweden, UK and Japan is recommended.
- Lack of reliable and well described data in the literature, which is essential in order to perform further suitable analysis of the quantity of IWH available in different regions and to further promote the use of this energy.
- The inclusion of the following information in further assessments is recommended:
    - Typology of IWH potential (physical, technical or economical potential).

  - Methodology used to account the IWH potential (bottom-up or top-down).
  - Temperatures at which the energy content is calculated.
  - Year of the data used in the calculations.
  - The type of IWH stream (liquid or gas).
  - The exact scope of the study (industrial sectors and activities that are considered).

Considering the generation of new estimations, two articles of this thesis aimed to increase the knowledge in this topic. In the first article the estimation of the IWH potential in Spain. Therefore, a literature search was done and the methodologies and studies which publish key figures expecting to found someone which can be transferable to other regions. A validation process was performed and, among the literature search, three methodologies were found to be potentially transferable to other regions. Those three methodologies defined key figures in which the industrial energy consumption or industrial CO_2 emissions were related with the IWH potential. An adaptation process was needed to combine the available input data (energy consumption and CO_2 emissions from the industry) and the industrial sectors scope from the original methodology and Spain:

- The IWH potential for Spain was identified for the period 2001-2013. In this period, Spanish annual industrial waste heat potential ranged from 54.3 to 151.1 PJ.
- The IWH potential was also estimated in the same period for the two most industrialized regions in Spain. Therefore, the potential ranged from 8.6 to 29.7 for Catalonia, and 7.2 to 11.9 for the Basque Country.
- The degree to which they can be transferred strongly depends on similarities between the original and target systems.

In the second article, the IWH potential from the non-metallic mineral industry for Europe was estimated. A bottom-up approach considering the individual CO2 emissions per site was used. This approach was originally developed for the UK; so, the approach was adapted to EU. In this study it was found that:

- The countries with the largest potentials were Germany (average potential 23.01 PJ/y), Italy (average potential 18.99 PJ/y), France (average potential 17.17 PJ/y), and Spain (average potential 15.97 PJ/y).
- The non-metallic mineral subsector with more potential was cement.
- The results obtained showed good agreement with former assessments in the literature.
- The influence of socio-economic parameters highlighted the importance of plotting more than one year when assessing these types of potentials. That is why, the period 2007-2012 was analysed.

Finally, regarding the technologies to recover and re-use IWH, TES was selected as promising technology because of its ability of matching both temporally and geographically the IWH source and a possible heat demand sink. Around 50 industry case studies, in which both on-site and off-site recovery systems are considered were here reviewed and discussed taking into account the characteristics of the heat source, the heat sink, the TES system, and the economic, environmental and energy savings. The main conclusions of this review are:

- More case studies regarding on-site than off-site reuse and recovery of IWH were found.
- On-site recovery and re-use was identified in the following industrial activities: energy-intensive manufacturing industry, vehicle engines, power plants, and incineration plants. Among the energy-intensive manufacturing subsectors, the basic metals subsector is by far the one which has drawn more attention and the only one with pilot plant scale studies.
- In on-site systems, water (or steam) storage tanks was the most used on-site TES systems while power generation and space heating and cooling was the most recurrent applications for the on-site reuse of IWH.
- Water (or steam), erythritol and zeolite were the TES materials used in more industries and space comfort and electricity generation were the more recurrent applications.

- However, many difficult to assess the economic and environmental feasibility of the systems due to:
    - Lack of high scale studies with real performance.
    - Lack of policies motivating the use of this heat source.
    - Temporal variability of the energy prices.

8.2 Contribution of the thesis to the IWH mapping

The realisation of this thesis led to an increase of estimations worldwide (Paper 2). Moreover, estimations published after the realisation of the first paper of this thesis have been found in the literature [6][30]. All those values are used to update the figure from the first paper of the thesis (Figure 21).

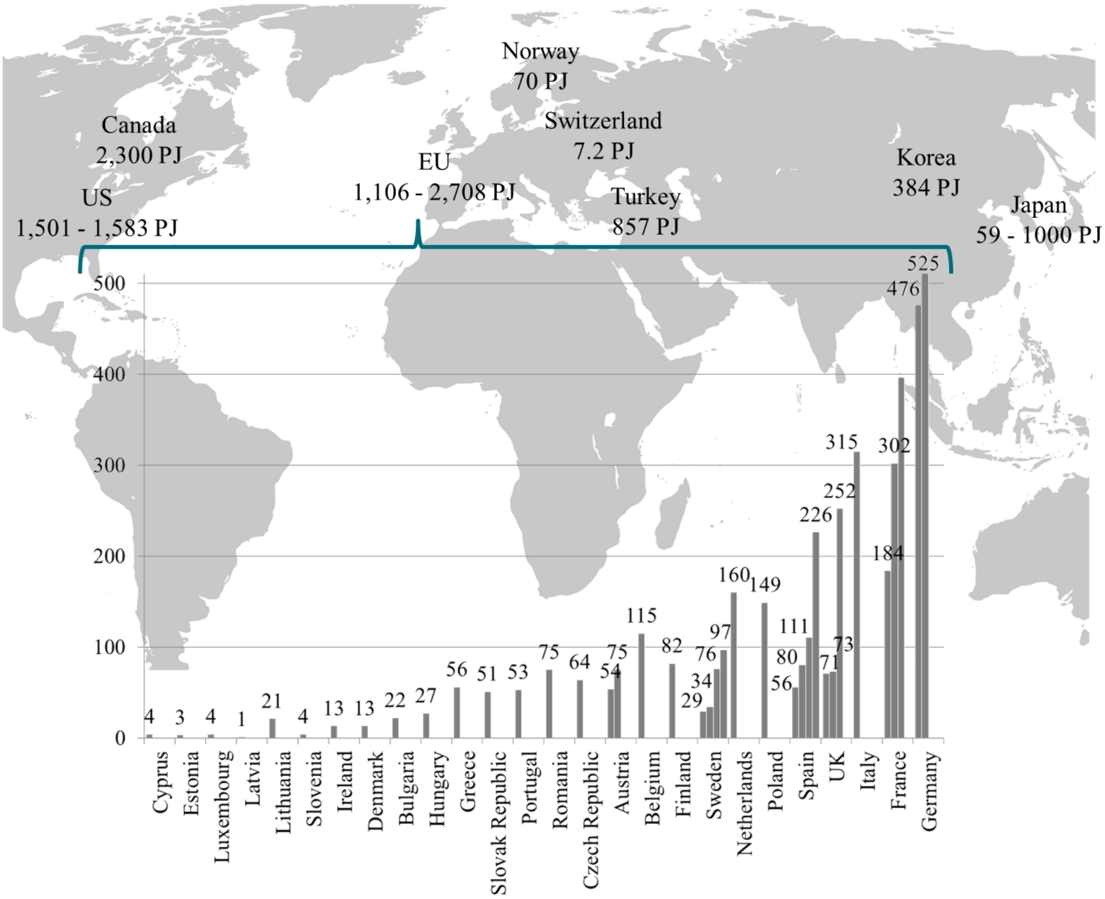

Figure 21. Updated worldwide map from Paper 1

8.3 Recommendations for future work

From the research carried out and presented in this thesis, some points arise which are not addressed in this thesis (neither in the literature) and are considered relevant in this topic. Some recommendations identified for future work are:

- Focus on regions with significant IWH potential.

  On one hand, there are some areas worldwide in which because of the concurrence of energy consuming activities, high IWH potential is expected. That is the case, for example, of Chile, in which the metal extraction and mining related processes need a significant amount of the total energy consumption of the country. On the other hand, there are some countries in which even though the theoretical potential is not that significant, they have both the technology and the infrastructures (for example district heating networks) to take advantage of this heat source.

- Generation of transferable key figures.

  The transfer of key figures is considered as a medium accuracy approach. However, the last study in the literature in which key figures are published refer to 2008. More current key figures are needed in order to easily estimate the potential in different regions or industrial sectors. Once identified regions or sectors with important potentials, more accurate approach could be applied.

- Characterization of IWH in specific sectors.

  There are some specific energy-intensive industrial sectors or processes which are quite homogenous at country or continental scale. Those sectors are worth to be deeply analysed in order to identify the potential of reusing IWH to achieve both economic and environmental savings.

- Technology optimization.
  High-temperature (high-quality) heat is unused in some subsectors mainly due to corrosive chemicals contained in the waste heat stream which reduce the quality

of the heat. Among the possible solutions, protective coatings are able to prevent or inhibit the direct action of a potentially aggressive medium on the substrate.

- Use of alternative approaches.

  When addressing the IWH topic, other approaches should be also taken into consideration. For example, life cycle assessments, embodied CO_2, or economic approaches.

9 Other research activities

In this section, the other contributions made by the author are divided into journal and conferences and, moreover, into contributions related to the thesis and other contributions.

9.1 Journal papers contributions

9.1.1 Thesis related journal contributions

1. Brueckner S, Liu S, Miró L, Radspieler M, Cabeza LF, Laevermann E. Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. Applied Energy 151 (2015) 157-167.
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9.1.2 Other journal papers contributions

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9.2 International conferences

9.2.1 Thesis related conferences contributions

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3. Miró L, Brückner S, Lävermann E, Cabeza LF. Estimation and use of the industrial waste heat (IWH) potential. EuroSun 2014 - International Conference of Solar Energy and Buldings. France, 2014.

4. Miro L, Brueckner S, McKenna R, Cabeza LF. Industrial waste heat (IWH) recovery potential assessment in Spain. INNOSTORAGE - Advances in Thermal Energy Storage, Israel, 2016.

9.2.2 Other conferences contributions

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9.3 Scientific foreign-exchanges

The PhD candidate did three short (up to three months) research stays abroad during the realization of this thesis.

9.3.1 ZAE Bayern (Garching, Germany)

The ZAE Bayern research centre expertise focuses in energy optimized processes and buildings, photovoltaics and energy storage. During the stay in this centre, under the supervision Dr. Stefan Hiebler, the candidate developed two different work topics: (1) A comparative analysis of TES materials when analyzing the same thermal characteristics by means of two different equipment: a T-History and a differential scanning calorimeter, and (2) A state-of-the-art of the available methodologies to estimate IWH at regional scale. Both works led to scientific articles and international conference contributions.

9.3.2 Karlsruhe Institute of Technology (Karlsruhe, Germany)

The candidate worked during the research stay at the Institute for Industrial Production (IIP) from Karlsruhe Institute of Technology (KIT) in the evaluation of the IWH recovery potential of the non-metallic mineral industry in Europe using a method based in CO_2 emissions. This research stay led to a scientific article and some international conference contributions.

9.3.3 IFEU (Heidelberg, Germany)

During the research stay at IFEU, the candidate collaborated in a German-scale research project called “NENIA – Use of industrial waste heat for district heating”. In this context, the candidate worked on the classification and feasibility analysis of IWH streams from the 11.BImSchV, a German emission ordinance for the industry. Moreover, the candidate is currently working in a collaborative article regarding her work at IFEU.

9.4 Other activities

9.4.1 Book chapters participation

1. Cabeza LF, Martorell I, Miró L, Fernández AI, Barreneche C. Introduction to thermal energy storage systems. Advances in Thermal Energy Storage. Woodhead Publishing LTD, 2014.
2. Fernández AI, Barreneche C, Miró L, Brueckner S, Cabeza LF. Thermal Energy Storage (TES) systems using heat from waste. Advances in Thermal Energy Storage Systems. Methods and Applications. Woodhead Publishing LTD, 2015. ISBN: 978-1-78242-088-0.
3. Cabeza LF, Martorell I, Miró L, Fernández AI, Barreneche C. Introduction to thermal Energy Storage (TES) systems. Advances in Thermal Energy Storage Systems. Methods and Applications. Woodhead Publishing LTD, 2015. ISBN: 978-1-78242-088-0.
4. Fernández AI, Barreneche C, Martínez M, Miró L, Cabeza LF. Chapter 32. TES Materials: Embodied Energy and CO_2 Footprint. Volume 5. Energy Storage - Handbook of Clean Energy Systems. John Wiley & Sons Inc. 2015. ISBN: 978-1-118-38858-7.

9.4.2 Projects participation

1. El almacenamiento de energía térmica como herramienta de mejora de la eficiencia energética en la industria (ENE2011-22722).
2. Identificación de barreras y oportunidades sostenibles en los materiales y aplicaciones del almacenamiento de energía térmica (ENE2015-64117-C5-1-R (MINECO/FEDER)).
3. Abengoa Solar NT. Experimentación en planta piloto sobre el almacenamiento de energia tèrmica para centrales termosolares.
4. CENIT. Abengoa Solar NT. CONSOLIDA.
5. Gas Natural. Almacenamiento térmico en caliente para refrigeración solar por absorción.

6. Abengoa Solar NT. Investigación sobre almacenamiento térmico sobre plantes solares de Abengoa Solar.
7. Abengoa Solar NT. Caracterización de partícules, análsis cinético y diseño de reactivos.

9.4.3 Experts networks participation

1. Annex 25 - ECES IA - IEA - Surplus Heat Management using Advanced TES for CO_2 mitigation
2. Red Temática Nacional de Almacenamiento Térmico de Energía

9.4.4 Dissemination articles

1. Barreneche C, Solé A, Miró L, Martorell I, Fernández AI, Cabeza LF. New methodology developed for DSC for the analysis of phase change materials. Thermal Analysis UserCom. Mettler-Toledo 37 (2013).

9.4.5 Master and Degree thesis supervision

1. Luz Angela Ocampo Torres. Estimación del calor residual en el proceso de fabricación del cemento. University of Lleida, 2015.
2. Denet Soler Toledo. Análisis y cuantificación del potencial de calor residual de las industrias manufactureras en Chile. University of Antofagasta, 2016.

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