

# Carbon and ecological footprints as tools for evaluating the environmental impact of coal mine ventilation air

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1 **ABSTRACT**

2 Coal mines ventilation gases are an important source of methane emissions. Common  
3 ventilation systems are designed to ensure safe working conditions in the shafts, leading to  
4 huge ventilation gas flow rates. Traditionally, low attention has been paid to such emissions  
5 because of their low methane concentration. However, it is necessary to take into account  
6 that although the concentration of methane is very low (typically < 1 %), the volume of air  
7 that ventilation systems move is large, and therefore these emissions constitute the largest  
8 source of greenhouse gases from underground coal mines.

9 This work proposes the use of ecological and carbon footprints approaches as a tool for  
10 determining the relative importance of these emissions in comparison to the other direct  
11 and indirect environmental impacts from the coal mining activity. The study has been  
12 performed in the main ventilations shafts of the mining company HUNOSA, located at NW  
13 Spain (bituminous coal). Results indicate that ventilation air methane is a key fraction of  
14 the total emissions of greenhouse gases releases in this activity (60-70 %).

15

16 **Keywords:** coal mining, ventilation air, carbon footprint, ecological footprint, methane

17

## 18 1. INTRODUCTION

19 Although Western Europe's coal industry has been declining since the 1950s, as prices for  
20 imported coal have decreased and local extraction costs have increased, the worldwide  
21 situation is markedly different. In 2007, coal accounted for 27 % of world energy  
22 consumption (International Energy Outlook, 2010), and about 64 % of this coal was  
23 shipped to electricity producers and 33 % to industrial consumers. According to the  
24 IEO2010 Reference case (International Energy Outlook, 2010), the provisions of world coal  
25 consumption will grow an average of 1.1 % per year from 2007 to 2020, and 2.0 % per year  
26 from 2020 to 2035. Therefore, the production of primary energy, in general, and of coal, in  
27 particular, is expected to largely increase in the future. These forecasts contrast with the  
28 more exigent environmental regulations. In United States, coal mining is one of the most  
29 extensively regulated industries. Since the first comprehensive national surface mining law  
30 in the late 1970s, the Surface Mining Control and Reclamation Act (SMCRA), many other  
31 regulations have been developed. In the European Union (EU), a set of environmental  
32 directives -that have had a significant effect on the mining industries of member nations-  
33 have been developed.

34 Although the large environmental impact of coal mining from the point of view of water  
35 and soil pollution is well-accepted, much less attention has been paid to gaseous emissions.  
36 At this point, ventilation emissions (needed in order to ensure safe concentrations of  
37 methane within the shaft) were traditionally considered as non-pollutant emissions.  
38 However, these emissions contain significant amounts of methane (0.1-1%) which is a  
39 powerful greenhouse gas (GHG), with Global Warming Potential (GWP) more than twenty  
40 times higher than the corresponding to CO<sub>2</sub>. Furthermore, emissions from coal mining

41 account for 22 % of emissions from energy sector, which is the second largest contributor  
42 to anthropogenic methane emissions (about 30 %) (Karakurt et al., 2011). Due to this  
43 reason, a comprehensive work is needed on both inventorying and developing alternatives  
44 for these emissions (Su et al., 2005).

45 To the best of our knowledge, systematic studies about the relative weight of these  
46 emissions in comparison to the other direct and indirect impacts of the coal mining activity  
47 have not been reported. In the present work, we use two tools for doing this study, the  
48 ecological footprint (EF) and the carbon footprint (CF). The so-called “carbon footprint”, a  
49 term used by different organisms, such as the British Standards Institution and the  
50 International Organization for Standardization (ISO), is focused on describing the GHG  
51 emissions attributable to providing a specific product or service. The main purpose of  
52 estimating CFs is to provide information for policy-making, for supply chain management,  
53 and to facilitate a shift by retailers and consumers toward low carbon products. By contrast,  
54 EFs is defined as the amount of life-supporting natural capital, expressed in biologically  
55 productive area, which is necessary to meet the resource demand and waste absorption  
56 requirements of a given activity. Therefore, in the calculation of ecological footprint, data  
57 on carbon dioxide emissions are translated into the area, in global hectares, required to  
58 absorb these carbon emissions. But, add to these emissions, other considerations such as the  
59 use of water and land, the emissions of no global warming gases are also considered in the  
60 evaluation of ecological footprint (Monfreda et al., 2004). It is remarkable that nowadays,  
61 there are international standards for measuring and certificating the carbon footprint in  
62 processes and organizations, as GHG Protocol and ISO 14064-1.

63 This work is focused on the calculation of carbon footprint and ecological footprint to the  
64 coal mines situated in Asturias (North of Spain), which belong to the Spanish mining  
65 company (HUNOSA). The final scopes of these calculations were to determine the relative  
66 importance of ventilation mine air emissions on the overall mining activity emissions, as  
67 well as to quantify the effect of the treatment of these emissions on their environmental  
68 performance. The studied mines are representative of the small-sized bituminous coal  
69 mines of Western Europe. Although there are previous studies dealing with the  
70 environmental effect of VAM, this work is, to the best of our knowledge, the first  
71 quantitative study performed (using ecological indicators) for determining the relative  
72 importance of these emissions in the overall environmental impact of coal mining.

73

## 74 **2. DESCRIPTION AND RESULTS OF CARBON FOOTPRINT**

75 The extraction of bituminous coal in Asturian mines is performed in small-sized (if  
76 compared to common US or Asian shafts) underground mines. The production of the shafts  
77 used for this study is summarised in Table 1, whereas the location of the shaft is sketched  
78 in Fig.1. The low capacity of these shafts, the location of the deposits that in most cases  
79 present difficult accesses, as well as the depth of each deposit, determines the selected  
80 method for extraction. Underground mining requires more energy than surface mining due  
81 to larger requirements for hauling, ventilation, and water pumping, among other  
82 considerations. These requirements lead to more important environmental impacts, which  
83 must be also taken into account in the evaluation of CF and EF.

84 Coal mining is associated with significant social and environmental impacts. Depending on  
85 the limits or boundaries of the system under study, the relative importance of various  
86 activities could vary notably. In this work, the study was limited to the extraction of coal.  
87 The boundaries of the system under study are shown in Fig. 2. The major contributions of  
88 this system to carbon footprint include:

89 - Gaseous emissions released in the generation of electricity: most of the operations  
90 carried out in the shaft are developed by electricity-powered machinery. Among  
91 these activities, the drilling, blasting, ventilation, dewatering, are quantitatively  
92 considered as the most relevant. The drilling is the process of making a cylindrical  
93 hole with a tool for exploration, blasting preparation or tunnelling. Blasting is the  
94 removal of mined material by fracturing the rock with explosives, although this  
95 process is also accomplished by electrical devices. Ventilations fans, needed for  
96 ensuring safe conditions within the shaft are another important electrical  
97 consumption. The last electrical consumption to be considered is the needed for  
98 pumping infiltration water out of the shaft (in order to avoid shaft flooding).

99 In order to quantify the environmental impact of the electricity generation, it is  
100 necessary to take into account the relative importance of the different power sources  
101 (thermal energy, hydraulic, nuclear, wind power, etc.), these percentages being  
102 provided by the electrical company supplier. The following distribution of power  
103 sources in the generation of the electricity was considered: thermal energy (43 %),  
104 cogeneration (23 %), nuclear energy (8 %), hydraulic energy (5 %), wind energy  
105 (18 %) and biomass and wastes (3 %). In this way, the power (kWh) of electricity  
106 obtained by each source is obtained. It is considered that the primary energy

107 corresponding to 1 kWh of electricity is typically above 3.6 MJ (Annual Energy  
108 Review 1995, 1996). Actual generation efficiencies, limited by the Second Law of  
109 Thermodynamics and design practicalities, fall short of this. In Table 2, the average  
110 heat input per kWh of net generation, and the thermal conversion efficiency is  
111 summarized for the power sources used. In the generation of electricity, add to CO<sub>2</sub>  
112 emissions, also other GHGs are emitted, although in minor proportion (mainly, CH<sub>4</sub>  
113 and N<sub>2</sub>O). Non-CO<sub>2</sub> emissions are converted into units of carbon dioxide equivalent  
114 (CO<sub>2</sub>-eq) using Global Warming Potentials (GWP) of 21 for CH<sub>4</sub> and 310 for N<sub>2</sub>O.  
115 Emissions factors –that is, the CO<sub>2</sub>-eq generated per GJ of generated electricity- for  
116 the different power sources (IPCC Guidelines for National Greenhouse Gas  
117 Inventories, 2006) are also summarized in Table 2.

118 - Ventilation air: ventilation is a process of entering fresh air in the working area of  
119 the shaft in order to dilute the methane up to safe limits. The extracted air is  
120 removed to the outlet, operation carried out by the fans. This exhaust air contains,  
121 greenhouse gases, mainly CH<sub>4</sub> and CO<sub>2</sub>. Depending on the characteristics of the  
122 shaft, SO<sub>2</sub> or H<sub>2</sub>S could also be in important concentrations, but this is not the case  
123 of HUNOSA shafts. The quantity of gas emitted depends on the coal rank and depth  
124 of seam. High-rank coals, such as anthracite, have the highest GHG emissions,  
125 whereas peat or lignite have the lowest (Karakurt et al., 2011). Asturian coal is  
126 mainly bituminous, thus intermediate emissions will be emitted. The importance of  
127 the depth is related to the pressure over the coal, increasing the concentration of  
128 methane in exhausted gases with the depth. Infrared measurements of both inlet and  
129 outlet gases, determined that the average increase in CO<sub>2</sub> concentration in the six

130 shafts under study is about 0.2 %, whereas CH<sub>4</sub> concentrations vary between 0.05  
131 and 0.4 % (Table 3). Concentrations of NO<sub>x</sub>, as well as sulphur gases as H<sub>2</sub>S or SO<sub>2</sub>  
132 were negligible in all cases. Due to the methane GWP, methane has its most  
133 important effect in global warming.

134 - Soil gases absorption: the mining here described is an underground process, thus,  
135 the surface may be only slightly altered, and in fact, can act as a CO<sub>2</sub>-eq drain.  
136 Table 3 summarized also the surface of each shaft. It is considered that the  
137 assimilation factor depends on the land uses (IPPC, 2001), varying if it is a forest  
138 (3.67 t CO<sub>2</sub>-eq·ha<sup>-1</sup>·year<sup>-1</sup>), cultivable surface (1.98 t CO<sub>2</sub>-eq·ha<sup>-1</sup>·year<sup>-1</sup>), pasture  
139 (0.84 t CO<sub>2</sub>-eq·ha<sup>-1</sup>·year<sup>-1</sup>), built-up land (1.98 t CO<sub>2</sub>-eq·ha<sup>-1</sup>·year<sup>-1</sup>), sea (0.24 t  
140 CO<sub>2</sub>-eq·ha<sup>-1</sup>·year<sup>-1</sup>) or continental water (0.24 t CO<sub>2</sub>-eq·ha<sup>-1</sup>·year<sup>-1</sup>). In this work, it  
141 was considered an emissions-to-land (assimilation) factor of 3.67 t CO<sub>2</sub>-eq·ha<sup>-1</sup>·  
142 year<sup>-1</sup> (IPPC, 2001).

143 Fig. 3 shows the t<sub>CO2</sub>-eq emitted by ton of extracted coal in each shaft, existing differences  
144 until 0.97 t<sub>CO2</sub>-eq/t coal among them. It is remarkable that in Fig. 3 only two contributions  
145 (generation of electricity and ventilation gases) appear, whereas no mention is made to soil  
146 absorption. This is due to the drain contribution of the soil, that is, instead of emitting CO<sub>2</sub>,  
147 the soil traps CO<sub>2</sub>-eq, with values of t<sub>CO2</sub>-eq retained nearly negligible (about 20 t<sub>CO2</sub>-  
148 eq/year·shaft) in comparison to the emissions of the other two contributions. If the analysis  
149 is made based on the specific contributions to carbon footprint here enounced, it is  
150 observed a notorious relevance of ventilation gases to the total footprint (77-94 %).  
151 Likewise, a deeper insight in the contribution to carbon footprint of ventilation emissions  
152 reveals that those shafts with the highest carbon footprint are those with both the highest



153 concentration of methane emissions (Sotón and María Luisa) and highest flow rate of  
154 ventilation gases (Candín). The reason is the high effect on the global warming of CH<sub>4</sub> (21  
155 times the CO<sub>2</sub>). As it is showed in Table 3, there are three shafts with the highest methane  
156 concentration (0.4 %): Maria Luisa, San Nicolás and Sotón. However, the flow rate of San  
157 Nicolás shaft is considerable reduced in comparison with the others. On the other hand,  
158 although Candín exhibits lower CH<sub>4</sub> concentration, the flow rate is considerably higher  
159 than the other shafts. At this point it is convenient to consider that the low explosive limit  
160 of methane is 5 % at ambient temperature, and considering a wide safety factor, the  
161 flowrate of each shaft is fitted in order be always below 1 % (or even lower).

162

### 163 **3. DESCRIPTION AND RESULTS OF ECOLOGICAL FOOTPRINT**

164 The Ecological Footprint measures the amount of surface required to produce all the  
165 resources that consume an activity, considering also the absorption of residual materials  
166 (wastes, emissions, etc.) it generates. In the calculation of the ecological footprint of the  
167 coal mining, add to the contributions previously described for the carbon footprint which  
168 contributes to the ecological footprint by the CO<sub>2</sub>-eq emissions –that is, global warming  
169 gases-, other factors that have also different environmental impacts should be considered:

- 170 - No global warming gases generated in the electricity production (non GHG  
171 emissions): the machinery used in the mining activity works by electricity, whose  
172 production, add to the global warming gases previously mentioned, could also  
173 generate other compounds that can affect negatively the environment. In fact, there  
174 is a notorious contribution to the ecological footprint by the SO<sub>2</sub> generated in the

175 electric power production. The SO<sub>2</sub> contributes to acidification, thus its effect on the  
176 ecological footprint can be taken into account considering the area necessary to  
177 absorb the SO<sub>2</sub> generated. About 70 percent of the total area in Europe has an  
178 assimilation capacity of less than  $20 \cdot 10^{-3} \text{ H}^+\text{eq} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$ ; the rest of the area has a  
179 critical load ranging from 20 to  $50 \cdot 10^{-3} \text{ H}^+\text{eq} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$  (Holmberg et al., 1999).  
180 Considering in this work an assimilation factor of  $20 \cdot 10^{-3} \text{ H}^+\text{eq} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$  (the worst  
181 and most conservative scenario), and converting  $t_{\text{SO}_2}$  in H<sup>+</sup>eq, the area needed to  
182 absorb a ton SO<sub>2</sub> is 155 ha.

183 - Water consumption: in order to take into account the water used in the coal mining  
184 extraction, the water used in a process should be defined. In this way, two  
185 components of the water can be distinguished (Allan, 1997): green water, referred to  
186 the volume of rainwater consumed during the process; or, blue water, water  
187 withdrawn from rivers, lakes, or underground used in the extraction process. In the  
188 case of HUNOSA shafts, no rivers, lakes or underground waters are affected in any  
189 of them, thus the blue water has no application in our case. On the other hand, as it  
190 was previously mentioned, important amounts of water are extracted from the shafts  
191 in the dewatering operation, mainly due to infiltrations from the surface. Thus, we  
192 can consider that the water extracted during the process corresponds to green water.  
193 For the calculation of the contribution of this green water to the ecological footprint,  
194 it was used the average rain in Asturias corresponding to 2009,  $5790 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$   
195 (Instituto Nacional de Meteorología, 2011). Considering as infiltration the volume  
196 of water extracted from the shafts, the surface where rain water reached this volume  
197 is 3275 ha. It should be taken into account that there is not water acidification

198 because of the geochemical properties of the soil (high limestone concentration and  
199 low sulphur content of the coal). Furthermore, studied shafts are located in a very  
200 rainy region, leading to high infiltration rates and allowing low residence times of  
201 the water inside the shafts.

202 Furthermore, in the calculation of the ecological footprint,  $t_{CO_2\text{-eq}}$  calculated for the carbon  
203 footprint should be converted in surface (ha) necessary to absorb these gases. In this way,  
204 the carbon assimilation factors associated to land use previously described in the soil  
205 absorption point are employed. Concretely, in this work, it was supposed the factor  
206 corresponding to forests, that is  $3.67 \text{ t}_{CO_2\text{-eq}} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ .

207 Fig. 4 shows the total ecological footprint of each HUNOSA shaft. It is observed that there  
208 are three main contributions: electric consumption, which includes the  $CO_2\text{-eq}$  emitted and  
209 the non GHG emissions, the ventilation gases, and the water contribution. As in the case of  
210 carbon footprint, no soil contribution appears in the plot, since it acts as drainage of gases.  
211 In the same way, the main ecological footprint is due to either the electric consumption or  
212 the ventilation gases, being the last one less relevant in percentage (17-60 %), due to the  
213 important contribution of the non GHG emissions to the ecological footprint. Considering  
214 the overall coal production and the seven shafts, the contribution of ventilation emissions to  
215 the ecological footprint is of 47 %.

216 If the carbon and ecological footprints are compared, it is observed that the main  
217 differences between different shafts are caused by the different amount of methane released  
218 in the ventilation gases. The amount of methane released depends on different parameters,  
219 such as the design of the ventilation system (flow rate), the number of, and the fraction of

220 stopes that are under operation at a given moment stopes (which is continuously changing)  
221 and the gassy nature of the extracted coal. Within the reported shafts, there are many  
222 different situations. For example, the shaft with lower methane emissions (Carrio) has coal  
223 stems with low gas content and the ventilation system was designed for working with  
224 tenths of stopes, but nowadays only one stope is really working. By contrast, in Candín  
225 shaft most of the stopes are working and the coal is more gassy. In the case of Sotón and  
226 Maria Luisa shafts, the ventilation system has been designed to working parameters similar  
227 to the ones currently used, therefore no extra dilution of methane is observed.

228

#### 229 **4. TECHNOLOGIES TO MITIGATE CARBON AND ECOLOGICAL** 230 **FOOTPRINT OF COAL MINING EXTRACTION**

231 From both Fig. 3 and 4, it is deduced that the most important contribution to environmental  
232 impact of the coal mining extraction corresponds to the ventilation of gases generated in the  
233 shafts. Methane, due to its high global warming potential, represents the most relevant  
234 impact of these gases, thus any action for reducing methane emissions in the ventilation  
235 gases will present important benefits in the carbon (until 70 %) and ecological (until 40 %)  
236 footprints.

237 In order to use in the industry the methane extracted from the ventilation, the concentration  
238 should be increased. Since both flow rate and methane concentration are given by safety  
239 considerations (ensure methane concentration in the shaft largely below the explosive limit  
240 of these mixtures), end-of-pipe concentration technologies are the only alternative for this

241 purpose. Effective technology to increase methane concentration is yet not available at  
242 large scale (Su et al., 1997).

243 Other alternative for this purpose is the direct combustion of these emissions, since GWP of  
244 methane is about twenty time the corresponding to CO<sub>2</sub>. Because of the low concentration  
245 of methane, classical combustion strategies are not economical. However, non-conventional  
246 combustion technologies, such as catalytic reverse flow reactors (Fissore et al., 2005),  
247 catalytic gas turbines (Su et al., 2003) or heat-recirculating combustion method  
248 (Budzianowsky and Miller, 2009) can allow the combustion of gas streams with very low  
249 methane concentrations, being even possible to benefit the energy content (combustion is  
250 an exothermic reaction) of these emissions for low-temperature applications (sanitary  
251 water, etc.).

252 At this point, reverse flow reactors (RFRs), especially in their catalytic operation; have  
253 been proposed for harnessing low concentrations of methane contained in the up-cast air of  
254 coal mines. The RFR operates under forced unsteady-state conditions, created by  
255 periodically reversing the feed flow direction. The heat released during the exothermic  
256 reaction is trapped inside the reactor bed between consecutive flow reversals and is used to  
257 preheat the cold feed up to the reaction temperature. The RFR is thus an integrated device  
258 where both reaction and heat exchange takes place with high thermal efficiency. As the  
259 methane is oxidised, effectively it is removed from coal mine ventilating air, even when  
260 CH<sub>4</sub> concentrations are below 1000 ppm, and this is done without an external source of  
261 energy. Heat recovered during these exothermic reactions can, for example, be used to raise  
262 steam and drive a steam turbine, or be used directly where significant thermal loads are  
263 present (drying processes, warming of intake ventilating air in cold regions), which in turn

264 displaces other sources of primary energy currently utilised and presents even greater  
265 benefits in terms of CO<sub>2</sub> emissions (Marin et al., 2009).

266

## 267 **5. CONCLUSION**

268 This work reports, by calculation of carbon and ecological footprint, the environmental  
269 impact of the coal mines, in order to determine the relative importance of ventilation mine  
270 air emissions on the overall mining activity emissions, as well as to quantify the effect of  
271 the treatment of these emissions on their environmental performance. For doing this, all the  
272 coal mines belonged to the public mining company of the North of Spain (HUNOSA) were  
273 taken into consideration. These mines are considered representative of the small-sized  
274 bituminous coal mines of Western Europe.

275 From reported work, it is deduced that the most important contribution to environmental  
276 impact of the coal mining extraction corresponds to the ventilation of gases generated in the  
277 shafts. Methane, due to its high global warming potential, represents the most relevant  
278 impact of these gases, thus any action for reducing methane emissions in the ventilation  
279 gases will present important benefits in the carbon (until 70 %) and ecological (until 40 %)   
280 footprints. Therefore, the implementation of commercial technologies for the  
281 treatment/valorisation of these emissions will lead to significant decreases in the carbon  
282 footprint (up to 70 %).

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285 **ACKNOWLEDGMENTS**

286 This work was supported by the Research Fund for Coal and Steel of the European Union  
287 (contract UE-10-RFCR-CT-2010-00004). Elena G. Ongallo (HUNOSA) is acknowledged  
288 by her contribution to this work.

289

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- 325



326 **Table 1.** Annual productions of coal from the six shafts under study

327

<b>Shaft</b>	<b>Coal production (kt/year)</b>
Candín	106
Maria Luisa	187
Monsacro	201
San Nicolás	226
Carrío	121
Sotón	141
Santiago	334

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331 **Table 2.**Thermal efficiency (net) and the average heat input per kWh of net generation

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<b>Power source</b>	<b>Thermal efficiency (net) (%)<sup>1</sup></b>	<b>Average heat input per kWh of net generation (GJ/kWh)<sup>2</sup></b>	<b>Emission factor (tCO<sub>2</sub>-eq/GJ)<sup>1</sup></b>
Solar energy	30	0.012	-
Thermal energy (coal and fuel)	40	0.009	0.097
Cogeneration	40	0.009	0.056
Nuclear	35	0.010	-
Hydraulic	33	0.011	-
Wind energy	35	0.010	-
Biomass	22	0.008	0.112
Wastes	22	0.008	0.100

333 <sup>1</sup> Suggested in reference (6)

334 <sup>2</sup> Calculated as primary energy (conversion from heat to electricity at 100 % efficiency) divided by the net  
335 thermal efficiency

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337 **Table 3.** CH<sub>4</sub> concentrations of exhaust air ventilation and surface of the shafts

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<b>Shaft</b>	<b>CH<sub>4</sub> concentration (%)</b>	<b>Surface (ha)</b>
Candín	0.18	8.1
Maria Luisa	0.40	4.4
Monsacro	0.20	5.9
San Nicolás	0.40	16
Carrio	0.05	4.4
Sotón	0.40	9.4
Santiago	0.20	6.8

339

340 **FIGURE CAPTIONS:**

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343 **Figure 1.** Geographical situations of the shafts considered in this study.

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345 **Figure 2.** System boundaries for the mining activity used in the measurement of Carbon

346 Footprint and Ecological Footprint in this work.

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348 **Figure 3.** Contributions to carbon footprint, tCO<sub>2</sub>-eq per t of extracted coal, of the gases

349 emitted in electricity generation (white) and as a consequence of the ventilation emissions

350 (red)

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352 **Figure 4.** Contributions to ecological footprint (ha) per t of extracted coal of the gases

353 emitted in the generation of electricity (white), gases emitted in the ventilation (red), and

354 water infiltrations\*10 (black)

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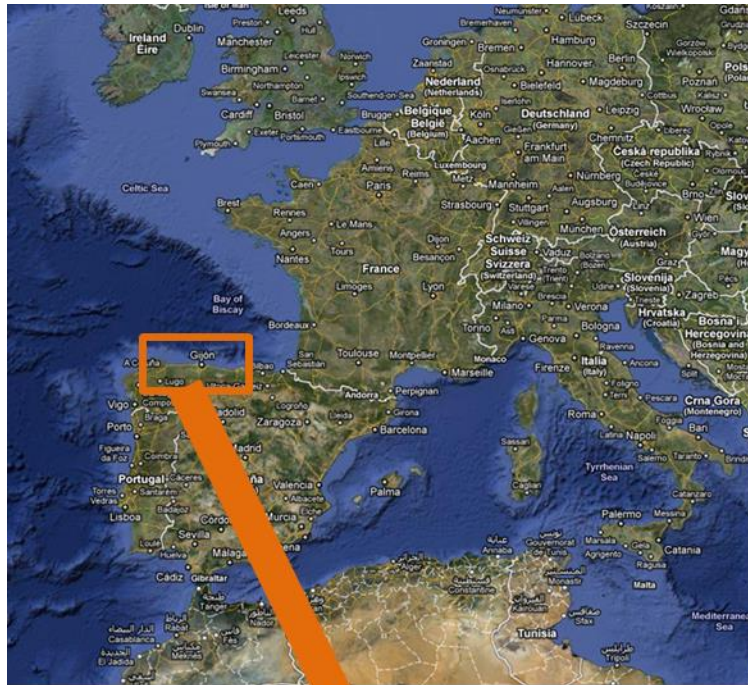
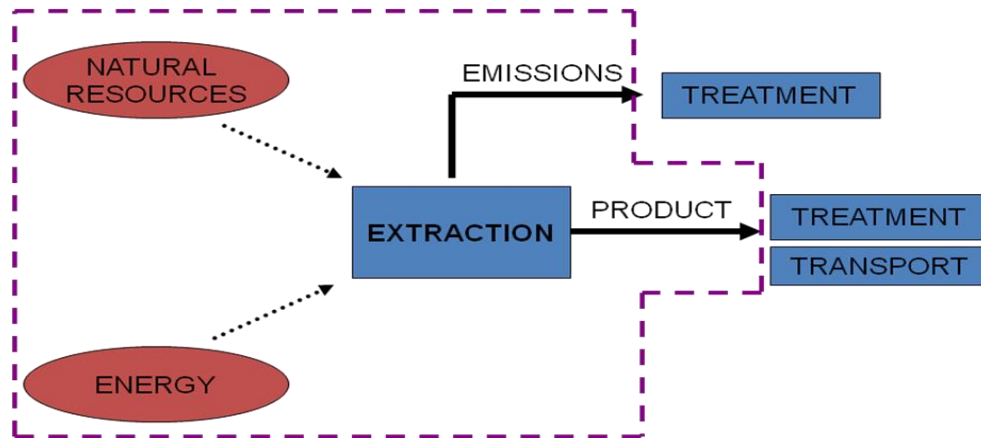


Fig. 1

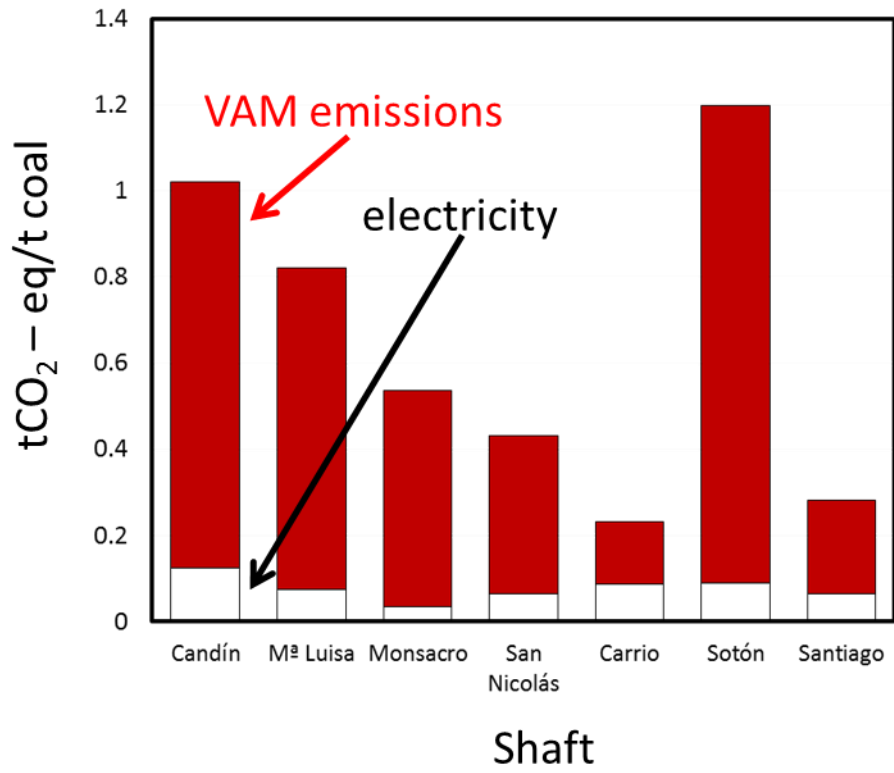
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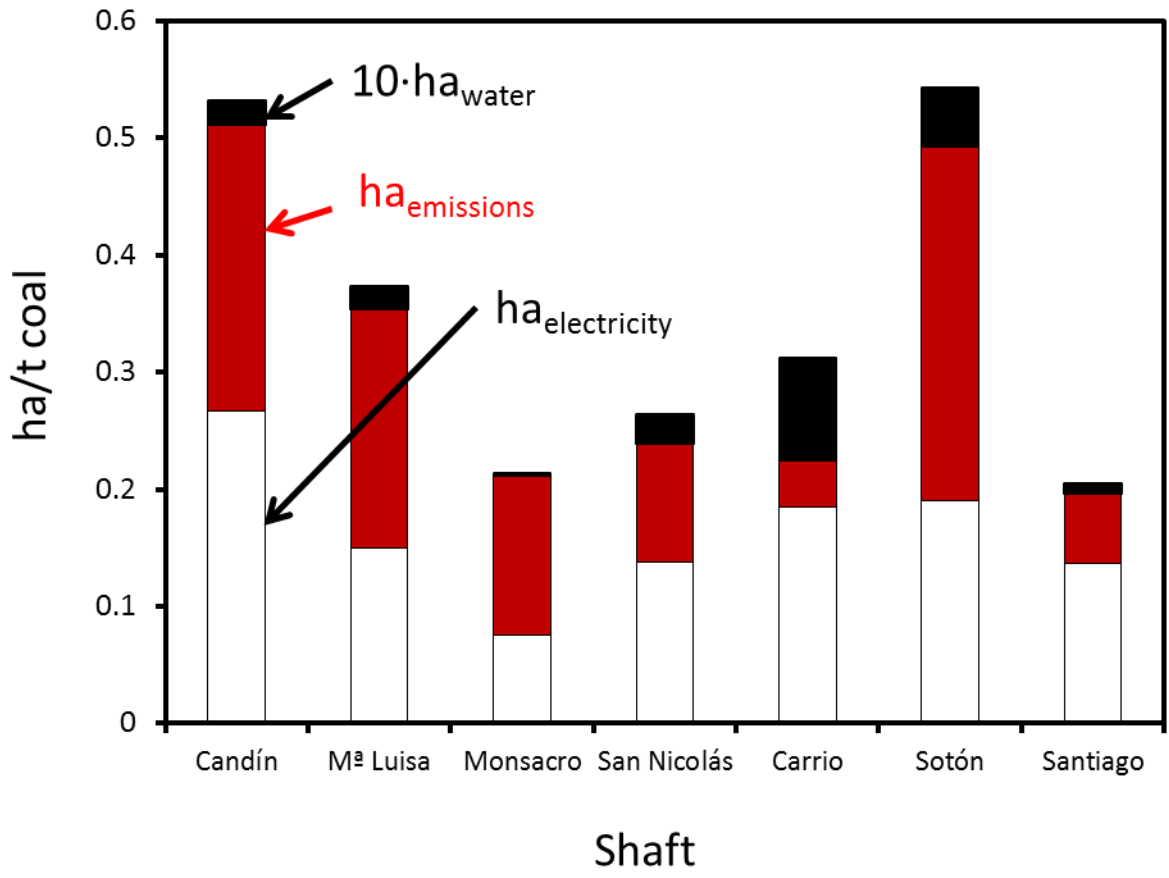
**Fig. 2**

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**Fig. 3**



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**Fig. 4**