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The CO_2 Reduction Potential of using Black Pellets for Energy Production in Romania

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In this study, a contextual analysis of the CO_2 reduction potential by using black pellets for energy production in Romania was performed. Black pellets have similar fuel properties to that of coal, thus representing a sustainable and environmentally friendly alternative for power generation. To assess the CO_2 emissions reduction potential of the black pellet technology, two value chains for energy production were compared: one utilizing black pellets and the other using coal as the primary fuel source. The value chain of black pellets consists of biomass harvesting, the transportation of biomass from its source to the black pellets production plant, which incorporates pretreatment and steam explosion units, and finally, the utilization of black pellets for power production. The coal value chain encompasses coal mining, the transportation of the extracted coal to the power plant, and subsequent power generation. The total CO_2 emissions for power generation in a 50 MW using black pellets and coal amounted to 16.27 and 272.10 kton/y, respectively. This substantial difference in emissions primarily stems from the higher emissions associated with coal extraction and the release of CO_2 during coal combustion for power production. It is important to emphasize that power generation from black pellets results in net-zero emissions during combustion since biomass captures and stores CO_2 throughout its lifecycle. The results of this analysis demonstrate the environmental advantages attainable by replacing coal with black pellets, thus promoting a more sustainable approach to energy production.

1. Introduction

Use of black pellets as fuel for energy production has gained importance due to their potential for reduced emissions compared to traditional fossil-based fuels since they are produced from biomass (wood or forestry residues). In addition, they have good properties such as low moisture content and high heating value (21.3 MJ/kg) that make them suitable for direct substitution for coal (del Alamo Serrano and Tranås, 2019). Despite its advantages, competitive market for biomass creates challenges for widespread utilization of black pellets. A similar situation is observed in Romania due to increasing demand for feedstock and the proliferation of black pellet producers searching for raw materials since there has been a decline in the wood exploitation and processing, mainly as a result of limited access to forests, instabilities in legislation and bureaucratic hurdles even though there is interest for greening the power production sector in Romania (Birgen and Sannan, 2023). To build on this interest and create a basis for environmental gains, this study aims to provide a contextual analysis for the CO_2 reduction potential of using black pellets for energy production in Romania. A value chain perspective is followed since it can cover a wide variety of aspects necessary for a realistic evaluation of a new technology as employed by other researchers in the field for biomass utilization (Caporusso et al., 2022). Coal substitution with biomass has been studied for co-gasification to improve environmental performance (Sofia et al., 2013), indicating the potential for 16% decrease in CO_2 emissions. However, black pellets have the possibility of entirely replacing coal that would increase the gains even more.
The term "black pellet" is used to describe the torrefaction of pelletized materials (Kudo et al., 2019) or the resultant product obtained from pelletization of torrefied materials (Rudolfsson et al., 2017). Pellets formed without heat treatment are commonly known as white pellets. Due to the darkening of pellet colour during high-temperature treatment, the term "black pellets" is applied to distinguish them from the established white pellets. However, the designation "torrefied pellets" is also employed for fuels subjected to torrefaction. In both literature

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and commercial use, the production of black pellets frequently involves steam, which serves as a distinguishing factor. Various methods, including steam explosion (Arbaflame), torrefaction under pressurized steam (conducted at 245-265 °C, 10-39 bar) (Kudo et al., 2019), steam torrefaction (experiments at 245-265 °C) (Arteaga-Pérez et al., 2017), and steam treatment (Valmet) are employed in black pellet production. These thermal processes have shown to increase the fuel properties such as hydrophobicity and surface characteristics increasing their desirability for green transition of the power production industry (Andersone et al., 2021). Steam explosion is the scope of this study due to its promising performance in production of high-quality black pellets.

2. Methodology

2.1 Value chain description

To evaluate the potential reduction in CO_2 emissions associated with the use of black pellets for energy production, two distinct value chains are examined. These value chains are classified as follows: the first involves a coal-based power plant (used as a reference case), and the second entails a power plant utilizing black pellets. Both power plants have a capacity of 50 MW for the generation of heat and power. Figure 1 provides a schematic representation of the two outlined value chains.

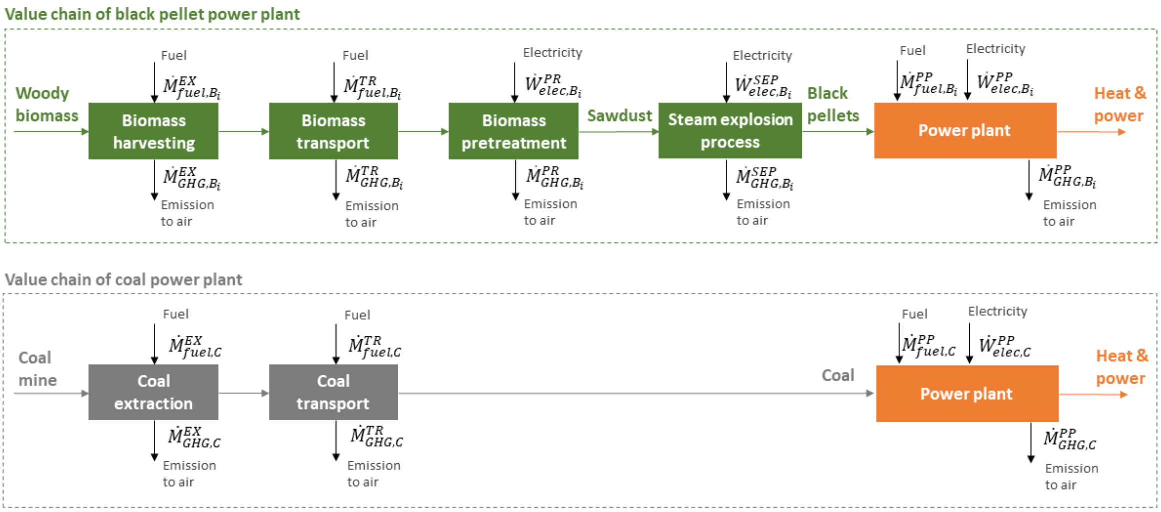

Figure 1: Value chains used in this study, which entails combustion of black pellets produced from steam explosion of woody biomass in a power plant (top), and combustion of coal in a power plant (bottom) based on a previously developed concept by del Alamo Serrano and Tranås (2019).

2.2 Value chain model

Both value chains commence from the extraction or harvesting of feedstock at the source, through transportation, and concluding with utilization within the power plant. To calculate the fuel demand for a plant with a capacity of 50 MW ($W_{capacity}$), expressed in the energy content of the supplied fuel and the higher heating value of the fuel, during 8000 hours of annual operation (t_{annual}), the following formulas are employed for both:

$$\dot{M}_{coal,C} = W_{capacity} / HHV_{coal} \times t_{annual} \times (3600\ s/h) \times (10^{-6}\ kton/kg)$$
(1)

$$\dot{M}_{blackpellet,B_i} = W_{capacity} / HHV_{blackpellet} \times t_{annual} \times (3600\ s/h) \times (10^{-6}\ kton/kg)$$
(2)

where $\dot{\mathbf{M}}_{\mathbf{coal,C}}$ and $\dot{\mathbf{M}}_{\mathbf{blackpellet,B_i}}$ are the annual coal and black pellet requirements in kton/y (kilotons per year), respectively, while $\mathbf{HHV_{coal}}$ and $\mathbf{HHV_{blackpellet}}$ denote the higher heating value of coal and black pellets.

$$\dot{M}_{blackpellet,B_i} = \dot{M}_{sawdust,B_i} \times y_{blackpellet} \quad (3)$$

$$\dot{M}_{sawdust,B_i} = \dot{M}_{wood,B_i} \times y_{sawdust} \quad (4)$$

where $\dot{M}_{sawdust,B_i}$ and $\dot{M}_{wood,B_i}$ are annual amounts of sawdust and wood in kton/y, respectively, and $y_{blackpellet}$ and $y_{sawdust}$ are yields of sawdust to black pellets and wood to sawdust.

2.3 CO_2 emissions from value chain of black pellet power plant

Biomass harvesting consists of cutting trees with diesel-powered chain saws. The diesel consumption rate for wood cutting is specified as 2 liters per cubic meter (Ghaffariyan et al., 2018), ($m_{diesel,wood}$). The associated CO_2 emissions resulting from diesel use are estimated as 2.64 kg CO_2 per liter of diesel ($m_{CO_2,diesel}$). Emissions from biomass harvesting are assumed only to be due to diesel use as given in Equation 5 and 6:

$$\dot{M}^{EX}_{GHG,B_i} = \dot{M}^{EX}_{fuel,B_i} \times m_{CO_2,diesel} \quad (5)$$

$$\dot{M}^{EX}_{fuel,B_i} = \dot{M}_{wood,B_i} \times m_{diesel,wood} / d_{wood} \quad (6)$$

Biomass transportation is transporting the harvested biomass to a biomass pretreatment facility. This transportation is assumed to be carried out using trucks fuelled by diesel. The emissions arising from this transport operation, denoted as $\dot{M}^{TR}_{GHG,B_i}$, are mainly due to diesel consumption, as given by Equation 7 and 8.

$$\dot{M}^{TR}_{GHG,B_i} = \dot{M}^{TR}_{fuel,B_i} \times m_{CO_2,diesel} \quad (7)$$

$$\dot{M}^{TR}_{fuel,B_i} = \dot{M}_{wood,B_i} \times m_{diesel,truck} \times L_{wood,Bi} / m_{load,truck} \quad (8)$$

where $\dot{M}^{TR}_{fuel,B_i}$ is the annual diesel consumption for biomass transport, $m_{diesel,truck}$ is the diesel consumption of the truck, (0.3 liters per km) $m_{load,truck,B_i}$ is the load capacity of the truck, assumed to be 12 tons per shipment (internal communication with a Romanian company), and L_{wood} is the average transport distance from the biomass source to the plant, taken as 200 km per shipment (internal communication with a Romanian company).
Biomass pretreatment is the production of sawdust from wood (log debarking, milling, and sieving). Emissions arising from this pretreatment, denoted as $\dot{M}^{PR}_{GHG,B_i}$, are primarily due to electricity consumption ($m_{CO_2,elec}$) estimated at 0.281 kg CO_2 per kWh of electricity (based on the Romanian average for 2022) given as:

$$\dot{M}^{PR}_{GHG,B_i} = \dot{W}^{PR}_{elec,B_i} \times m_{CO_2,elec} \quad (9)$$

$$\dot{W}^{PR}_{elec,B_i} = \dot{M}_{wood,B_i}(w^{dm}_{elec,B_i} + w^{s}_{elec,B_i}) \quad (10)$$

where $\dot{W}^{PR}_{elec,B_i}$ is the annual electricity consumption for pretreatment, and w^{dm}_{elec,B_i} (36.7 kWh/t) and w^{dm}_{elec,B_i} (7 kWh/t) are the electricity consumption per unit of input solid feedstock for log debarking and milling, and sieving.
Steam explosion is the process where sawdust is transformed into black pellets, and the associated emissions are primarily attributed to the electricity use of its components, in kWh per ton of input solid feedstock. These are dust receiving and scalping w^{rc}_{elec,B_i} (1.5 kWh/t), pre-drier w^{predry}_{elec,B_i}(15 kWh/t), dust screening and sieving w^{ss}_{elec,B_i} (4 kWh/t), dried dust milling w^{dmill}_{elec,B_i} (11 kWh/t), steam explosion unit w^{SEU}_{elec,B_i} (25 kWh/t), post-drier $w^{postdry}_{elec,B_i}$ (26 kWh/t), black pellets milling w^{bpmill}_{elec,B_i} (4 kWh/t), and pelleting, w^{pellet}_{elec,B_i}(103 kWh/t). The greenhouse gas emissions from the steam explosion process can be calculated from Equations 11 and 12:

$$\dot{M}^{SE}_{GHG,B_i} = \dot{W}^{SEP}_{elec,B_i} \times m_{CO_2,elec} \quad (11)$$

$$\dot{W}^{SEP}_{elec,B_i} = \dot{M}_{sawdust,B_i}(w^{rc}_{elec,B_i} + w^{predry}_{elec,B_i} + w^{ss}_{elec,B_i} + w^{dmill}_{elec,B_i} + w^{SEU}_{elec,B_i} + w^{postdry}_{elec,B_i} + w^{bpmill}_{elec,B_i} + w^{pellet}_{elec,B_i}) \quad (12)$$

where $\dot{W}^{SEP}_{elec,B_i}$ and $\dot{M}_{sawdust,B_i}$ are the total electric power consumed in the steam explosion process in a year and the annual amount of sawdust used in kton per year, respectively.
Emissions from power production using black pellets, denoted as $\dot{M}^{PP}_{GHG,B_i}$, arise from two primary sources: fuel oil used in auxiliary burners $\dot{M}^{PP}_{fuel,B_i}$ (0.06 litre/GJ input fuel), and internal power consumption, given by $\dot{W}^{PP}_{elec,B_i}$.

It is important to note that emissions arising from the combustion of black pellets themselves are zero due to biomass definition. The calculation for $\dot{M}^{PP}_{GHG,B_i}$ is as follows:

$$\dot{M}^{PP}_{GHG,B_i} = \dot{M}^{PP}_{fuel,B_i} \times m_{CO_2,diesel} + \dot{W}^{PP}_{elec,B_i} \times m_{CO_2,elec} \quad (13)$$

$$\dot{W}^{PP}_{elec,B_i} = W_{capacity}\,(\eta_{nom} - \eta_{net}) \quad (14)$$

where $\dot{W}^{PP}_{elec,B_i}$ represents the internal power consumption given as the difference between nominal and net power production. Here η_{nom} (33%) and η_{net} (30%) are the efficiencies associated with nominal and net power production, respectively, and $W_{capacity}$ is the plant capacity set at 50 MW for this specific case.

2.4 CO_2 emissions from value chain of coal power plant

Coal extraction has emissions due to mining activities given as $m^{EX}_{GHG,C}$ (tons CO_2 per ton coal). These emissions are calculated using $\dot{M}_{coal,C}$, the annual amount of coal extracted, the type of coal conversion factor (11.9 TJ/kton for lignite), the effective CO_2 emissions factor (94,600 CO_2/TJ), the conversion factor (10^6 tons of CO_2 per ton of coal), and the exclusion factor (0.017). The coal extraction emissions ($\dot{M}^{EX}_{GHG,C}$) are calculated as:

$$\dot{M}^{EX}_{GHG,C} = \dot{M}_{coal,C} \times m^{EX}_{GHG,C} \quad (15)$$

Coal transport is the transportation of the extracted coal to a coal power plant, using trucks powered by diesel fuel. The emissions associated with this ($\dot{M}^{TR}_{GHG,C}$) are due to diesel consumption and calculated as:

$$\dot{M}^{TR}_{GHG,C} = \dot{M}^{TR}_{fuel,C} \times m_{CO_2,diesel} \quad (16)$$

$$\dot{M}^{TR}_{fuel,C} = \dot{M}_{coal,C} \times m_{diesel,truck} \times L_{coal,C} \,/\, m_{load,truck,C} \quad (17)$$

where $\dot{M}^{TR}_{fuel,C}$ is the annual diesel consumption for coal transport, $m_{diesel,truck}$ is the diesel consumption rate of the truck, $m_{load,truck,C}$ is the load capacity of the truck for coal transport (32 tons per shipment; internal communication), and $L_{coal,C}$ is the average transport distance from the coal source to the power plant (90 km), estimated based on the distance between Hunedoara coal mine and Paroșeni power station in Romania.
Emissions stemming from power production using coal ($\dot{M}^{PP}_{GHG,C}$) are due to the use of utilities such as fuel oil in auxiliary burners $\dot{M}^{PP}_{fuel,C}$, internal power consumption $\dot{W}^{PP}_{elec,C}$, and emissions due to the combustion of coal $m^{PP}_{GHG,C}$. The calculation of $\dot{M}^{PP}_{GHG,C}$ is given as follows

$$\dot{M}^{PP}_{GHG,C} = \dot{M}^{PP}_{fuel,C} \times m_{CO_2,diesel} + \dot{W}^{PP}_{elec,C} \times m_{CO_2,el} + m^{PP}_{GHG,C} \times W_{capacity} \times \eta_{net} \quad (18)$$

where $m^{PP}_{GHG,C}$ is the emissions in kg CO_2 generated per kWh of electricity generated, which is 0.69 kg CO_2/kWh.

3. Results

3.1 Feedstock availability in Romania

The quantity of black pellets needed for a 50 MW power plant is calculated as 67.61 kton/y, employing the same calculation approach as applied to coal. In this study, the feedstock employed for black pellet production is sawdust, with an estimated volume of 141.55 kton/y. This estimation is based on yield data indicating 2.09 kg of sawdust per kg of black pellets coal (del Alamo Serrano and Tranås, 2019).

Table 1: Annual quantities of coal and black pellets (derived from wood and sawdust) required for the operation of a 50 MW power plant.

Coal power plant		Black pellet power plant	
Coal higher heating value (MJ/kg)	25.82	Black pellet higher heating value (MJ/kg)	21.3
Coal amount (t/h)	6.97	Black pellet (t/h)	8.45
Coal amount (kton/y)	55.77	Black pellet amount (kton/y)	67.61
		Sawdust amount (kton/y)	141.55
		Wood amount (kton/y)	157.28

To meet the sawdust demand, approximately 157.28 kton/y of wood logs are required, utilizing the mass conversion yield of 1.1 kg of wood per kg of sawdust, obtained from the same reference. Table 1 provides a summary of the annual quantities of coal and black pellets required for the operation of a 50 MW power plant. In 2017, the total roundwood removal amounted to 15×10^6 m^3, with $4{,}849 \times 10^3$ m^3 designated for use as fuel. If we assume the wood density as 0.53 t/m^3, the amount corresponds to 2,570 kton as obtained from European Bioenergy Outlook (2019). Therefore, the amount of wood required for a 50 MW power plant (157.28 kton/y) represents approximately 6.13% of the wood fuel harvested in Romania in 2017. Total roundwood usage for purposes other than fuel in the same year amounted to 10.15×10^6 m^3, equivalent to 5,380 kton of wood which indicates an extra utilization possibility.

3.2 Comparison of CO_2 emissions from black pellet vs coal powered power plant

Table 2 presents the comparison of the CO_2 emissions from power production using black pellets versus coal for both value chains. The provided table outlines the environmental impact in terms of CO_2 emissions (in kilotons per year) for each stage of the black pellets and coal value chains involved in energy production.

Table 2: CO_2 emissions (kton CO_2/y) for the value chain of power produced from black pellets and coal.

	Black pellets value chain [kton CO_2/y]	Coal value chain [kton CO_2/y]
Harvesting/extraction	1.57	173.85
Transport	2.08	0.12
Pretreatment	1.93	-
Steam explosion	7.54	-
Power production – fuel	0.23	0.23
Power production – electricity	2.93	2.93
Power production – combustion	0	134.97
TOTAL	16.27	272.10

The most notable contrast is evident in the harvesting/extraction phase, where coal significantly outpaces black pellets in CO_2 emissions. This discrepancy is primarily due to the inherently higher emissions associated with coal extraction compared to biomass harvesting for black pellets. In the transport phase, black pellets show higher emissions compared to coal. This may be attributed to the bulkier nature of biomass and the larger amount necessary, requiring more energy for transportation. In the pretreatment phase, only black pellets have associated emissions. The absence of values for coal implies that pretreatment is not applicable so does not contribute to emissions in the coal value chain. Similar to pretreatment, the steam explosion phase exclusively contributes to emissions in the black pellets value chain. In the power production phase, coal exhibits substantially higher emissions compared to black pellets. This difference stems from the higher emissions associated with burning coal for power generation, in addition, power generation from black pellets yields net-zero emissions from combustion, as biomass captures and stores CO_2 throughout its lifetime.

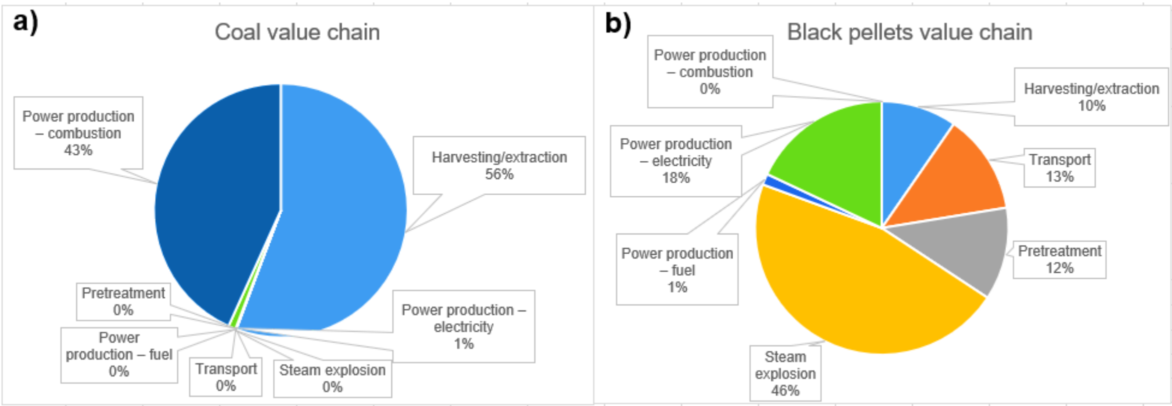

Figure 2: Distribution of emissions for coal and black pellets value chains.

The total annual CO_2 estimates for power generation using black pellets and coal stand at 16.27 and 272.10 kton of CO_2, respectively. The overall emissions for the entire value chain emphasize that power generation from black pellets results in significantly lower CO_2 emissions compared to coal. This conclusion aligns with the broader environmental benefits of utilizing biomass as a renewable energy source, highlighting the potential of black pellets to contribute to a more sustainable and low-carbon energy landscape. Figure 2 shows the distribution of emission for each block in the respective value chain. Extraction and combustion emit 99% of total emissions in coal value chain. While there is more even distribution in black pellets with steam explosion having the highest emissions of 46%.

4. Conclusions

In this comprehensive analysis of the CO_2 reduction potential associated with using black pellets for energy production in Romania, various aspects were examined. An in-depth assessment of biomass feedstocks available in Romania revealed the importance of precise distribution data for accurate evaluation of feedstock availability. To gauge the CO_2 emissions reduction potential of black pellet technology, a comparative evaluation of two energy production value chains was conducted—one utilizing black pellets and the other coal as a fuel source. The results demonstrated a significant disparity in total CO_2 estimates, with power generated from black pellets emitting only 16.27 kton CO_2/year compared to 272.10 kton CO_2/year for coal. This substantial difference is primarily attributed to the higher emissions associated with coal extraction and the release of CO_2 during its combustion for power production. The analysis underscores that power generation from black pellets leads to net-zero emissions from combustion, as biomass captures and stores CO_2 throughout its lifetime. This finding accentuates the environmentally favourable impact of adopting black pellets as a renewable energy source in Romania.

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