Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Life-cycle assessment of coal mining wastes upcycling

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ABSTRACT: Coal extraction generates coal mining wastes (CMW) that lead to additional environmental burdens. This study assesses the potential environmental benefits of using these CMW as secondary materials in the production of precast concrete cladding panels. Potential environmental impacts are measured using life cycle assessment (LCA). The system under assessment is a multi-functional system, including both the management of CMW and the production of concrete panels. Company data have been used to perform the assessment. Preliminary results show, for the business-as-usual (BAU) scenario, that the main impacts associated with wastes management are due to diesel consumption and direct emissions to groundwater. For the concrete panel production, the impacts are primarily induced by cement production. This BAU scenario will be compared to a recycling scenario where CMW are incorporated into concrete production. Based on this comparative LCA, recommendations as to the use of CMW into construction products will be provided.

1 INTRODUCTION

In order to meet the Paris agreement, governments and stakeholders of the civil society call for phasing down or transitioning away from coal as an energy source. Yet, according to the International Energy Agency in 2021, coal fired power generation reached 769 TWh, a level higher than before resulting in record levels in terms of CO_2 emissions as well (IEA, 2022a). Thermal coal accounted for 78% of the total coal consumption, which reached almost 8 billion tons in 2022 (IEA, 2022b).

This coal is extracted from various mine sites leading to important volumes of coal mining wastes (CMW). Some authors report than for each ton of coal produced, 0.4 to 0.5 ton of waste is generated (Pactwa et al., 2020). In Poland, for example, around 35 million tons of CMW is generated every year (Warcholik et al., 2014). Wastes associated with hard coal extraction and processing can lead to environmental and social issues when stored. Storage of

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coal mining waste can lead to soil and/or water pollution depending on the sulfur or heavy metals content of the wastes. Fire hazard is also a risk associated with the storage of CMW that can lead to atmospheric pollution (Pactwa et al., 2020).

Apart from environmental and social concerns, handling and storing mining wastes also has an economic cost for mining companies and the society. Direct costs for mining companies include for example the workforce, equipment and fuel needed to handle the wastes from the production plant to the waste storage area. Given the social and environmental issues, monetized externalities can also be associated with CMW costs As per Wang et al. (2020), the costs associated with the waste storage in terms of land function loss and use sum up to 3.57 USD/t.

To limit the amount of CMW stored and the associated economic, social and environmental costs, solutions to use them as secondary raw materials are being explored. One of their use as secondary raw materials could be as geomaterials in the construction sector (Vo et al. 2022). The research project MINRESCUE is exploring this pathway by assessing the inclusion of CMW as raw materials for the production of precast concrete panels to be used in industrial buildings. In order to assess the potential environmental benefits associated with this solution, a comparative life cycle assessment (LCA) has been performed considering, on the one hand, a *business-as-usual (BAU)* scenario representing how CMW are today handled and, on the other hand, a *recycling* scenario where these CMW are used as secondary materials for concrete panel productions. In this work, an emphasis is put firstly on the modelling of the *BAU* scenario and its resulting environmental impacts (Section 2) and secondly on the key parameters to focus on in the modelling of the *recycling* scenario (Section 3).

2 LIFE CYCLE ASSESSMENT OF THE BUSINESS-AS-USUAL SCENARIO

Over the last decades, LCA has gained interest as a decision-support tool to assess the environmental performance of products and services to support company or policy decision-making. LCA considers a so-called life cycle perspective, covering all life cycle stages in a cradle-to-grave perspective (i.e. from raw materials extraction to end-of-life disposal). It accounts for both direct and indirect impacts, in a multi-criteria framework that includes various impact categories (e.g. carbon footprint, toxicity-related issues, resource consumption). In particular, LCA enables i) the identification of environmental hotspots; ii) the comparison of different scenarios to identify the best performing scenario and potential burden-shifts from one impact category/life cycle stage to another. The implementation of LCA is framed by ISO standards (14040 and 14044) and follows four different steps, as hereafter detailed (see Sections 2.2, 2.3 and 2.4).

2.1 *Definition of the BAU scenario*

This study focuses on two different industrial activities in their current functioning:

i) Coal mining, with focusing on waste management operations and considering currently operating mine sites in Poland in particular, the BAU scenario considers current on-site operations, where part of the mining waste is reused (e.g. in roadbed) while the remaining part is disposed of through on-site stockpiling.
ii) Precast concrete elements production, focusing on pre-cast concrete panels currently produced by the NTS company in Italy. The BAU scenario in particular entails considering the current concrete mix (i.e. including cement, sand, gravel, filler, additive and water) as used by the NTS company.

2.2 *Goal and scope*

The product system here under study can be considered a multifunctional system providing two different functions: i) the management of solid wastes resulting from coal processing; ii) the production of pre-cast concrete panels.

It is decided to capture both functions in the functional unit of this study, rather than privileging one over the other. In this context, the functional unit is defined as:

The management of 1 ton of solid wastes resulting from coal processing, and the production of 1 pre-cast concrete panel.

The system boundaries include: i) the production and consumption of reagents, ancillary materials, energy and water; ii) the direct emissions to the environment generated by the operations under study; iii) the transport of raw materials; and iv) the production of the infrastructure and equipment.

Moreover, these boundaries cover all unit operations associated with:

- The processing of wastes prior to their final disposal or reuse;
- The final disposal or reuse of the wastes;
- The production of concrete;
- The casting of concrete into pre-cast panels.

The upstream coal mining and processing operations have been here excluded from the boundaries.

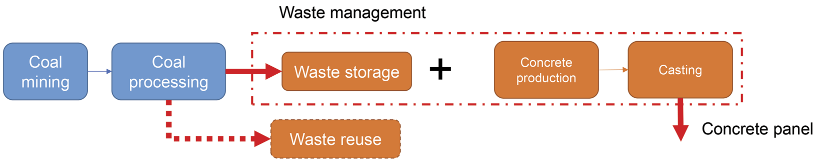

Figure 1. System boundaries for the BAU scenario.

The environmental impacts have been calculated using the Simapro LCA software, considering the European life cycle impact assessment method (EF method 3.0; Fazio et al. 2018). This method, established by the Joint Research Centre (JRC) of the European Commission (EC), encompasses 16 impact categories recommended by the JRC in the context of the European Product and Organization Environmental Footprint (PEF/OEF), which aims to establish a common method to measure and communicate the life cycle environmental performance of products and organizations in the EU.

2.3 *Life Cycle Inventory (LCI)*

The foreground system (i.e. all processes for which specific data have been collected and used in the modelling) has been modelled primarily using data provided by companies. These data were completed with generic data (e.g. from the ecoinvent LCI database) and assumptions in cases of data gaps.

The compiled inventory encompasses data about:

- Energy consumption, including the electricity necessary to concrete mixing and casting into pre-cast panel as well as the diesel necessary to fuel the machinery operating the coal waste storage area. Data about electricity consumption were obtained from calculations based on technical specifications related to the used equipment. As for data on fuel consumption, the latter were drawn from the ecoinvent LCI database, in the absence of data specific to the machinery implemented on-site.
- Raw materials and chemicals consumption, in particular for manufacturing concrete, which requires various constituents such as concrete, sand, gravel and other additives. This concrete mix is based on the actual mix as used by the NTS company for manufacturing of its precast concrete products.
- Water consumption, for concrete production.
- Transport, especially regarding the supply of concrete constituents to the NTS manufacturing plant.

- Infrastructure, considering the concrete mixing plant as a whole. In particular, it is assumed that the plant is solely made of “low-alloyed” steel, with deriving the total weight of the plant from technical specifications.
- Equipment, necessary to handling waste and operating the coal waste storage area (e.g. conveyor belt, stackers, bulldozers). In the absence of specific information regarding each piece of equipment implemented on-site, generic data drawn from the ecoinvent LCI database were used as a proxy for modelling some pieces of equipment.
- Land occupation, considering the superficial land occupation and transformation induced by the coal waste storage area.
- Emissions to the environment, in particular considering potential long-term emissions of substances to groundwater, resulting from the waste storage area. The quantification of these emissions is based on a geochemical model, as currently implemented in the widely used LCI database ecoinvent. The model is adapted by using specific on-site data obtained from one mine site. These data encompass the coal tailings composition, the characteristics of the waste storage area and specific data regarding the climatic conditions.

2.4 *Life cycle impact assessment and interpretation*

In a life cycle perspective, the management of 1 ton of solid wastes resulting from coal processing, and the production of 1 pre-cast concrete panel potentially induces a total of 607 kg CO_2-eq (climate change), 0.197 CTUh (human toxicity, non-cancer effects) and 0.192 kg P-eq (eutrophication, freshwater). The complete list of impacts, considering the 16 impact categories from the EF method 3.0, is detailed in Table 1.

Overall, the production of concrete panels stands for the main contributor to the environmental impacts, as it dominates the impacts for 15 impact categories out of 16 (with contributions ranging from 84.1% to 100%; Table 1). Coal wastes management only stands out in the case of freshwater eutrophication, as it accounts for 69.4% of the impacts.

With reference to the production of concrete panels, the use of cement stands out as the main environmental hotspot as it accounts for the largest share of impacts with respect to all impact categories (more than 60% of the impacts for all categories excepting water use, for which cement represents about 40% of the impacts – Figure 2). Aside from cement, the use of electricity (in particular for the casting process) appears to have a relatively modest contribution to the impacts, regarding the “ozone depletion”, “ionizing radiation”, “land use”, “water use” and “resource use, fossils” impact categories (more than 10% of the impacts).

The impacts induced by coal waste management are essentially driven by the machinery operating on-site as well as direct emissions to environment (Figure 3). In particular, the diesel consumed by the machinery is responsible for the most significant part of the impacts with respect to 11 impact categories out of 16, with bulldozers and ZGOT stackers respectively accounting for about 60% and 40% of these impacts. Four impact categories, namely toxicity-related categories and freshwater eutrophication, direct emissions of substances to groundwater account for the largest share of the impacts (more than 90% of the impacts). Finally, impacts relative to “land use” are due to the land occupation and transformation as induced by the coal waste storage area.

3 MODELLING THE RECYCLING SCENARIO

3.1 *Definition of the product system*

Regarding the recycling scenario, the boundaries of the system cover the same functional reality as the BAU scenario (cf. Section 2.2). In comparison with the BAU scenario, this recycling scenario includes unit operations associated with the preparation of waste and its transport to the concrete panel production site.

Table 1. Resulting impacts for the functional unit under assessment and contribution of each part of the functional unit considering 16 impact categories from the EF method 3.0.

Impact category	Unit	Concrete panel production	Waste management
Climate change	kg CO2 eq	6.04E+02 99.47%	3.21E+00 0.53%
Ozone depletion	kg CFC11 eq	2.40E-05 97.26%	6.75E-07 2.74%
Ionising radiation	kBq U-235 eq	1.97E+01 99.01%	1.98E-01 0.99%
Photochemical ozone formation	kg NMVOC eq	1.43E+00 98.94%	1.53E-02 1.06%
Particulate matter	disease inc.	1.36E-05 98.79%	1.67E-07 1.21%
Human toxicity, non-cancer	CTUh	1.97E-01 100.00%	1.81E-07 0.00%
Human toxicity, cancer	CTUh	2.07E-07 91.24%	1.99E-08 8.76%
Acidification	mol H+ eq	1.86E+00 99.26%	1.38E-02 0.74%
Eutrophication, freshwater	kg P eq	8.13E-02 30.61%	1.84E-01 69.39%
Eutrophication, marine	kg N eq	5.42E-01 99.10%	4.95E-03 0.90%
Eutrophication, terrestrial	mol N eq	5.89E+00 99.09%	5.41E-02 0.91%
Ecotoxicity, freshwater	CTUe	8.24E+03 84.10%	1.56E+03 15.90%
Land use	Pt	2.67E+03 88.54%	3.46E+02 11.46%
Water use	m3 depriv.	8.40E+01 99.91%	7.44E-02 0.09%
Resource use, fossils	MJ	3.38E+03 98.73%	4.35E+01 1.27%
Resource use, minerals and metals	kg Sb eq	3.02E-03 99.95%	1.49E-06 0.05%

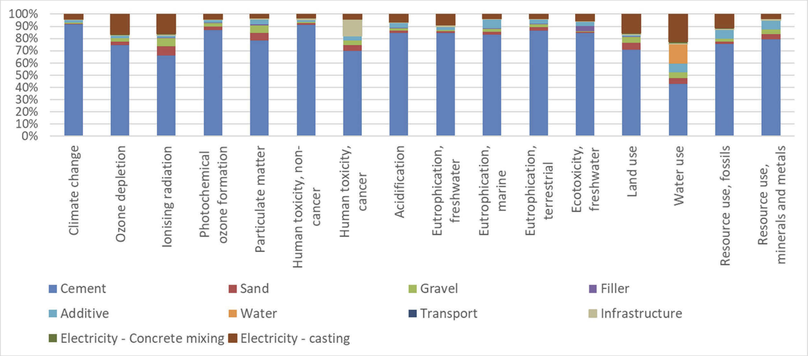

Figure 2. Contributions to the environmental impacts of concrete panel production, considering 16 impact categories from the EF method 3.0.

As the project is still on-going, the actual mix-design to produce a concrete panel with the incorporation of CMW is not yet fully finalized. Once crushed at the right granulometry, the CMW would be mixed with natural aggregates in a proportion yet to be quantified (cf.

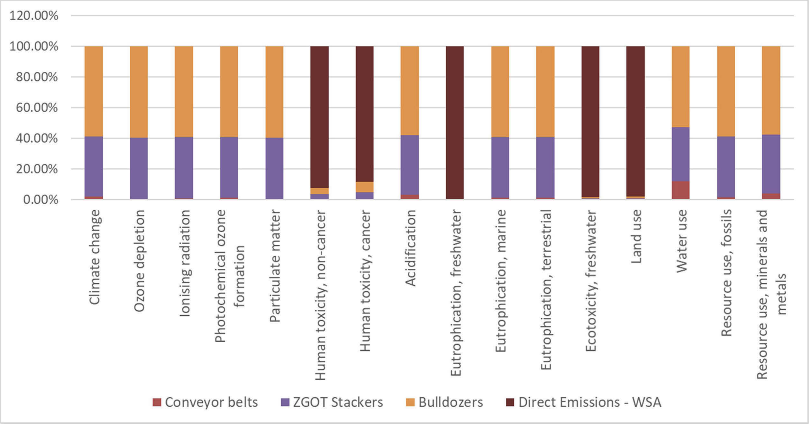

Figure 3. Contributions to the environmental impacts of coal wastes management, considering 16 impact categories from the EF method 3.0.

Section 3.2) to obtain the concrete to be used in the panel production. CMW would replace both a fraction of fine and coarse natural aggregates in the concrete production.

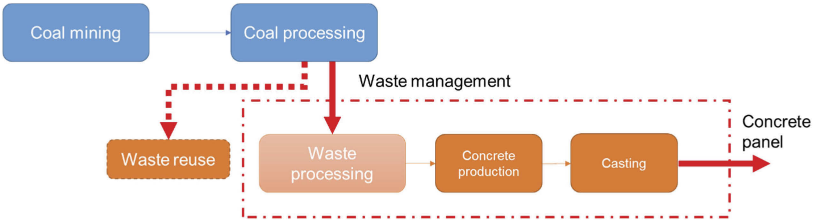

Figure 4. System boundaries for the recycling scenario.

3.2 *Accounting for recycled products durability*

In the framework of the MINRESCUE project a comprehensive investigation has been performed by the last author's group on the performance of concrete containing recycled CMWGs from different sources, with preliminary results reported in detail in (del Galdo et al., 2022). The investigation has considered compressive and flexural strength, fracture energy and shrinkage and has confirmed, as from some exemplary results on compressive strength shown in Figure 5, that, while the mechanical properties suffer some reduction because of the replacement of natural aggregates with CMWGs, when the latter are employed to replace fine aggregates or a combination of fine and coarse aggregates, an overall set of mechanical performance can be obtained which still complies with those required by several engineering applications.

This, on the one hand, paves the way for a valorization of CMWGs in the construction industry and on the other hand, strengthens the motivation for this study, corroborating first of all the possibility that the intended precast structural elements can be produced with concrete incorporating CMWGs as a recycled aggregate in partial replacement of natural ones and furthermore that the expected service life could be comparable, though quantitative assessment of durability performance for the aforesaid concretes is still on-going.

3.3 *Differences expected against the business as usual scenario*

Given the results presented in Section 2.4 and the product system presented in Section 3.1, some results of the comparison of the recycling scenario against the BAU scenario could be

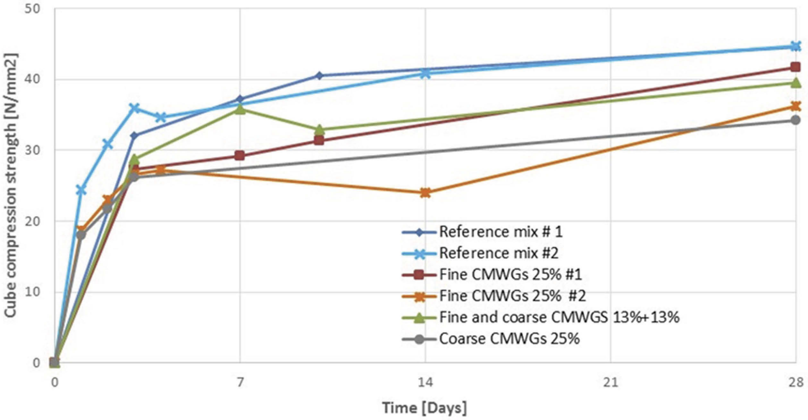

Figure 5. Evolution of cube compressive strength for mixes incorporating different types and replacement percentages of CMWGs.

anticipated. Firstly, for the BAU system, the concrete panel production is the higher contributor for a large majority of the impact categories and in this concrete panel production, cement production is the highest contributor. In the envisioned recycling scenario, CMW will replace sand and gravel but not cement; those impacts won't so not be diminished by the inclusion of CMW in the concrete mix.

However, recycling of CMW will have a direct effect on different impact categories. It will firstly diminish all impacts associated with on-site CMW management and in particular, the impact for which the direct emissions are the greatest contributor (Figure 3). Among these impacts, the category "Eutrophication freshwater" will be the most affected by the consideration of the recycling scenario (cf. Table 1).

If the recycling scenario will directly lower some of the impact categories, its specific unit process will however have other impacts. It is the case of the waste processing unit process that consists of an energy consumption to obtain the desired wastes granulometry. It is also the case of the waste transport from the mining site to the plant producing the concrete panels. The type of energy used and the transportation distance could be parameters that have strong influence on the resulting comparison. Given this fact, sensitive and scenario assessments will be performed on those parameters in order to find the tipping point where the recycling scenario may no longer be more environmentally friendly than the BAU scenario.

4 CONCLUSIONS

In order to conclude this study, work still needs to be done. In particular, durability performance of the concrete panel containing CMW should be quantified, the mix between primary and secondary materials for the recycling scenario should be defined and finally, the LCA of the recycling scenario should be performed to compare the results against the ones obtained for the BAU scenario.

Results of the comparison between the BAU and the recycling scenario would lead to recommendations for both the mine operators and the concrete panel producers on the development of an optimized scenario regarding different parameters such as the distance between the mine site and the producer of the concrete panels. This optimized scenario should minimize the environmental impacts associated with the inclusion of CMW into concrete production moving from linear to circular economy.

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