Report

The Potential for Sustainable Biomass in the Romanian Energy Sector

Activity 10

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SUMMARY
The main objective of this activity is to provide a contextual analysis for the CO2 reduction potential of using black pellets for energy production in Romania. The secondary objectives are to map currently available technologies for using biomass in the energy sector, to do a detailed analysis of black pellets technology, to do a comparative analysis of black pellets technologies, and to estimate CO2 emissions reduction potential of the black pellet technology. Black pellets have properties similar to that of coal, thus is a promising environmentally friendly alternative for energy production. Black pellets can be produced from biomass such as wood or wood waste that can be cultivated in Romania. Precise distribution of wood waste products and amounts can be useful for more accurate evaluation of feedstock availability in Romania. Steam explosion and steam torrefaction technologies are the most utilized for black pellets production. The total CO2 estimates for power generated from black pellets and coal amount to 16.27 and 272.10 kt of CO2 per year, respectively. The significant difference in emissions is mainly due to the higher emissions associated with coal extraction and the release of CO2 during the combustion of coal for power production. Finally, power generation from black pellets results in net-zero emissions from combustion since biomass captures and stores CO2 during its lifetime.

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1. Introduction

The main objective of this activity is to provide a contextual analysis for the CO2 reduction potential of using black pellets for energy production in Romania. The secondary objectives are listed below:

- Mapping of currently available technologies for using biomass in the energy sector
- Detailed analysis of black pellets technology
- Comparative analysis of black pellets technologies
- Estimation of CO2 emissions reduction potential of the black pellet technology

2. Technologies for using biomass in the energy sector

Biomass can be defined as renewable organic material originating from plants and animals. Figure 1 illustrates the primary sources of biomass categorized according to the classifications established by the U.S. Energy Information Administration [1], along with specific examples.

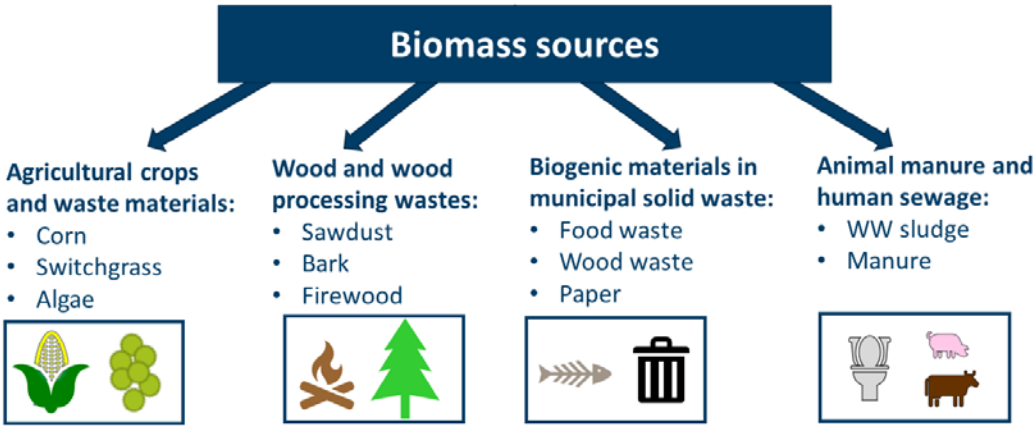

Figure 1 Mapping of commonly used biomass sources.

Edible agricultural crops such as corn, sugar cane, palm oil and soybean have widely been used in the production of 1st generation biofuels. The food versus fuel conflict has resulted in utilization of agricultural residues and inedible crops like switchgrass and straw, categorized as 2nd generation biofuels, while biofuels produced from algae and seaweed are classified as 3rd generation biofuels.

Additionally, biogenic materials originating from municipal solid waste, including food and wood waste, along with animal manure and human sewage, are processed in waste incineration and biogas plants to generate energy carriers. Proper management of these waste streams is important to minimize their adverse impact on the environment and human health.

Traditionally, wood has been the main biomass source used in households mainly for heating purposes through direct combustion/burning. Over the years, wood (including waste wood or low-quality wood) and wood processing wastes (bark, sawdust, mill residues) have been utilized for the generation of higher quality biomass fuels.

The main biomass conversion products are shown in Figure 2, split into four main categories and their respective examples.

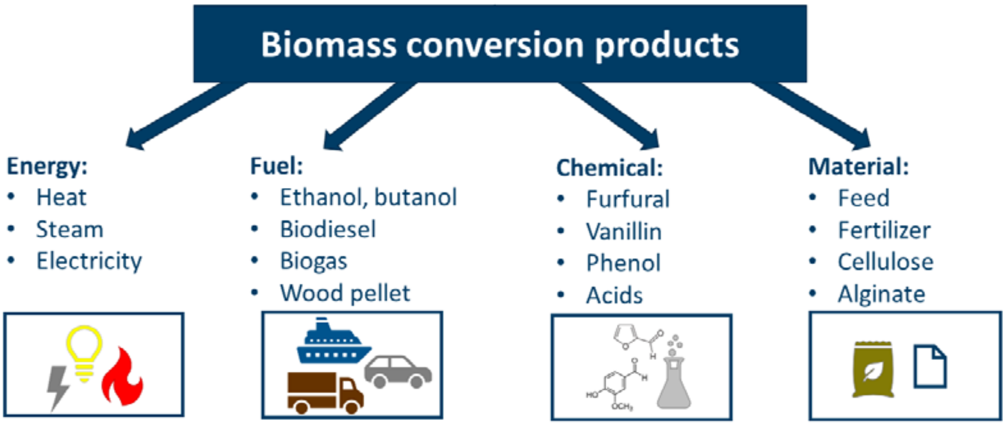

Figure 2 Mapping of common biomass conversion products.

Biomass can be converted to energy in the form of heat which can be directly used or utilized for steam production, while electricity can be generated using steam and gas turbines. Fuels can be produced from biomass feedstocks as well. For example, ethanol can be produced from sugar cane (1^{st} generation biofuels). Similarly, other edible, nonedible crops, agricultural residues, and algae (2^{nd} and 3^{rd} generation) can be converted to higher alcohols (butanol, propanol). Biogas, consisting primarily of methane (approximately 60% v/v), carbon dioxide (approximately 40% v/v) and trace amounts of other gases like hydrogen and hydrogen sulfide, can be produced from biogenic municipal solid waste, human sewage, and animal manure. Used vegetable oils, oil crops (rapeseed), animal fats and lipids can be converted to biodiesels e.g., mainly fatty acid methyl esters (FAME), hydrotreated vegetable oil (HVO), and dimethyl ether (DME).

Wood and wood-processing waste can be developed into wood pellets and chips for increasing their energy density and heating value that results in a more favorable market position. Their use as fossil-based coal replacement in the existing coal power plants can reduce greenhouse gas emissions that can help reach the 40% reduction target by 2030 [2]. Properties of commonly used biomass fuels and coal are given in Table 1 [3]. Black pellets are the focus of this analysis, which is also referred to as steam explosion pellets or advanced wood pellets.

Table 1 Properties of biomass fuels commonly used in energy sector and coal (adapted from [3]).

	Wood chips	Wood pellets	Black pellets	Torrefied pellets	Hard coal
Heating value (GJ/ton)	10-12	17	19.5-21.3	21-22	25
Bulk density (kg/m^3)	300	650	750	750	850
Energy density (GJ/m^3)	3	11	14.5-15.5	17	21
Co-firing rate (%)	3-5	5-8	100		N/A
Dust delivered (%)		3-7	<1	5-10	

Despite its potential, there are several challenges for this transition due to differences in fuel properties. For example, use of wood chips or similar biomass such as chips, sawdust, agricultural residues can cause logistical problems during storage, transport, and handling due to their low bulk density (approximately 35% of that of coal) and loose structure. Related to this, dust content is another disadvantage due to the risk of dust explosion that is 3-7 times greater for wood pellets compared to black pellets. Moreover, lower energy density and heating value require larger amounts to replace the coal for producing the same energy output. To alleviate this challenge, biomass co-firing with coal (using a mix of coal and biomass as a fuel) has emerged. Co-firing rates (mixing ratios of different fuels) of wood chips and wood pellets have been reported as 3-4% and 5-8% [3], respectively, while it is 100% for black pellets. Advantages of black pellets compared to other biomass alternatives to replace coal can be summarized as follows:

- Higher heating value, energy density and co-firing rate, implying more suitable coal replacement in the existing coal power plants and coal handling infrastructure.
- Higher bulk density, thus easier handling.
- Lower dust content, thus lower risk of dust explosion.
- Water resistance, advantageous in storage and handling.

It is also important to note that the possibility of using black pellets produced from biomass, which is biological and renewable as 100% replacement to fossil coal, result in 100% saving of CO_2 emissions during combustion, creating a great potential for lowering emissions in the energy sector.

Biomass can also be converted into chemicals (furfural, vanillin, phenol, acids) and materials (feed, fertilizer, protein, alginate, biochar, cellulose). The former is produced mainly in biorefineries where a variety of products including energy carriers are generated from biomass (lignocellulosic biomass, black liquor) using a variety of conversion technologies. The latter can be produced as the main product utilizing different technologies or can also be a by-product. Production of chemicals and materials alongside of energy and energy carriers thus improves the plant output economically and environmental performance through increased resource efficiency and creates a market for products from biomass. An overview of biomass conversion technologies is shown in Figure 3.

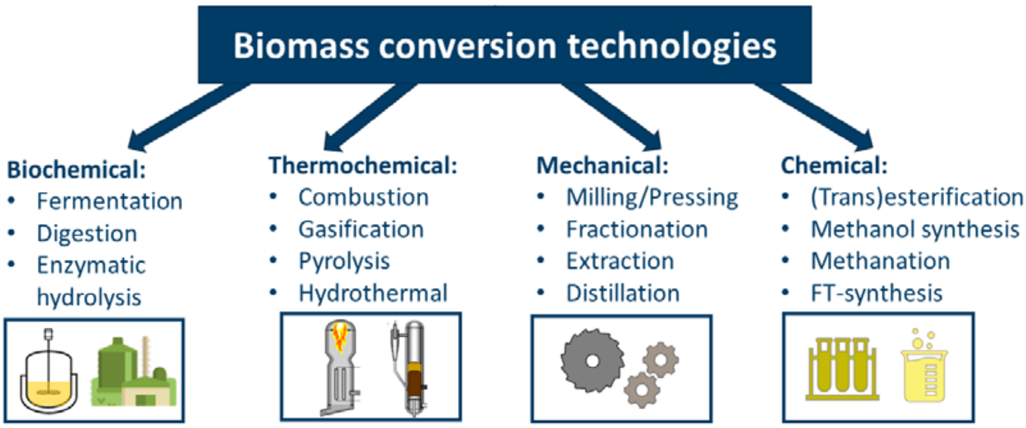

Figure 3 Mapping of main biomass conversion technologies.

Biochemical conversion technologies primarily yield liquid and gaseous biofuels, while thermochemical processes generate solid, gaseous, and liquid biofuels, except for direct combustion (burning) which produces heat. Mechanical processes result in both liquid and solid biofuels, while chemical biomass conversion processes specifically produce liquid biofuels.

Biochemical biomass conversion processes are performed under relatively low temperature and pressure, using microorganisms and/or enzymes. For example, fermentation that is mainly employed for liquid biofuel production (alcohols; ethanol etc.) with typical operating temperatures up to 55 °C and normal pressure using bacteria or yeast or a mixture of these. Another process is anaerobic digestion that generates biogas, a mixture of methane and carbon dioxide from biological feedstocks such as food waste and sewage sludge. Ethanol is used as a vehicle fuel. Biogas also forms in solid waste landfills and can be collected from these sites. After proper treatment, biogas can be used as a replacement for fossil-based natural gas. Digestion is transformation of larger molecules into smaller ones using enzymes under controlled temperature and pH to ensure optimal enzyme conditions. Hydrolysis can be done with or without enzymes, typically in the presence of acids. Digestion and hydrolysis are often applied prior to fermentation to convert complex biomass into fermentable feedstock.

Thermochemical biomass conversion processes have more severe operating conditions that can be performed with or without catalysts and under high temperature. Combustion occurs at temperatures higher than 1000 °C and is the most common technology, being responsible for over 97% of the world's bioenergy production (e.g., burning of wood). Heat generated by combustion can be utilized for heating buildings and water, for industrial process heat, and for generating electricity in steam turbines. Both pyrolysis and gasification are thermal decomposition processes in which biomass feedstock materials are heated in closed, pressurized vessels called gasifiers at high temperatures. They mainly differ in the operating temperatures and amount of oxygen present during the conversion process. Gasification is achieved by subjecting biomass to elevated temperatures, typically higher than 700 °C, in a controlled environment with precise quantities of oxygen and/or steam, all while avoiding the process of combustion (less oxygen available). The main gasification product is a gas mixture, mainly carbon monoxide, hydrogen, and carbon dioxide that can be further utilized as an energy carrier. This mixture is called syngas (synthesis gas) when it contains mainly carbon monoxide and hydrogen. Syngas can be utilized as a fuel for diesel engines, for heating through combustion, and for producing electricity using gas turbines. A syngas mixture can also be reacted to produce liquid fuels using the Fischer–Tropsch (FT) process which is a chemical biomass conversion process. During pyrolysis, biomass is thermally decomposed at a temperature in the range of 500 to 800 °C, within an inert atmosphere where free oxygen is nearly completely absent. Biomass pyrolysis yields a range of products such as charcoal, bio-oil, renewable diesel, methane, and hydrogen. Torrefaction is a mild form of pyrolysis (lower temperature) employed to produce torrefied pellets, with the aim of reducing the moisture and volatile content of biomass.

Another class of thermochemical biomass conversion technologies is hydrothermal processes that are employed for feedstocks with higher moisture content (wet biomass) that produce different products in different phases (gas, aqueous, oil, solid). Hydrothermal processes have a wide range of operating temperatures (300 - 700 °C) and pressures (50 - 400 bar) that result in different product mixtures [4]. For example, hydrothermal liquefaction (HTL) is a thermal depolymerization process that produces mainly crude-like oil called bio-oil or biocrude, while hydrothermal carbonization produces a solid product mainly which is called hydrochar.

2.1 Black pellets technology

Black pellet term refers to the torrefaction of pelletized materials [5] or the resulting product of pelletization of torrefied materials [6]. Pellets produced without heat treatment are often referred to as white pellets. Since the color of the pellets turn into a darker color under high temperature treatment, the name of the resulting product is black pellets to separate them from the established white pellets. However, the term “torrefied pellets” is also used for fuels that are treated with torrefaction. In literature and in commercial applications, black pellets production process often involves steam which can be used to distinguish them.

Various methods such as steam explosion (Arbaflame) [7], torrefaction under pressurized steam (conducted at 245-265 °C, 10-39 bar) [5], steam torrefaction (experiments at 245-265 °C) [8], and steam treatment (Valmet) [9] are utilized in the production of black pellets. However, the Verdo process differs from these methods as it does not involve steam or torrefaction. In Verdo's process, lignin and residual wood fibre biomass are compressed and pelletized, akin to the production of white pellets [10]. Although Verdo’s product is also referred to as black pellets, the change in color is not a result of heat treatment (such as torrefaction) but rather arises from the natural color of their feedstock. Therefore, the Verdo approach falls outside the scope of this study.

2.1.2 Steam explosion

During steam explosion, biomass is heated under high pressure steam and then the pressure is suddenly released to achieve explosive decompression that yields black pellets. The operating temperature can be in the range of 170-250 °C and the pressure can be between 12 and 17 bar, while the residence time can vary from 10 seconds to 10 minutes [11]. The energy required for production of untreated pellets and steam exploded pellets has been reported to be 4.83 MJ/kg and 7-8 MJ/kg, respectively [12]. Even though the energy demand is higher, the overall cost can be reduced due to lowered costs of post-processing, transportation, and storage (supply logistic costs of biomass can be up to 50% of production costs) as a result of improved mechanical strength, durability (lower dusting and material losses), grindability (lower energy demand), energy density and hydrophobicity (possible to employ mechanical drying compared to more energy intensive heat drying). There are other benefits of using black pellets that occur during its thermal conversion (combustion and gasification) such as lower alkali content (less slagging and fouling), stable combustion, and lower inorganic content (fewer particulate emissions and improved ash quality). Characteristics of steam exploded black pellets are given in Table 2, adapted from [11]. The black pellets were produced using the wood pellets based on 75% soft wood and 25% hard wood supplied by Zilkha Biomass Energy, Texas, U.S. There is no further information about the steam explosion conditions.

Table 2 Properties of steam exploded black pellets, adapted from [11].

Proximate analysis	Moisture (at 105 °C)	4.2%
	Volatile matter (dry basis)	76.8%
	Fixed carbon (dry basis)	22.3%
	Ash (at 550 °C dry basis)	0.9%
Ultimate analysis	Carbon	52.6%
	Hydrogen	5.8%
	Nitrogen	<0.1%
	Oxygen	40.6%
	Energy content (LHV) (MJ/kg)	19.3
Physical properties of pellet	Color	Dark brown
	Water resistance	High (Hydrophobic)
	Durability	High
	Diameter (mm)	6
	Mean length (mm)	17
	Bulk density (kg/m^3)	740
Ash fusion temperatures (oxidizing conditions)	Shrinking temperature (°C)	1050
	Deformation temperature (°C)	1480
	Hemisphere temperature (°C)	1490
	Flow temperature (°C)	1500

Steam explosion of agricultural residues have also been studied due to their potential of cheap supply. Residues from palm oil production, namely empty fruit bunch and palm kernel shell were steam exploded and their fuel properties were compared to that of softwood Douglas fir. Douglas fir is an important species found mostly in North America and Europe and it was found to be resilient to droughts and suggested for wider plantation in Romania [13]. Steam explosion that was performed at 220 °C for 5 min increased the high heating value of empty fruit bunch from 18.54 to 22.42 MJ/kg; of palm kernel shell from 21.51 to 21.99 MJ/kg, and of softwood from 18.82 to 19.50 MJ/kg. In the meantime, while moisture content decreased, the ash content increased for all three feedstocks [14].

2.1.3 Steam torrefaction

Steam torrefaction was developed in response to observed improvements in fuel quality, including enhanced heating value and grindability attributed to steam addition. Pressurized steam, specifically saturated steam, has the potential of penetrating into feedstock particles and actively participating in the torrefaction reactions.

In a pressurized steam torrefaction study, two types of hardwood, namely rubber tree and acacia tree, were utilized as the feedstocks [5]. Raw pellets were placed inside a continuously stirred stainless-steel autoclave, along with some added water and flushing with N_2 within the autoclave. The reactor setup ensured that the raw pellets came into contact exclusively with the pressurized steam, generated by the inherent moisture of the raw pellets, which was sufficient to establish the required reaction conditions. The pressurized steam torrefaction was conducted at temperatures of 180, 200, 220 and 250 °C, while the measured pressure was in the range of 10-39 bar. The properties of the resulting black pellets are given in Table 3.

Table 3 Properties of black pellets from pressurized steam torrefaction, adapted from [5].

		Proximate analysis (wt.%-dry)			Ultimate analysis (wt.%-dry)				
Feedstock	Sample	Ash	Volatile matter	Fixed carbon	C	H	N	O	HHV (MJ/kg)
Rubber tree	Raw	2.25	84.2	12.93	50.1	6.17	0.22	43.5	17.9
	180 °C	1.98	85.14	12.88	50.2	6.09	0.26	43.5	17.8
	200 °C	1.97	84.07	13.96	52.6	6.04	0.22	41.1	19
	220 °C	2.05	80.9	17.04	54.4	6.08	0.23	39.3	20
	250 °C	2.85	71.27	25.88	56.9	6.00	0.2	36.9	21.2
Acacia tree	Raw	1.1	88.7	10.7	50.6	6.21	0.03	43.2	18.2
	180 °C	0.6	87.1	12.4	50.8	6.17	0.21	42.8	18.3
	200 °C	0.8	84.9	14.2	52.7	6.24	0.25	40.8	19.4
	220 °C	0.7	79.7	19.6	54.2	6.20	0.22	39.4	20.1
	250 °C	0.6	75.1	23.6	56.8	6.05	0.02	37.1	21.2

Bark is an important forestry/wood residue that has been tested as a feedstock for steam torrefaction as well. When Douglas-fir bark was subjected to steam torrefaction at 220 °C for 5 minutes, notable improvements in its fuel characteristics were observed. Specifically, the higher heating value increased from 19.13 to 22.48 MJ/kg, the carbon content increased from 46.98 to 54.52 wt.%, and the oxygen content decreased from 45.63 to 38.32 wt.%. However, there were some trade-offs as the bulk density decreased from 310 to 275 kg/m^3, and the ash concentration increased from 2.114 to 4.128 wt.% [15].

2.1.4 Dry torrefaction

Dry torrefaction is a conventional torrefaction technique that is done by heating biomass at atmospheric pressure in the presence of an inert gas. Despite its benefits of increasing the heating value, combustibility, grindability, and hydrophobicity of various biomass feedstocks, there are some drawbacks. Notably, it decreases bulk density and increases ash content, which can be unfavorable for storage and transport. Furthermore, biomass subjected to dry torrefaction tends to become brittle and challenging to pelletize, and the need for pre-torrefaction drying results in a lower overall energy efficiency [5].

In a dry torrefaction study conducted using rubber tree as the feedstock, temperatures of 250, 260, 270 and 280 °C were employed. The most favorable outcomes were achieved at 280 °C, where the higher heating value increased from 17.9 to 24.4 MJ/kg. Simultaneously, the carbon content increased from 50.1 to 65.5 wt.%, while the oxygen content decreased from 43.5 to 29 wt.%. In the same study, dry torrefaction was also applied to acacia tree feedstock, resulting in similar enhancements of fuel properties [5].

2.1.5 Dry torrefaction with air

A study on dry torrefaction explored the use of air instead of the conventionally more expensive nitrogen as the process medium. The impact of temperature (220, 260, 300 °C), pressure (gauge pressures of 0, 200, 400 and 600 kPa), residence time (15, 25, 35 min), and the choice between air and nitrogen as the medium was investigated using poplar wood as the biomass feedstock [16]. The findings revealed that torrefaction carried out in pressurized air resulted in higher energy density, an increased fuel ratio, and a similar energy yield compared to torrefaction performed with nitrogen. Elevated pressure levels contributed to improved fuel properties, with temperature exerting the most significant influence. The higher heating value of the torrefied biomass when using air as the medium ranged from 19.44 (at 220 °C, 15 min, 0 kPa) to 27.56 MJ/kg (at 300 °C, 35 min, 400 kPa). In comparison, when using nitrogen as the medium, the higher heating value ranged from 19.50 (at 220 °C, 15 min, 600 kPa) to 26 MJ/kg (300 °C, 35 min, 600 kPa). The results suggest that air can effectively substitute nitrogen in the torrefaction process. However, mechanical properties such as grindability were not considered in this study which are important in the industrial applications of torrefied biomass.

2.1.6 Wet torrefaction

Wet torrefaction, using hot-compressed water as the medium, has been suggested as an alternative to dry torrefaction to address the challenge of low pelletability. In this process, water becomes chemically active, and the resulting product is generated through a depolymerization-nucleation mechanism at relatively low temperatures. Despite the enhancements in fuel properties, wet torrefaction introduces certain complexities into the process, such as the substantial energy requirement for heating a large volume of water (equivalent to 5 times the biomass amount) and the necessity for post-drying. Additionally, the process generates wastewater containing metals and organics, requiring the use of a pressure-tight reactor which contribute to the overall costs [5]. In a wet torrefaction study conducted with rubber tree as feedstock, temperatures of 180, 200, 220 and 250 °C were employed. The most favorable results were achieved at 250 °C, where the higher heating value increased from 17.9 to 24.8 MJ/kg, while the carbon content increased from 50.1 to 64.7 wt.%, and the oxygen content decreased from 43.5 to 29.3 wt.%. In the same study, wet torrefaction was also applied to acacia tree feedstock, resulting in similar levels of improvement in fuel properties [5].

2.2 Comparison of black pellets technologies

Torrefaction and steam explosion are the primary methods employed in the production of black pellets, as outlined above. For a comparative assessment, the typical parameters for these processes are given in Table 4.

It is worth noting that the temperature, pressure and residence time ranges for both steam explosion and torrefaction technologies largely overlap, as seen in Table 4. The main difference between these processes lies in the choice of reaction mediums, which can be steam, water, inert gases (nitrogen) and air, or a combination of these. It is important to note that steam explosion and steam torrefaction differ with respect to the reactor configuration: the former involves a sudden pressure release, while the latter can maintain steam within the system through a batch operation.

Table 4 Parameters of main black pellet production technologies.

	Steam explosion	Steam torrefaction	Dry torrefaction	Dry torrefaction (with air)	Wet torrefaction
Temperature (°C)	170-250	180-250	250-280	220-300	180-250
Pressure (bar)	12-17	10-39	39	1-6	39
Residence time	10 seconds - 10 minutes	5-10 minutes	5-10 minutes	15-35 minutes	5-10 minutes
Medium	Steam	Steam	Inert (nitrogen)	Air	Water
Commercial application	Yes	Yes	Yes	No	No

The selection of the medium is important, as it can introduce additional operating costs, particularly when inert gases such as nitrogen are used. Furthermore, if large quantities of the medium are required during the biomass conversion process, it can lead to the generation of waste streams. This is especially important for overall plant costs on a commercial scale since the treatment and disposal of waste streams can incur significant expenses.

Due to these considerations, wet torrefaction was found to be less favorable, while stream torrefaction proved advantageous, primarily because the moisture content of the feedstock itself was sufficient to generate the required steam.

Equipment specifications for each process may need to be adjusted based on the specific operating conditions. For example, when operating at high temperatures, such as in torrefaction, there is a potential for the generation of corrosive components from the biomass during the conversion process. Consequently, non-corrosive reactors become necessary to mitigate this issue effectively. Likewise, when operating at high pressures, it is crucial to employ pressure-tight reactors or vessels capable of withstanding these elevated pressures. This aspect is essential not only for operational efficiency but also for ensuring safety.

Although these technologies have predominantly been applied to wood (both soft and hardwood), there have also been some studies and commercial applications involving agricultural and forestry/wood residues for black pellets production. Notably, the first full-scale commercial plant by Arbaflame producing black pellets started operations in 2003, with a capacity of 70,000 tonnes [7]. These black pellets have been used in converting two coal plants owned by Ontario Power Generation in Canada into 100% biomass plants, a transformation completed in 2015 [3].

Nevertheless, there is currently limited comprehensive analysis available regarding the use of various feedstock and their suitability for different black pellet production technologies. Existing literature primarily focuses on the development of the technologies themselves rather than conducting extensive assessments of different feedstocks. Consequently, there remains insufficient data for a meaningful comparison of these technologies in terms of conversion performance, encompassing aspects such as fuel/mass yield and improvements in energy density. Moreover, even though commercial production and utilization of black pellets for energy generation exist, these systems are proprietary, safeguarding their technical details, specifications, and feedstock information.

3. Contextual analysis of the CO_2 reduction potential of black pellets

Two distinct value chains are considered to assess the potential reduction in CO_2 emissions when using black pellets for energy production. These value chains are categorized as follows: the first is a coal-based power plant (reference case), while the second is a power plant utilizing black pellets, both with a 50 MW capacity to produce heat and power. A schematic representation of the two value chains is given in Figure 4.

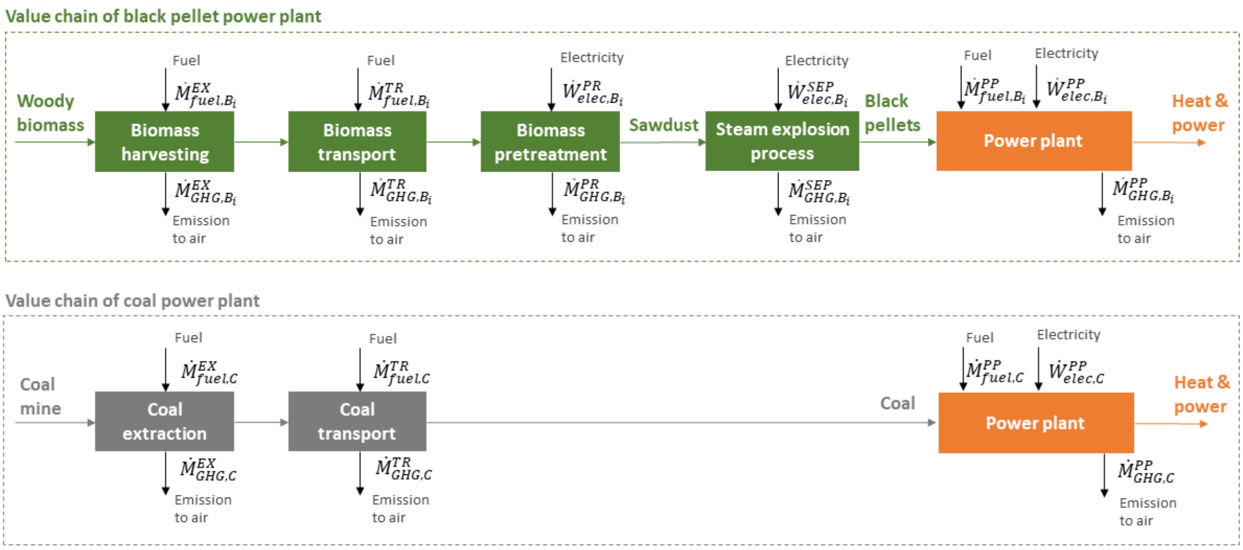

Figure 4 Schematic representation of the overall value chain considered in this project, which entails combustion of black pellets produced from steam explosion of woody biomass in a power plant, and combustion of coal in a power plant based on a previously developed concept [17].

Both value chains cover the entire process, starting from feedstock extraction or harvesting at the source, transportation, and ultimately, utilization within the power plant. To estimate the fuel requirement for a 50 MW plant capacity (denoted as $W_{capacity}$), defined in terms of the energy content of the fuel supplied to the power plant, as well as the higher heating value of the fuel, and 8000 hours of annual operation (represented as t_{annual}), the following formulas are utilized for coal and black pellets:

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

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

$$\dot{M}_{blackpellet,B_i} = \dot{M}_{sawdust,B_i} \times y_{blackpellet}$$

$$\dot{M}_{sawdust,B_i} = \dot{M}_{wood,B_i} \times y_{sawdust}$$

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

The amount of black pellet required for a 50 MW power plant is estimated to be 67.61 kilotons/year, following the same calculation methodology employed for coal. In this project, the feedstock utilized for black pellet production is sawdust, with an estimated amount of 141.55 kilotons/year. This is based on the yield data of 2.09 kg sawdust per kg of black pellets (referred to as $y_{blackpellet}$), as obtained from [17]. Furthermore, to fulfil the demand for sawdust, an estimated 157.28 kilotons/year of wood logs are required, using the mass conversion yield of 1.1 kg of wood per kg of sawdust (denoted as $y_{sawdust}$), also obtained from the same reference. Table 5 summarizes the annual amounts of coal and black pellets (sourced from wood and sawdust) to operate a 50 MW power plant.

Table 5 Estimation of annual fuel amount for coal based and black pellet-based power plants data from [17].

Coal power plant		**Black pellet power plant**	
Coal HHV (MJ/kg)	25.82	Black pellet HHV (MJ/kg)	21.3
Coal amount (t/h)	6.97	Black pellet (t/h)	8.45
Coal amount (kt/y)	55.77	Black pellet amount (kt/y)	67.61
		Sawdust amount (kt/y)	141.55
		Wood amount (kt/y)	157.28

3.1 Feedstock availability in Romania

3.1.1 Wood availability

Potential available wood for energy production and other relevant data for Romania are presented in Table 6 [18]. The total forest area increased approximately 500 kilo hectares from 1990 to 2015, while the available forest stock in Romania increased from 1.3×109 m3 to 1.9×109 m3, representing an annual growth rate of 1.5%. Extrapolating this trend, the available forest stock is projected to reach approximately 2.2×109 m3 by 2025.

Table 6 Romanian forest area, 2015 in kilo hectares [18].

Total land area	Total area of forests and other wooded land	Forests	Forests available for wood supply	Other wooded land
23,907	6,951	6,861	4,627	90

In 2017, the total roundwood removal amounted to 15×10^6 m^3, with 4,849×10^3 m^3 designated for use as fuel. If we assume the wood is of Douglas fir variety, with a density of 0.53 t/m^3 (denoted as d_{wood}) [19], 4,849×10^3 m^3 of fuelwood (V_{wood}) corresponds to 2,570 kilotons (M_{wood}) as calculated below:

$$M_{wood} = V_{wood} \times d_{wood}.$$

Therefore, the amount of wood required for a 50 MW power plant (157.28 kt/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 kt of wood.

3.1.2 Wood waste availability

It is worth noting that in 2016, the volume of wood waste, which includes wood packaging, waste from the wood processing industry, demolition construction waste, and other sources [20], amounted to 3,284 kilotons. This considerable amount has the potential to be utilized for black pellets and subsequent energy generation [18]. However, the precise distribution of this waste volume has not been reported.

Sawdust represents one of the most prevalent forms of wood processing waste, generated through various processes like cutting, sizing, and smoothing. Typically, in sawmill processes, sawdust is produced at a yield ranging from approximately 12 to 25 kg of sawdust per 100 kg of wood [21]. Assuming a sawdust yield of 0.2 kg per kg of wood, an amount of 707.75 kt of wood needs to be processed to generate the required 141.55 kt of sawdust per year for a 50 MW power plant, as considered in this study and shown in Table 5. This volume corresponds to 13.15% of the total roundwood removed in Romania in 2017 for purposes other than fuel.

3.2 CO_2 emissions from value chain of black pellet power plant

3.2.1 Biomass harvesting

Biomass harvesting consists of cutting trees with diesel-powered chain saws. According to the literature [22], the diesel consumption rate for wood cutting is specified as 2 liters per cubic meter, denoted as $m_{diesel,wood}$. The associated CO_2 emissions resulting from diesel use are estimated as 2.64 kg CO_2 per liter of diesel, represented as $m_{CO_2,diesel}$ [23]. Emissions that arise from biomass harvesting are assumed solely to be due to diesel use, as given by the following formulas:

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

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

3.2.2 Biomass transport

Biomass transportation consists of 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 the formulas below:

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

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

where $\dot{M}^{TR}_{fuel,B_i}$ is the annual diesel consumption for biomass transport, $m_{diesel,truck}$ is the diesel consumption rate of the truck, set at 0.3 liters per km [24], $m_{load,truck,B_i}$ 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, estimated at 200 km per shipment (internal communication with a Romanian company).

3.2.3 Biomass pretreatment

Biomass pretreatment involves the production of sawdust from wood, which includes processes like 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 [25]) and given by

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

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

where $\dot{W}^{PR}_{elec,B_i}$ is the annual electricity consumption for biomass pretreatment, and w^{dm}_{elec,B_i} (36.7 kWh/t) and w^{dm}_{elec,B_i} (7 kWh/t) are the specific electricity consumption per unit of input solid feedstock for log debarking and milling, and sieving, respectively.

3.2.4 Steam explosion process

Steam explosion is the process through which sawdust is transformed into black pellets, and the associated emissions are primarily attributed to the electricity use of its various constituents, measured in kWh per ton of input solid feedstock. These constituents and their respective electricity consumptions rates 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 stemming from the steam explosion process can be calculated from the following formula:

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

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

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 kt per year, respectively.

3.2.5 Black pellet combustion power plant

Emissions resulting from power production using black pellets, denoted as $\dot{M}^{PP}_{GHG,B_i}$, arise from two primary sources: the use of utilities, specifically 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:

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

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

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.

3.3 CO_2 emissions from value chain of coal power plant

3.3.1 Coal extraction

Coal extraction involves various mining activities, and the emissions resulting from these activities are expressed as $m^{EX}_{GHG,C}$ (tons CO_2 per ton coal). These emissions are determined based on several factors, including the type of coal conversion factor (11.9 TJ/kt 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) [26]. Emissions from coal extraction, denoted as $\dot{M}^{EX}_{GHG,C}$, are calculated as follows:

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

where $\dot{M}_{coal,C}$ is the annual amount of coal extracted.

3.3.2 Coal transport

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

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

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

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.

3.3.3 Coal combustion power plant

Emissions arising from power production using coal, denoted as $\dot{M}_{GHG,C}^{PP}$, result from several factors, including the use of utilities such as fuel oil in auxiliary burners $\dot{M}_{fuel,C}^{PP}$, internal power consumption $\dot{W}_{elec,C}^{PP}$, and emissions due to the combustion of coal $m_{GHG,C}^{PP}$. The calculation of $\dot{M}_{GHG,C}^{PP}$ is given as follows:

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

where $m_{GHG,C}^{PP}$ is the emissions in kg of CO_2 generated per kWh of electricity generated, which is set at 0.69 kg CO_2/kWh) [17].

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

For a comparison of the CO_2 emissions from power production using black pellets versus coal, an estimation of CO_2 emissions for both value chains are presented in Table 7.

Table 7 CO_2 emissions (kton CO_2/year) for the value chain of power produced from black pellets and coal.

	Black pellets value chain	Coal value chain
Harvesting/extraction	1.57	173.85
Transport	2.08	0.12
Pretreatment	1.93	n/a
Steam explosion	7.54	n/a
Power production	3.16	138.12
TOTAL	**16.27**	**272.10**

The total CO_2 estimates for power generated from black pellets and coal amount to 16.27 and 272.10 kt of CO_2 per year, respectively. The significant difference in emissions is mainly due to the higher emissions associated with coal extraction and the release of CO_2 during the combustion of coal for power production. In contrast, power generation from black pellets results in net-zero emissions from combustion since biomass captures and stores CO_2 during its lifetime.

4 Conclusions

A contextual analysis for the CO_2 reduction potential of using black pellets for energy production in Romania was performed in this activity. First, currently available technologies for using biomass in the energy sector were mapped. Steam explosion and steam torrefaction technologies were found to be the most utilized for black pellets production suitable for industrial scale applications. The analysis covered the evaluation of biomass feedstocks available in Romania for black pellets production which showed that the precise distribution of wood waste products and amounts can be useful for more accurate evaluation of feedstock availability. Estimation of CO_2 emissions reduction potential of the black pellet technology was done by comparing two value chains for energy production: one using black pellets and the other using coal as a fuel source. Results showed that the total CO_2 estimates for power generated from black pellets and coal amount to 16.27 and 272.10 kt of CO_2 per year, respectively. The significant difference in emissions is mainly due to the higher emissions associated with coal extraction and the release of CO_2 during the combustion of coal for power production. It is important to note that the power generation from black pellets results in net-zero emissions from combustion since biomass captures and stores CO_2 during its lifetime.

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