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Life Cycle Assessment of Using Firewood and Wood Pellets in Slovenia as Two Primary Wood-Based Heating Systems and Their Environmental Impact

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Abstract: Sustainable use of biomass energy sources can reduce dependency on fossil fuels. Wood biomass is the primary source for heating in Slovenia, with firewood and wood pellets having the highest share. Slovenia's largest consumers of wood fuels are households primarily using wood from their forests or imported wood pellets. This research used a life cycle assessment to analyze and evaluate the environmental impacts of using firewood and wood pellets for household heating in Slovenia for the first time. The results showed that wood logs have a considerably greater effect on stratospheric ozone depletion, ozone formation, and fine particulate matter (PM) formation. The impact on global warming was lower due to short transportation distances and using log boilers with high combustion efficiency (0.016 and 0.041 kg CO_2 eq for wood log and wood pellet combustion, respectively). An increase in transportation distance from 100 km to 1000 km resulted in an 84.9% increase in the values for the categories ozone formation and human health, a 120.4% increase for fossil resource scarcity, and a 102.4% increase in global warming, supporting the premise that short distribution routes are necessary for more sustainable use of the energy source.

Keywords: firewood; wood pellets; life cycle assessment; sustainable energy use; Slovenian heating systems

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1. Introduction

The crucial elements of the European Green Deal (EGD) are clean, affordable, and secure energy. Decarbonization of the energy system is necessary to achieve the 2030 and 2050 climate targets. To achieve this goal, sustainable management of natural resources is essential by creating a sector mainly based on renewable sources, phasing out coal, and reducing gas emissions [1]. Data available for the gross final energy use and the targets set for 2020 show that Sweden has the highest share among EU states, ahead of Finland, Latvia, and Denmark. Slovenia is 11th regarding the share of renewables (>20%) in the EU; however, it is still short of the set target for 2020 (25%) [2].

The average household energy use in 2018–2022 was 45.4 TJ [3]. The main share was spent on space heating (61%), lighting and electrical devices (17%), and sanitary water heating. The structure of energy use is shown in Figure 1. Wood fuels, the primary energy source for heating in Slovenia, dominate energy use. Data for 2022 showed that wood fuels had a share of 34%, followed by natural gas with 10%. Other sources had a share below 10%, with extra light oil at 9%, district heating with almost 7%, ambient heat (nearly 6%), liquefied petroleum gas (almost 3%), and solar energy (1%) [3,4].

Dependency on fossil fuels can be reduced through sustainable implementation of biomass-powered household heating systems. Biomass is considered a renewable energy source, and its use can contribute towards greater sustainability in the energy sector but also presents numerous environmental and socio-economic challenges. The main challenge of using wood for heating in the regions where sustainable forest management practices are implemented is the air pollution generation from wood combustion. Nevertheless, due to improvements in the performance of combustion appliances, emissions have been reduced significantly in the last 20 years [5,6].

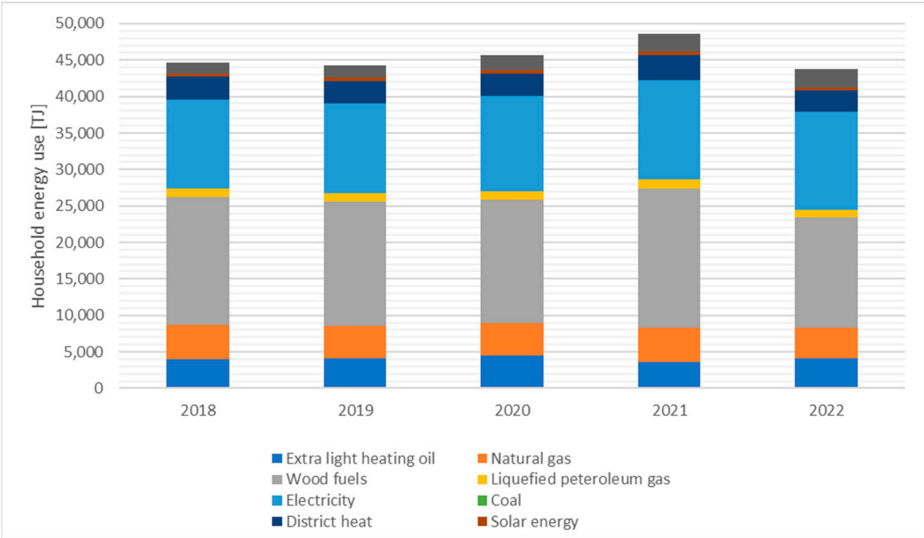

Figure 1. Household energy use 2018–2022 by energy source [3].

Biomass as Energy Source for Residential Heating Systems

Biomass is a natural storage of energy and represents a traditional energy source. The advantage of using biomass as an energy source lies in its relatively large availability and usability potential [7]. The revised renewable energy directive (EU Directive 2023/2413) states that woody biomass should be used in line with the principle of cascading use of biomass in the following order: wood-based products, extending the service life of wood-based products, re-use, recycling, bioenergy, and disposal according to their economic and environmental added values [8–10]. The high share of renewable energy sources in power systems in the Republic of Slovenia could be reached using biomass in cogeneration plants, as biomass use could reduce the need to export electricity in summertime and import electricity in wintertime [11]. Biomass is considered a renewable energy source; however, it has to be taken into account that the provision of wood and subsequent activities require inputs from non-renewable sources, thereby modifying the assumption of 100% renewable products [12,13]. The life cycle assessment (LCA) is primarily used for analyzing the environmental impacts of products or services. For wood supply, several LCA analyses have been carried out [13]; however, they dealt with country-specific wood supply networks, primarily in Europe. The LCA of Austrian and Slovenian raw wood production was recently published [14]. Firewood is still commonly used as a primary energy source worldwide [15–17]. Through a critical review of the literature and available secondary sources, no LCA studies and research available for wood-based heating systems in Slovenia could be found.

Biomass from forestry is classified into roundwood production and primary and secondary residues. The appropriate exploration of forest biomass can play a role in providing sustainable energy sources [18]. Primary residues are logging residues and other pre-commercial thinning, while secondary residues cover woodchips and pellets, sawdust, and black liquor [19]. Data on felling and removal statistics shows that at the EU-28 level, removals have been lower than increments. Together with the expansion in forest areas, the result was an increase in woody biomass stocks in the forest [20]. At the EU level, energy accounts for nearly half (48%) of the total use of woody biomass. Wood energy use has been increasing, with wood pellet consumption playing a factor, as the use of wood pellets results in reduced greenhouse gas emissions and particulate matter and less ash generation [20,21].

Forests in Slovenia cover 58% of the total area with 1 M ha of economic value. From 2018 to 2022, 4.8 million gross cubic meters (m^3) of timber was removed on average annually [4]. Most of the timber is used to produce industrial wood, with 73.1% of the share being industrial wood. Within the industrial wood products' manufacturing majority, the timber utilized comes from softwood species (>75%), with the highest use as sawlogs and veneer (>70%). In the case of hardwoods, the highest use, 58.3%, is for heating [3]. Data for 2016–2020 show similar trends, although an annual average of 5.4 million m^3 of timber was produced [22]. The logs felled in Slovenia are primarily used for firewood or exported due to the limited processing capacity in Slovenia that impedes their conversion into high-value timber products [22].

In Slovenia, four types of wood fuels are used for heating purposes. The most common is firewood, followed by wood pellets, wood chips, and briquettes, although the use of wood briquettes is negligible. Most commonly, biomass is used in residential households [23]. The annual final consumption of firewood for heating is, on average, 1 million t. The average consumption of pellets is more than ten times smaller, with 77 t on average in 2018–2022. The average final consumption of wood chips, briquettes, and waste for heat production is 31,000 t. Wood biomass prevails as the primary source for heat production, and combined, it makes up more than 50% of the share [3]. In Slovenia, there are five main types of raw wood categories [3]:

- roundwood,
- sawlogs and veneer logs,
- round and split pulpwood,
- other industrial roundwood, and
- wood fuel.

Based on the Slovenian Statistical Office (SURS) data, 10% of the raw wood is produced for wood fuel (2018–2022, SURS), as seen in Figure 2.

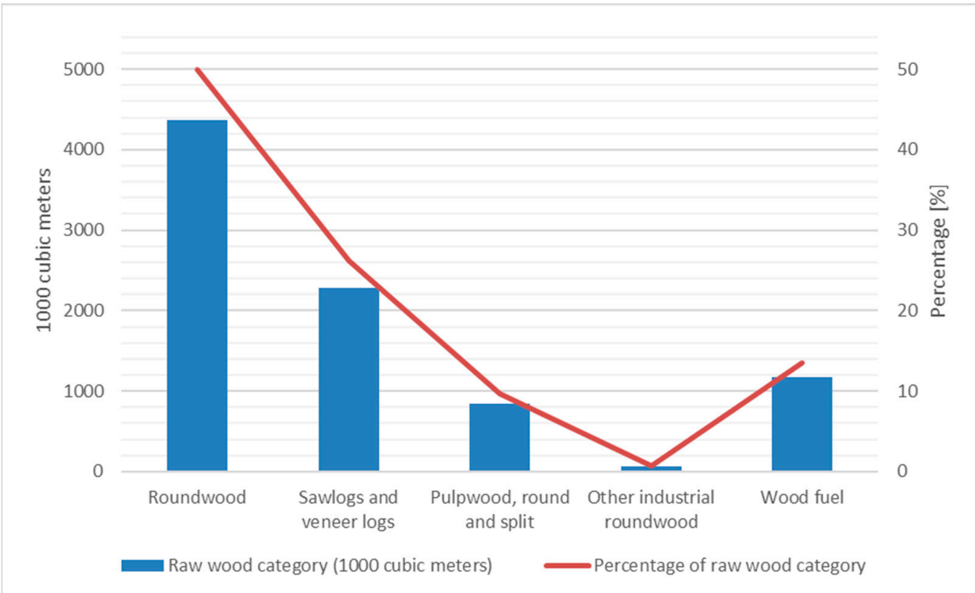

Figure 2. Raw wood categories and percentages [3].

Wood fuel production in Slovenia is specific, as most of the forest is privately owned (77%), 20% is state-owned, and municipalities own 3%. The cumulative area of privately owned forest is almost 910,000 ha, belonging to 282,500 forest properties and more than 400,000 individual owners, with most of the forest property area being 3.2 ha [24]. Most of the forestry work is done by the owners or their family members (93%). The most used machinery are chainsaws and tractors with three-point linkage winches regardless of the size of the forest holding [25]. Of the felled hardwood, 83% is used for heating for personal use [26].

The largest consumers of wood fuels in Slovenia are households using firewood predominantly acquired from their forest or the market. The largest single consumer of wood for energy is the district heating system in Ljubljana, which utilizes the co-incineration of coal and wood using more than 100,000 t of wood chips per year [27]. The primary consumers of wood pellets are also households, followed by larger public buildings and other users. Slovenia is a net exporter of wood pellets and predominantly imports wood pellets from Romania, Austria, Bosnia, and Herzegovina [27]. Compared to traditional use of firewood, wood pellets are burned in pellet stoves with a higher combustion efficiency than conventional heating systems (wood stoves). Wood pellets have a higher energy density and thus require less storage space than firewood. However, pellet production requires more complex industrial processing, which, in principle, leads to higher life cycle environmental impacts [28]. Slovenian domestic pellet production amounted to 164,000 t in 2022, with 23 predominantly smaller registered producers producing up to 10,000 t of pellets annually. Pellets are mostly exported due to higher export market price. Data from the period 2018–2022 show that Slovenian wood pellet export has on average exceeded 150,000 t, including re-export as Slovenia exports to Austria and imports from it [3,23]. In 2022, the exports amounted to 164,679 t, while imports amounted to 125,614 t [23], implying that most of the wood pellets for heating are imported. Data on trade imports and exports from 2022 show that the top five countries from which Slovenia has imported wood pellets are Austria (23.9%), Ukraine (17.7%), Croatia (13.3%), Slovakia (11.7%), and Romania (10.9%). Most of the pellets were exported to Italy (80%), followed by Austria (15%) [3]. Most wood fuels in Slovenia are used for central heating (82.3%). The annual average in 2018–2022 for central heating was 14.1 TJ of wood fuel, and for local heating, 2.7 TJ of wood fuel [3].

The following working phases can be distinguished when extracting wood fuels directly from forests [29,30]:

- Felling and processing: cutting a tree from its stump so that the tree falls to the ground, delimbing and cross-cutting the trunk to predetermined lengths.
- Skidding: transportation of wood from the felling site to the extraction routes and transportation of timber along the extraction routes to the landing sites.
- Debarking: partially or entirely removing the bark from a log.
- Transporting wood on forest and public roads.
- Producing wood fuel: production of different wood fuels with cutting and splitting activities.

A few LCAs of wood fuel heating systems have been published, but the research available is still limited [5,28,31–33]. Differences in relevant processes and systems' boundaries exist, and comparison is challenging. In 2006, Petersen Raymer published research where LCA analysis was performed for the use of fuel wood, sawdust, and pellets in Norway [32]. More recently, five types of wood biomass chains were analyzed: firewood obtained from traditional skidding systems, firewood obtained using aerial cableway removal systems, class B wood chips, class A wood chips, and class A1 wood chips, which are used for domestic heating systems in Italy [34]. Life cycle environmental impact assessment of firewood production was performed for long and short supply chains in Italy [33]. Quinteiro et al. performed an LCA analysis of wood pellets and wood split logs for residential heating [28]. Recently, Zgheib et al. performed an LCA analysis of wood-log and pellet scenarios in France. The results showed that the pellet scenario presented higher impacts for all studied categories due to the manufacturing step [5]. Even though sustainable approaches of using forest and sawmill residues for wood pellet production are predominantly used, a trade-off exists between the benefits in reducing the need for fossil fuels and local pollution.

The aim of the present work was to evaluate the environmental impact of using locally obtained firewood and imported wood pellets for heating in Slovenia and compare the effect of transport on the environmental impact of using wood pellets for heating.

2. Materials and Methods

2.1. Objectives and Scope

Aim of the research was to analyze and evaluate the environmental impacts of two types of most used wood biomass for household heating in Slovenia—firewood and wood pellets. To achieve the aim, we set the following two specific objectives:

1. Quantify life cycle environmental impacts of heat produced from firewood and from wood pellets.
2. Analyze the environmental hotspots of two biomass options and compare the effect of transportation distance.

2.2. System Definition and Boundaries

The systems modeled were compared based on 1 MJ of thermal energy produced as the functional unit. This functional unit was then used in the LCA of heating systems [20,23] and extends the comparison to other domestic heating systems. All of the energy and mass flows in the inventory are normalized to the functional unit (Figure 3).

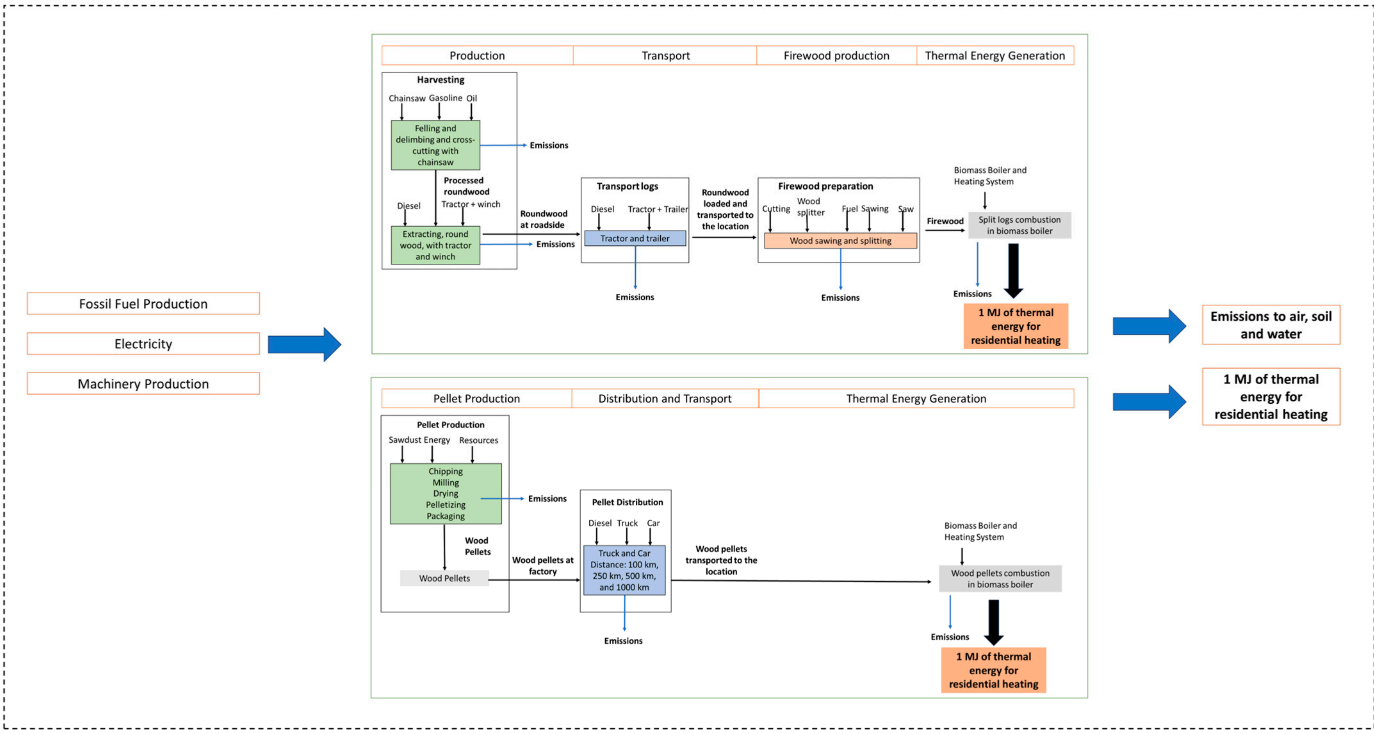

Figure 3. System boundaries of the firewood-based residential system evaluated.

2.2.1. Firewood as a Source of Heat

Wood production covers all operations carried out during infrastructure establishment, stand establishment, wood felling, extraction, loading, and transport to the firewood production site. Close-to-nature forestry in Slovenia uses predominantly irregular shelterwood systems as forest management systems. In Slovenia, 95% of forests regenerate naturally [27]. A gate-to-grave apporach was used for the analysis which considers the impacts from acquiring the raw material until the end of life. The boundary of LCA does not include tree seeding, site preparation, and fertilizer and herbicide treatments because of close-to-nature silvicultural practice used in Slovenia, like Italy [25]. Timber harvesting includes relevant processes, such as felling, delimbing, crosscutting, and extracting to forest road. The most common and traditional system predominantly used in private forests is a technology implemented in a combination of felling with chainsaws and skidding with tractors. The process begins in a forest stand, with the following stages [28]:

1. Felling of standing trees, delimbing, and cross-cutting.
2. Skidding with an agricultural tractor equipped with a three-point attachment winch, or a regular agricultural tractor, which takes place on a skid trail and continues to a truck road.
3. Transporting the wood.

Wood transport to the firewood production facility (usually a household location) is primarily done with a tractor and a trailer where logs are sawed and split. For wood combustion in furnaces, the biomass log boiler approach was modeled due to the common use of biomass boilers for central heating. Regarding biomass feedstock, the scenario was modeled assuming the combustion of wood logs needed to produce 1 MJ of thermal energy. System boundaries consist of three main activities, as shown in Figure 3.

Harvesting

For the chainsaw, a service life of 2500 h was assumed, and fuel consumption of 0.97 L/h and lubricant consumption of 0.39 L/h were considered. The productivity for chainsaw operations was calculated by Kühmaier et al. and was 5.5 m^3/h for felling, delimbing, and crosscutting [13]. For the extraction of trees with tractor and winch, a 63-kW tractor with a service life of 7000 h and a weight of 3.5 t was considered, as tractors with winches are the most common form of wood extraction in Slovenia [18]. According to [29], the tractor and winch had a fuel consumption of 4.42 kg/h and productivity was on average 4.96 m^3/h [10]. Logs were then cut into appropriate lengths for splitting with a chainsaw with a productivity of 16 m^3/h.

Transport

For the transport of wood with a tractor and trailer, a 63-kW tractor with a service life of 7000 h and a weight of 3.5 t was considered, and a small agricultural trailer with a service life of 1200 h and a weight of 1500 kg was assumed. The payload was estimated at 10 t, and the average fuel consumption was 1.25 L/h [10]. Average transportation distance was 10 km, which considers transportation of cut logs to the log splitting facility (i.e., household).

Firewood Preparation

Wood is split with a log splitter with tractor drive (power takeoff method - PTO). This is a more common approach in Slovenia than the use of cutting–splitting machines, due to the nature of forest ownerships and the use of firewood primarily for their purposes. Data from 2020 estimate that there are almost 30,000 wood splitters in Slovenia, while the number of combined wood splitters–cutters is considerably lower (estimated at 2500) [3]. After splitting, wood is sawn with a circular saw.

The productivity of the wood splitter and circular saw was calculated in Slovenia for two different wood splitters and circular saws by two authors [30,31]. For this research, average values from both studies were calculated and used. The productivity of wood splitters was calculated as 1.94 m^3/h. Fuel consumption for the splitter was 0.71 L/h. The productivity of circular saw was 2.7 m^3/h, and energy use was 0.749 kWh per m^3 [30,31].

Combustion of Firewood in Biomass Boiler

This scenario considers a biomass boiler with a nominal power of 30 kW and an average combustion efficiency of 80%. A typical lifetime of 20 years was also assumed, and the number of heating hours per season is 1600 [5]. Using wood for central heating is more common in Slovenia compared to local heating. Commonly, heat transfer is indirect through a heat exchanger, which transfers the combustion heat to water. Mixed hardwood species with an average heating value of 14.5 MJ/kg were used for wood combustion.

2.2.2. Wood Pellets as a Source of Heat

As Slovenia imports pellets for use for residential heating, the background process of pellet production was considered from the Ecoinvent database. Secondly, distribution considered different scenarios, namely 100 km, 250 km, 500 km, and 1000 km, representing the import transportation distances. The baseline scenario selected represents an average distance based on the countries with the highest percentage of imports. The system boundary included the production of wood pellet stove, distribution, and generation of 1 MJ of heat to compare wood log-based and wood-pellet heating systems effectively. To assess the effect of transportation distance on the generation of 1 MJ of heat from wood pellets, the same amount of pellets (1 bag weighing 15 kg) using different transportation distances and the Ecoinvent background process for transportation with a truck (functional unit: kg·km) were modeled.

For pellet production, the use of sawdust from logging and wood residues from operations was considered. The average heating value was 18 MJ/kg. The system boundary included:

- pellet production process,
- distribution to the distributor,
- transport from the distribution center to the final consumer, and
- combustion of pellets in a wood pellet stove.

2.2.3. Life Cycle Assessment Modeling and Software

The LCA modeling was carried out by following ISO standards, specifically EN ISO 14040, EN ISO 14041, EN ISO 14042, and EN ISO 14043. Although EN ISO 14044 supersedes EN ISO 14041, EN ISO 14042, and EN ISO 14043, the content has not changed significantly, and the predecessor standards were followed.

The research is based on primary and secondary data. Primary data for productivity were used from the available literature and secondary sources. Secondary data were extracted from the Ecoinvent database, which is recognized as one of the most comprehensive databases for performing LCA studies. SimaPro 9.5 software was used to perform the life cycle analysis and generate the emission factors. The environmental impacts of the processes were calculated utilizing the ReCiPE 2016 midpoint v1.08 method. Life cycle impact assessment (LCIA) translates emissions and resource extractions into limited environmental impact scores utilizing so-called characterization factors. Midpoint indicators focus on single environmental problems [32]. Regarding biomass feedstock, both scenarios were modeled assuming the combustion of wood logs and pellets needed to produce 1 MJ of thermal energy.

3. Results and Discussion

3.1. Impact Assessment

Table 1 presents the impact assessment for categories covered by the ReCiPe 2016 midpoint v1.08 method. Wood logs have a considerably higher impact on stratospheric ozone depletion, ozone formation, and fine particulate matter (PM) formation than wood pellet combustion. Variables that affect PM composition, size, and effect depend on the furnace combustion and pollutant removal efficiency, as well as the fuel type and composition. Wood pellet furnaces generally have higher efficiency, and wood pellets have greater energy density, resulting in better combustion performance [31]. Values for global warming were lower for the wood log scenario, which can be attributed to the short transportation distances and the use of biomass boilers with high combustion efficiency. Research in Portugal showed that the global warming impact of the pellet system was lower than that of wood logs; however, the forest management differs, and transportation distances for using log woods are considerably longer, which is not the case for using firewood in Slovenia. Furthermore, fireplace and stove efficiency was lower than wood pellet stove [28]. Fine particulate particle formation considers particulates (PM < 2.5 μm) and SO_2 and NO_X emissions. The highest contribution is emissions of PM < 2.5 μm, which is higher for wood log combustion and amounts to 74% compared to 64% for wood pellet combustion. SO_2 formation is more elevated in pellet combustion (6% to 15.6%, respectively), which can be associated with nucleation, agglomeration, and condensation processes involving the NO_X and SO_2 species [31]. The considerably higher impacts of the pellet stove system on fossil resource scarcity and freshwater eutrophication result mainly from electricity use during the production stage of pellets. The main contributor to fossil resource scarcity is hard coal and natural gas depletion for electricity generation [28]. The impacts on terrestrial acidification can be attributed to SO_2 emissions during the combustion process, while a higher effect on marine ecotoxicity results from the nitrates emitted during electricity generation [28]. Electricity use is higher for wood pellets due to the pellet production process. The higher ionizing radiation impact of the wood pellets can be attributed to the nuclear contribution to the national electricity mix [35]. The higher impact of water consumption for the combustion of wood pellets can be attributed to the production of pellets.

Table 1. Impact assessment for categories considered for the baseline scenario (10 km transportation for wood logs and baseline transportation scenario of 500 km for wood pellets).

Impact Category	Unit	1 MJ of Thermal Heat from logs_10 km	1 MJ of Thermal Heat Generated from Pellets_500 km
Global warming	kg CO_2 eq	0.016	0.041
Stratospheric ozone depletion	kg CFC11 eq	2.19×10^{-7}	5.97×10^{-8}
Ionizing radiation	kBq Co-60 eq	0.00048	0.0039
Ozone formation, Human health	kg NO_x eq	0.00017	0.00026
Fine particulate matter formation	kg $PM_{2.5}$ eq	9.50×10^{-5}	1.18×10^{-5}
Ozone formation, Terrestrial ecosystems	kg NO_x eq	0.00018	0.00027
Terrestrial acidification	kg SO_2 eq	8.57×10^{-5}	0.00017
Freshwater eutrophication	kg P eq	6.55×10^{-6}	1.25×10^{-5}
Marine eutrophication	kg N eq	1.58×10^{-6}	2.05×10^{-6}
Terrestrial ecotoxicity	kg 1,4-DCB	0.14	0.39
Freshwater ecotoxicity	kg 1,4-DCB	0.00065	0.0016
Marine ecotoxicity	kg 1,4-DCB	0.00093	0.0023
Human carcinogenic toxicity	kg 1,4-DCB	0.0011	0.0031
Human non-carcinogenic toxicity	kg 1,4-DCB	0.039	0.054
Land use	m^2a crop eq	0.034	0.046
Mineral resource scarcity	kg Cu eq	4.72×10^{-5}	0.00013
Fossil resource scarcity	kg oil eq	0.0028	0.011
Water consumption	m^3	4.35×10^{-5}	0.00029

The process that contributes the most to the global warming impact in split log combustion is the combustion process (82.3%), followed by the splitting of wood (10.6%). Due to the short transportation distances, transport has a 2.6% contribution. The rest of the contribution comes from felling, cutting trees, and logs, as presented in Table S1 (Supplementary Material). A sensitivity analysis that models different transportation distances showed that 15 km and 20 km transportation of logs with tractor and trailer does not have a higher impact on global warming, particle size formation, stratospheric ozone formation, and ozone depletion compared to 10 km transportation distance which is shown in the Table S2 (Supplementary Material) Research conducted in Italy showed that combustion has the highest contribution in short-term supply and that transportation can considerably contribute to the global warming potential, as the difference in transportation process contribution between short-chain supply and long-chain supply of firewood obtained was 51% [33]. The most critical phase of using wood logs in terms of ozone formation and terrestrial acidification is firewood combustion, consistent with published data [28,33]. The combustion phase amounts to 95% of the impact, and transportation of cut logs to the firewood production facility is negligible in terms of its contribution due to short transportation routes.

3.2. Airborne Emissions

The main airborne emissions connected to global warming are fossil carbon dioxide, dinitrogen monoxide, biogenic methane, and fossil methane. A comparison of wood log combustion and 500 km wood pellet combustion is presented in Table 2.

Table 2. Airborne emissions for wood log combustion and baseline scenario for wood pellet combustion.

Substance	Unit	1 MJ of Thermal Heat from logs_10 km	%	1 MJ of Thermal Heat Generated from Pellets_500 km	%
Carbon dioxide, fossil	kg CO_2 eq	0.083	50.9	0.034	84.0
Carbon dioxide, land transformation	kg CO_2 eq	9.13×10^{-5}	0.6	1.59×10^{-4}	0.4
Dinitrogen monoxide	kg CO_2 eq	0.0059	36.3	0.0016	3.9
Methane, biogenic	kg CO_2 eq	8.47×10^{-4}	5.2	2.63×10^{-4}	0.6
Methane, fossil	kg CO_2 eq	0.0011	6.8	0.0044	10.7
Sulfur hexafluoride	kg CO_2 eq	2.12×10^{-5}	0.1	1.06×10^{-4}	0.3

The main contributor to airborne emissions is CO_2; however, split log combustion accounts for 51% of airborne emissions compared to 84% for wood pellet consumption. The emissions are higher in split log consumption. Research conducted by Ozgen et al. showed that wood pellet combustion has lower emissions of CO_2 compared to different firewood combustion scenarios [36]. Split log combustion also results in higher emissions of N_2O, which is consistent with published data. Reyes et al. published data on emissions of NO_2 during the combustion of firewood and wood pellets that shows that concentration was higher in firewood combustion compared to pellet combustion: 993 ppb and 204 ppb, respectively [37]. Biogenic CH_4 emissions are higher in firewood combustion, which can be attributed to the biogenic CH_4 released in the forest during the decomposition of the residues left on the felling site [38]. Higher fossil CH_4 emissions from wood pellet combustion are associated with heat generation for wood drying during pellet production [28]. Similarly, higher emissions of sulfur hexafluoride can be attributed to the pellet production process [28].

The two main contributors to ozone formation emissions (terrestrial ecosystems) are NO_x and non-methane volatile organic compounds (NMVOCs). Both stem from the combustion of wood pellets and split logs [39,40]. In split log combustion, NO_x accounts for 87.4% of airborne emissions, followed by NMVOCs (11.8%). The remaining airborne emissions attributable to ozone formation have a contribution of less than 0.7%. In comparison, NO_x has a 92.0% contribution in the combustion of wood pellets. The contribution of NMVOCs is 7.3%, and the amount of NMVOCs emitted is lower than split logs combustion, with 1.97×10^{-5} and 2.11×10^{-5} kg NO_x emitted, respectively. Higher quantities of NMVOC compounds emitted in log boilers are in accordance with available literature data [36,41].

3.3. Sensitivity Analysis for Wood Pellet Combustion

Wood pellet combustion is used in Slovenia; however, mostly imported pellets are used, as most of the national production is exported due to higher export market prices [3,42]. As Slovenia imports most pellets from Austria, Ukraine, Croatia, Slovakia, and Romania [3], a sensitivity analysis was performed to determine how an increase in transportation distance of wood pellets, representing the transport needed for import, affects the impact on indicators global warming, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), and terrestrial acidification, which is shown in Figure 4. An increase in transportation distance of pellets from 100 km to 1000 km showed an increase in process contribution from 18.5% to 50.0% to effects on global warming, thus becoming the primary source of emissions affecting global warming, which is consistent with published literature [33]. The increase in transportation distance results in a greater impact on stratospheric ozone depletion and fossil scarcity. The increase in transportation distance from 100 km to 1000 km results in an 84.9% increase in the values for the impact category ozone formation, human health and a 120.4% increase in the values for the impact category fossil resource scarcity (Table S3—Supplementary Material), which can be attributed to diesel consumption. Similarly, the impact category global warming is also affected by transportation distance, as an increase from 100 km to 1000 km results in a 102.4% increase in the impact category values (0.028 compared to 0.057 kg CO_2 eq). Sadaghiani et al. studied the usage of wood pellets as a sustainable heat source compared to the use of diesel as a primary source of electricity and heat in remote communities in Canada. Their LCA results indicate that the major impact categories affected by transport are ozone depletion, ecotoxicity, and global warming [43].

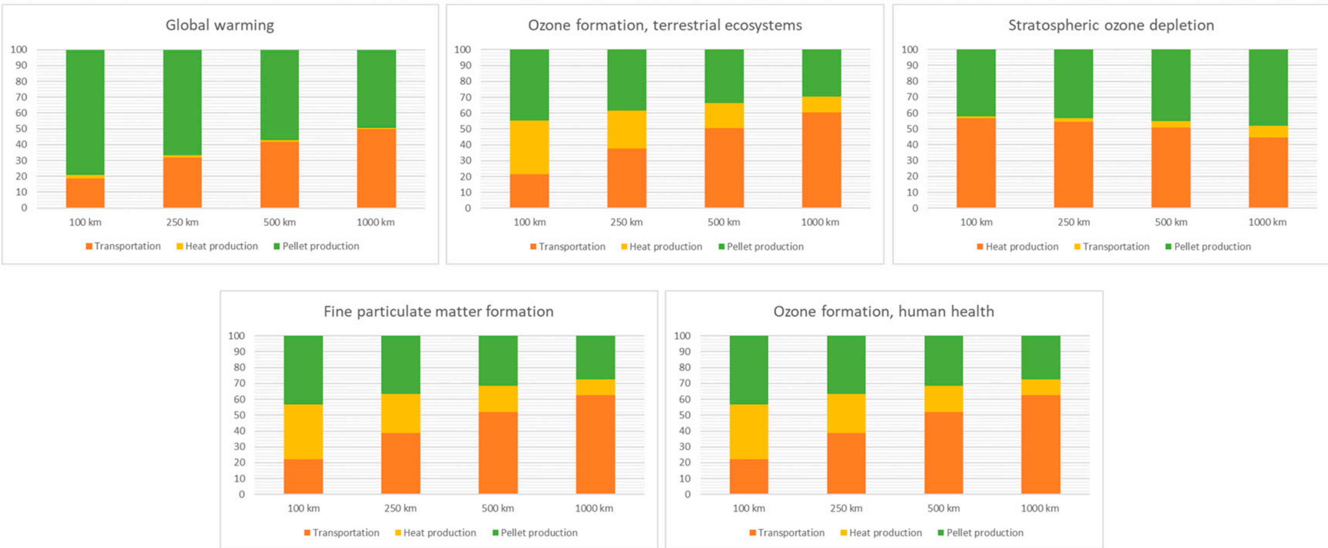

Figure 4. Specific categories of environmental impacts of wood pellet combustion for four transportation distances modeled.

Research by Quinteiro et. al. showed that pellet production stage is the main hotspot for contribution to the total impact score for global warming, fossil resource scarcity, freshwater eutrophication, and marine eutrophication, which is consistent with the results of our research [44]. The main causes of the impacts are mainly due to the use of electricity during pellet production. Similarly, thermal energy generation is the hotspot for ozone formation in the short-distance scenario (100 km), consistent with the results of Quinteiro et al. The impact is mainly due to the NO_x emissions from pellet combustion [44].

The results for other impacts show that the contribution of wood pellet distribution on the total life cycle environmental impact is highly dependent on the transportation distance scenario. Due to short transportation distances in the wood log combustion scenario, the transportation phase does not significantly affect the environmental impact. Research by Sgarbossa et al. concluded that the transportation of wood pellets becomes the main contributor to the life cycle environmental impact for all categories except for human toxicity potential beyond a certain transportation distance, which was 1185 km for global warming potential and 437 km for ozone depletion potential [38]. The results of the research cannot be directly compared due to differences in the methods used; however, the selected functional unit was the same in both studies. The sensitivity results support the relevance of considering a “short-chain-typology” to minimize the impacts of the wood pellet supply chain, as shortening the distance also affects airborne emissions. The amount of fossil CO_2 emitted decreases by 32.2% when comparing 500 km and 100 km transportation scenarios, with values of 0.034 and 0.023 kg CO_2 eq, respectively (Table S4 in the Supplementary Material).

A comparison of wood log combustion and shorter transportation distances for wood pellets shows that global warming and fossil resource scarcity values are still higher for wood pellet combustion. However, they are considerably lower than the 1000 km transportation distance (Table S3 in the Supplementary Material). Fossil resource scarcity is the category the most affected by the transportation phase, which is supported by the findings of Quinteiro et al. [28]. For the indicator ozone formation (human health), a shorter transportation distance of wood pellets results in the value being in the range of wood log combustion (0.00019 and 0.00017 kg NO_x eq, respectively). Quinteiro et al. modeled different wood pellet production scenarios. The results showed that the distribution phase of pellets has a significant contribution to global warming and fossil resource scarcity indicators, with contributions ranging from 17 to 20% and from 20 to 24%, due to diesel consumption on the road. For household wood pellet production, the distribution phase does not play a role [44].

3.4. Cumulative Energy Demand

The amount of primary energy needed for thermal heat generation for both scenarios was also calculated and is shown in Figure 5. Cumulative energy demand (CED) of a product or a system characterizes the direct and indirect energy use during the life cycle [45].

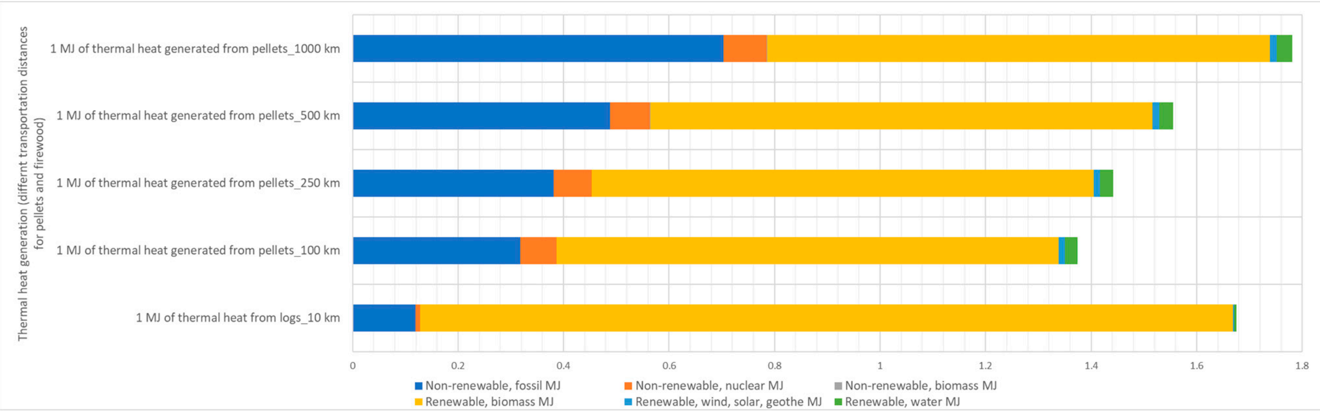

Figure 5. Comparison of cumulative energy demand for firewood and wood pellets with different transportation distances.

CED calculation showed that for 1 MJ of thermal energy generated from firewood combustion in a biomass boiler, 1.67 MJ of primary energy is needed. For the generation of 1 MJ of thermal heat from wood pellet combustion, the amount of primary energy needed is lower for transportation distances up to 500 km, which requires 1.55 MJ of primary energy. For 1000 km transportation distance, which can be the case in Slovenia due to imports from Romania and Ukraine, the primary energy needed is higher (1.78 MJ) than the primary energy needed for firewood. The most significant contributor to higher primary energy use is renewable biomass consumed, which is higher in firewood consumption due to the resources extracted from the wood, with 1.5 MJ of primary energy needed compared to 0.9 MJ for wood pellets. For wood pellets, predominantly sawdust and wood residues from logging are used, accounting for lower renewable biomass energy demand. CED was recently determined for pellet production, and the results indicated positive energy balance with wood pellet combustion; however, the transport distances modeled are different, and the electricity mix is different compared to how it was modeled for Poland [46]. Primary energy, except for renewable biomass, is higher when pellets are used for heat generation due to the energy needed during the pellet production process. The increase in transportation distance of wood pellets has the highest effect on non-renewable fossil energy use, as an increase from 500 km to 1000 km results in a 43.7% increase in the use of fossil non-renewable energy. The results support the relevance of "short-chain-typology" to minimize the impacts of the whole supply chain.

4. Conclusions

In this research, LCA of firewood combustion and wood pellet combustion in Slovenia was performed for the first time to evaluate the environmental impacts of two wood-based heating systems. Wood combustion is predominantly used in Slovenia for heating due to the nature and structure of settlements, the abundance of forests, and the primarily private forest ownership structure. Wood pellets are the second most common wood-based fuel used for residential heating, and in previous years, subsidies have been granted for switching to wood pellet boiler heating in Slovenia.

The research showed that split log combustion resulted in higher values for the impact categories stratospheric ozone depletion, ozone formation, and fine particulate matter (PM) formation. The values for global warming were also lower in split log combustion compared to wood pellet combustion. Although in some studies, values for global warming were lower in wood pellet combustion, short transportation distance and combustion efficiency of wood log boilers play a crucial role in accounting for lower values in split log combustion in our research. The wood pellet combustion resulted in lower airborne emissions of CO_2 and NO_x compared to wood logs, supporting the premise that split log combustion can contribute to local air pollution and that wood pellets can offer an alternative.

To determine the environmental impact of wood pellet combustion, the contribution of transport must be considered, especially when the majority of the pellets used for heating are imported. For this purpose, a sensitivity analysis was conducted comparing different transportation distances in the range of 100 to 1000 km. The rise in transportation distance from 100 km to 1000 km resulted in an 84.9% increase in the values for the impact category ozone formation, human health and a 120.4% increase in the values for fossil resource scarcity. Transportation distance also significantly affected global warming, as an increase from 100 to 1000 km resulted in a 102.4% increase in the impact category values. The sensitivity analysis supports the premise that short transportation routes are more sustainable and have lower environmental impact, highlighting the need to optimize the supply chain and develop strategies for sustainable and more efficient use of woody biomass energy systems.

A possible future development of this research would include a comparison of the environmental impact of imported wood pellets and domestically produced wood pellets from forest and sawmill residues, which can provide a starting point for the optimization of the environmental performance of the supply chain and the overhaul of government subsidy policies regarding use of wood pellets.

Supplementary Materials: The following data are available at https://www.mdpi.com/article/10.3390/su16041687/s1, Table S1 Process contribution to indicators of global warming for generation of 1 MJ of thermal heat from wood logs, Table S2: Impact assessment for categories considered for wood log scenarios with respect to the transportation distance, Table S3: Impact assessment for categories considered for wood pellet scenarios with respect to the transportation distance, and Table S4: Airborne emissions for wood pellet transportation scenarios.

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