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

Laia Miró[1], Russell McKenna[2], Tobias Jäger[2,Ɨ], Luisa F. Cabeza[1,*]
[1]GREA Innovació concurrent, Edifici CREA, Universitat de Lleida, Pere de Cabrera s/n, 25001-Lleida (Spain)
[2]Institute for Industrial Production (IIP), Chair of Energy Economics, Karlsruhe Institute of Technology (KIT), Hertzstraße 16, 76187 Karlsruhe (Germany)
[Ɨ]Present address: Institute for Micro Process Engineering, Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen
*Corresponding author e-mail: lcabeza@diei.udl.cat

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Abstract

Industrial waste heat (IWH) is a key strategy to improve energy efficiency and reduce CO_2 emissions in industry. But its potential for different countries remains unclear due to a non-existent or inconsistent data basis. The objective of this paper is to assess the IWH potential of the European non-metallic mineral industry, using databases which comprise CO_2 emissions of more than 400 industrial sites as well as country- and sector-specific parameters. This sector is selected because of its homogenous nature, meaning that most sites carry out similar or the same processes, which facilitates site-level modelling with subsector-level assumptions. The bottom-up approach is employed to derive the IWH potential for this industry over the period 2007 – 2012. Average results in this period show an IWH potential per site of 0.33 PJ/a and a potential for the whole sector of 134 PJ/a. The countries with the largest IWH potentials are Germany, Italy, France, and Spain with yearly average potentials of 23, 19, 17 and 16 PJ, respectively. The subsector with most IWH potential is cement. Further work should focus on the improvement of methodologies to assess the IWH potential, in particular through a techno-economic assessment of links between IWH sources and potential sinks.

Keywords

Industrial waste heat; energy recovery; CO_2 emissions; non-metallic mineral industry; cement industry

Abbreviations

Abbreviation	Definition	Units
IWH	Industrial waste heat	[PJ]
E-PRTR	European Pollutant Release and Transfer Register	[-]
EU ETS	European Union Emissions Trading System	[-]
NACE	Nomenclature of Economic Activities	[-]
GIS	Geographic information system	[-]
K_T	Overall emission factor for the subsector	[tCO_2/PJ]
C_T	Total emissions of the site	[tCO_2]
F_C	Combustion emission fraction	[-]
η_C	Efficiency conversion from fuel to heat	[-]
L_F	Load factor	[-]
R_F	Recovery fraction	[-]

1 Introduction

Nearly a third of the world's energy consumption and 36% of carbon dioxide emissions are attributable to manufacturing industry. Three industrial sectors are responsible for 70% of these emissions: iron and steel, non-metallic minerals, and chemicals and petrochemicals [1]. Some of these CO_2 emissions are emitted at temperatures which can be used as a new heat source in the same industry or in another industry/sector/application [3]. In order to improve energy efficiency and reduce energy demand there is an increasing interest in taking advantage of these underutilized heat sources before other options. This waste heat is an underutilised resource, in part because the quantity and quality of both heat resources and demand is not fully known [4]. However, there is a lack of detailed and well-explained literature regarding IWH recovery potential assessments and the factors affecting its utilization [5, 6], which is mainly due to a poor data basis. Industrial sites worldwide do not publish their waste heat stream characteristics and important technical parameters that are needed to quantify the potential differ between countries.

Miró et al. [7] reviewed the worldwide industrial waste heat recovery potentials and related them to the energy consumed for the whole industrial sector and the country. In this article, around 1/6 of the data published was considered unreliable and the authors already state a lack of reliable and well explained IWH assessments. Brueckner et al. [8] reviewed and compared more than 30 methods found in the literature to estimate the IWH within regions. These methods were classified according to the study scale, data collection and chosen approach. As in the previous study (Miró et al. [7]) the authors also noted that, for a lot of countries no country-specific data are available, and many studies apply key figures from other countries.

Due the lack of data, most literature focusses on the state or regional scale. At county scale, Bonilla et al. [9] and Lopez et al. [10] quantified the IWH recovery potential of The Basque Country (Spain) at 51 GJ based on published data from the regional energy department, and proposed different recovery technologies (heat pumps, heat exchangers, Rankine cycles, cogeneration, etc.) and their respective recovery fractions. At the same scale, an analysis based on questionnaires can be found in Broberg et al. [11], who assessed the Swedish IWH recovery potential by scaling up a bottom-up county-scale study in the largest energy intensive companies located in two counties. Results indicated a total waste heat potential of 75.6 PJ/a. Similarly, Brueckner et al. [12] estimated the IWH for Germany (127 PJ/a) by means of a bottom-up analysis based on emission report data from the production companies. Regarding the approach considered, Miró et al. [13] assessed the Spanish IWH recovery potential by means of transferring key figures from other countries and analysed the differences obtained by using different approaches for the years 2009 and 2013. In the case of UK, McKenna et al. [14] estimated the IWH recovery potentials in the UK industry based on the CO_2 emitted in the different industrial sites involved in the European Union Emissions Trading System (EU ETS). This study quantifies the average IWH potential in the period 2000-2003 with 65-144 PJ, by taking into account specific subsector parameters like the combustion emission fraction, the load factor, etc. This study was later used by Hammond and Norman [15] to consider recovery options for use on-site, upgrading the heat to a higher temperature, conversion of the heat to fulfil a chilling demand, conversion of the heat to power and transport of the heat to fulfil an off-site heat demand.

At a European scale, Persson et al. [16] assessed the maximal excess heat volumes from fuel combustion activities for facilities in the energy and industrial sectors based on carbon dioxide emissions data from 2010 and recovery efficiencies. In the case of the non-metallic mineral sector, a total potential of 592.4 PJ was found. However, this study is a top-down approach and the assumptions considered are very general (e.g. 25% recovery efficiency in the non-metallic mineral industrial sector), which can be improved by using a bottom-up method. An overview of the studies mentioned is given in Table 1. Moreover, it is worth mentioning the European projects in relation with this topic. On one hand, the Heat Recovery in Energy Intensive Industries project [6] which was launched in 2008 with the aim of developing a pilot model for an approach to process heat recovery in energy intensive industries based on existing technologies. The authors quantified the ORC potential in Europe in 2556 MW [17]. On the other hand, the ongoing Industrial Thermal Energy Recovery Conversion and Management project (I-ThERM [18]) is willing to investigate, design, build and demonstrate innovative plug and play waste heat recovery solutions and the optimum utilization of energy within and outside the plant perimeter for selected applications with high replicability and energy recovery potential in the temperature range 70ºC- 1000ºC.

It is clear that there is a lack of highly accurate studies assessing the IWH recovery potential for larger regions like the European Union. Therefore, this paper proposes the use of an existing bottom-up method which is explained in [14] and is based on CO_2 emissions of specific sites. The data needed to assess the IWH recovery potential in the European Union is retrieved from the European Pollutant Release and Transfer Register (E-PRTR) [19]. The scope of the study includes 28 European countries (EU27 and Norway) limited to the subsectors cement, lime and glass from the non-metallic mineral sector. The reason for this focus is due to the highly homogenous nature of the subsector. In comparison to other subsectors the processes carried out at each site are very similar or the same. This allows a bottom-up methodology to be employed (as in [14]) that only requires differentiated assumptions at the subsector as opposed to the individual site level. Other emissions from this sector (oxides of nitrogen, sulphur dioxide, dust, etc.) are not considered in the study.

Table 1 Overview of studies in the literature

Source	Area	Methodology
Bonilla et al. [8]	Basque Country (Spain)	Bottom-up, statistical data
Lopez et al. [9]	Basque Country (Spain)	Bottom-up, statistical data
Broberg et al. [10]	Sweden	Bottom-up, questionnaires
Miró et al. [12]	Spain	Bottom-up, key figures
McKenna et al. [13]	UK	Bottom-up, EU ETS
Hammond and Norman [14]	UK	Bottom-up, EU ETS
Persson et al. [15]	European Union	Top-down approach

The article is divided into five main sections. In section 2, the approach used to assess IWH recovery potential is fully explained. The results obtained are presented and described in the following section, showing general results for Europe and their distribution on a site level as well as for the countries with most potential (Germany, Italy, France and Spain). Section 4 includes a comparison of the results with existing heat recovery potential studies, a sensitivity analysis of the parameters used in the approach and a discussion of the weaknesses of the analysis. The article closes in section 5 with the conclusions.

2 Methodology

The methodology is based on the one presented by McKenna et al. [14] in 2010. This is a bottom-up approach, as top-down methods are considered limited in terms of resolution and accuracy. This method was originally applied to the UK based on data for the period 2000-2003 and using the emission allowances reported in the European Commission National Allocation Plan. 60% of the UK industry of industry was covered in terms of energy use, and 90% of energy-intensive sectors.

The technical industrial waste heat potential (IWH_T) at the site level is determined based on Eq. 1:

$$IWH_T = R_F \cdot \frac{C_T \cdot F_{C,i} \cdot \eta_{c,i}}{K_{T,n} \cdot L_{F,i}} \qquad \text{Eq.1}$$

where:

IWH_T is the total technical IWH recovery potential [PJ],

R_F is the recovery fraction for the heat [-],

C_T is the total emissions of the site [tCO_2],

$F_{C,i}$ is the combustion emission fraction in subsector i [-],

$\eta_{C,i}$ is the efficiency conversion from fuel to heat in subsector i [-],

$K_{T,n}$ is the overall emissions factor for the subsector in country n [tCO_2/PJ], and

$L_{F,i}$ is the load factor in subsector i [-].

In most industrial processes, there are two types of emissions, related to the process (i.e. chemical reactions) and the fuel combustion respectively. For example, in cement manufacturing, CO_2 is emitted because of combustion but also because of the decomposition of calcium carbonate to calcium oxide at about 900 ºC [2]. Hence making the process more energy efficient does not necessarily reduce the process emissions but only the combustion ones. This is why the parameter $F_{C,i}$ is employed in Equation 1.

For further use, the methodology has to be adapted for the E-PRTR database, from which the total emissions of the site C_T can be retrieved. In this database information concerning the amounts of pollutant releases to air, water and land as well as off-site transfers of waste and pollutants in waste water is provided. These data represent the total annual emission releases during normal operations and accidents. Releases and transfers must be reported only if the emissions of a facility are above the activity and pollutant thresholds set out in the E-PRTR regulation. It covers 65 economic activities since 2007, whereby the activities considered in the scope of this study are listed in Table 2.

Table 2 Subsectors considered in this assessment according to E-PRTR directive [19,20]

PRTR activity database nomenclature	**Production capacity threshold (t per day)**	**CO_2 releases to air threshold (kt/year)**	**Nomenclature used in this study**
3. c.(i) Cement clinker in rotary kilns	500	100	CEMENT
3. c.(ii) Lime in rotary kilns	50	100	LIME
3. c.(iii) Cement clinker or lime in other furnaces	50	100	CEMENT / LIME
3. (e) Installations for the manufacture of glass, including glass fibre	20	100	GLASS

Further, the employed subsector and country-specific parameters required in Equation 1 are given in Table 3. The range of heat recovery fractions (R_F) reflects the fact that not all the heat in an exhaust stream might be recovered. Typically half of the sensible heat in an exhaust stream might be technically recoverable. The combination of the emissions (C_T), the combustion emission fraction (F_C) and the overall emission factor (K_T) represents the total site fuel consumption. The efficiency conversion from fuel to heat (η_C) reflects the fact that not all of the primary fuel use is converted to heat, and the load factor (L_F) relates the working time per year (average capacity utilization).

Table 3 Specific parameters per subsector used in the assessment

Variable	**Description**	**Value**		**Source**
R_F	Heat recovery fraction	Case 1: 10% (low) Case 2: 20 % (high)		[14,21]
F_C	Combustion emission fraction in the subsector	Cement	0.38	[1,2,21-24]
		Cement/Lime	0.41	
		Lime	0.44	
		Glass	0.63	
η_C	Efficiency conversion from fuel to heat in the subsector	Cement	0.90	[14,21]
		Cement/Lime	0.90	
		Lime	0.90	
		Glass	0.86	
L_F	Load factor in the subsector	Cement	0.95	[14,21]
		Cement/Lime	0.95	
		Lime	0.95	
		Glass	0.80	
K_T	Overall emission factor in the subsector per each country	(see Appendix)		[2,22,25]

All these parameters (Table 3) allow modelling the industrial sectors selected in sufficient detail to enable a good degree of confidence about the results (Fig 1). The total CO_2 emissions, number of sites, and emission factor are calculated and shown in the Appendix per country and per year.

The three main strengths of this assessment are identified as the temporal evolution of the potentials, the large region of study considered, and the approach. Firstly, this study considers a six-year period, whereas only one-year or average values are available in the literature. This allows a temporal trend to be indicated and assess related economic factors as well as technological changes. Secondly, 28 countries are considered and the regional parameters of the study are adapted specifically to each year and to each country while most of the literature available focuses on smaller areas. Finally, real site-level data is used in this bottom-up approach assessment which contributes to the accuracy of the results, and the exact locations of the heat sources allows the deployment of the technologies and strategies to reuse this heat.

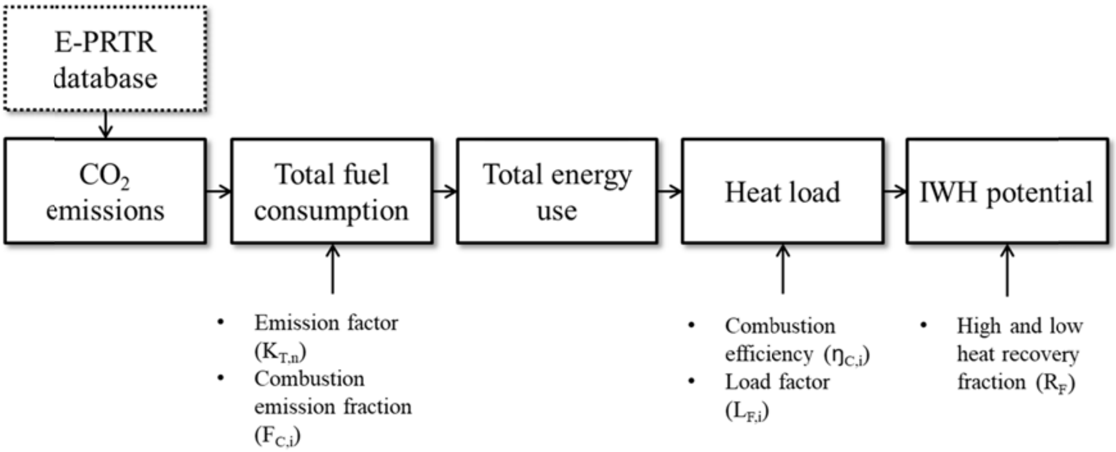

Fig. 1 Diagram of the methodology applied to the industrial sites, based on [14,21]

3 Results

3.1 Europe

Table 4 shows the average CO_2 emissions distribution in the non-metallic mineral industrial sector in the period 2007 – 2012 [16], where it can be seen that the most influencing subsector regarding CO_2 emissions is cement.

Table 4 Average CO_2 emissions distribution (in %) in the non-metallic mineral industrial sector 2007-2012, nomenclature according E-PRTR [19]

	CO_2 emissions of the non-metallic mineral sector (%)			
	Cement	**Cement/Lime**	**Glass**	**Lime**
Europe	63.4	26.9	4.1	6.1
Germany	58.0	27.7	4.1	10.1
Italy	92.6	3.3	2.6	1.4
France	78.8	0.0	8.8	12.4
Spain	91.1	3.4	2.1	3.5

Table 5 lists the number of active sites (the ones which exceed Table 2 thresholds) per year and their total emissions from 2007 to 2012. Both parameters show a decrease over the whole period, whereby the decrease over the period 2007-2009 is more accentuated than the one in the period 2010-2012.

Fig 2 summarizes the high IWH recovery potential per subsector depending on the year considered. As expected, the cement subsector is, by far, the most strongly influencing in the non-metallic mineral industry (63% of the total sector emissions), and glass is the least strongly influencing (4% of the total sector emissions). In this figure also the production (in M€) [24] and the carbon intensity (in tCO_2/€) of the non-metallic mineral sector is shown. The trend that those two parameters show might indicate both the effect of an economic crisis (reduction of the production) as well as an improvement of the efficiency measures (reduction of the emissions per unit of production).

Table 5 Number of sites with emissions per year and per subsector, EU27 and Norway

	Emissions ($MtCO_2$) [16]	Number of active sites (units) [16]	Average emissions per site ($MtCO_2$)	Average IWH potential per site (PJ)
2007	197.8	376	0.53	0.47
2008	187.9	378	0.50	0.44
2009	145.9	338	0.43	0.37
2010	150.8	351	0.43	0.37
2011	147.3	343	0.43	0.37
2012	137.2	328	0.42	0.36

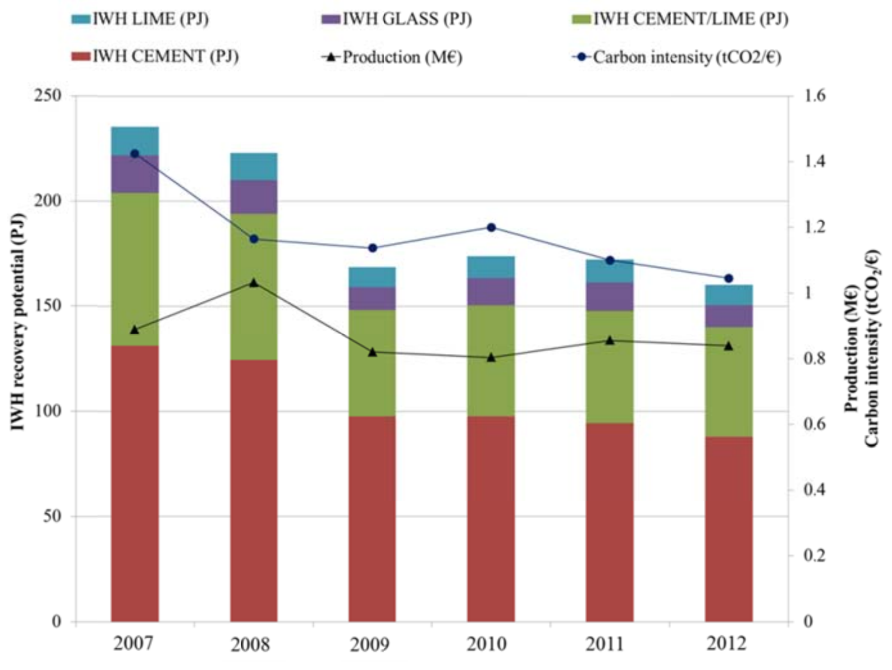

Fig. 2 High IWH recovery potential per year and per subsector, EU27 and Norway

From a more general point of view, the IWH recovery potentials per year from the non-metallic mineral sector are listed for the rest of the European countries (EU27 and Norway) in Table 6. Since two exhaust fractions have been considered (section 2), a range of IWH recovery potentials is obtained. Germany, France, Spain and Italy are shown in the following section in more detail.

Table 6 IWH recovery potential per year for the European countries (EU27 + Norway) considered in this study except Germany, France, Spain and Italy, in PJ

IWH potential (PJ)	2007	2008	2009	2010	2011	2012
Austria (AT)	2.1-4.1	2.2-4.3	1.8-3.6	1.6-3.3	1.4-2.9	1.2-2.3
Belgium (BE)	5.5-11.0	5.3-10.6	4.1-8.3	3.8-7.7	3.9-7.8	4.2-8.4
Bulgaria (BG)	1.9-3.8	1.9-3.8	1.0-2.0	0.5-1.0	1.1-2.3	4.2-8.4
Cyprus (CY)	0.6-1.2	0.6-1.3	0.5-1.1	0.5-0.9	0.4-0.7	0.4-0.7
Czech Republic (CZ)	2.1-4.3	2.6-5.3	1.8-3.6	2.0-3.9	2.0-4.0	1.9-3.7
Denmark (DK)	1.4-2.7	1.1-2.2	0.8-1.5	0.7-1.4	0.8-1.6	0.9-1.7
Estonia (EE)	0.5-1	0.5-1.0	0.2-0.5	0.3-0.6	0.4-0.7	0.4-0.7
Finland (FI)	0.9-1.8	0.9-1.8	0.6-1.2	0.7-1.5	0.6-1.3	0.7-1.3
Greece (EL)	5.3-10.6	5.2-10.4	4.0-7.9	3.2-6.4	1.8-3.6	2.1-4.1
Hungary (HU)	1.5-2.9	1.4-2.9	0.9-1.8	0.8-1.6	0.6-1.2	0.7-1.3
Ireland (IE)	1.9-3.8	1.6-3.3	1.1-2.2	0.9-1.9	0.8-1.7	0.9-1.8
Latvia (LV)	0.2-0.4	0.2-0.4	0.2-0.4	0.4-0.7	0	0.4-0.9
Luxemburg (LU)	0.5-0.9	0.4-0.9	0.4-0.9	0.4-0.8	0.4-0.9	0.4-0.9
Netherlands (NL)	0.9-1.8	0.8-1.7	0.8-1.6	0.7-1.3	0.8-1.6	0.4-0.9
Norway	0.7-1.5	0.7-1.4	0.7-1.4	0.5-1.0	0.6-1.2	0.6-1.2
Poland (PL)	6.4-12.8	6.7-13.5	5.9-11.7	6.4-12.7	7.6-15.2	6.6-13.1
Portugal (PT)	3.5-6.9	3.4-6.7	3.5-6.9	2.9-5.9	2.4-4.8	2.3-4.6
Romania (RO)	5.0-10.0	4.9-9.8	3.4-6.8	3.1-6.2	3.3-6.6	3.4-6.7
Slovakia (SK)	2.3-4.5	2.4-4.8	2.2-4.5	2.2-4.4	2.3-4.6	2.1-4.3
Slovenia (SI)	0.5-1.0	0.5-1.0	0.5-0.9	0.3-0.6	0.2-0.4	0.2-0.4
Sweden (SE)	1.7-3.4	1.9-3.7	1.5-2.9	1.7-3.3	1.7-3.5	1.9-3.8
UK (UK)	9.5-19.1	8.2-16.3	4.2-8.4	4.8-9.7	4.5-9.1	4.6-9.2
Total EU-27	116.5 – 232.7	109.5 - 219.0	82.9 – 165.7	85.8 – 171.6	84.7 – 169.1	78.7 – 157.4

To be able to reuse industrial waste heat, it is essential to know the location of the emitting sources and from which processes they are coming from. Therefore, Fig 3 shows the location of the 403 facilities analysed in this article. The size of the circles represents the average IWH recovery potential in PJ in the period 2007-2012. In the plot, the predominance of the cement subsector as well as the concentration of most of the sites in Germany, Italy, France and Spain can be seen, as well as the predominance of the cement/lime activities in Poland and Greece. The average IWH recovery potential in Europe (EU27 and Norway) in the period 2007-2012 is 0.33 PJ/a per site and 133.82 PJ/a in the non-metallic minerals sector.

Regarding the location of the sites, in the EU cement is mainly delivered by road. The maximum distance over which cement can economically be transported by road is generally said to be between 200 and 300 km [2]. However, where cement plants are located near water (sea, inland waterways), transport over longer distances is more common. Furthermore, having easy access to rail networks facilitates transport over longer distances in certain circumstances [2]. The factors help to explain the distribution of cement plants across the EU.

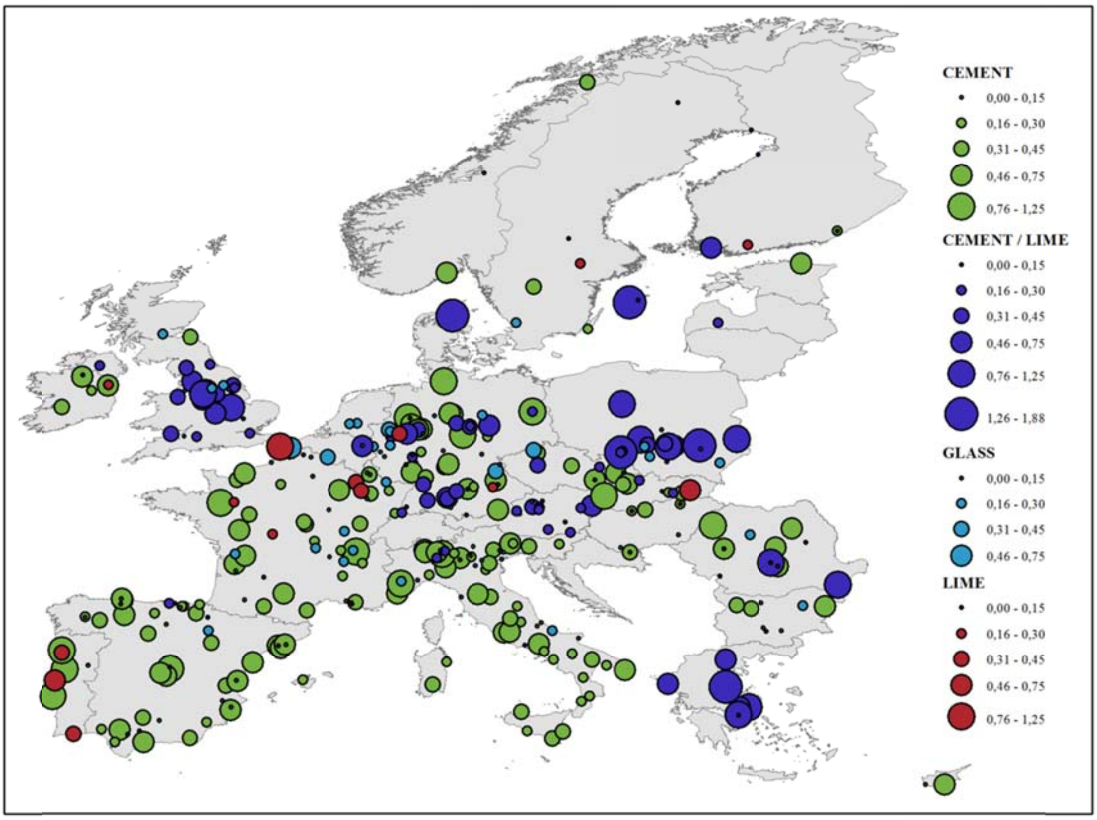

Fig. 3 Location and average IWH recovery potential in the period 2007-2012 of the sites considered, in PJ

3.2 Highest IWH recovery potential countries

In this section, the focus is on the results obtained for Europe and for the highest IWH recovery potential countries, which in descending order are: Germany, Spain, France and Italy.

In general, a decreasing trend can be observed (accentuated in the 2008-2009 period), in the IWH recovery potential through the considered timeline. This profile may be due mainly to the economic crisis and also because of the use of more efficient kiln processes [2]. Therefore, IWH is plotted together with CO_2 emissions from the sector.

Fig 4 to 7 show the time evolution from 2007 to 2012 of both the CO_2 emissions and the IWH recovery potential found for the different subsectors from Germany, Italy, France and Spain respectively. Their yearly average IWH potentials (considering both the low and high case) are 23, 19, 17 and 16 PJ, respectively.

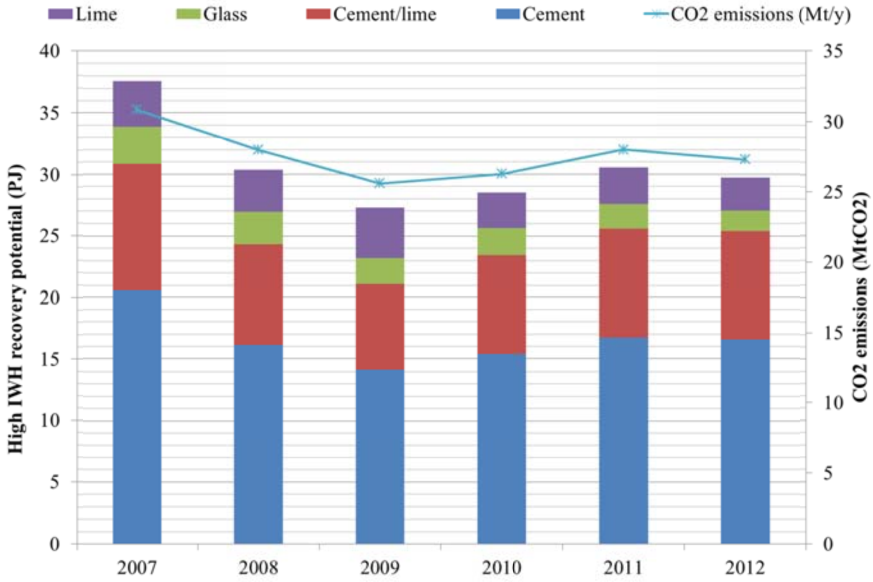

Fig. 4 High IWH recovery potential and CO_2 emissions in the period 2007-2012 in Germany

Germany and France show the lowest value in 2009 and a slight recuperation until 2012 while Italy and Spain show a clear decreasing trend through this whole period. The total potential ranges during the period 2007-2012, taking into account maximum and minimum values reached by the high IWH recovery potential here calculated, are 27.0 % in Germany, 37.3 % in Italy, 46.0 % in France and 50.0 % in Spain. As expected, the influence of the cement subsector can also be seen in the IWH recovery potentials.

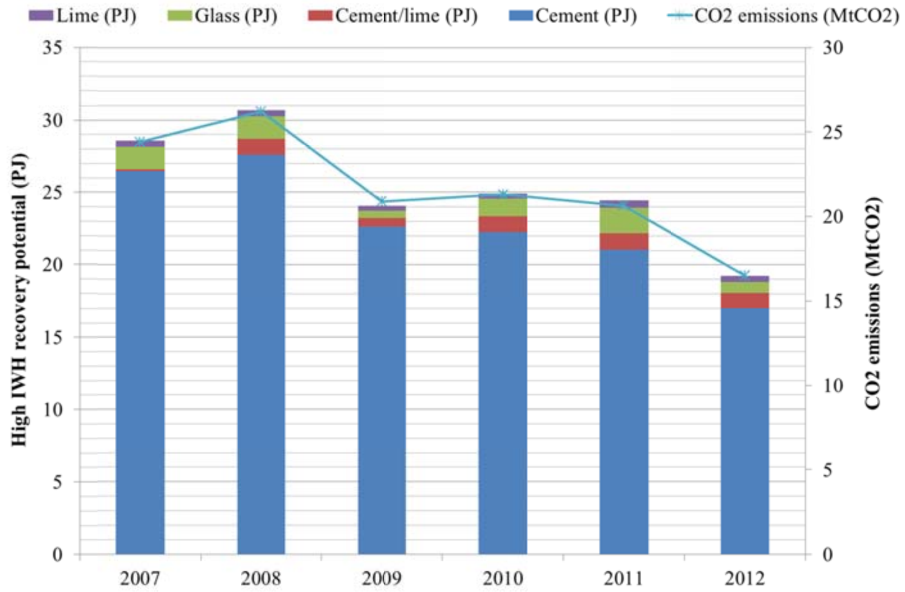

Fig. 5 High IWH recovery potential and CO_2 emissions in the period 2007-2012 in Italy

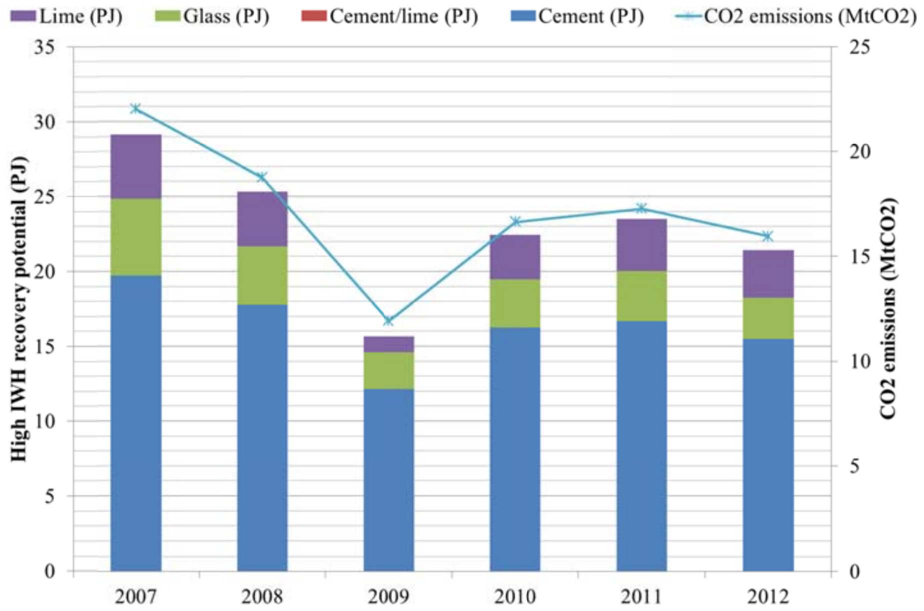

Fig. 6 High IWH recovery potential and CO_2 emissions in the period 2007-2012 in France

The average IWH recovery potential (taking into account high and low values) per site in the period 2007-2012 is 0.35 PJ/a for Germany, 0.28 PJ/a for Italy, 0.31 PJ/a for France and 0.31 PJ/a for Spain.

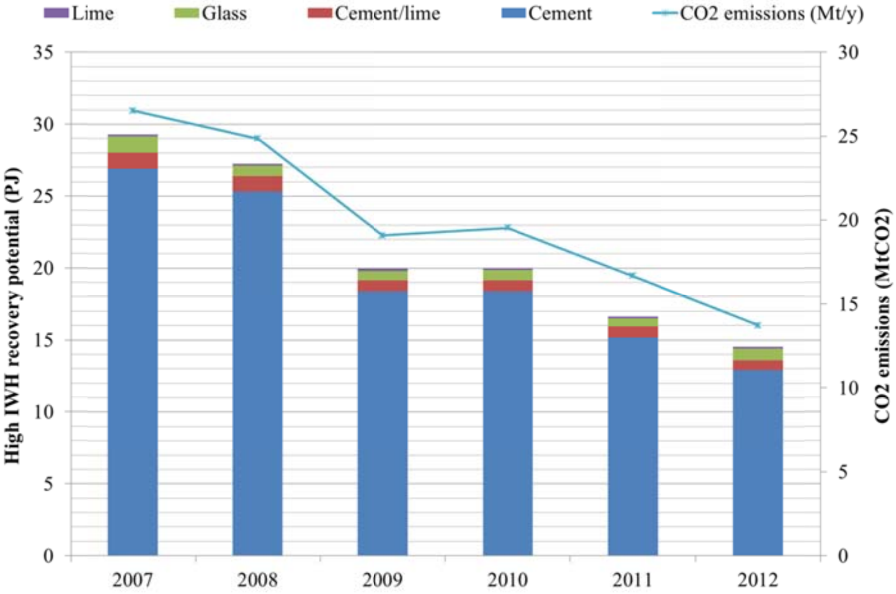

Fig. 7 High IWH recovery potential and CO$_2$ emissions in the period 2007-2012 in Spain

4 Discussion

In this section, the results are discussed, a sensitivity analysis is carried out, the results are compared to those of existing studies, and ~~the~~ finally the methodology is discussed with some suggestions for further work.

At a European scale, IWH results show a clear decreasing trend which was expected to be because of the economic crisis and/or the use of more efficient processes in the sector. In fact, the effect of the economic crisis on the one hand can be seen clearly by comparing the years 2008 and 2009. On the other hand, the effect of more efficient processes can be partially observed if the carbon intensity is introduced which decreases constantly from 2007 on. However, the strong decrease of the carbon intensity between 2007 and 2009 can also be due to structural changes, such as a shortfall in capacity resulting from retired and aged plants [27].

A sensitivity analysis is carried out in order to evaluate the influence of the different input parameters of this approach, following Eq. 1. As shown in Fig 8, all the input parameters exhibit one of two different behaviours: directly and linear proportional or indirectly proportional. Carbon emissions, heat recovery fraction, combustion emission fraction and efficiency conversion from fuel to heat are directly proportional increasing parameters. On the contrary, the emissions factor of the sector and the load factor are indirectly proportional parameters.

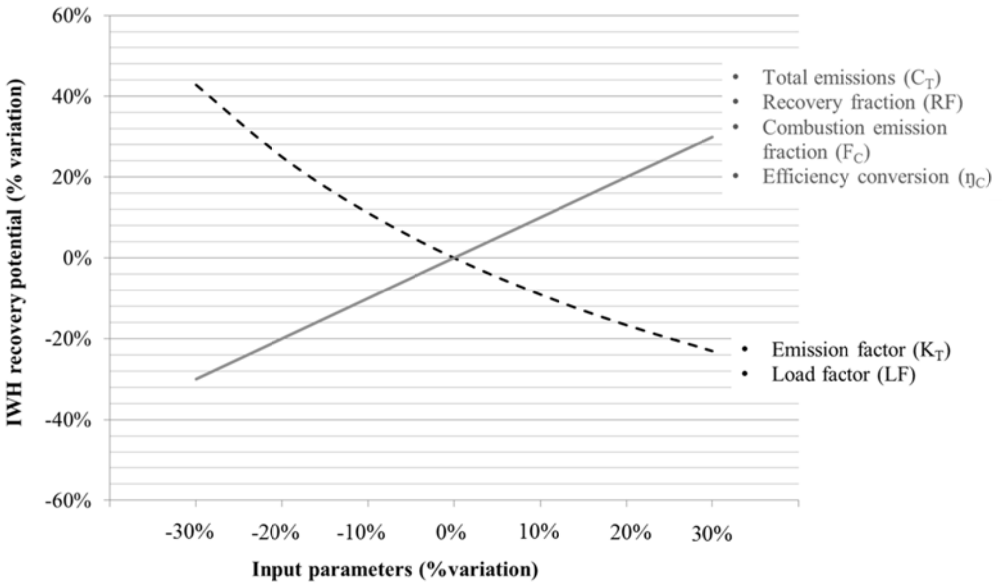

Fig. 8 Sensitivity analysis of relevant parameters employed in this study, low scenario considered.

In order to assess the feasibility of the results obtained in this evaluation, a comparison with existing studies is carried out. However, as there is a lack of literature on this topic, only the cases of Spain, UK and Europe are comparable. In the case of Spain, a study was performed by Miró et al. [13] in which the Spanish IWH recovery potential was assessed by transferring key figures originally designed for another country (Sweden and Germany). They based the calculations on the fuel consumption per sector and show the results for the years 2009 and 2013. Focusing on the Spanish non-metallic mineral sector (Fig 9), both assessments agree in the scale of potentials and state a decline in the IWH recovery potential between 2009 and 2013 (which has already been referred to the economic crisis).

In the case of the UK, the potential found for the non-metallic mineral sector was assessed by McKenna et al. [14] for the period 2000-2003. The scope of the analysis performed by McKenna et al. [14] is wider in terms of the assessed sectors, however, it is possible to select within the results the corresponding to cement, lime, and glass subsectors to compare. For these subsectors the average potential obtained for 2000-2003 was 7.02-14.04 PJ. In this study the IWH recovery potential for UK in 2007 (the closest year) is found to be in the range of 9.5-19.1 PJ and therefore somewhat higher.

Moreover, a study published by Persson et al. [16] assessed the IWH recovery potential for energy and industrial sectors in European countries in 2010. In the case of the non-metallic mineral sector, a potential of 592.4 PJ was found for Europe (this study: 85.8-171.6 PJ), 78 PJ for Spain (this study: 9.5-18.5 PJ) and 38.9 PJ for the UK (this study: 4.8-9.7 PJ). These values represent 3 to 5 times the ones presented in this study. Persson et al. [16] also based the calculations on annual CO_2 emissions per site; however they report maximal potentials by applying an unrealistic 25% recovery percentage in the non-metallic mineral industry. Therefore higher values than the ones presented in this article were expected.

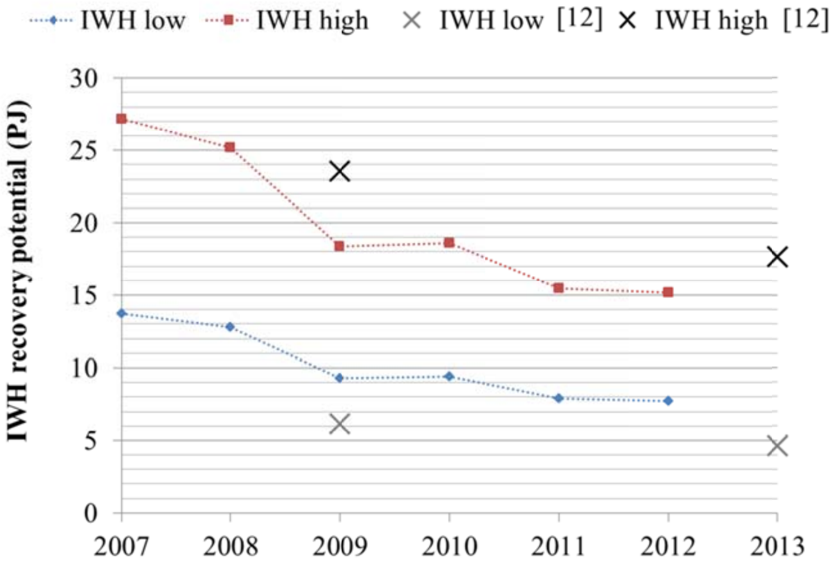

Fig. 9 Comparison of the IWH recovery potential in the Spanish non-metallic mineral industry found in this study and in Miró et al. [13]

Weaknesses due to the assumptions applied in the approach of this article to assess the IWH potential lead to uncertainties that should be mentioned:

- Some of the parameters used in this assessment refer to the whole non-metallic mineral sector and are not specific for the subsectors considered (cement, lime and glass) as the specific data is not available.
- The E-PRTR database only collects site emissions above certain CO_2 and capacity thresholds (Table 2) which means that smaller industrial sites are not considered. It is therefore expected that the results of this assessment represent an underestimation of the potential in this sector, as many industrial sites are not considered which do not exceed the capacity or emissions threshold.
- Emission values reported in this database can be measured, calculated or estimated [19]. These last two characteristics of the database can add more uncertainty to the reported values.

Moreover, it should be mentioned in this context, that the potential determined here is a technical potential (based on current technologies whilst ignoring spatial and temporal constraints). Taking into account investment decisions, regulatory frameworks and the existing infrastructure such as district heating networks, the economic and the feasible potentials are expected to be somewhat below this. Finally, it should also be mentioned that already used IWH is not subtracted from the assessed potential, as this data is not available. In fact, some of the companies in the non-metallic mineral sector have already developed on-site heat recovery technologies. According to the Best Available Technologies documents related to this sector [2,22], the currently available and the proposed heat recovery applications for these subsectors are those shown in Table 7. On one hand, regarding the available applications, on-site recovery like drying processes or recuperative furnaces are mentioned. On the other hand, proposed applications include district heating, power generation or lime drying.

To achieve a widespread use of IWH, further work is required in mainly three areas: the methodologies used to assess the potential, finding ways to use this potential and assessing whether it is economically feasible to do so. The lack of methodologies or key figures to assess the potential of other regions or industrial sectors (specially the energy intensive sectors) has already been stated by other authors. The use of websites in which the excess heat per site is published (like in Bayern [28], Saxony [29] or Netherlands [30]) should be encouraged. In addition, further work should develop methods and tools to analyse the IWH potential in non-homogenous sectors, in which processes and technologies differ greatly between sites (e.g. Chemicals, Food and Drink). Regarding the possible use of this excess heat, the available technologies and possibilities are already published, but real facilities using this heat are practically non-existent or they do not publish their characteristics. More research is required in order to link up the sources of IWH identified in this article with nearby demand sinks. This research should also consider the temperature and temporal profile of heat demand in industry, in order to effectively match the quantity (energy) and quality (exergy) of this resource with an appropriate sink. Finally, an exhaustive economic analysis should be performed and adapted to each case, taking into account that power and energy prices per region are different, in order to analyse the feasibility of its use.

Table 7 Currently available and proposed heat recovery technologies [2,22]

Sector	**Currently available recovery applications**	**Proposed recovery applications**
Cement	Heat from cement clinker kiln used for the drying and dry grinding processes (raw material drying and grinding/milling, slag drying, sand drying, fuel drying and grinding)	Heat from clinker coolers or kiln off-gases could be used for district heating or to generate power by means of a ORC
Lime	n.r.	• Installation of heat exchangers for long rotary kilns to recover surplus heat from flue gases or to permit the use of a wider range of fuels • Use of surplus heat from rotary kilns to dry limestone for other processes such as limestone milling
Glass	Regenerative and recuperative furnaces	n.r.

*n.r. not-reported

5 Conclusions

Currently there is a lack of accurate assessments of the IWH recovery potential in the literature, which are required for the development of IWH as a new energy source. The use of this excess heat can reduce industrial energy demand and increase energy efficiency. Due to the homogeneity of the sector, this article quantifies and discusses the IWH recovery potential from the non-metallic mineral industry for all of Europe, which is of special interest because of its high energy intensity.

A bottom-up approach based on the site emissions reported in the E-PRTR database is applied during the period 2007-2012 and focusing on the European cement, lime and glass subsectors. The influence of economic factors highlights the importance of analysing more than one year when assessing these types of potentials, as most the other studies only published a one-year value or an average over several years. This approach is based on the CO_2 emissions of the 403 industrial sites from the non-metallic mineral sector considered in this study. Besides the carbon dioxide emissions, other country- and subsector-specific input parameters used in the analysis are: the subsector emission factor and fuel split; the combustion, the process emission fraction, the combustion efficiency, the load factor, and the exhaust fraction.

The results show that cement is the subsector with highest potential in Europe and the identified countries with higher potential in the period 2007-2012 are Germany (average potential in this period 23.01 PJ), Italy (average potential in this period 18.99 PJ), France (average potential in this period 17.17 PJ), and Spain (average potential in this period 15.97 PJ). Moreover, average results from the period 2007-2012 in Europe show a potential per site of 0.33 PJ/a and a potential in the sector of 133.82 PJ/a. The results obtained are validated by comparison with former assessments for the non-metallic mineral industrial sector, which are roughly in agreement for specific countries. For Europe as a whole, the IWH potential is found to be about one-fifth of the value in the only existing study, but this can be explained by the use of a very high heat recovery fraction of 25% in the latter case.

The main strengths of this analysis are the possibility to identify temporal changes of the potentials as a period of 6 years is analysed, the large region considered (28 countries) and the accurate bottom-up approach. On the other hand, the weaknesses of the approach are mainly derived from the use of the E-PRTR database as well as some simplifying assumptions involved in the method. In this database, not all facilities are included if they do not exceed the capacity or emission thresholds. Therefore, the technical potential assessed in this article is expected to be lower than the actual potential. The employed method also does not account for the temperature and temporal profile of the IWH potential, both of which are important factors for linking this source with a suitable sink (i.e. demand). Other weaknesses are due to the use of parameters which refer to the whole non-metallic mineral sector and not specifically for the three subsectors considered in this study.

Further work is required to achieve a widespread use of IWH. Efforts should be mainly focused in the improvement of the methodologies and approaches to assess IWH recovery potential, e.g. to consider temperatures and temporal profiles of IWH, including for other non-homogenous sectors, to link the potential (sources) and its use in form of cold, heat or power (sinks) and to analyse the economic feasibility of its use.

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Appendix

Table 8 Non-metallic mineral subsector CO2 emissions per country and year, based on E-PRTR [19] database

Total CO_2 emissions (tCO_2)	2007	2008	2009	2010	2011	2012
Austria (AT)	3,648,000	4,018,000	3,509,000	3,045,500	2,698,000	2,104,000
Belgium (BE)	9,276,000	9,117,000	7,561,000	7,866,000	6,742,000	7,562,000
Bulgaria (BG)	3,833,000	3,643,000	1,815,000	971,000	1,818,000	1,581,000
Cyprus (CY)	1,470,000	1,500,000	1,280,000	1,092,000	841,000	809,000
Czech Republic (CZ)	3,271,000	4,078,000	3,006,000	3,152,000	3,360,000	3,073,000
Denmark (DK)	2,760,000	2,240,000	1,510,000	1,420,000	1,680,000	1,660,000
Estonia (EE)	1,170,000	1,190,000	521,000	624,000	827,000	764,000
Finland (FI)	1,403,000	1,400,000	897,000	1,100,000	940,000	949,000
France (FR)	22,017,000	18,756,000	11,910,000	16,640,000	17,272,000	15,958,000
Germany (DE)	30,840,000	27,984,000	23,954,000	26,260,000	27,997,000	27,289,000
Greece (EL)	10,590,000	9,919,000	7,446,000	6,425,000	3,635,000	4,378,000
Hungary (HU)	2,626,000	2,665,000	1,738,000	1,450,000	1,223,000	1,347,000
Ireland (IE)	4,027,000	3,590,000	2,271,000	1,956,000	1,758,000	2,060,000
Italy (IT)	24,409,000	26,208,000	20,892,000	21,306,000	20,651,000	16,491,000
Latvia (LV)	363,000	358,000	328,000	670,000	0	835,000
Luxemburg (LU)	907,000	873,000	847,000	869,000	876,000	824,000
Netherlands (NL)	930,000	879,000	824,000	753,000	835,000	553,000
Norway	1,420,000	1,352,000	1,356,000	904,000	1,209,000	1,192,000
Poland (PL)	12,142,000	12,223,000	10,602,000	11,731,000	14,013,000	12,070,000
Portugal (PT)	6,970,000	6,752,000	5,586,000	5,883,000	4,877,000	4,562,000
Romania (RO)	7,388,000	7,220,000	5,085,000	4,593,000	4,865,000	4,994,000
Slovakia (SK)	3,155,000	3,328,000	3,119,000	3,040,000	3,230,000	2,975,000
Slovenia (SI)	898,000	979,000	702,000	581,000	411,000	477,000
Spain (ES)	26,527,000	24,860,000	19,080,000	19,553,000	16,683,000	13,727,000
Sweden (SE)	2,780,000	3,052,000	2,417,000	2,736,000	2,868,000	3,139,000
UK (UK)	12,971,000	10,908,000	5,704,000	6,349,000	6,106,000	6,275,000

Table 9 Non-metallic mineral subsector number of sites, based on E-PRTR [19] database

Number of sites (units)	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Austria (AT)	10	10	11	10	9	7
Belgium (BE)	13	13	13	13	12	12
Bulgaria (BG)	7	7	5	3	7	4
Cyprus (CY)	2	2	2	2	1	1
Czech Republic (CZ)	8	9	8	9	9	9
Denmark (DK)	1	1	1	1	1	1
Estonia (EE)	1	1	1	1	1	1
Finland (FI)	5	5	4	5	4	4
France (FR)	54	50	40	49	50	48
Germany (DE)	65	62	57	58	56	54
Greece (EL)	9	8	8	7	6	6
Hungary (HU)	7	8	5	6	6	6
Ireland (IE)	5	5	5	5	5	5
Italy (IT)	52	62	56	58	61	55
Latvia (LV)	1	1	2	1	0	1
Luxemburg (LU)	3	3	3	3	3	3
Netherlands (NL)	4	3	3	2	3	1
Norway	2	2	2	3	2	2
Poland (PL)	18	18	18	18	19	18
Portugal (PT)	8	8	8	8	7	8
Romania (RO)	13	11	9	9	8	8
Slovakia (SK)	7	8	9	9	8	9
Slovenia (SI)	2	2	2	2	1	1
Spain (ES)	47	46	42	43	42	39
Sweden (SE)	7	8	6	6	6	7
UK (UK)	25	25	18	20	16	17

Table 10 Emission factor sector of the non-metallic mineral sector, based on EUROSTAT [24] database and [25]

Emission factor sector (tCO_2/TJ)	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Austria (AT)	68.72	72.33	74.86	71.51	72.90	70.00
Belgium (BE)	67.59	69.45	72.84	82.87	71.19	62.80
Bulgaria (BG)	74.88	72.23	70.01	73.28	66.98	67.39
Cyprus (CY)	85.58	85.49	86.45	86.31	83.84	83.75
Czech Republic (CZ)	60.76	61.21	64.71	63.85	64.82	65.01
Denmark (DK)	75.03	76.52	74.26	74.11	76.10	76.20
Estonia (EE)	84.64	85.37	80.34	76.75	84.43	79.34
Finland (FI)	59.66	58.59	56.83	57.71	57.04	55.94
France (FR)	60.69	58.73	59.79	58.41	57.95	58.37
Germany (DE)	63.55	71.75	73.02	71.39	70.53	70.30
Greece (EL)	77.55	74.36	73.15	77.67	79.61	83.11
Hungary (HU)	69.12	67.31	67.98	68.25	67.47	68.74
Ireland (IE)	77.79	79.19	75.34	77.44	77.83	83.61
Italy (IT)	63.33	65.43	62.97	63.30	65.66	66.43
Latvia (LV)	73.17	72.72	68.11	95.87	114.18	111.65
Luxemburg (LU)	86.93	90.61	85.46	93.72	91.62	83.89
Netherlands (NL)	50.24	49.38	48.26	49.24	49.56	49.63
Norway	70.39	68.43	74.40	72.41	71.81	71.15
Poland (PL)	76.14	76.04	77.83	82.13	84.70	85.12
Portugal (PT)	76.69	76.59	78.58	79.58	81.73	88.03
Romania (RO)	55.84	60.88	59.87	52.59	57.11	67.83
Slovakia (SK)	51.95	54.60	58.48	57.37	57.40	59.82
Slovenia (SI)	67.22	69.77	78.81	74.69	78.56	83.43
Spain (ES)	65.22	65.52	69.07	70.31	71.92	67.92
Sweden (SE)	65.23	64.32	63.97	63.70	64.91	64.77
UK (UK)	53.93	53.92	54.50	54.04	53.82	54.80