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Life cycle assessment of residential heat production from wood pellet combustion in the Northwest region of Russia

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Abstract: The increasing global demand for energy and the negative environmental impacts of fossil fuel exploitation have driven interest in sustainable energy solutions, such as wood. The Russian Federation, as one of the world's largest pellet producers, has an opportunity to utilise pellets domestically. This study addresses the lack of publicly available life cycle assessment (LCA) studies on pellet production and utilisation in Russia, specifically examining the environmental impact of residential heat production from locally produced wood pellets. Utilising primary data from the Northwest region, the study follows ISO 14040 and 14044 standards and employs the ReCiPe 2016 (H) Midpoint v. 1.1 method to assess environmental impacts. The results indicate that the production of pellets is the dominant contributor to the global warming impact category, marine eutrophication, and fossil resource scarcity, while transportation has the least impact across all categories. Sensitivity analyses confirm the robustness of these findings, revealing that using natural gas for pellet drying increases emissions for global warming and fossil resource scarcity, and increasing transportation distance significantly raises emissions across all categories. The findings provide valuable insights for policymakers and stakeholders aiming to enhance the sustainability of similar bioenergy systems.

Keywords: bioenergy; biofuels; climate change; environmental impact; forest residues

Increasing global demand for energy production, negative environmental effects from fossil fuel exploitation, and fossil fuel exhaustibility (Shafiee, Topal 2009) have led to a growing interest in sustainable and environmentally friendly energy solutions. According to the Renewable Energy Directive II (EC 2018), Europe aims to achieve a 32% share of renewable energy in total energy consumption by the year 2030. Bioenergy is becoming a more frequently utilised alternative to fossil fuels when compared to other renewable energy resources (Mandley et al. 2020). Woody biomass is a unique resource that can be derived in different forms from a variety of sources and used for the production of heat, electricity, and transportation fuel (Malmsheimer et al. 2008; Guo et al. 2015).

To facilitate the transition from fossil fuels to renewable bioenergy, bioenergy production options should be carefully assessed. Life cycle assessment (LCA) is a commonly used tool for evaluating the environmental impact of a product system throughout its entire cycle. In recent years, numerous studies have analysed the life cycle of various bioenergy production scenarios (Agostini et al. 2020; Martín-Gamboa et al. 2020; Musule et al. 2021). Many aspects of bioenergy production, such as the

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impacts of different biomass feedstock on biofuel production (Sjølie, Solberg 2011; Morrison, Golden 2016), the nature of the biofuels themselves (Alizadeh et al. 2023), conversion technologies (Carotenuto et al. 2022), and transportation options (Pierobon et al. 2015; Vera et al. 2019) have been thoroughly evaluated. Several studies focused on wood chips production and utilisation (Fitzpatrick 2016; Hammar et al. 2017; Klavina et al. 2017). Other studies investigated the impact of briquettes (Alanya-Rosenbaum et al. 2018; Medina-Ríos et al. 2021; Sahoo et al. 2021).

One of the most studied and utilised biofuels is wood pellets (Musule et al. 2021). Numerous LCA studies have analysed various scenarios of pellet production and bioenergy generation from pellet utilisation. For instance, Pergola et al. (2018) compared the environmental impact of pellet production from roundwood logs to pellets from sawmill residues (mainly sawdust). Another paper by Lu and Hanandeh (2017) studied various biofuel and bioenergy production scenarios using different conversion technologies for woodchips and wood pellets. Ahmadi et al. (2020) investigated the difference between power generation in Canada from the gasification of woodchips originating from softwood harvesting residues to the gasification of pellets, combustion of pellets, and pyrolysis of woodchips. McKechnie et al. (2011) examined emissions related to electricity production from co-firing pellets obtained from different sources. Porsö and Hansson (2014) assessed the environmental impacts of district heat production via the combustion of wood pellets produced from poplar and willow. Wang et al. (2017) compared emissions from heat production via combustion of wood pellets to heat production via combustion of coal in Changchun City, China.

Due to increased pellet production and their higher combustion and heating efficiency compared to conventional firewood, pellets are becoming more commonly used for household heat production. Several LCA studies have focused on assessing the environmental impact of pellet combustion for residential heat generation. For example, Sgarbossa et al. (2020) evaluated the environmental profile of four wood pellet supply chains for heat production from different types of biomass feedstock. Research performed by Quinteiro et al. (2019) examined the environmental impact of residential heat production in Portugal by comparing alternative maritime pine wood pellet production scenarios. Pa et al. (2013) evaluated emissions related to pellet combustion for residential heat production in British Columbia. Röder and Thornley (2017) investigated the use of waste wood as a bioenergy feedstock for heat production in the United Kingdom. A study conducted by Ferreira et al. (2018) compared heat production from the combustion of wood pellets to pellets produced from grape stalks. Another study published by Quinteiro et al. (2020) compared the environmental impact of heat production via combustion of pellets produced at the sawmill to pellets produced at the household level. Sadaghiani et al. (2023) assessed the emissions related to heat generation from pellet combustion in remote communities in Canada and compared it to heat generated from diesel utilisation. Topić Božič et al. (2024) conducted an LCA that compared the effects of heat production via combustion of wood pellets vs. firewood at the household level in Slovenia.

Despite being one of the biggest pellet producers in the world, Russia has not been extensively studied in terms of life cycle assessment of pellet production and utilisation. According to FAOSTAT (2024), over two million tons of wood pellets were produced in 2022. More recently, the export of wood pellets has decreased, creating an opportunity for the transition from fossil fuels to the more environmentally friendly option of utilising the produced and unsold pellets within Russia for energy needs. Closing this gap in scientific literature is important given the amount of pellets produced in the Russian Federation and the recent trends in pellet export from Russia. This study aims to fill that gap. Using primary data on pellet production in the Arkhangelsk area of the Northwest region of Russia, provided by the executive director of the Russian Pellet Union, this LCA evaluates the environmental impact of residential heat production from pellet combustion.

MATERIAL AND METHODS

LCA is a widely utilised method for assessing the environmental impact associated with a product by gathering all relevant inputs and outputs of the product system, evaluating all the impacts associated with every step of the life cycle, and interpreting the results according to the defined goal and scope of the LCA. The current study was performed in ac-

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cordance with ISO 14040 and ISO 14044 standards (ISO 2006a, b). The assessment was performed using OpenLCA software (Version 2.1.1, 2024) and Ecoinvent 3.4 database (Ecoinvent 2017). OpenLCA software, as well as Ecoinvent database, were selected for this project because they comply with the ISO standards, are widely accepted in the scientific community, have all the necessary features and capabilities to undertake the project, and are affordable and easily accessible. The ReCiPe 2016 (H) Midpoint v. 1.1 (Huijbregts et al. 2017) was used as a method for quantitative life cycle impact assessment (LCIA) across the following impact categories:

– global warming (GW);
– freshwater eutrophication (FE);
– marine eutrophication (ME);
– terrestrial acidification (TA);
– fine particulate matter formation (FPMF);
– fossil resource scarcity (FRS);
– ozone formation (human health; OFHH);
– ozone formation (terrestrial ecosystems; OFTE).

This particular impact assessment method was chosen because it complies with ISO standards of transparency, scientific rigour, and consistency. It provides a comprehensive and harmonised set of midpoint impact assessment categories that are suitable for this LCA, and it is widely accepted in the scientific community.

Goal and scope. The goal of this study is to evaluate the environmental impact of residential heat production in the Northwest region of Russia from the combustion of wood pellets locally produced from sawmill residues in a pellet furnace. A gate-to-grave approach of LCA was applied with system boundaries consisting of the following steps: (*i*) sawmill residue collection at the sawmill; (*ii*) pellet production; (*iii*) packed pellet distribution; and (*iv*) thermal energy production and waste disposal. The production of fuels, lubricants, low-density polyethylene (LDPE) bags, as well as ash disposal from biofuel combustion, were also accounted for. The production of capital goods (buildings, equipment, and machinery) was excluded due to the scarcity of relevant data, the potential to increase uncertainty, and low relevance to the key impact categories that are analysed in this study (Silva et al. 2018). 1 MJ of thermal energy produced as a result of combustion of pellets was chosen as the functional unit. A number of sensitivity analyses were performed in order to assess the influence of methodological assumptions and inputs on the environmental impact. The first sensitivity analysis investigates an alternative life cycle impact assessment method to compare the general trends in environmental impact categories. The choice of a particular impact assessment method can influence the results and interpretation of an LCA. Therefore, using an alternative impact assessment method helps to avoid methodological bias, ensures the robustness of the result, and facilitates a more comprehensive understanding of the environmental impacts. The first sensitivity analysis compares the outcomes of bioenergy production evaluated using the ReCiPe 2016 (H) Midpoint impact category method with those obtained from the ILCD (International Reference Life Cycle Data System) 2011 methodology (European Commission, Joint Research Centre, Institute for Environment and Sustainability 2011). The ILCD 2011 Midpoint method was selected as an alternative due to the similarity in the analysed impact categories. These two LCIA methods can be compared across six impact categories. Specifically, the GW, FE, ME, TA, FPMF, and FRS impact categories in the ReCiPe LCIA method correlate with the climate change (CC), freshwater eutrophication (FE), marine eutrophication (ME), acidification, particulate matter (PM), and mineral, fossil, and renewable resource depletion (MFRRD) impact categories in the ILCD 2011 Midpoint method. The second sensitivity analysis assesses the impact of different transportation distances of pellet transportation on the environment. This particular parameter was selected based on the existing literature that highlights the significance of emissions related to the transportation distance in bioenergy production scenarios on overall environmental impact (Beagle, Belmontt 2019; Topić Božič et al. 2024). The third sensitivity analysis focuses on an alternative source of heating used during the drying step of the pelletisation process. This aspect was chosen for the third sensitivity analysis as it is one of the most analysed parameters in bioenergy LCA studies (Martín-Gamboa et al. 2020), and the choice of energy source during the pelletisation stage can significantly affect the sustainability of the bioenergy production process. A more detailed explanation regarding sensitivity analyses is provided in the 'Sensitivity analysis' section.

Description of the region. The bioenergy production scenario has been modelled using primary

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data obtained via a questionnaire from the executive director of the Russian Pellet Union. The Russian Pellet Union is an independent, non-governmental association of pellet producers created to provide a platform for pellet producers to solve the current problems of the industry in the domestic and foreign markets. It is a self-regulated organisation that interacts with government agencies and pellet companies, to solve problems regarding production, logistics, domestic consumption, etc. The Union members account for more than 60% of the production and export of wood pellets in Russia. For this study, several representatives of the pellet production industry in Russia were contacted, but only one industry professional agreed to collaborate. The data describes the production of wood pellets from sawmill residues in the Arkhangelsk area of Northwest Russia and the subsequent local thermal energy production via pellet combustion at the household level. The Arkhangelsk area is located in the Northwest part of Russia and occupies 590 thousand km^2, of which more than 60% is covered with boreal forests dominated by coniferous tree species. The local climate is subarctic, with long, cold winters and short summers. The average temperature in winter is 11.6 °C; the average summer temperature is 13.6 °C. The region has roughly one million inhabitants. This region was selected because it is a major hub for forestry and timber processing with several pellet production mills located in the area. We were able to gather data about one pellet mill that is located in the centre of the Arkhangelsk region (in the suburban industrial area approximately 15 km away from the city of Arkhangelsk), but we were asked not to disclose the name of the facility.

Description of the system. Initially, trees (predominantly Scots pine, with smaller shares of spruce, Siberian fir, and larch) are mechanically harvested for lumber production and transported as logs to a timber mill. At the mill, timber processing generates sawmill residues, such as sawdust, wood chips, and wood shavings, which are collected for pellet production. The pellet production process occurs at the same facility where the biomass is collected. Since the biomass used for pellet production is a by-product that would otherwise be disposed of as waste, the scope of this LCA excludes harvesting, log transportation, and sawmill residue production. Therefore, the system boundaries include the following steps: (*i*) pellet production, (*ii*) pellet transportation, and (*iii*) pellet combustion and waste disposal (Figure 1). Pellet combustion and waste disposal are combined into a single process as it is supported by the software and aligns with common practices in the literature (Dias et al. 2017; Ruiz et al. 2018; Quinteiro et al. 2019). Combining these processes ensures a more streamlined and accurate representation of the system, as the waste generated (e.g. ash) is directly tied to combustion activity.

The pellet production stage starts with grinding woodchips and larger residues in a grinder. The process is repeated until the desired size of biomass is achieved. Afterwards, the sawdust collected as sawmill residues is combined with the

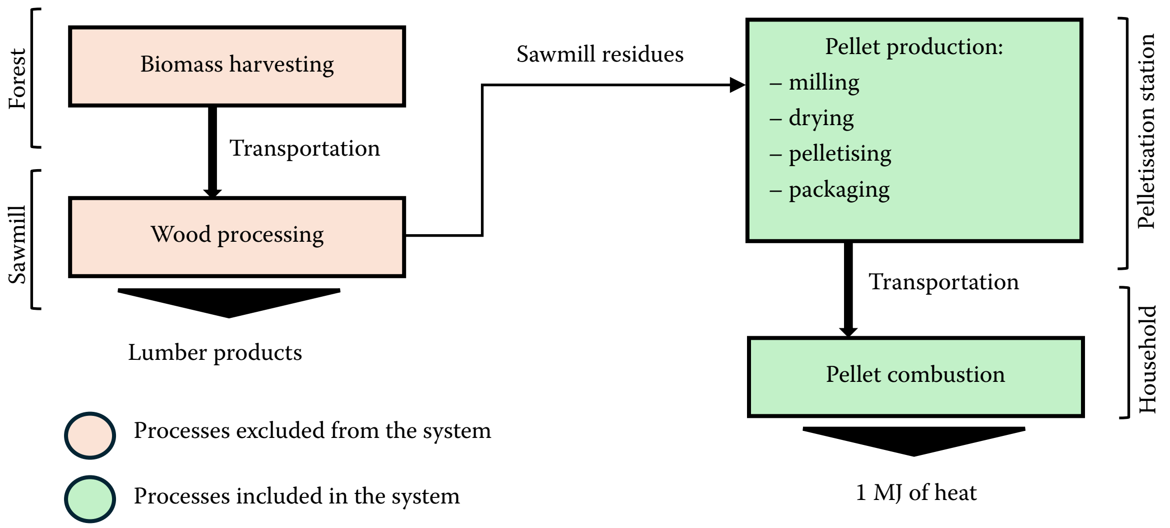

Figure 1. Flow chart of the system boundaries of heat production

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ground biomass produced during the previous stage and then supplied to the drying drum. During drying, the exhaust air is captured along with small fractions of biomass using a vacuum and deposited down into the hammer mill for further fine crushing. It is important to mention that woodchips and larger residues are used as fuel during the drying process. In a hammer mill, biomass is milled to the size of sawdust (4 mm length, 1.5 mm diameter). Next, sawdust is supplied to a cyclone in order to separate the dust from the air. After being filtered from the air, the dust is supplied to the straight screw conveyor and into the pelletiser. The pelletisation process occurs in the press-granulator under high pressure and at a temperature of 250–300 °C. Wood dust is glued together via adhesive (e.g. maize starch) in the form of cylindric pellets. Then, pellets are cut by a special blade that is installed in the granulator. The size of produced pellets is 10–30 mm in length and 6–10 mm in diameter. Cut pellets are hot and have to be cooled down. Pellets are put through a cooler equipped with fans. The cooling process changes the properties of the pellets to achieve the desired moisture content, firmness, and temperature. The characteristics of the produced pellets are presented in Table 1. After cooling, the pellets are moved from the cooler to a holding bunker equipped with a scale via a scraper conveyor. At the holding bunker, pellets are packed into small bags (10 kg, 25 kg, 50 kg), large bags (250 kg, 500 kg, 1 000 kg), or containers (20 feet or 40 feet long). Once packed, pellets are stored at the pellet production facility at the storage warehouses.

It is important to note that the pellet producer can sell pellets directly to the consumer, as it is a part of the company's business model. The pellets are held in storage containers at the production facility and, when purchased, can be delivered directly to the consumer. Avoiding the additional step of distributing packed pellets from the producer to a dealer provides the pellet producer with greater control over the quality of service, pricing, and customer relationships. This pellet distribution method for pellets is considered and analysed in our study. The final step is the production of thermal energy at the household level. We assumed the combustion of wood pellets took place in a pellet furnace with a nominal power output of 25 kW, followed by the disposal of ash at a landfill. A 25-kW pellet furnace was selected for this study due to its widespread availability on the Russian market, cost-effectiveness, and sufficient heating capacity for typical residential homes ranging from 200 m² to 300 m². Pellet combustion efficiency is considered to be 90%. Waste disposal at a landfill was selected as the end-of-life option because the alternative option of utilising ashes as a fertiliser is not feasible in the region due to the climate conditions limiting private gardening.

Table 1. Characteristics of pellets

Characteristic	Unit	Amount
Moisture content	%	7
Ash content	%	0.5
Low heating value	$MJ·kg^{-1}$	17
Bulk density	$kg·m^{-3}$	630
Carbon content	%	49.70

Source: Data obtained from the executive director of the Russian Pellet Union via questionnaire

Life cycle inventory. The inventory data used for this LCA are provided by the executive director of the Russian Pellet Union and completed with the data from the Ecoinvent 3.4 database (Ecoinvent 2017). Main input and output flows used for the LCA are presented in Table 2. A biogenic carbon neutrality status of biomass used for energy production was applied as it is common practice when conducting LCAs (Ruiz et al. 2018; Quinteiro et al. 2019; Martín-Gamboa et al. 2020). The rationale behind the assumption of carbon neutrality is that the CO_2 emissions occurring during biomass combustion are balanced out by the carbon sequestered during biomass growth. In this study, the assumption of carbon neutrality is further supported by the fact that sawmill residues not utilised for pellet production and subsequent heat generation would still be disposed of through alternative means, such as combustion or landfilling. In these alternative scenarios, the amount of biogenic emissions released would be comparable to those generated by the biomass being used for pellet production and subsequent combustion. It is crucial to highlight that the concept of carbon neutrality applies exclusively to biogenic emissions and does not encompass non-biogenic emissions, such as those resulting from fossil fuel consumption and other emission sources associated with pellet production and bioenergy generation. These non-biogenic emissions have been carefully ac-

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Table 2. Inventory data for the production of 1 MJ of heat energy from the combustion of pellets in a pellet furnace

Flow	Unit	Amount	Data description
Pellet production (1 kg)			
Electricity, high voltage	kWh	0.096	Ecoinvent database, electricity production mix, APOS, U – RU
Heat, central or small, non-fossil	MJ	0.11232	heat production, wood chips from industry, 50 kW furnace
Lubricant oil	kg	8.4e-5	Ecoinvent database, lubricant oil, APOS, U – GLO
Maize starch	kg	0.005	Ecoinvent database, maize starch, APOS, U – GLO
LDPE bags	kg	0.00228	Ecoinvent database, packaging film, low-density polyethylene, APOS, U – GLO
Saw dust	kg	0.45	primary data
Wood chips	kg	0.45	primary data
Wood shavings	kg	0.1	primary data
Water	m^3	3.0e-5	primary data
Distribution			
Truck			freight lorry, light (< 3.5 t) commercial vehicle
Distance	km	20	primary data
Conversion and waste disposal			
Pellets	kg	0.05882	primary data, moisture content 7%, lower heating value 17 $MJ \cdot kg^{-1}$
Electricity, low voltage	kWh	0.005	Ecoinvent database, electricity, low voltage, APOS, U – RU
Furnace			Ecoinvent database, furnace, pellets, 25 kW, APOS, U – GLO
Transportation of combustion waste (ash) to landfill	km	30	freight lorry, heavy (~ 25 t) commercial vehicle
Ash	kg	2.9e-4	primary data

LDPE – low-density polyethylene; APOS – allocation at the point of substitution; U – undefined; RU – Russia; GLO – global

counted for in our analysis. This concept can also be applied to the drying process and pellet combustion process.

Data for the production of 1 kg of pellets was collected from a primary source via a questionnaire and supplemented with the Ecoinvent database (Ecoinvent 2017). The main biomass materials used for pellet production are equal parts sawdust and wood chips, with a small share of mostly softwood shavings. A high-voltage Russian electricity production mix was used for power generation during the pellet production process. Heat energy, necessary for the drying phase, was generated from the combustion of wood chips in a 50-kW furnace. Wood chips were sourced from wood processing activities at the mill. The Ecoinvent database (Ecoinvent 2017) was used to gather input information for LDPE bags, lubricant oil, and maize starch. The distribution step of the LCA includes the transportation of pellets over a distance of 20 km from the pellet producer to the consumer by a light commercial vehicle. This particular distance was selected due to the prevalence of centralised district heating in Russia's national heating system. The Russian centralised district heating system is the largest in the world and serves over

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70% of the population (Korppoo, Korobova 2012). Most of the population lives in apartment buildings in cities. 90% of the heating in urban areas is from centralised heating plants that utilise conventional fossil fuels to produce heat. On the other hand, inhabitants of rural areas live mostly in private houses and only 20% of the heat energy comes from district heating plants. The pellet production facility described in this study is located outside of the general urban area, where district heating ceases to be the default option. Several rural inhabited areas are located around 20 km away from the pellet production facility, hence the decision to select a transportation distance of 20 km. The rationale behind utilising a light commercial vehicle is its economic feasibility and accessibility. A small number of inhabitants live in rural areas that are relatively close to the pellet mill, which results in short transportation distances and lower quantities of pellets that need to be transported. At the conversion step of the LCA, the production of 1 MJ of thermal energy was calculated. During this step, pellets are directly combusted in the 25-kW pellet furnace. After the combustion process, it is assumed that the combustion waste will be collected by a state-operated waste management service using a large heavy-duty truck as part of a weekly collection route. The waste will then be transported approximately 30 km from the household to a designated landfill.

The ISO 14044 guideline for LCA (ISO 2006b) recommends avoiding allocation whenever possible. As the energy and resource demands within the system boundaries of this study were associated solely with the production of a single product, allocation was not performed.

RESULTS AND DISCUSSION

Life cycle impact assessment. Table 3 shows the impact assessment results from the generation of 1 MJ of heat energy. Figure 2 represents the contribution of each step of the life cycle assessment to a particular impact category analysed.

GW is regarded as the most relevant and extensively studied impact category in bioenergy life cycle assessments (Martín-Gamboa et al. 2020; Musule et al. 2021) due to its direct link to climate change. GW quantifies the greenhouse gas emissions associated with bioenergy systems, providing a clear metric to evaluate their environmental performance and contribution to climate change. Evaluation of global warming from the production of 1 MJ of thermal energy showed emissions of 0.015 kg of CO_2 equivalent (eq), mostly accrued from pellet production (44.4%) and pellet combustion and waste disposal (40.6%), with 15% emission related to the transportation stage. Despite the fact that comparing LCAs can be challenging due to variations in system, temporal, and spatial boundaries, functional units, methodological choices, differences in feedstock, conversion technology, etc., some similarities can be found in LCAs with particular parameters. A review conducted by Martín-Gamboa et al. (2020) showed that GW values from 0 to 0.025 g CO_2 eq use waste biomass as feedstock for pellet production, utilise biomass for drying during the pelletisation process, assume carbon neutrality of biomass for biogenic emissions, and have low transportation distances. The parameters of the system in our LCA, as well as the GW emissions, overlap with the parameters mentioned in the review. The freshwater eutrophication impact category results show the emission of 5.85e-6 kg of P eq contributed by pellet production (42.5%) and combustion (49.5%). Marine eutrophication emissions amounted to 1.42e-6 kg of N eq coming predominantly from the pellet production stage (85.7%). Terrestrial acidification impact amounted to the emission of 8.29e-5 kg of SO_2 eq and is mainly related to the combustion stage of the life cycle (61.4%), followed by pellet production (29.2%) and transportation (9.4%). Fine particular matter formation impact category analysis shows the emission of 7.35e-5 kg PM2.5 eq generally from the combustion stage (74.5%) and pellet production stage (20.5%). Fossil resource scarcity emissions are equal to 0.0045 kg of oil eq, coming from all three stages of the life cycle in significant shares: pellet production – 49.4%, transportation – 16.7%, and pellet combustion and waste disposal – 33.9%. The analysis of ozone formation (human health) and ozone formation (terrestrial ecosystem) showed practically identical results with the main contributor being the stage of pellet combustion and waste disposal (74%).

Overall, the combustion and waste disposal stage of the life cycle is the most impactful step within the current LCA, as it is the main contributor in five out of the eight impact categories (FE, TA, FPMF, OFHH, and OFTE). The remaining impact categories (GW, ME, FRS) are most influenced by the pel-

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Table 3. Results of impact assessment of the production of 1 MJ of heat energy

Impact category	Unit	Amount
Global warming (GW)	kg CO_2 eq	0.015
Freshwater eutrophication (FE)	kg P eq	5.85e-6
Marine eutrophication (ME)	kg N eq	1.42e-6
Terrestrial acidification (TA)	kg SO_2 eq	8.29e-5
Fine particulate matter formation (FPMF)	kg PM2.5 eq	7.35e-5
Fossil resource scarcity (FRS)	kg oil eq	0.0045
Ozone formation (human health; OFHH)	kg NO_x eq	0.00012
Ozone formation (terrestrial ecosystems; OFTE)	kg NO_x eq	0.00012

let production step, with the transportation step being the least impactful and never exceeding 17% of contribution to any impact category. These findings correspond with the existing literature. For example, Quinteiro et al. (2019) assessed the impact of small-scale thermal energy production in Portugal from the combustion of pellets produced from maritime pine logs. Their findings showed that the main contributor to GW and FRS is pellet production, whereas thermal energy generation has the greatest impact on OFTE, OFHH, and TA. Moretti et al. (2014) analysed the effects of thermal energy production from pellet combustion in Southern Italy and also concluded GW was the most impacted by the pellet production process. In another study, Topić Božič et al. (2024) conducted an LCA to assess the effects of domestic heat production in Slovenia from combustion of wood pellets produced from sawmill residues. The results of their LCA showed that the pellet production process has the greatest impact on GW even when transportation distances for pellet distribution reach 500 km.

Sensitivity analysis. Three sensitivity analyses were conducted to assess the impact of the methodological assumptions and data used within the framework of this LCA. The first sensitivity analysis consists of the application of an alternative LCIA method to examine whether the same trend

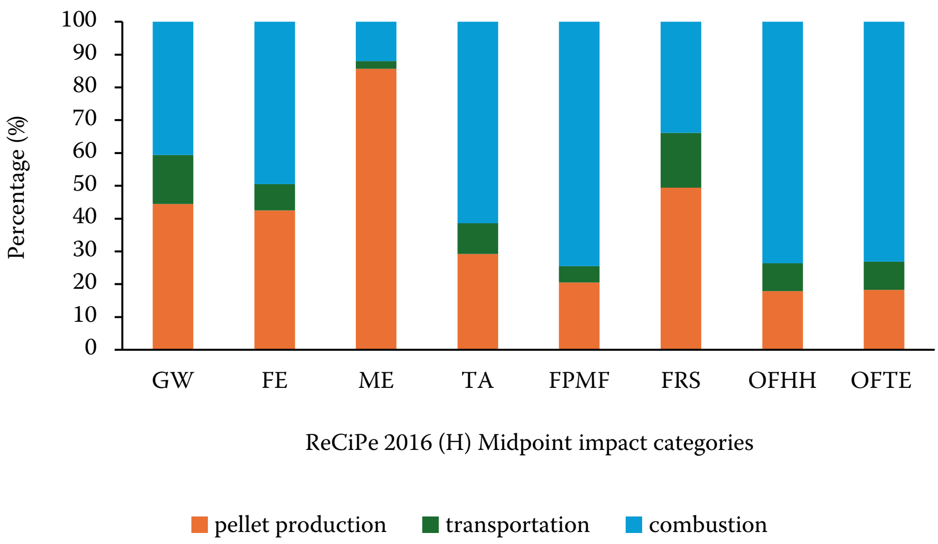

Figure 2. Contribution of each step in life cycle assessment (LCA) by impact category using ReCiPe 2016 (H) Midpoint life cycle impact assessment (LCIA) method

GW – global warming; FE – freshwater eutrophication; ME – marine eutrophication; TA – terrestrial acidification; FPMF – fine particulate matter formation; FRS – fossil resource scarcity; OFHH – ozone formation (human health); OFTE – ozone formation (terrestrial ecosystems)

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in results is observed. The results of the evaluation of ILCD impact categories are presented in Figure 3. Similar trends were observed when analysing the results of the contribution of each stage of the LCA for all impact categories, with the exception of marine eutrophication. When utilising the ILCD method, the results showed that the main impact is related to the combustion and waste disposal step of LCA (67%), with pellet production contributing 25%, and the remaining 8% being attributed to the transportation stage. This result is expected considering the difference in methodological approaches these two methods implement in this particular impact category (Colucci et al. 2021). Such discrepancies in the marine eutrophication impact category come from the higher characterisation factors for nitrogen oxides (NO_x), simpler midpoint modelling approach, and lack of regionalisation in ILCD 2011 compared to ReCiPe 2016 (European Commission, Joint Research Centre, Institute for Environment and Sustainability 2011; Huijbregts et al. 2017).

The second sensitivity analysis consists of the evaluation of the alternative source of heat used during the drying stage in the pelletisation step of the LCA. Many pellet production facilities in the Northwest region of Russia generate heat for the drying stage of the pelletisation by combusting sawmill residues, as is the case in the current study. However, there are facilities that obtain the heat for the drying step from other sources. For this sensitivity analysis, the production of 1 MJ of thermal energy was assessed with the use of natural gas for the drying of biomass for pellet production since it is one of the most common sources of heat in the Arkhangelsk area in the Northwest region. The results of the impact assessment are presented in Table 4. The GW and FRS impact categories showed a higher number of emissions, compared to the baseline scenario. Both GW and FRS impact categories showed increased emissions by 6.5% and 4.3%, respectively, due to the increased emissions during pellet production. The results of ME and OFTE impact categories remained the same, whereas the overall impact on FE, TA, FPMF, and OFHH decreased. The most significant impact reduction is observed in the OFHH impact category with the amount of NO_x eq emissions decreased by 8.7%. Other impact categories showed lower impact reduction with the results not exceeding 2% reduction. These results correlate with the existing LCA studies that have assessed alternative sources of heat for the drying step of pelletisation. The LCA conducted by Padilla-Rivera et al. (2017) demonstrated that the production of one ton of packed pellets using sawmill residues in the form of sawdust, shavings, and woodchips for heating during the drying stage of the pelletisation process emits

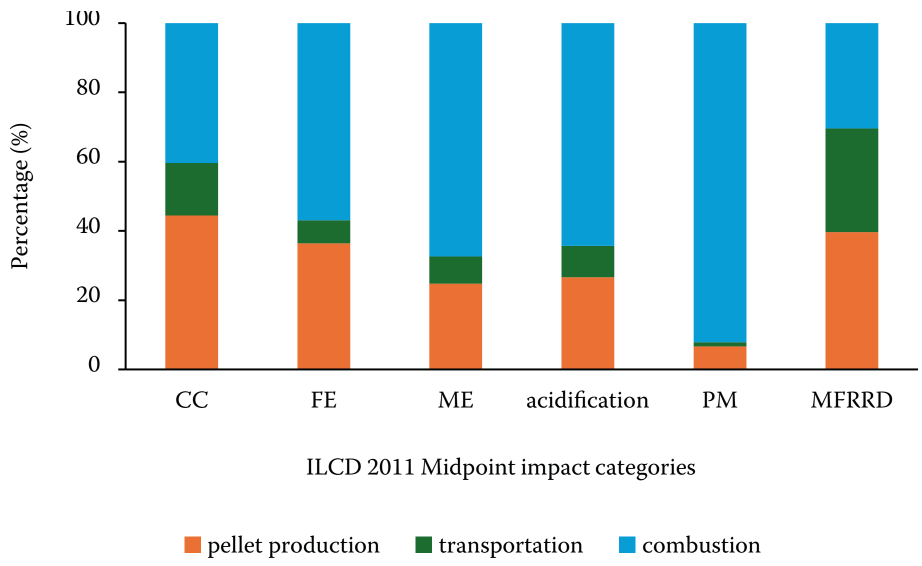

Figure 3. Contribution of each step in life cycle assessment (LCA) by impact category using ILCD 2011 Midpoint method

CC – climate change; FE – freshwater eutrophication; ME – marine eutrophication; PM – particulate matter; MFRRD – mineral, fossil, and renewable resource depletion

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Table 4. Sensitivity analysis results by impact category

Impact categories	Unit	Baseline scenario	Sensitivity analysis 2	Sensitivity analysis 3
		amount	amount	amount
Global warming (GW)	kg CO_2 eq	0.015	0.016	0.025
Freshwater eutrophication (FE)	kg P eq	5.85e-6	5.82e-6	7.69e-6
Marine eutrophication (ME)	kg N eq	1.42e-6	1.42e-6	1.55e-6
Terrestrial acidification (TA)	kg SO_2 eq	8.29e-5	8.20e-5	0.00011
Fine particulate matter formation (FPMF)	kg PM2.5 eq	7.35e-5	7.22e-5	8.81e-5
Fossil resource scarcity (FRS)	kg oil eq	0.0045	0.0047	0.0075
Ozone formation (human health; OFHH)	kg NO_x eq	0.00012	0.00011	0.00016
Ozone formation (terrestrial ecosystems; OFTE)	kg NO_x eq	0.00012	0.00012	0.00016

Baseline scenario – transportation distance of 20 km with waste biomass used for drying; sensitivity analysis 2 – natural gas used for drying; sensitivity analysis 3 – transportation distance of 100 km

2.84 kg CO_2 eq, whereas drying using natural gas emits 20.25 kg CO_2 eq. In a study published by Benetto et al. (2015), utilising wood chips for drying during the pellet production process significantly reduced the impact on GW, FE, and FRS compared to drying using natural gas, grape marc pellets, or electricity from the grid.

The third sensitivity analysis tests the assumed transportation distance. The chosen distance of 20 km in the baseline scenario is due to the proximity of the pellet production facility to the residential areas. For this sensitivity analysis, the distance of 100 km was chosen due to the potential for the pellet production company to increase their distribution networks to smaller rural inhabited areas. Several of these settlements are located further from the centre of the Arkhangelsk region at a distance of 100 km from the pellet production facility. Rural communities living further from the urbanised area lack centralised heating and are more likely to have an increased demand for alternative heat sources. The results of this sensitivity analysis can help identify potential environmental impacts and opportunities for optimising logistics. Additionally, the same lightweight truck was kept as the means of transportation as opposed to transportation of pellets by train because it is not an economically viable method for the relatively low demand for pellets in the area associated with the small number of rural inhabitants. The results of LCIA showed significantly increased emissions in all impact categories assessed, with the biggest growth of 50% for GW and FRS, and almost 30% for FE, TA, OFHH, and OFTE (Table 4). These results correlate with the existing literature. Topić Božič et al. (2024) observed an increase of 85% in OFHH, 120% in FRS, and 102% in GW if the distance pellets are transported by truck is increased from 100 km to 1 000 km. Another LCA study published by Cleary and Caspersen (2015) showed a 37% decrease in GW related to the transportation of pellets in Canada when the transportation distance is decreased from 1 889 km (where 250 km are covered by truck, and 1 635 km by train) to 1 350 km by train.

The results of this study provide a comprehensive evaluation of the environmental impacts associated with residential heat production from wood pellets in the Northwest region of Russia, utilising primary data specific to the Arkhangelsk area.

CONCLUSION

This study evaluated the environmental impact of residential heat production in the Northwest region of Russia using wood pellets derived from sawmill residues through a life cycle assessment (LCA) following ISO 14040 and ISO 14044 standards. The analysis, based on a gate-to-grave approach, included sawmill residue collection, pellet production, pellet distribution, and thermal energy production and ash disposal. The ReCiPe 2016 (H) Midpoint v. 1.1 method was employed to assess the environmental impacts across several categories.

The results indicated that pellet combustion and waste disposal is the most impactful stage in the life cycle, contributing significantly to freshwater eutrophication (FE), terrestrial acidification (TA),

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fine particulate matter formation (FPMF), and ozone formation (both OFHH and OFTE). Pellet production was the dominant contributor to global warming (GW), marine eutrophication (ME), and fossil resource scarcity (FRS). Transportation had the least impact across all categories.

Sensitivity analyses confirmed the robustness of these findings. When an alternative LCIA method (ILCD 2011 Midpoint) was applied, similar trends were observed, with minor deviations in marine eutrophication impacts due to methodological differences. The evaluation of an alternative heat source for pellet drying (natural gas) resulted in higher emissions for GW and FRS, while other impact categories showed reduced impacts. Increasing the transportation distance from 20 km to 100 km significantly raised emissions across all impact categories, emphasising the importance of proximity between the pellet manufacturer or distributor and end users.

This study highlights the environmental benefits and drawbacks of using wood pellets for residential heating in the Northwest region of Russia. While pellet combustion and production stages are the most significant contributors to environmental impacts, optimising the supply chain, particularly in terms of transportation distance and heat sources for drying, can mitigate some of these impacts. The findings provide valuable insights for policymakers and stakeholders aiming to enhance the sustainability of bioenergy systems.

The importance of aspects of the transportation process, as highlighted in the current study, underscores the need for future LCA studies to investigate alternative transportation methods and transportation distances. Additionally, subsequent studies could compare the findings of this study with those of other bioenergy production scenarios. These scenarios might include:

– The use of different biofuels, such as wooden chips or firewood, to assess their comparative environmental impact.
– The use of various biomass sources, such as logging residues or bioenergy plantations, used for biofuel production to identify the most suitable feedstock options.
– The use of different conversion technologies, such as pyrolysis or gasification, to determine their potential for emission reduction.

The findings from such comparative analyses can provide critical insights for policymakers, enabling them to make more informed decisions on climate change mitigation strategies.

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REFERENCES

Agostini A., Giuntoli J., Marelli L., Amaducci S. (2020): Flaws in the interpretation phase of bioenergy LCA fuel the debate and mislead policymakers. The International Journal of Life Cycle Assessment, 25: 17–35.

Ahmadi L., Kannangara M., Bensebaa F. (2020): Cost-effectiveness of small-scale biomass supply chain and bioenergy production systems in carbon credit markets: A life cycle perspective. Sustainable Energy Technologies and Assessments, 37: 100627.

Alanya-Rosenbaum S., Bergman R.D., Ganguly I., Pierobon F. (2018): A comparative life-cycle assessment of briquetting logging residues and lumber manufacturing coproducts in Western United States. Applied Engineering in Agriculture, 34: 11–24.

Alizadeh P., Mupondwa E., Tabil L.G., Li X., Cree D. (2023): Life cycle assessment of bioenergy production from wood sawdust. Journal of Cleaner Production, 427: 138936.

Beagle E., Belmont E. (2019): Comparative life cycle assessment of biomass utilization for electricity generation in the European Union and the United States. Energy Policy, 128: 267–275.

Benetto E., Jury C., Kneip G., Vázques-Rowe I., Huck V., Minette F. (2015): Life cycle assessment of heat production from grape marc pellets. Journal of Cleaner Production, 87: 149–158.

Carotenuto A., Di Fraia S., Uddin M.R., Vanoli L. (2022): Comparison of combustion and gasification for energy recovery from residual woody biomass. International Journal of Heat and Technology, 40: 888–894.

Cleary J., Caspersen J.P. (2015): Comparing the life cycle impacts of using harvest residue as feedstock for small- and large-scale bioenergy systems (part I). Energy, 88: 917–926.

Colucci V., Manfrida G., Mendecka B., Talluri L., Zuffi C. (2021): LCA and exergo-environmental evaluation of a combined heat and power double-flash geothermal power plant. Sustainability, 13: 1935.

Dias G.M., Ayer N.W., Kariyapperuma K., Thevathasan N., Gordon A., Sidders D., Johannesson G.H. (2017): Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario, Canada. Applied Energy, 204: 343–352.

https://doi.org/10.17221/88/2024-JFS

EC (2018): Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources. Official Journal of the European Union. Brussels, European Commission. Available at: http://data.europa.eu/eli/dir/2018/2001/oj

Ecoinvent (2017): Ecoinvent database, Version 3.4. Dusseldorf, Swiss Centre for Life Cycle Inventories. Available at: https://support.ecoinvent.org/ecoinvent-version-3.4

European Commission, Joint Research Centre, Institute for Environment and Sustainability (2011): International Reference Life Cycle Data System (ILCD) Handbook – Recommendations for Life Cycle Impact Assessment in the European Context. EUR 24571 EN. 1st Ed. Luxemburg, Publications Office of the European Union: 143.

FAOSTAT (2024): Forestry Production and Trade. Rome, Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/faostat/en/#data/FO

Ferreira J., Esteves B., Cruz-Lopes L., Evtuguin D.V., Domingos I. (2018): Environmental advantages through producing energy from grape stalk pellets instead of wood pellets and other sources. International Journal of Environmental Studies, 75: 812–826.

Fitzpatrick J.J. (2016): Environmental sustainability assessment of using forest wood for heat energy in Ireland. Renewable and Sustainable Energy Reviews, 57: 1287–1295.

Guo M., Song W., Buhain J. (2015): Bioenergy and biofuels: History, status, and perspective. Renewable and Sustainable Energy Reviews, 42: 712–725.

Hammar T., Hansson P.A., Sundberg C. (2017): Climate impact assessment of willow energy from a landscape perspective: A Swedish case study. GCB Bioenergy, 9: 973–985.

Huijbregts M.A.J., Steinmann Z.J.N., Elshout P.M.F., Stam G., Verones F., Vieira M., Zijp M., Hollander A., van Zelm R. (2017): ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment, 22: 138–147.

ISO (2006a): ISO 14040. Environmental Management – Life Cycle Assessment – Principles and Frameworks. Geneva, International Organization for Standardization. Available at: https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en

ISO (2006b): ISO 14044. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. Geneva, International Organization for Standardization. Available at: https://www.iso.org/standard/38498.html

Klavina K., Romagnoli F., Blumberga D. (2017): Comparative life cycle assessment of woodchip uses in pyrolysis and combined heat and power production in Latvia. Energy Procedia, 113: 201–208.

Korppoo A., Korobova N. (2012): Modernizing residential heating in Russia: End-use practices, legal developments, and future prospects. Energy Policy, 42: 213–220.

Lu H.R., El Hanandeh A. (2017): Assessment of bioenergy production from mid-rotation thinning of hardwood plantation: Life cycle assessment and cost analysis. Clean Technologies and Environmental Policy, 19: 2021–2040.

Malmsheimer R.W., Heffernan P., Brink S., Crandall D., Deneke F., Galik C., Gee E., Helms J.A., McClure N., Mortimer M., Ruddell S., Smith M., Stewart J. (2008): Forest management solutions for mitigating climate change in the United States. Journal of Forestry, 106: 119–171.

Mandley S.J., Daioglou V., Junginger H.M., van Vuuren D.P., Wicke B. (2020): EU bioenergy development to 2050. Renewable and Sustainable Energy Reviews, 127: 109858.

Martín-Gamboa M., Marques P., Freire F., Arroja L., Dias A.C. (2020): Life cycle assessment of biomass pellets: A review of methodological choices and results. Renewable and Sustainable Energy Reviews, 133: 1–13.

McKechnie J., Colombo S., Chen J., Mabee W., MacLean H. (2011): Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. Environmental Science and Technology, 45: 789–795.

Medina-Ríos E., Morales-Máximo M., López-Sosa L.B., Aguilera-Mandujano A., Corral-Huacuz J.C. (2021): Life cycle analysis (LCA) of the production of wood waste briquettes from *Pinus* spp.: Case study San Francisco Pichátaro, México. IOP Conference Series: Earth and Environmental Science, 912: 012011.

Moretti M., De Boni A., Roma R. (2014): Economic and environmental sustainability of forestry measures in Apulia Region Rural Development Plan: An application of life cycle approach. Land Use Policy, 41: 284–289.

Morrison B., Golden J.S. (2016): Southeastern United States wood pellets as a global energy resource: A cradle-to-gate life cycle assessment derived from empirical data. International Journal of Sustainable Energy, 37: 134–146.

Musule R., Bonales-Revuelta J., Mwampamba T.H., Gallardo-Alvarez R., Masera O., García C.A. (2021): Life cycle assessment of forest-derived solid biofuels: A systematic review of the literature. BioEnergy Research, 15: 1711–1732.

Pa A., Bi X.T., Sokhansanj S. (2013): Evaluation of wood pellet application for residential heating in British Columbia based on a streamlined life cycle analysis. Biomass and Bioenergy, 49: 109–122.

Padilla-Rivera A., Barrette J., Blanchet P., Thiffault E. (2017): Environmental performance of eastern Canadian wood pellets as measured through life cycle assessment. Forests, 8: 1–18.

Pergola M., Gialdini A., Celano G., Basile M., Caniani D., Cozzi M., Gentilesca T., Mancini I.M., Pastore V., Romano S., Ventura G., Ripullone F. (2018): An environmental and economic analysis of the wood-pellet chain: Two case studies in Southern Italy. The International Journal of Life Cycle Assessment, 23: 1675–1684.

https://doi.org/10.17221/88/2024-JFS

Pierobon F., Zanetti M., Grigolato S., Sgarbossa A., Anfodillo T., Cavalli R. (2015): Life cycle environmental impact of firewood production – A case study in Italy. Applied Energy, 150: 185–195.

Porsö C., Hansson P.A. (2014): Time-dependent climate impact of heat production from Swedish willow and poplar pellets – In a life cycle perspective. Biomass and Bioenergy, 70: 287–301.

Quinteiro P., Tarelho L., Marques P., Martín-Gamboa M., Freire F., Arroja L., Dias A.C. (2019): Life cycle assessment of wood pellets and wood split logs for residential heating. Science of the Total Environment, 689: 580–589.

Quinteiro P., Greco F., da Cruz Tarelho L.A., Righi S., Arroja L., Dias A.C. (2020): A comparative life cycle assessment of centralized and decentralized wood pellets production for residential heating. Science of the Total Environment, 730: 139162.

Röder M., Thornley P. (2018): Waste wood as bioenergy feedstock. Climate change impacts and related emission uncertainties from waste wood based energy systems in the UK. Waste Management, 74: 241–252.

Ruiz D., San Miguel G., Corona B., López F.R. (2018): LCA of a multifunctional bioenergy chain based on pellet production. Fuel, 215: 601–611.

Sadaghiani S., Mafakheri F., Chen Z. (2023): Life cycle assessment of bioenergy production using wood pellets: A case study of remote communities in Canada. Energies, 16: 5697.

Sahoo K., Alanya-Rosenbaum S., Bergman R., Abbas D., Bilek E.M. (2021): Environmental and economic assessment of portable systems: Production of wood-briquettes and torrefied-briquettes to generate heat and electricity. Fuels, 2: 345–366.

Sgarbossa A., Boschiero M., Pierobon F., Cavalli R., Zanetti M. (2020): Comparative life cycle assessment of bioenergy production from different wood pellet supply chains. Forests, 11: 1–16.

Shafiee S., Topal E. (2009): When will fossil fuel reserves be diminished? Energy Policy, 37: 181–189.

Silva F.B., Yoshida O.S., Diestelkamp E.D., Oliveira L.A. (2018): Is it relevant to include capital goods in the life cycle assessment of construction products? In: VI Congresso Brasileiro em Gesao do Ciclo de Vida – Anais, Brasília, June 17–20, 2018: 1–6. Available at: https://ipt.br/2022/03/18/is-it-relevant-to-include-capital-goods-in-the-life-cycle-assessment-of-construction-products/

Sjølie H.K., Solberg B. (2011): Greenhouse gas emission impacts of use of Norwegian wood pellets: A sensitivity analysis. Environmental Science & Policy, 14: 1028–1040.

Topić Božič J., Fric U., Čikić A., Muhič S. (2024): Life cycle assessment of using firewood and wood pellets in Slovenia as two primary wood-based heating systems and their environmental impact. Sustainability, 16: 1687.

Vera I., Hoefnagels R., van der Kooij A., Moretti C., Junginger M. (2019): A carbon footprint assessment of multioutput biorefineries with international biomass supply: A case study for the Netherlands. Biofuels, Bioproducts and Biorefining, 14: 198–224.

Wang C., Chang Y., Zhang L., Pang M., Hao Y. (2017): A lifecycle comparison of the energy, environmental and economic impacts of coal versus wood pellets for generating heat in China. Energy, 120: 374–384.

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