



RESEARCH ARTICLE

Environmental life-cycle assessment of waste-coal pellets production

Dawid P. Hanak^{1,*}

¹Centre for Climate and Environmental Protection, Energy and Power Theme, School of Water, Energy and Environment, Cranfield University, Bedford, Bedfordshire, MK43 0AL, UK

*Corresponding author. E-mail: d.p.hanak@cranfield.ac.uk

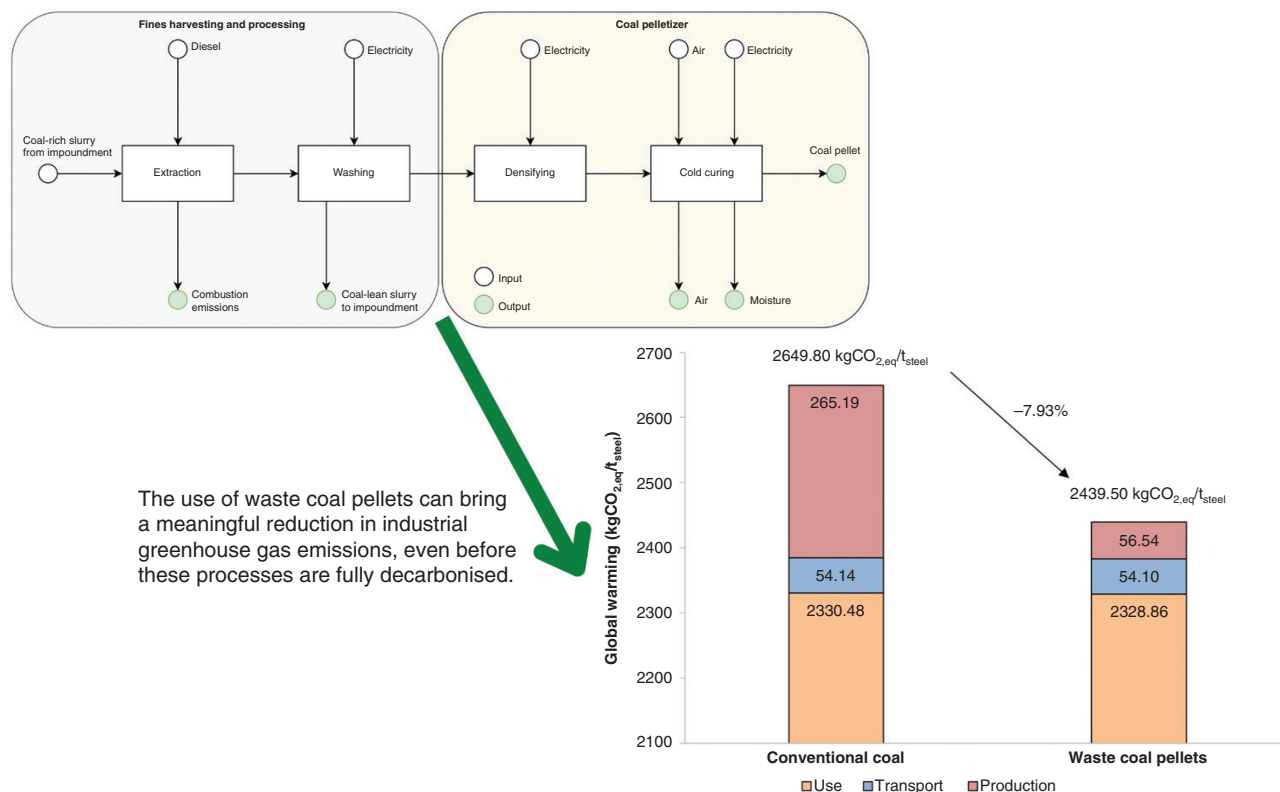
Abstract

Industrial decarbonization is crucial to keeping the global mean temperature <1.5°C above pre-industrial levels. Although unabated coal use needs to be phased out, coal is still expected to remain an important source of energy in power and energy-intensive industries until the 2030s. Decades of coal exploration, mining and processing have resulted in ~30 billion tonnes of waste-coal tailings being stored in coal impoundments, posing environmental risks. This study presents an environmental life-cycle assessment of a coal-processing technology to produce coal pellets from the waste coal stored in impoundments. It has been shown that the waste-coal pellets would result in the cradle-to-gate global warming of 1.68–3.50 kgCO_{2,eq}/GJ_{ch}, depending on the source of electricity used to drive the process. In contrast, the corresponding figure for the supply of conventional coal in the US was estimated to be 12.76 kgCO_{2,eq}/GJ_{ch}. Such a reduction in the global-warming impact confirms that waste-coal pellets can be a viable source of energy that will reduce the environmental impact of the power and energy-intensive industries in the short term. A considered case study showed that complete substitution of conventional coal with the waste-coal pellets in a steelmaking plant would reduce the greenhouse-gas emissions from 2649.80 to 2439.50 kgCO_{2,eq}/t_{steel}. This, in turn, would reduce the life-cycle greenhouse-gas emissions of wind-turbine manufacturing by ≤8.6%. Overall, this study reveals that the use of waste-coal pellets can bring a meaningful reduction in industrial greenhouse-gas emissions, even before these processes are fully decarbonized.

Received: 19 August 2021; Accepted: 13 October 2021

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Graphical Abstract



Keywords: coal impoundments; LCA; environmental-impact assessment; renewable energy; decarbonization; fossil fuels

Introduction

Decarbonization of the energy and industrial sectors is essential for meeting the Paris Agreement targets of keeping the global mean temperature at <2°C and aiming to limit it to 1.5°C above pre-industrial levels [1]. The global use of fossil fuels, especially coal, needs to be phased out as soon as possible [2]. Yet, it is expected that coal will remain an important fuel in power generation and energy-intensive industries until the 2030s at least, especially in countries whose energy sectors heavily rely on coal-fired power plants, such as China, India and Poland [3]. For this reason, carbon capture and storage are essential for coal-fired power generation to achieve the net-zero targets [4]. Coal, however, will have a role to play in enabling our transition to a net-zero economy. Namely, the production of iron and steel relies heavily on the supply of metallurgical coal. For example, an onshore 2-MW wind turbine requires 240 tonnes of steel [5]. Currently, ~70% of the steel is produced via the integrated steelmaking route. Production of 1 tonne of steel via this route requires 780 kg of metallurgical coal. It means that ~187 tonnes of metallurgical coal is required to produce steel for a single onshore 2-MW wind turbine [6]. This figure reduces to 36 tonnes of metallurgical coal when the steel is produced in an electric arc furnace, as this route requires only 150 kg of coal per tonne

of steel [6]. Therefore, despite the global activities to reduce reliance on fossil fuels, coal may still be required to support the construction, steelmaking and cement industries. This continuing reliance on coal comes with environmental challenges, in addition to the widely recognized contribution to CO₂ emissions. For example, the development of new coal mines will add to already substantial methane emissions of 40 Mt/y from existing coal mines [7]. Moreover, each tonne of coal extracted from a new coal mine results in 4 kg of CH₄ emitted into the atmosphere [8]. With the global-warming potential being 28–36 times that of CO₂ over 100 years [9], methane emissions are a significantly higher contributor to global warming. To achieve an imminent reduction in greenhouse-gas emissions before the use of coal is fully phased out, alternative coal sources to supply industrial processes need to be explored.

Decades of coal exploration, mining and processing have resulted in significant volumes of coal tailings and waste. It has been estimated that the waste produced during coal production corresponds to ≤40% of the total amount of material extracted [10] and that the amount of coal fines and tailings produced reached ~30 billion tonnes (bt) in the top 10 coal-producing countries in 2014 [11]; these countries generate ~1 bt/y of coal waste. Such coal waste is typically stored in impoundments next to the coal mine, posing environmental risks [12]. Recovery and reuse

of this by-product can supply a significant fraction of the industrial coal demand and open a more economic route to land remediation and restoration.

Various technologies for waste-coal recovery have been proposed and investigated in the current literature, including flotation, oil agglomeration and centrifugal separation. However, conventional flotation may not be the most effective way to recover waste coal if the coal tailings comprise large volumes of fines and clays [13, 14]. Although the use of enhanced gravity separators can ensure efficient operation, it may still be difficult to reduce the water content in the final product [15]. For this reason, Taha *et al.* [16] assessed the technical viability of recovering coal from waste-coal tailings via froth flotation. In this process, the waste coal is first crushed, ground and washed before being mixed with diesel and methyl iso-butyl carbinol that were used as collector and frother. Diesel, or other bridging oils, are used to attract naturally hydrophobic coal particles to form coal agglomerates that can be later separated by screening. Their analysis indicated that flotation could recover >60% of coal from the waste material. The final product was shown to contain low ash and sulphur amounts, and had a high heating value of ≥ 31.4 MJ/kg. Such heating value is comparable to figures reported for conventional coal [17]. Taha *et al.* [16] also conclude that in addition to providing an alternative source of coal to new coal mines, recovery of the waste coal will reduce the environmental risks of storing waste in impoundments, such as leaching of heavy metals. Although the approach presented by Taha *et al.* [16] demonstrated technical viability of the froth flotation, it still relies on diesel as a conventional non-polar collector, consequently increasing the demand for fossil fuels. For this reason, Chiodza *et al.* [18] considered algal lipids as a potential alternative to conventional collectors, such as diesel. This was because algal lipids have similar physico-chemical properties to diesel. For the algal lipids to be used as a collector, these need to be chemically modified to produce fatty acid methyl esters via transesterification [19].

The study by Chiodza *et al.* [18] confirmed that modified algal lipids are a viable bio collector for waste coal via froth flotation, recovering coal with low ash and sulphur content. The combustibles recovery reached 47.1%.

This is in line with the study by Yaşar *et al.* [20] who proposed to use the sunflower-oil process for waste-coal recovery. This study showed that the use of sunflower oil can also result in a significant reduction in the ash (45%) and the sulphur (57%) content, and a clean-coal yield of 46.8%. To overcome the limited recovery of coal from the waste-coal fines via flotation methods, Sriramoju *et al.* [21] proposed to apply a centrifugal separation of the coal fines via ultra-fine grinding and density gradient centrifugation. In this two-stage process, the raw coal is first floated and the tailings are wet-ground. The final coal product was then separated from the ground slurry in a high-speed centrifugal separator, also known as a densifier. This approach resulted in the coal yield of $\leq 60\%$, which was higher than

that reported for the froth flotation. Therefore, the use of densifying equipment as a part of the waste-coal recovery system appears to be a viable option.

Recovery of the waste coal from existing coal impoundments is one way to avoid the need for opening new coal mines, with the added benefit of reducing the global warming per unit amount of energy supplied from coal. However, the environmental benefits of using waste coal remain unexplored, especially in light of the decarbonization of power and industrial sectors. A study by Babbitt and Lindner [22, 23] has compared the global-warming impact of waste-coal disposal with waste-coal recovery. Their study showed that coal disposal is associated with only 0.2% of the global warming caused by coal extraction. As a result, replacing conventional coal with recovered waste coal can result in a $\geq 20\%$ reduction in global warming associated with coal use. However, the study by Babbitt and Lindner [22, 23] neither discusses the specific waste-coal recovery process nor assesses the environmental benefits of using waste coal for industrial decarbonization.

Therefore, this study aimed to evaluate the environmental benefits of waste-coal recovery from impoundments via densification of the waste-coal slurry. The environmental life-cycle assessment (LCA) was performed and the ReCiPe impact indicators for the waste-coal pellets and conventional coal were benchmarked. The environmental viability of the waste-coal processing technology was assessed considering a range of conventional and low-carbon energy sources and actual energy grids in the USA. Moreover, a stochastic LCA was performed to quantify the effect of process uncertainty on the environmental performance of the considered technology. Finally, the implications of replacing the conventional coal with waste-coal pellets in industrial processes was assessed.

1 Methods

1.1 Environmental LCA

This work performs the LCA of the coal-pellet production. The assessment was conducted in line with the requirements of the standardized LCA approach (ISO14040:2006) in OpenLCA using the US Life Cycle Inventory Database by the National Renewable Energy Laboratory (NREL) [8]. This work used the harmonized method to LCA (ReCiPe method [24]) and reported the following ReCiPe impact indicators:

- Midpoint indicators: (Table 1)
 - global warming
 - fossil-fuel depletion
 - freshwater ecotoxicity
 - human toxicity
 - marine ecotoxicity
 - marine eutrophication
 - terrestrial acidification
 - particulate-matter formation

- photochemical-oxidant formation
- End-point indicators:
 - damage to ecosystems
 - damage to human health
 - damage to resource availability.

It needs to be noted that the main aim of this study was to assess whether the recovery of waste coal from impoundments can reduce the global warming associated with the coal supply to industrial processes. The secondary goal was to evaluate the potential benefits to terrestrial and marine

ecosystems, and human health. Therefore, all ReCiPe mid-points were estimated for the considered cases to accurately estimate the end-point indicators. However, only those with values of >0.001 unit/GJ_{ch} were reported in this study.

The ReCiPe method can be performed considering different cultural perspectives representing different expectations of how technology development can mitigate the damage in the future [24]. These cultural perspectives can be summarized as:

- individualist perspective (optimistic) expects that the technology can mitigate damages in the short term;

Table 1: Overview of the ReCiPe midpoints [24]

Indicator	Description
Global warming (kg CO _{2,eq} /GJ _{ch})	Represents the atmospheric greenhouse-gas emissions that lead to increased global warming. Increased temperature causes damage to human health and ecosystems
Fossil-fuel depletion (kg oil _{eq} /GJ _{ch})	Represents the increased cost associated with an increase in fossil-fuel extraction (i.e. conventional oil is cheaper to extract than enhanced oil recovery)
Freshwater ecotoxicity (kg 1,4-DCB _{eq} /GJ _{ch})	Represents environmental persistence, accumulation in freshwater systems and toxicity of a specific chemical. Emission into the environment causes damage to ecosystems
Human toxicity (kg 1,4-DCB _{eq} /GJ _{ch})	Represents environmental persistence, accumulation in the human food chain and toxicity of a specific chemical. Emission into the environment causes damage to human health and ecosystems
Marine ecotoxicity (kg 1,4-DCB _{eq} /GJ _{ch})	Represents environmental persistence, accumulation in the marine systems and toxicity of a specific chemical. Emission into the environment causes damage to ecosystems
Marine eutrophication (kg N _{eq} /GJ _{ch})	Represents run-off of plant nutrients from the soil into riverine or marine systems, causing an increase in nutrients level. Nutrient enrichment can cause damage to ecosystems
Terrestrial acidification (kg SO _{2,eq} /GJ _{ch})	Represents the atmospheric deposition of inorganic substances (sulphates, nitrates, phosphates) that can change the acidity of soil. A suboptimal level of inorganic substances causes damage to ecosystems
Particulate-matter formation (kg PM10 _{eq} /GJ _{ch})	Represents the air pollution of particulate matter that results in aerosols creation in the atmosphere. Increased aerosols concentration causes damage to human health
Photochemical-oxidant formation (kg NMVOCs/GJ _{ch})	Represents the air pollution of NOx and non-methane volatile organic compounds (NMVOCs) that cause the formation of ozone in the atmosphere. Increased concentration of aerosols can cause damage to human health

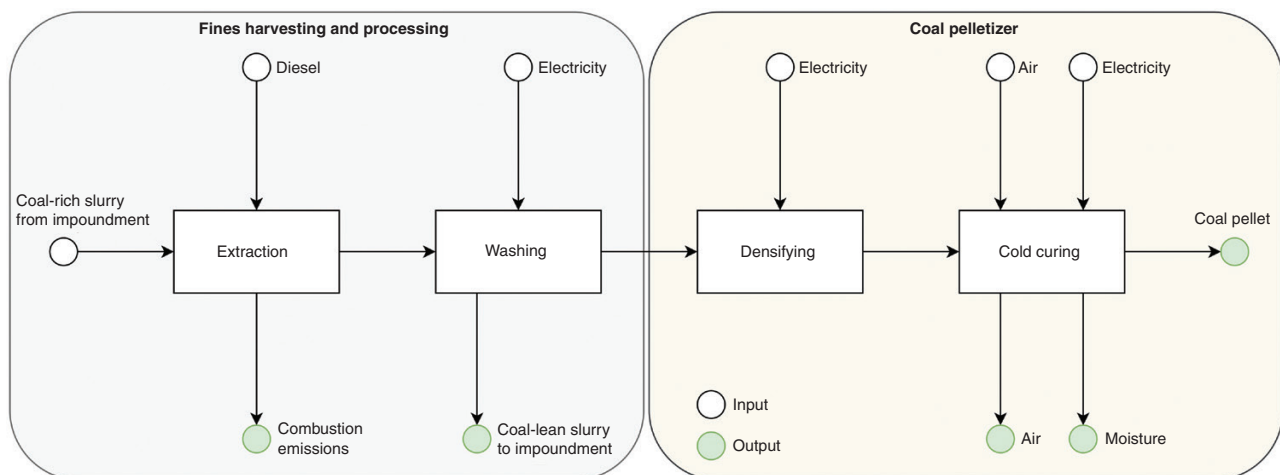


Fig. 1: Block flow diagram of coal-processing technology.

- hierarchist perspective (baseline) expects that the technology can mitigate damages in the midterm;
- egalitarian (pessimistic) expects that the technology can mitigate damages in the long term.

The hierarchist perspective was taken as a default cultural perspective in this study. The process included in the scope of this study includes four distinctive stages, as detailed in Section 1.2, representing the cradle-to-gate system boundary. The consumption of materials and energy required to construct the machinery and equipment is not included in this study [25]. Unless otherwise stated, the functional unit used in this analysis was 1 gigajoule of chemical energy (GJ_{ch}) stored in the coal pellets. Therefore, the results shown in this report are normalized, using the higher heating value of the final product of $28.85 \text{ GJ}_{\text{ch}}/\text{t}$.

1.2 Goal and scope

The ultimate goal of this LCA study was to determine whether replacing conventional coal with waste-coal pellets would result in a reduction in the global-warming impact of coal use in the midterm. The secondary goal was to evaluate the potential benefits in terms on human and environmental health.

The scope of this assessment included extraction and washing of waste-coal fines from impoundments, coal-pellets production and pellets curing. The coal-processing technology considered in this study aims to produce a pelletized coal product from waste material stored in coal-waste impoundments. The four distinct phases of the process are shown in Fig. 1. Transport is not considered in this analysis.

In the first step of the considered process, a coal-rich slurry is extracted from the waste-coal impoundment

Table 2: Extraction-process inputs and outputs

Parameter	Input	Output
Coal-rich slurry impoundment (t/hr)	250	
Diesel (L/hr)	106	
Coal-rich slurry extracted (t/hr)		250
CO_2 emission (kg/hr)		284.48
CO emission (kg/hr)		1.70
NO_x emission (kg/hr)		2.27
HC emission (kg/hr)		0.52
PM emission (kg/hr)		0.02

Table 3: Summary of atmospheric emissions from diesel combustion [28]

Diesel emission (Euro V)	Value (g/L)
CO_2	2684.00
CO	16.08
NO_x	21.44
HC	4.93
PM	0.21

using front-end loaders and pit trucks. The extracted slurry usually comprises 20–25% suspended solid coal waste. Therefore, before the coal waste can be pelletized, it is further processed in a washing unit that uses a combination of a scalping screen, two-stage froth cells and a centrifuge to reduce the moisture content from 75–80% to 20–25%. The washed fines are then transported for treatment using the formula patented by Changeover Technologies [26] and subsequently fed into the densifying unit. In the densifying unit, the formula binds the fines at a molecular level, producing smooth-faced pellets. The produced pellets are then transported to a cold-curing unit, where they are exposed to air for an extended period. At this stage, the pellets attain their final strength and water-resistance. Moreover, the moisture content is further reduced to 5–18%, depending on the atmospheric conditions. The entire process takes place at atmospheric temperature and pressure. Therefore, the only energy requirement for the process is associated with the electricity required to drive the machinery.

1.3 Inventory analysis

The inputs and outputs for the analysed coal-processing technology have been provided by Changeover Technologies. The data provided included energy and material balances for each step of the process, enabling cradle-to-gate analysis.

At the extraction step, 250 t/hr of coal-rich slurry is harvested from the coal impoundment (Table 2). This

Table 4: Washing-process inputs and outputs

Parameter	Input	Output
Coal-rich slurry extracted (t/hr)	250	
Electricity (kW_{el})	503.55	
Feed conveyor (kW_{el})	18.65	
Scalping screen (kW_{el})	18.65	
Feed-slurry pump (kW_{el})	74.60	
Froth cells (kW_{el})	111.90	
Centrifuge (kW_{el})	186.50	
Tailings-slurry pump (kW_{el})	74.60	
Product conveyor (kW_{el})	18.65	
Extracted coal, wet (t/hr)		62.5
Coal-lean slurry to impoundment (t/hr)		187.5

Table 5: Coal-pelletizer inputs and outputs

Parameter	Input	Output
Densifying step		
Extracted coal, wet (t/hr)	62.5	
Electricity (kW_{el})	1443	
Coal pellets, wet (t/hr)		62.5
Cold-curing step		
Coal pellets, wet (t/hr)	62.5	
Electricity (kW_{el})	120	
Cured pellets, dry (t/hr)		50
Water vapour (t/hr)		12.5

step requires a pit front-end loader, two pit trucks and a plant front-end loader. Each unit is assumed to consume 26.5 litres of diesel per hour ($0.0265 \text{ m}^3/\text{hr}$) [27]. The emissions associated with diesel combustion were estimated based on the data reported by Resitogu *et al.* [28] and are presented in Table 3. Importantly, a study by Babbitt and Lindner [22, 23] showed that waste-coal disposal is only associated with 0.2% of the global warming caused by coal extraction. Therefore, the share of impacts from the first-life use of the waste was not considered in this study.

At the washing step, the high moisture content in the extracted coal-rich slurry is reduced to 20%. The only input to this process is the electricity to drive the moisture-separation equipment. For the washer processing 250 t/hr of coal-rich slurry, the energy requirement has been estimated to be $503.55 \text{ kW}_{\text{el}}$, as summarized in Table 4.

Once the coal fines have been harvested and washed, they are transported to the coal pelletizer for densification and cold-curing. At the densification step, the coal fines are mixed with a small fraction of the binder ($\sim 0.4\%$). Because of its marginal content and proprietary formulation, the binder has not been included in the analysis. The only input to this process is electricity to drive the process. It is also the case for the cold-curing process. The energy requirement for both steps is summarized in Table 5.

It is initially assumed that the electricity is supplied via the natural-gas combined-cycle power plant in the USA. This is because natural gas is still the major source of electricity in the USA [29]. The total energy requirement of the coal-processing technology is $0.034 \text{ kW}_{\text{el}}/\text{kg}_{\text{dry pellet}}$, corresponding to $1.16 \text{ kW}_{\text{el}}/\text{GJ}_{\text{ch}}$. Its environmental impact has been determined using the predefined electricity-generation process from natural gas available in the US

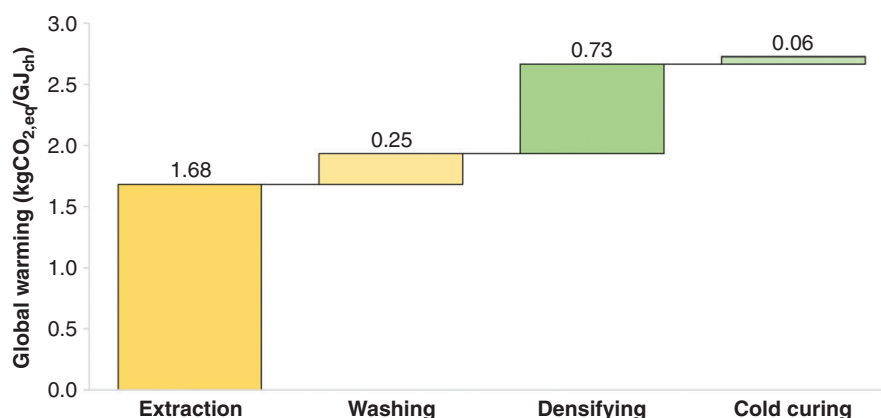


Fig. 2: Distribution of global warming for the coal-processing technology from a hierarchist perspective.

Table 6: Comparison of environmental midpoint impact categories for pellet coal and conventional coal from a hierarchist (baseline) perspective

Indicator	Waste-coal pellets	Conventional coal	Relative change (%)
Fossil-fuel depletion ($\text{kg oil}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	5.31	32.96	-83.87
Freshwater ecotoxicity ($\text{kg 1,4-DCB}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	0.05	0.35	-84.84
Human toxicity ($\text{kg 1,4-DCB}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	8.10	53.44	-84.83
Marine ecotoxicity ($\text{kg 1,4-DCB}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	0.05	0.36	-84.84
Marine eutrophication ($\text{kg N}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	0.05	0.36	-84.84
Terrestrial acidification ($\text{kg SO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$)	0.02	0.11	-77.46
Particulate-matter formation ($\text{kg PM}_{10,\text{eq}}/\text{GJ}_{\text{ch}}$)	0.01	0.03	-79.49
Photochemical-oxidant formation ($\text{kg NMVOCs}/\text{GJ}_{\text{ch}}$)	0.03	0.17	-83.84

Table 7: Comparison of fossil-fuel requirements for pellet coal and conventional coal

Fossil requirement	Waste-coal pellets	Conventional coal
Bituminous coal, combusted in industrial boiler ($\text{kg}/\text{GJ}_{\text{ch}}$)	0.000	0.015
Natural gas, combusted in industrial boiler ($\text{m}^3/\text{GJ}_{\text{ch}}$)	0.000	0.006
Gasoline, combusted in equipment ($\text{L}/\text{GJ}_{\text{ch}}$)	0.000	0.029
Residual fuel oil, combusted in industrial boiler ($\text{L}/\text{GJ}_{\text{ch}}$)	0.000	0.030
Diesel, combusted in industrial boiler ($\text{L}/\text{GJ}_{\text{ch}}$)	0.000	0.305
Diesel, combusted in equipment ($\text{L}/\text{GJ}_{\text{ch}}$)	0.073	0.000
Electricity ($\text{kW}_{\text{el}}/\text{GJ}_{\text{ch}}$)	1.433	1.343

Life Cycle Inventory Database by National Renewable Energy Laboratory [8].

2 Results and Discussion

2.1 Environmental-impact assessment under initial design conditions

The initial assessment of the coal-processing technology has revealed that its cradle-to-gate global warming would be $2.72 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$ if the electricity consumed by the process is supplied via a natural-gas combined-cycle power plant. To better appreciate the distribution of these emissions, the contribution of each process stage to the total global warming is presented in Fig. 2. The extraction and washing stages account for most of the global warming (71.2%), as their operation results in global warming of $1.93 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$.

GJ_{ch} . This is associated with the diesel used in the front-end loaders and pit trucks during extraction ($1.68 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$) and the use of electricity during washing ($0.25 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$). The coal-processing unit results in global warming of $0.79 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$ (28.8%). These emissions stem solely from the electricity required to drive the process equipment.

The initial analysis of the process implied that a significant reduction in global warming can be achieved if the front-end loaders and pit trucks were replaced with more environmentally friendly alternatives. Potential options include a fuel-switching from diesel to biodiesel, hydrogen or electrification of the process. In all cases, further analysis needs to be performed to ensure that indirect emissions associated with the production of the alternative fuels and energy vectors do not outweigh the benefits of replacing the direct emissions associated with diesel combustion. In the case of the coal-processing unit, the majority of the

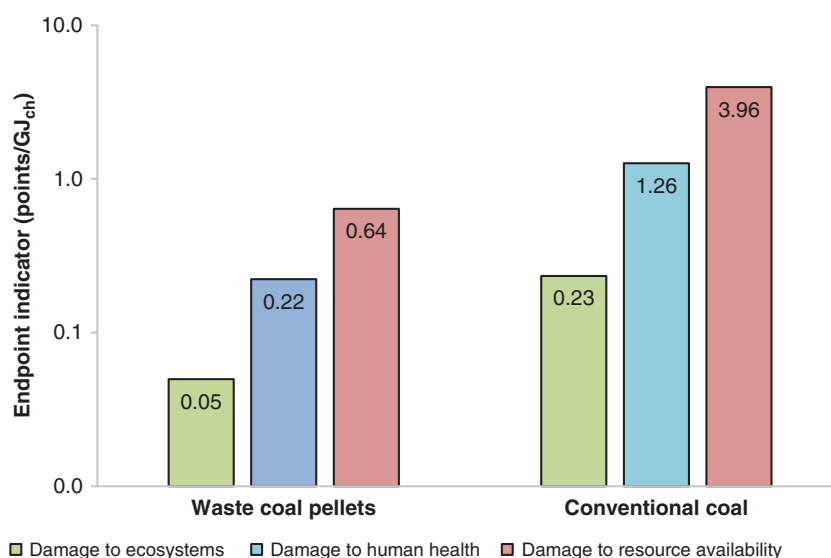


Fig. 3: Comparison of environmental end-point impact categories for waste-coal pellets and conventional coal from a hierarchist (baseline) perspective.

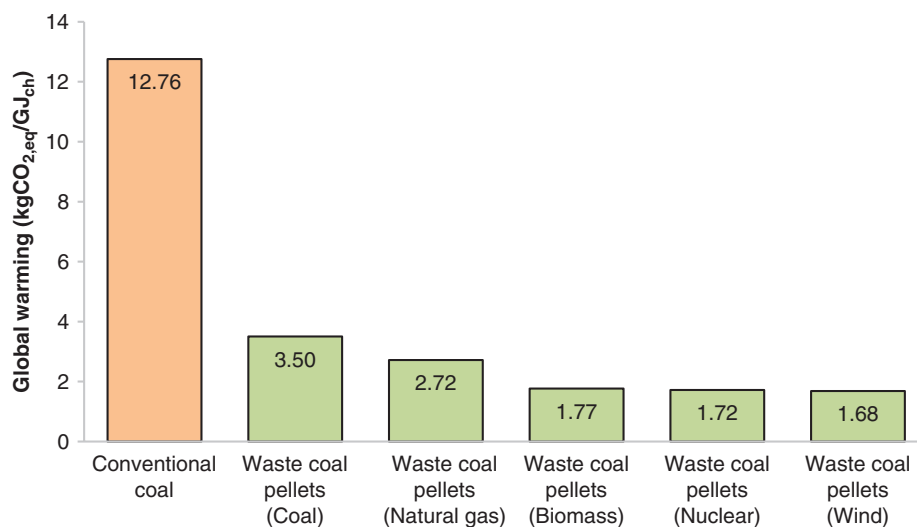


Fig. 4: Effect of electricity source on the global warming of waste-coal pellets from a hierarchist perspective.

global warming comes from the electricity requirement of the densifying unit. As the initial analysis considered that the electricity is produced in a natural-gas combined-cycle power plant, low-carbon alternatives, such as renewables and nuclear, should be considered for power generation.

2.2 Comparison of waste-coal processing and a conventional coal mine

The main aim of the waste-coal processing technology is to reduce the environmental impact of the coal supply to the industries that utilize coal as part of their operation, such as the steel industry. Therefore, its environmental performance needs to be compared with the coal supply from conventional coal mines. The cradle-to-gate global warming of the conventional coal supply in the USA was estimated to be $12.76 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$, assuming that the average calorific value of bituminous coal is $28.83 \text{ GJ}_{\text{ch}}/\text{t}$. These emissions mostly stem from the coal-mine operation associated with its diesel, residual oil and electricity requirement, and residual methane emissions (i.e. 4 kg CH_4 per tonne of coal extracted) specified in the NREL database [8].

By comparing the global warming of the conventional coal process and the waste-coal processing technology, including the harvesting and washing steps, it can be observed that the latter has the potential to reduce the global warming associated with coal supply by $\leq 78.7\%$. It is a significant reduction, considering that the operation of coal-processing technology is still driven by diesel and natural gas.

To understand the broader environmental performance of the waste-coal processing technology and the conventional coal-mining process, a range of midpoint indicators were assessed (Table 6). Considering the cradle-to-gate performance of both processes, it is apparent that the pelletized coal produced from the waste-coal impoundments can reduce our reliance on fossil fuels, as its contribution to fossil-fuel depletion is 83.9% lower than that in conventional coal mining. It can be explained by a significant reduction in the fossil fuels required to produce 1 GJ_{ch} equivalent of pellets compared to the conventional coal process (Table 7) [8].

In general, the supply chain of pelletized coal is much shorter and simpler than that of conventional coal. As a result, the formation of particulate matter, formation of photochemical oxidants, the negative effects on ecosystems via eutrophication and acidification routes, and human toxicity are reduced by $78\text{--}85\%$. This implies that the recovery of waste fines from coal impoundments is a viable way to improve the overall environmental performance of the coal supply to industrial performance.

Considering the end-point indicators, the coal pellets supplied via the waste-coal processing technology are expected to be associated with less damage to ecosystems, human health and resource availability compared to the coal supplied via the conventional mining process. Fig. 3 indicates that the damage to the ecosystem (species loss per year due to the environmental impact of a given process) will be reduced by 78.7% . Similarly, the damage to human health

Table 8: Comparison of environmental midpoint impact categories for pellet coal and conventional coal from a hierarchist (baseline) perspective

Indicator	Conventional	Waste-coal pellets (coal)	Waste-coal pellets (natural gas)	Waste-coal pellets (biomass)	Waste-coal pellets (nuclear)	Waste-coal pellets (wind)
Fossil-fuel depletion ($\text{kg oil}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	32.96	5.61	5.31	4.62	4.62	4.56
Freshwater ecotoxicity ($\text{kg 1,4-DCB}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	0.35	0.06	0.05	0.05	0.05	0.05
Human toxicity ($\text{kg 1,4-DCB}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	53.44	9.13	8.10	7.49	7.49	7.38
Marine ecotoxicity ($\text{kg 1,4-DCB}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	0.36	0.06	0.05	0.05	0.05	0.05
Marine eutrophication ($\text{kg N}_{\text{eq}}/\text{GJ}_{\text{ch}}$)	0.03	0.01	0.01	0.01	0.01	0.01
Terrestrial acidification ($\text{kg SO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$)	0.11	0.03	0.02	0.01	0.01	0.01
Particulate-matter formation ($\text{kg PM}_{10,\text{eq}}/\text{GJ}_{\text{ch}}$)	32.96	5.61	5.31	4.62	4.62	4.56
Photochemical-oxidant formation ($\text{kg NMVOCs}/\text{GJ}_{\text{ch}}$)	0.35	0.06	0.05	0.05	0.05	0.05

(disability-adjusted loss of life years due to the environmental impact of a given process) will be reduced by 82.4%. Finally, the damage to resource availability (surplus cost of using a given process) will be reduced by 83.9%.

2.3 Effect of the electricity source on environmental performance

The analysis presented above assumed that the electricity required to drive the waste-coal processing technology

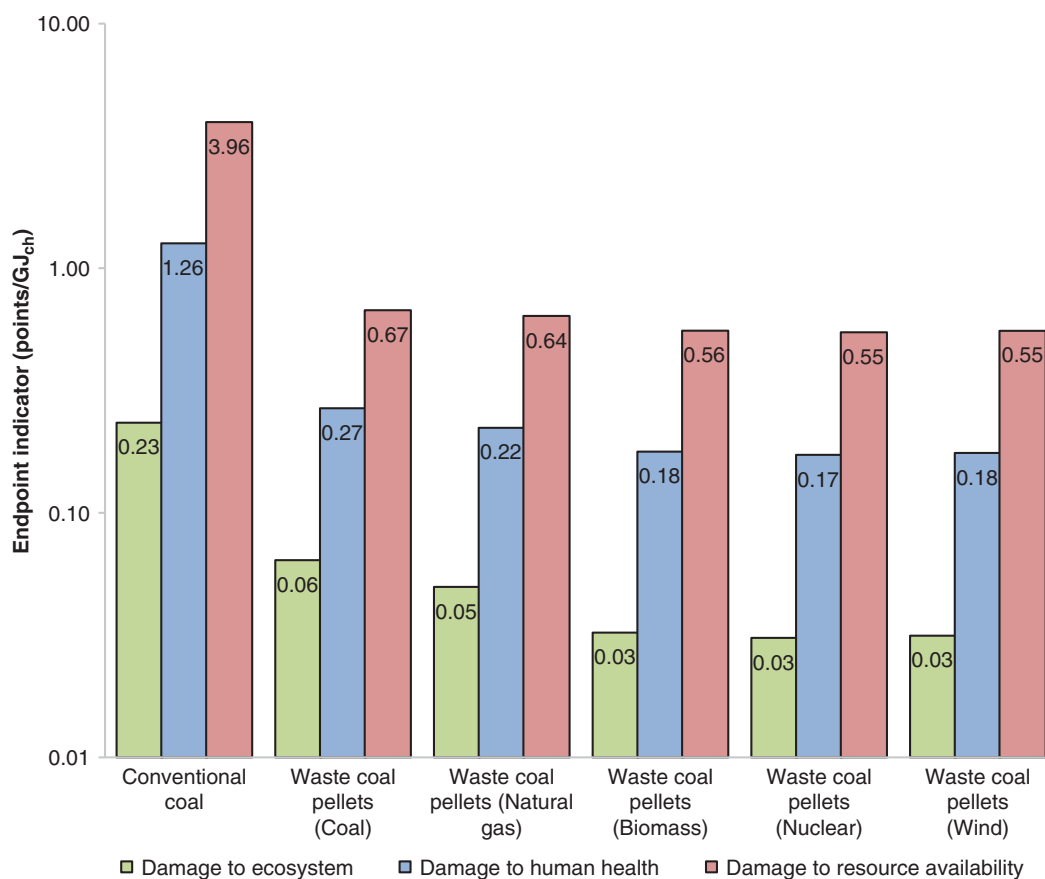


Fig. 5: Effect of electricity source in the waste-coal processing technology on damage to ecosystem, human health and resource availability from a hierarchist (baseline) perspective.

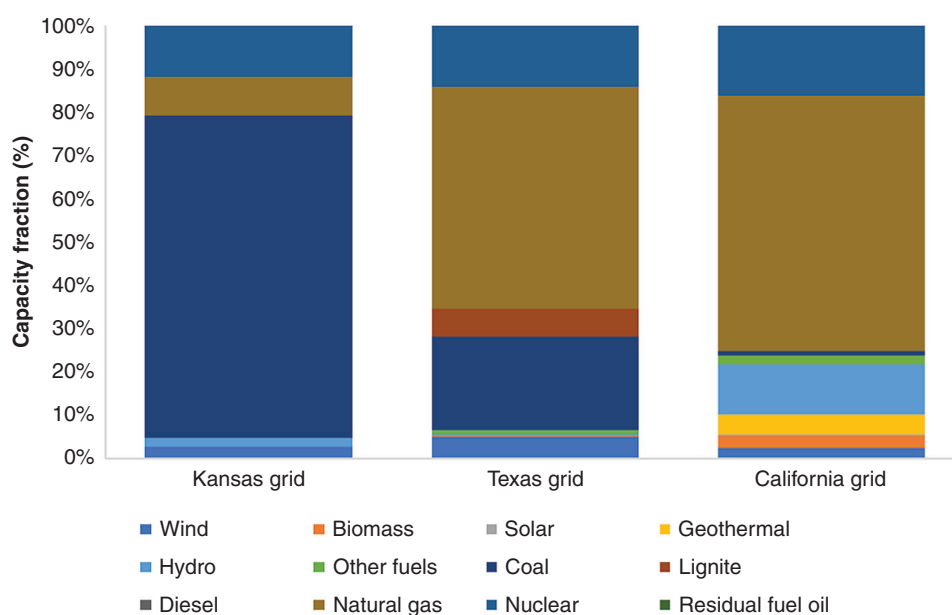


Fig. 6: Distribution of electricity sources in Kansas, Texas and California grids [8].

was supplied from a natural-gas combined-cycle power plant. Although the environmental performance of such a process is improved compared to the conventional coal process, it is worth exploring whether the use of other electricity sources would result in a further improvement in environmental performance. For comparison purposes, coal, biomass, nuclear and wind are considered as potential electricity sources for the waste-coal processing technology.

Fig. 4 demonstrates that if the considered process is driven by electricity produced in an unabated coal-fired power plant, its global warming will be 28.8% higher than that of a process driven by natural gas. Yet, the waste-coal pellets still remain competitive to conventional coal, offering a 72.6% reduction in global warming. A further reduction in global warming to 1.68–1.77 kgCO_{2,eq}/GJ_{ch} can be achieved if renewables (biomass and wind) or nuclear are considered as the electricity sources.

It can be also observed that the global warming for the waste-coal processing technology driven by wind electricity stems solely from the extraction step, as it was previously shown to result in global warming of 1.68 kgCO_{2,eq}/GJ_{ch}. It means that the coal-pelletizer operation does not contribute to global warming if it is driven by wind energy. A further reduction in global warming can be achieved by replacing diesel used as a fuel in the front-end loaders and pit trucks with low-carbon alternative fuels, such as biodiesel, hydrogen or low-carbon synthetic fuels. However, the influence of the cost of low-carbon fuel and replacing the existing equipment on the economic viability of the waste-coal processing technology needs to be assessed before these changes are considered.

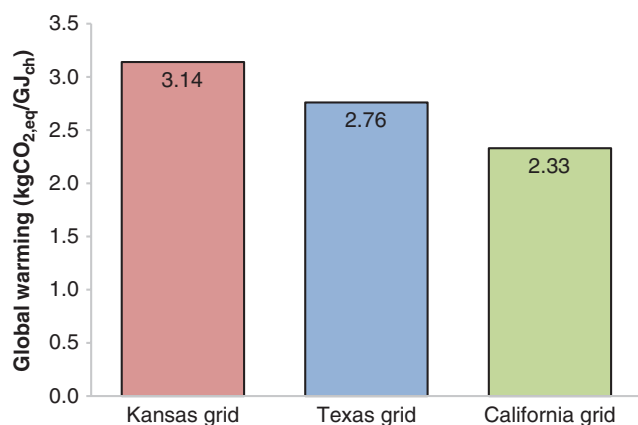


Fig. 7: Effect of electricity mix on the global warming of waste-coal pellets from a hierarchist perspective.

The effect of the electricity source on the environmental midpoint impact categories is presented in Table 8. It can be concluded that the use of renewables and nuclear sources will bring a further reduction in fossil-fuel depletion and human toxicity. The potential reductions in eutrophication, acidification, as well as the formation of particulate matter and photochemical-oxidant formation are less pronounced. This is because those stem mostly from the diesel requirement in the extraction and washing steps. For this reason, the added environmental benefits of using low-carbon electricity sources are small in terms of the potential reduction in the damage to ecosystems, human health and resource availability (Fig. 5).

It is likely that waste-coal processing technology will be driven by electricity from the grid. Therefore, it is worth examining how this process will perform under different grid conditions. Using the predefined processes in the database by the US Life Cycle Inventory Database by National Renewable Energy Laboratory [8], the grids in Kansas, Texas and California were considered. Fig. 6 presents the distribution of the electricity sources in selected local grids. It can be noted that the Kansas grid represents a scenario that is highly dependent on coal, natural gas and nuclear sources. On the contrary, the California grid represents a more balanced scenario that mostly relies on natural gas, nuclear and various renewables. The Texas grid represents a scenario of high dependency on fossil fuels, but with natural gas as the main source of electricity.

The results presented in Fig. 7 are in line with the discussion presented above. Namely, the global warming of the waste-coal processing technology will be lower in grids with a higher penetration of renewable energy, such as the California grid (2.33 kgCO_{2,eq}/GJ_{ch}). This is 25.8% lower than in the case of the most coal-reliant Kansas grid (3.14 kgCO_{2,eq}/GJ_{ch}). Nevertheless, this proves that the use of waste coal can be a viable option to replace conventional coal, considering the realistic grid conditions.

2.4 Effect of process uncertainty on environmental performance

The environmental performance of the waste-coal processing technology presented before relied on the deterministic assumptions provided by Changeover Technologies. Such an approach to environmental assessment does not account for any uncertainties and inaccuracies in the input/output data representing the process performance. As the environmental impact of the considered process depends

Table 9: Assumptions for the stochastic modelling

Parameter	Mean value	Coefficient of variation
Diesel consumption at extraction stage (m ³ /kg slurry)	4.2397E-7	20%
Electricity requirement at washing stage (kW _{el} h/kg extracted coal)	0.008060	20%
Electricity requirement at densifying stage (kW _{el} h/kg coal pellets)	0.023088	20%
Electricity requirement at cold-curing stage (kW _{el} h/kg cured pellets)	0.002400	20%

mostly on diesel and electricity consumption, these were considered as stochastic variables. It is assumed that each variable will be normally distributed with a coefficient of variation of 20% (Table 9). The stochastic assessment was performed to understand the impact of the selected stochastic variables on the environmental performance of the waste-coal processing technology driven by electricity from a natural-gas combined-cycle power plant.

The stochastic assessment (Fig. 8) has indicated that the mean value of the global warming, and hence the most likely value for this indicator, was shown to be $2.72 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$ with a standard deviation of $0.34 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$. There is a 95% probability that the global warming of the waste-coal processing technology process driven by natural gas will fall to within 2.05 and $3.39 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$ (2σ interval). It can be, therefore, concluded that the estimated mean

value is in line with the deterministic assessment. The full range for the global warming considering the $\pm 20\%$ variation in the electricity and diesel requirement was estimated to be between 1.38 and $4.17 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$.

2.5 Effect of coal-supply source on the global warming of industrial processes

To understand the benefits of using waste-coal pellets in industrial processes, a case study of a steelmaking plant is considered (Fig. 9). For this reason, the cradle-to-gate boundaries of the system originally stated in Section 1.2 have been extended to include coal transportation and use in the steelmaking process. For both waste-coal pellets and conventional coal, it was assumed that these were transported between the production site and the use site

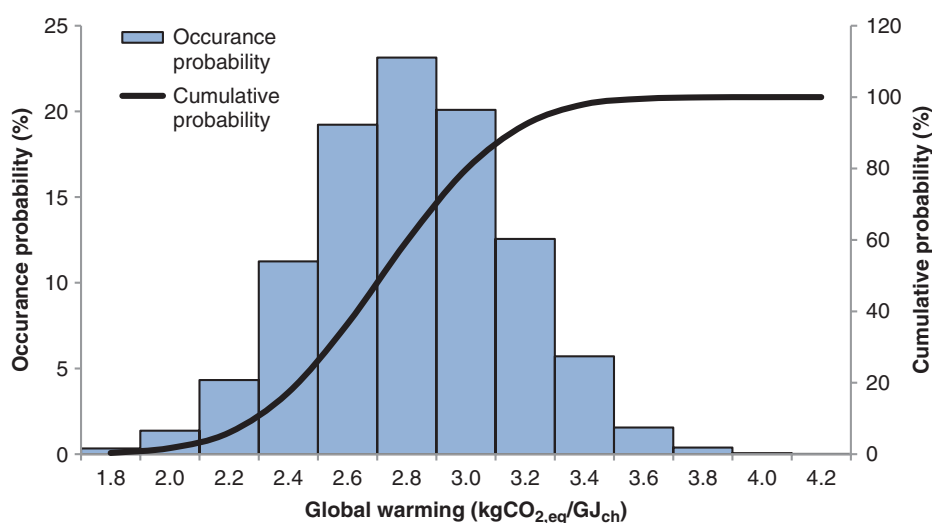


Fig. 8: Effect of uncertainty on global warming of the waste-coal processing technology from a hierarchist perspective.

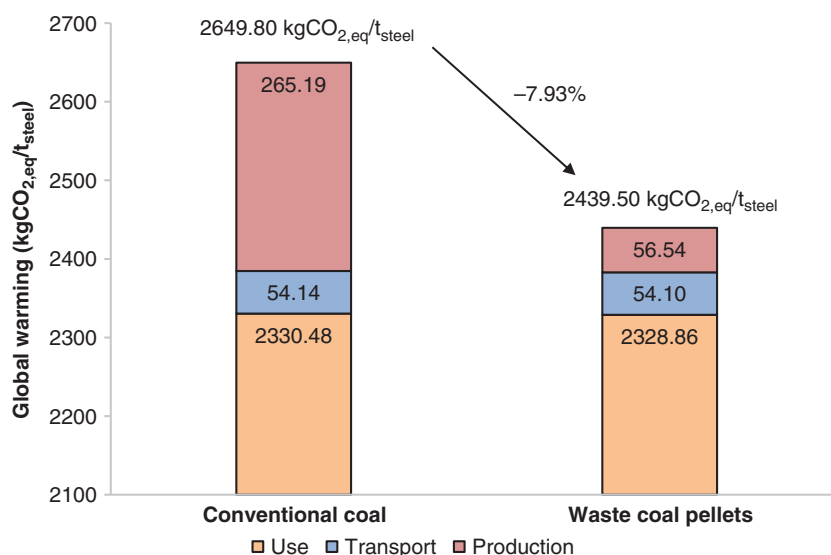


Fig. 9: Comparison of the global warming of waste-coal pellets and conventional coal application in a steelmaking plant from a hierarchist perspective.

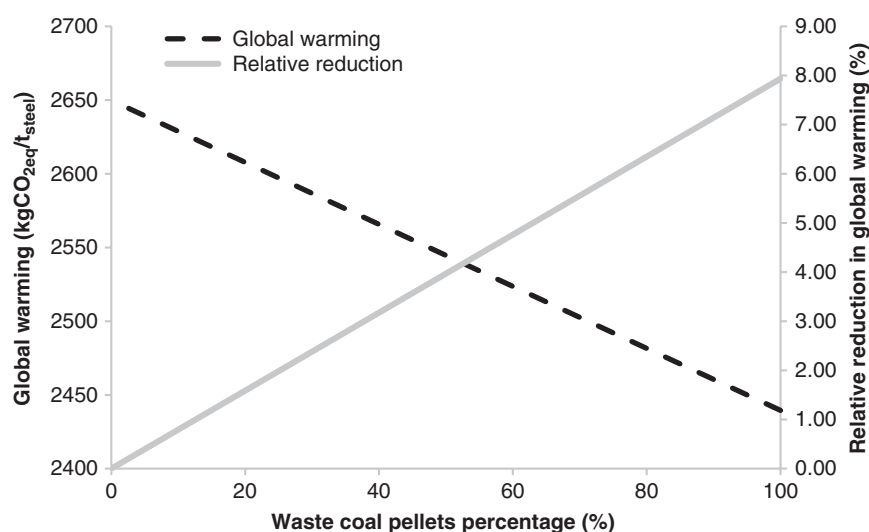


Fig. 10: Effect of waste-coal pellets percentage use in a steelmaking plant on specific CO₂ emissions.

Table 10: Comparison of lifetime emissions for onshore and offshore wind turbines made using steel produced from waste-coal pellets and conventional coal

Parameter	Onshore wind turbine	Offshore wind turbine
Steel requirement for turbine manufacturing ($t_{\text{steel}}/\text{turbine}$)	240	480
CO ₂ emissions per turbine made using waste-coal pellets ($\text{kgCO}_{2,\text{eq}}/\text{turbine}$)	585 480.0	1 170 960.0
CO ₂ emissions per turbine made using conventional coal ($\text{kgCO}_{2,\text{eq}}/\text{turbine}$)	635 952.0	1 271 904.0
Average turbine output (MW_{el})	2.0	4.0
Average load factor (–)	0.25	0.30
Annual operating time (h)	2190.0	2628.0
Lifetime (years)	20.0	20.0
Electricity produced ($\text{MW}_{\text{el}}\text{h}$)	87 600.0	210 240.0
Specific lifetime emissions for a turbine made of steel produced using waste-coal pellets ($\text{kgCO}_2/\text{MW}_{\text{el}}\text{h}$)	6.7	5.6
Specific lifetime emissions for a turbine made of steel produced using conventional coal ($\text{kgCO}_2/\text{MW}_{\text{el}}\text{h}$)	7.3	6.0

via a diesel-fuelled train. An average transport distance of 500 km was assumed. A steelmaking plant considered in this case study was assumed to produce galvanized-steel sheets. The characteristics of the considered transport type and industrial process were predefined in the US Life Cycle Inventory Database by the National Renewable Energy Laboratory [8]. To ensure that the results are representative of the steelmaking industry, the functional unit for this analysis was 1 tonne of galvanized-steel sheets.

As shown in Fig. 9, the global warming of steelmaking will be 2439.50 $\text{kgCO}_{2,\text{eq}}/\text{t}_{\text{steel}}$ when the coal is supplied from the waste-coal processing technology. This is 7.93% less than the global warming for the conventional process (2649.80 $\text{kgCO}_{2,\text{eq}}/\text{t}_{\text{steel}}$). Importantly, the global-warming figure for the steelmaking process using the conventional process is in line with the data reported in the literature [30, 31]. It needs to be emphasized that extraction of the conventional coal accounted for 10.0% (265.19 $\text{kgCO}_{2,\text{eq}}/\text{t}_{\text{steel}}$) of the global warming of the steelmaking plant. In contrast, the recovery of waste coal accounted only for

2.3% (56.54 $\text{kgCO}_{2,\text{eq}}/\text{t}_{\text{steel}}$) of the global warming of the entire process. It is also worth mentioning that coal transportation via diesel-fuelled trains accounted for 2.0% and 2.2% of the global warming of the entire process, respectively. Importantly, even a partial substitution of, for example, 40% waste-coal pellets in the coke oven will result in a 3.4% reduction in the CO₂-equivalent emissions of steelmaking, considering both coal processing, transport and use (Fig. 10). Overall, this analysis implied that decarbonization of the coal-supply chain can bring a meaningful reduction in industrial greenhouse-gas emissions, even before these processes are fully decarbonized.

It is important to emphasize that an imminent reduction in the global-warming impact of the steelmaking industry is essential to ensure net-zero energy production from renewable energy sources. Even though the operation of renewable energy sources does not result in CO₂ emissions, the manufacturing of their components and foundations requires steel. For example, an onshore 2-MW wind turbine requires 240 tonnes of steel [5]. Currently,

~70% of steel is produced via the integrated steelmaking route. Production of 1 tonne of steel via this route requires 780 kg of metallurgical coal. It means that 187.2 tonnes of metallurgical coal is required to produce steel for a single onshore 2-MW wind turbine [6]. This figure reduces to 36 tonnes of metallurgical coal when the steel is produced in the electric arc furnace, as this route requires only 150 kg of coal per tonne of steel [6]. Assuming a complete substitution of conventional coal with waste-coal pellets at a steelmaking plant, it was estimated that the indirect emissions associated with an onshore and offshore wind turbine can be reduced by 8.6% (Table 10). This further emphasizes the need for imminent decarbonization of the coal-supply chain, even though a full phase-out of coal use is needed to achieve the emission-reduction targets set out in the Paris Agreement.

3 Conclusions

This study aimed to perform the life-cycle environmental assessment of waste-coal processing technology and compare it with the performance of the conventional coal process. It is concluded that:

- the cradle-to-gate global warming of the waste-coal processing technology ($1.68\text{--}3.50 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$) is 78.7% lower than that of the conventional coal process ($12.76 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$);
- the uncertainty analysis has indicated that the global warming of the waste-coal processing technology driven by natural gas will fall to within 2.05 and $3.39 \text{ kgCO}_{2,\text{eq}}/\text{GJ}_{\text{ch}}$ (95% probability);
- use of the waste coal from impoundments can reduce our reliance on fossil fuels by 83.9% compared to that in conventional coal mining;
- the use of the coal pellets produced can result in an immediate reduction in industrial greenhouse-gas emissions, e.g. by 7.93% in the case of steelmaking;
- a complete substitution of conventional coal with waste-coal pellets would result in a reduction in the global warming of steelmaking from 2649.80 to $2439.50 \text{ kgCO}_{2,\text{eq}}/\text{t}_{\text{steel}}$, respectively. This, in turn, would reduce the life-cycle greenhouse-gas emissions of wind-turbine manufacturing by $\leq 8.6\%$.

Although the use of coal will need to be phased out to limit the mean global temperature increase to 1.5°C , this study proved that recovery of the waste coal from impoundments can reduce the greenhouse-gas emissions from power- and energy-intensive processes in the short term, before these processes are fully decarbonized. This work can be further extended to the cradle-to-grave life-cycle analysis by including the process in which waste-coal pellets are utilized. Moreover, to gain a complete picture of the viability of replacing conventional coal with waste-coal pellets, an economic assessment should be performed. Finally, alternative low-carbon fuels or energy vectors

should be considered in place of diesel-driven frond-end loaders and pit trucks at the extraction stage.

Acknowledgements

This publication is based on research conducted within the 'Environmental assessment of waste coal purification' project funded by Changeover Technologies. Data available on request.

Conflict of interest statement

None declared.

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Environmental life-cycle assessment of waste-coal pellets production

Hanak, Dawid P.

2021-12-20

Oxford University Press

<https://doi.org/10.1093/ce/zkab050>

Hanak DP. (2022) Environmental life-cycle assessment of waste-coal pellets production, Clean Energy, Volume 6, Issue 1, February 2022, pp. 765-778