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

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ABSTRACT

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

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

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

1. **INTRODUCTION**

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

Although the large environmental impact of coal mining from the point of view of water and soil pollution is well-accepted, much less attention has been paid to gaseous emissions. At this point, ventilation emissions (needed in order to ensure safe concentrations of methane within the shaft) were traditionally considered as non-pollutant emissions. However, these emissions contain significant amounts of methane (0.1-1%) which is a powerful greenhouse gas (GHG), with Global Warming Potential (GWP) more than twenty times higher than the corresponding to CO_2. Furthermore, emissions from coal mining account for 22 % of emissions from energy sector, which is the second largest contributor to anthropogenic methane emissions (about 30 %) (Karakurt et al., 2011). Due to this reason, a comprehensive work is needed on both inventorying and developing alternatives for these emissions (Su et al., 2005).

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

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

2. DESCRIPTION AND RESULTS OF CARBON FOOTPRINT

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

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

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

  In order to quantify the environmental impact of the electricity generation, it is necessary to take into account the relative importance of the different power sources (thermal energy, hydraulic, nuclear, wind power, etc.), these percentages being provided by the electrical company supplier. The following distribution of power sources in the generation of the electricity was considered: thermal energy (43 %), cogeneration (23 %), nuclear energy (8 %), hydraulic energy (5 %), wind energy (18 %) and biomass and wastes (3 %). In this way, the power (kWh) of electricity obtained by each source is obtained. It is considered that the primary energy corresponding to 1 kWh of electricity is typically above 3.6 MJ (Annual Energy Review 1995, 1996). Actual generation efficiencies, limited by the Second Law of Thermodynamics and design practicalities, fall short of this. In Table 2, the average heat input per kWh of net generation, and the thermal conversion efficiency is summarized for the power sources used. In the generation of electricity, add to CO_2 emissions, also other GHGs are emitted, although in minor proportion (mainly, CH_4 and N_2O). Non-CO_2 emissions are converted into units of carbon dioxide equivalent (CO_2-eq) using Global Warming Potentials (GWP) of 21 for CH_4 and 310 for N_2O. Emissions factors –that is, the CO_2-eq generated per GJ of generated electricity- for the different power sources (IPCC Guidelines for National Greenhouse Gas Inventories, 2006) are also summarized in Table 2.

- Ventilation air: ventilation is a process of entering fresh air in the working area of the shaft in order to dilute the methane up to safe limits. The extracted air is removed to the outlet, operation carried out by the fans. This exhaust air contains, greenhouse gases, mainly CH_4 and CO_2. Depending on the characteristics of the shaft, SO_2 or H_2S could also be in important concentrations, but this is not the case of HUNOSA shafts. The quantity of gas emitted depends on the coal rank and depth of seam. High-rank coals, such as anthracite, have the highest GHG emissions, whereas peat or lignite have the lowest (Karakurt et al., 2011). Asturian coal is mainly bituminous, thus intermediate emissions will be emitted. The importance of the depth is related to the pressure over the coal, increasing the concentration of methane in exhausted gases with the depth. Infrared measurements of both inlet and outlet gases, determined that the average increase in CO_2 concentration in the six shafts under study is about 0.2 %, whereas CH_4 concentrations vary between 0.05 and 0.4 % (Table 3). Concentrations of NO_x, as well as sulphur gases as H_2S or SO_2 were negligible in all cases. Due to the methane GWP, methane has its most important effect in global warming.

- Soil gases absorption: the mining here described is an underground process, thus, the surface may be only slightly altered, and in fact, can act as a CO_2-eq drain. Table 3 summarized also the surface of each shaft. It is considered that the assimilation factor depends on the land uses (IPPC, 2001), varying if it is a forest (3.67 t CO_2-eq·ha^{-1}·year^{-1}), cultivable surface (1.98 t CO_2-eq·ha^{-1}·year^{-1}), pasture (0.84 t CO_2-eq·ha^{-1}·year^{-1}), built-up land (1.98 t CO_2-eq·ha^{-1}·year^{-1}), sea (0.24 t CO_2-eq·ha^{-1}·year^{-1}) or continental water (0.24 t CO_2-eq·ha^{-1}·year^{-1}). In this work, it was considered an emissions-to-land (assimilation) factor of 3.67 t CO_2-eq·ha^{-1}·year^{-1} (IPPC, 2001).

Fig. 3 shows the t_{CO2}-eq emitted by ton of extracted coal in each shaft, existing differences until 0.97 t_{CO2}-eq/t coal among them. It is remarkable that in Fig. 3 only two contributions (generation of electricity and ventilation gases) appear, whereas no mention is made to soil absorption. This is due to the drain contribution of the soil, that is, instead of emitting CO_2, the soil traps CO_2-eq, with values of t_{CO2}-eq retained nearly negligible (about 20 t_{CO2}-eq/year·shaft) in comparison to the emissions of the other two contributions. If the analysis is made based on the specific contributions to carbon footprint here enounced, it is observed a notorious relevance of ventilation gases to the total footprint (77-94 %). Likewise, a deeper insight in the contribution to carbon footprint of ventilation emissions reveals that those shafts with the highest carbon footprint are those with both the highest concentration of methane emissions (Sotón and María Luisa) and highest flow rate of ventilation gases (Candín). The reason is the high effect on the global warming of CH_4 (21 times the CO_2). As it is showed in Table 3, there are three shafts with the highest methane concentration (0.4 %): Maria Luisa, San Nicolás and Sotón. However, the flow rate of San Nicolás shaft is considerable reduced in comparison with the others. On the other hand, although Candín exhibits lower CH_4 concentration, the flow rate is considerably higher than the other shafts. At this point it is convenient to consider that the low explosive limit of methane is 5 % at ambient temperature, and considering a wide safety factor, the flowrate of each shaft is fitted in order be always below 1 % (or even lower).

3. DESCRIPTION AND RESULTS OF ECOLOGICAL FOOTPRINT

The Ecological Footprint measures the amount of surface required to produce all the resources that consume an activity, considering also the absorption of residual materials (wastes, emissions, etc.) it generates. In the calculation of the ecological footprint of the coal mining, add to the contributions previously described for the carbon footprint which contributes to the ecological footprint by the CO_2-eq emissions –that is, global warming gases-, other factors that have also different environmental impacts should be considered:

- No global warming gases generated in the electricity production (non GHG emissions): the machinery used in the mining activity works by electricity, whose production, add to the global warming gases previously mentioned, could also generate other compounds that can affect negatively the environment. In fact, there is a notorious contribution to the ecological footprint by the SO_2 generated in the electric power production. The SO_2 contributes to acidification, thus its effect on the ecological footprint can be taken into account considering the area necessary to absorb the SO_2 generated. About 70 percent of the total area in Europe has an assimilation capacity of less than $20 \cdot 10^{-3}$ $H^+eq \cdot m^{-2} \cdot year^{-1}$; the rest of the area has a critical load ranging from 20 to $50 \cdot 10^{-3}$ $H^+eq \cdot m^{-2} \cdot year^{-1}$ (Holmberg et al., 1999). Considering in this work an assimilation factor of $20 \cdot 10^{-3}$ $H^+eq \cdot m^{-2} \cdot year^{-1}$ (the worst and most conservative scenario), and converting t_{SO2} in H^+eq, the area needed to absorb a ton SO_2 is 155 ha.

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

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

Furthermore, in the calculation of the ecological footprint, t_{CO2}-eq calculated for the carbon footprint should be converted in surface (ha) necessary to absorb these gases. In this way, the carbon assimilation factors associated to land use previously described in the soil absorption point are employed. Concretely, in this work, it was supposed the factor corresponding to forests, that is 3.67 t_{CO2}-eq·ha^{-1}·year^{-1}.

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

If the carbon and ecological footprints are compared, it is observed that the main differences between different shafts are caused by the different amount of methane released in the ventilation gases. The amount of methane released depends on different parameters, such as the design of the ventilation system (flow rate), the number of, and the fraction of stopes that are under operation at a given moment stopes (which is continuously changing) and the gassy nature of the extracted coal. Within the reported shafts, there are many different situations. For example, the shaft with lower methane emissions (Carrio) has coal stems with low gas content and the ventilation system was designed for working with tenths of stopes, but nowadays only one stope is really working. By contrast, in Candín shaft most of the stopes are working and the coal is more gassy. In the case of Sotón and Maria Luisa shafts, the ventilation system has been designed to working parameters similar to the ones currently used, therefore no extra dilution of methane is observed.

4. TECHNOLOGIES TO MITIGATE CARBON AND ECOLOGICAL FOOTPRINT OF COAL MINING EXTRACTION

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

In order to use in the industry the methane extracted from the ventilation, the concentration should be increased. Since both flow rate and methane concentration are given by safety considerations (ensure methane concentration in the shaft largely below the explosive limit of these mixtures), end-of-pipe concentration technologies are the only alternative for this purpose. Effective technology to increase methane concentration is yet not available at large scale (Su et al., 1997).

Other alternative for this purpose is the direct combustion of these emissions, since GWP of methane is about twenty time the corresponding to CO_2. Because of the low concentration of methane, classical combustion strategies are not economical. However, non-conventional combustion technologies, such as catalytic reverse flow reactors (Fissore et al., 2005), catalytic gas turbines (Su et al., 2003) or heat-recirculating combustion method (Budzianowsky and Miller, 2009) can allow the combustion of gas streams with very low methane concentrations, being even possible to benefit the energy content (combustion is an exothermic reaction) of these emissions for low-temperature applications (sanitary water, etc.).

At this point, reverse flow reactors (RFRs), especially in their catalytic operation; have been proposed for harnessing low concentrations of methane contained in the up-cast air of coal mines. The RFR operates under forced unsteady-state conditions, created by periodically reversing the feed flow direction. The heat released during the exothermic reaction is trapped inside the reactor bed between consecutive flow reversals and is used to preheat the cold feed up to the reaction temperature. The RFR is thus an integrated device where both reaction and heat exchange takes place with high thermal efficiency. As the methane is oxidised, effectively it is removed from coal mine ventilating air, even when CH_4 concentrations are below 1000 ppm, and this is done without an external source of energy. Heat recovered during these exothermic reactions can, for example, be used to raise steam and drive a steam turbine, or be used directly where significant thermal loads are present (drying processes, warming of intake ventilating air in cold regions), which in turn displaces other sources of primary energy currently utilised and presents even greater benefits in terms of CO_2 emissions (Marin et al., 2009).

5. CONCLUSION

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

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

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

Shaft	**Coal production (kt/year)**
Candín	106
Maria Luisa	187
Monsacro	201
San Nicolás	226
Carrio	121
Sotón	141
Santiago	334

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

Power source	**Thermal efficiency (net) (%)**[1]	**Average heat input per kWh of net generation (GJ/kWh)**[2]	**Emission factor (tCO_2-eq/GJ)**[1]
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

[1] Suggested in reference (6)

[2] Calculated as primary energy (conversion from heat to electricity at 100 % efficiency) divided by the net thermal efficiency

Table 3. CH_4 concentrations of exhaust air ventilation and surface of the shafts

Shaft	**CH_4 concentration (%)**	**Surface (ha)**
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

FIGURE CAPTIONS:

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

Figure 2. System boundaries for the mining activity used in the measurement of Carbon Footprint and Ecological Footprint in this work.

Figure 3. Contributions to carbon footprint, tCO_2-eq per t of extracted coal, of the gases emitted in electricity generation (white) and as a consequence of the ventilation emissions (red)

Figure 4. Contributions to ecological footprint (ha) per t of extracted coal of the gases emitted in the generation of electricity (white), gases emitted in the ventilation (red), and water infiltrations*10 (black)


Candín
María Luisa
San Nicolás
Carrio
Monsacro
Sotón
Santiago

Fig. 1

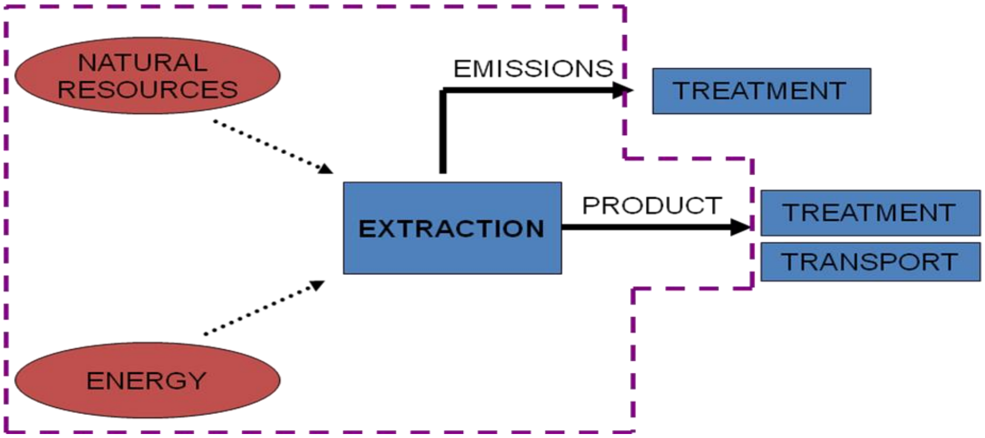

NATURAL RESOURCES
ENERGY
EXTRACTION
EMISSIONS
TREATMENT
PRODUCT
TREATMENT
TRANSPORT

Fig. 2

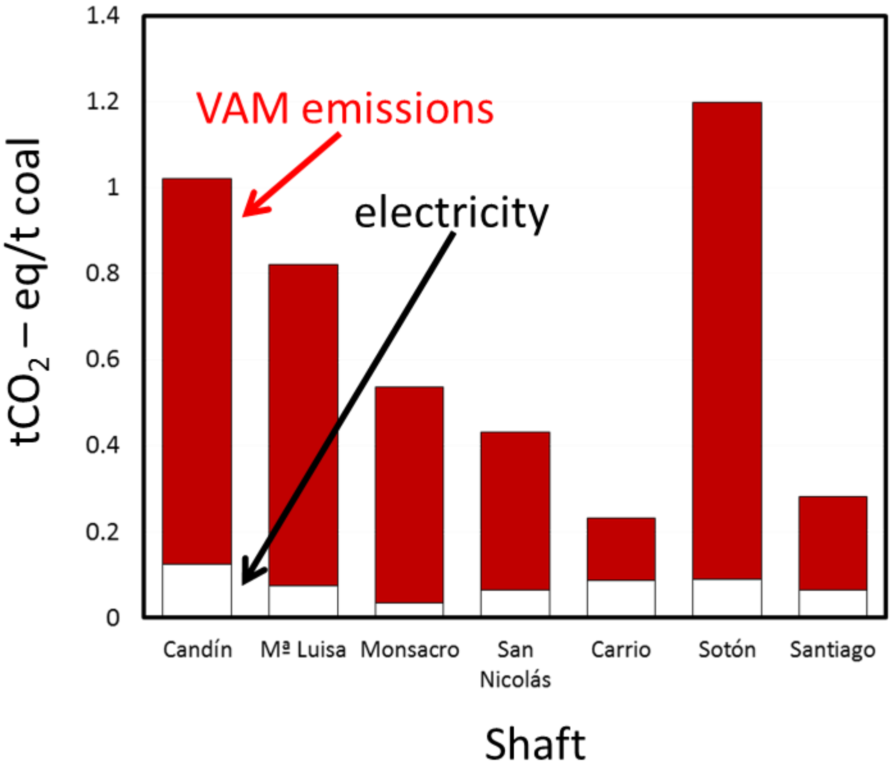
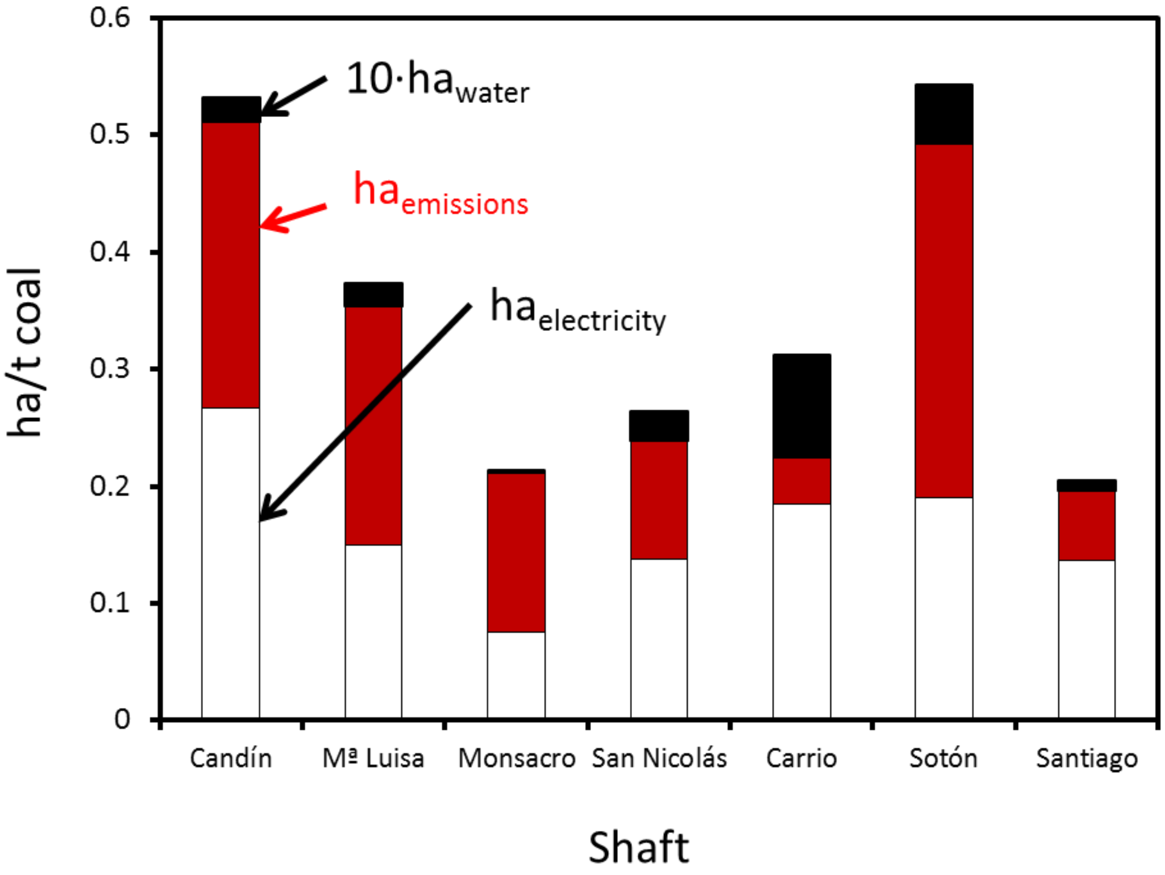

1.4
1.2
1
0.8
0.6
0.4
0.2
0
VAM emissions
electricity
tCO$_2$ – eq/t coal
Candín
Mª Luisa
Monsacro
San Nicolás
Carrio
Sotón
Santiago
Shaft

Fig. 3



ha/t coal
0.6
0.5
0.4
0.3
0.2
0.1
0
10·ha$_{water}$
ha$_{emissions}$
ha$_{electricity}$
Candín
Mª Luisa
Monsacro
San Nicolás
Carrio
Sotón
Santiago
Shaft

Fig. 4