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BIOMASS GASIFICATION POTENTIAL FOR SLOVENIA'S GREEN TRANSITION: E-MOBILITY

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Abstract In 2024, approximately fifty percent of the total kilometers driven by passenger vehicles in Slovenia were attributed to diesel-powered automobiles, underscoring the persistent dependence of the transportation sector on fossil fuels, which are major contributors to greenhouse gas emissions and global warming. Research further substantiates that the transportation sector constitutes the nation's predominant source of greenhouse gas emissions. In this context, e-mobility emerges as a key strategy for Slovenia's green transition in transportation. Additionally, biomass gasification represents a sustainable and environmentally friendly energy pathway that could support the country in achieving its environmental targets, while promoting the principles of the circular economy.

Keywords
green transition, renewable energy, forest biomass, biomass gasification, e-mobility

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1 Introducton

It could be said that, throughout history, the main driving force behind most significant developments has been the generation and use of energy. Since lignocellulosic materials (biomass) were the primary energy source, the world has evolved to a point where fossil fuels, especially crude oil and natural gas, produce energy predominantly [1]. The excessive use of fossil fuels in coal- and gas-based power plants has contributed to one of the most significant challenges of our time: global warming, causing a significant ecological imbalance. Biomass is estimated to contribute 10–14% of the world's power supply [1]. Increasing this contribution is a key goal for sustainable energy development, as the biomass gasification process has been proven to be environmentally friendly due to its neutral effect on atmospheric greenhouse gas accumulation [1]. The study explores Slovenia's energy situation, and discusses the potential benefits of implementing biomass gasification processes.

In Slovenia in 2024, roughly half of all the electric energy produced was from renewable energy sources (hydro-, wind- and solar power plants), and the other half was generated from the Nuclear power plant Krško, or thermal power plants. The exact contributions and percentages for the year 2024 are shown in Table 1 and Figure 1 [2].

Table 1: Sources of electric energy in Slovenia by annual electricity production

Source	Contribution	Percentage
Thermal power plants	3639 GWh	27.2%
Nuclear power plants	2772 GWh	20.7%
Renewable energy sources	6961 GWh	52.1%

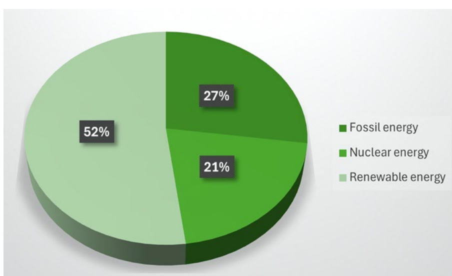

Figure 1: Sources of electric energy in Slovenia by annual electricity production

Although there is a high percentage of electricity that comes from renewables, the current mix, climate-wise, is still not optimal, as shown in Figure 1. The reason for this is that fossil fuel-based electricity releases CO_2 that has been locked underground for millions of years, adding net carbon to the atmosphere [3]. The question is – how is biomass as a source of energy different? In contrast to fossil fuels, the CO_2 released from biomass burning was previously absorbed by plants, forming a closed carbon cycle [3]. Biomass also emits lower levels of sulfur (SO_2) and heavy metals compared to coal [4], reducing acid rain and pollution. Unlike nuclear energy, biomass plants do not produce radioactive waste; they are smaller, cheaper, and more versatile in location [5, 6]. Although hydroelectric power is renewable, it can disrupt river ecosystems, block fish migration [7], and depend on fluctuating water levels. On the other hand, one of its crucial advantages is that biomass can be burned on demand. However, biomass combustion (burning biomass to produce heat that drives a steam turbine to produce electricity) is just one option for its usage. It turns out that, even though combustion presents higher generation efficiencies, gasification of biomass offers more benefits from an environmental point of view, since the CO_2 emissions are similar, but the amount of NO_x produced is much lower [8].

It is important to highlight that gasification also offers a diversity of co-products that could be of great use, such as syngas, which, typically, contains H_2, CO, CO_2, CH_4, H_2O, and trace amounts of higher hydrocarbons. Syngas is an important source for producing diesel or gasoline, hydrogen, fertilizers, methanol, and other chemicals. Furthermore, the product of biomass gasification is also a hydrogen-enriched gas, which is of great significance, because, among all the renewable energy sources, only biomass gasification can produce hydrogen directly. With a higher contribution of biomass gasification as a renewable source of electric energy, could the production of hydrogen through fossil fuels, which is currently 96%, be minimized [9].

Furthermore, Slovenia is one of Europe's most forested countries, with about 58% of its land (nearly 1.18 million hectares) covered by forests [10, 11]. The annual gross increment (annual forest growth) is around 8.7 million m^3 [12], from which approximately 3.8 million m^3 are conifers and roughly 5 million m^3 are non-conifers. Based on the data for 2020 from the Ministry of Agriculture, Forestry and Food of Slovenia, the annual potential (allowable) felling in Slovenia is 7.1 million m^3, however, in 2020, the total felling was only 4.2 million m³ (59% of the potential felling), of which 2.4 million m³ were non-conifers and 1.8 million m³ conifers [13]. Similar results were also presented by the Statistical Office of the Republic of Slovenia [14]. Based on these facts, it could be concluded that Slovenia has a significant unharvested potential of roughly 2 million m³ of conifers and 2.6 million m³ of non-conifers annually, totaling 4.6 million m³.

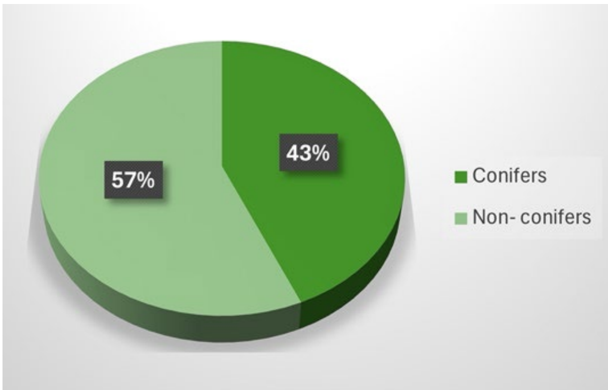

Figure 2: Unharvested potential of conifers and non-conifers

Studies have shown that removing mature, diseased, or overcrowded trees allows younger trees to thrive [15], enhances biodiversity [16], and reduces wildfire risks [17]. Moreover, young, fast-growing forests absorb more CO_2 than older, stagnant ones [18]. Harvesting wood and enabling new growth can sustain the forest-carbon cycle. These facts suggest that biomass is a highly suitable energy source for Slovenia, but the question remains: where could its use be implemented to maximize the benefits?

According to Slovenia's National Inventory Document (NID) for 2024 [19], the transport sector remains the most significant contributor to the country's greenhouse gas (GHG) emissions. Furthermore, according to the Statistical Office of the Republic of Slovenia, in 2024, national and foreign vehicles drove 22 billion kilometers-vkm on Slovenian road territory, of which 90% was by national vehicles. A total of 8.6 billion vkm (39%) were driven on motorways and highways. On Slovenian and foreign road territories, national vehicles drove 22.8 billion vkm, of which 79%, or approximately 18 billion vkm, were driven by passenger cars. Among these, diesel passenger cars represented the largest share (47%), equaling 10.7 billion vkm [20]. It is important to note that, in the context of green transition and minimizing the emissions from the transport sector to reduce the effects of global warming, the age of vehicles is relevant, as it was shown that over-aged vehicles emit a higher percentage of CO and other hydrocarbons [20]. Figures 3, 4, 5, and 6 show the number of vkm registered annually in Slovenia on the Slovenian and foreign road territory by type and age of vehicle.

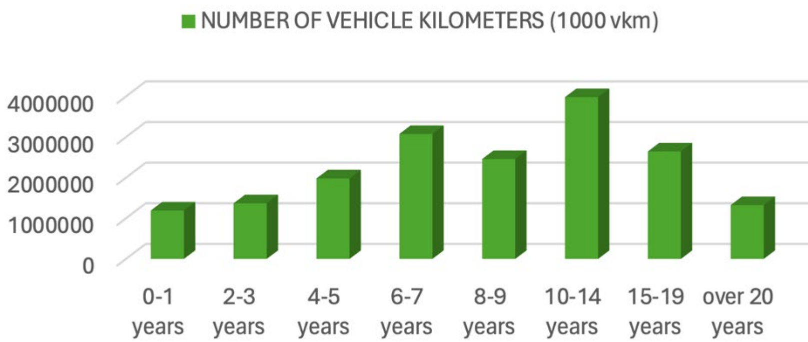

Figure 3: Number of vkm made by all passenger vehicles registered in Slovenia annually by age of vehicles

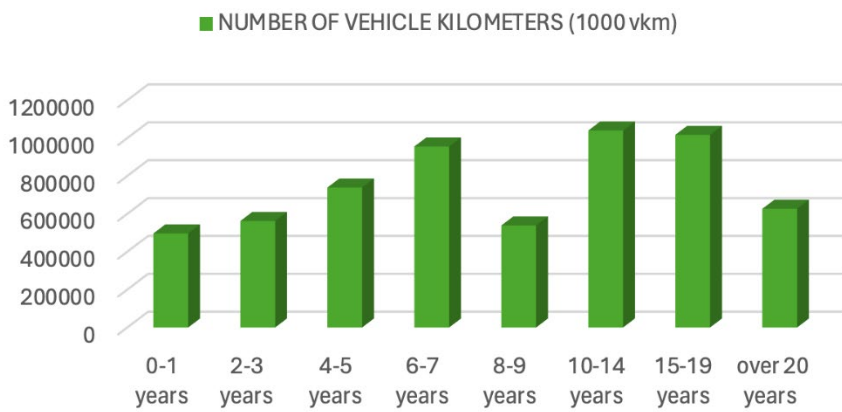

Figure 4: Number of vkm made by petrol-fueled passenger vehicles registered in Slovenia annually by age of vehicles

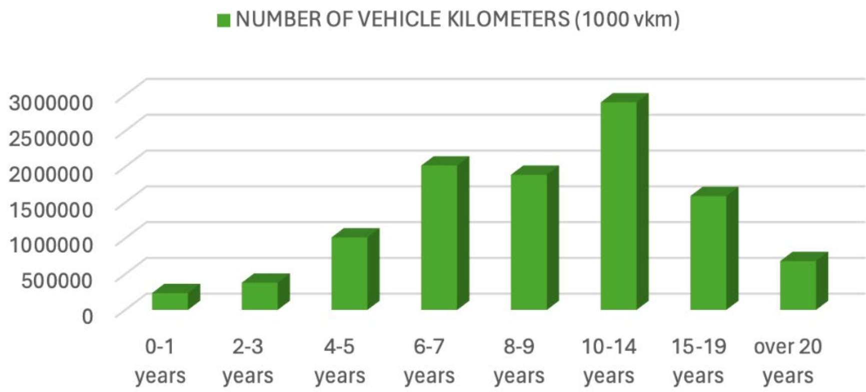

Figure 5: Number of vkm made by diesel-fueled passenger vehicles registered in Slovenia annually by age of vehicles

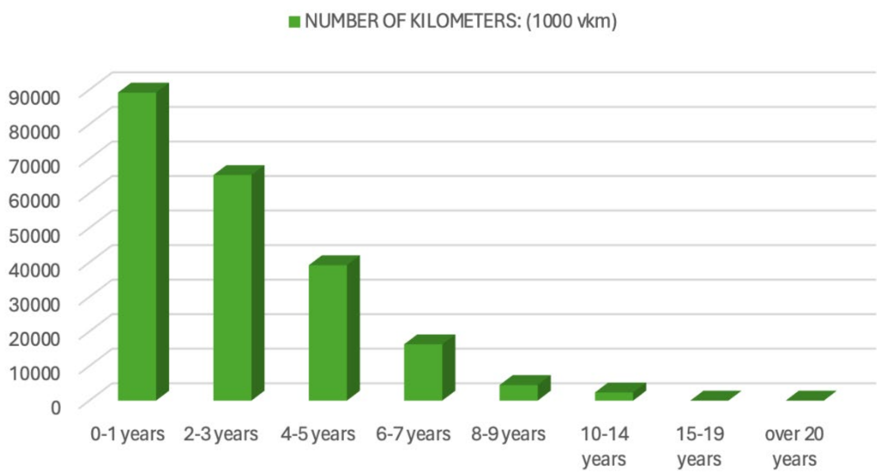

Figure 6: Number of vkm made by electric-fueled passenger vehicles registered in Slovenia annually by age of vehicles

These Figures illustrate how strongly Slovenia's transport sector still depends on fossil fuels, with nearly half of all vkm driven by diesel vehicles in 2024. This mobility pattern contributes substantially to greenhouse gas emissions, and highlights the country's reliance on imported petroleum. Biomass gasification offers a potential pathway to reduce fossil fuel dependency, providing green energy and supporting the transition toward e-mobility.

2 Methods

As stated above, roughly 22 billion vkm were made by Slovenian and foreign passenger vehicles on the Slovenian road-territory. The strategy for green transition in the transport sector via e-mobility would be to lower the number of vkm made by non-electric vehicles. To achieve that goal, a suitable infrastructure should be provided for the transition, such as enough electric energy and charging spots. The question is how much biomass gasification could contribute, in other words, how many vkm could be made by electric vehicles using the electric energy produced by biomass gasification? The Alternative Fuels Infrastructure Regulation (AFIR, EU 2023/1804) mandates fast-charging stations every 60 km along the TEN-T core road network by 2025 [21]. Slovenian highways and motorways are vital to the TEN-T core road network. Slovenia is an important transit country at the crossroads of the Baltic–Adriatic, Mediterranean, and Alpine-Western Balkans corridors. This is why the following calculations focus on Slovenian highways and motorways, where 8.6 billion vkm were driven by national and foreign vehicles [20]. To find out what percentage of electric energy is needed for driving 8.6 billion vkm with electric vehicles that could be covered by biomass gasification, it is first necessary to look at the Slovenian capacities, such as how much biomass is available for gasification. For the latter process non-confiners are beneficial, because they fall into the so-called hardwood species [22], which, in comparison to softwood species, have higher density and greater reactivity [23], which are critical properties in gasification. Slovenia has an unharvested potential of 2.6 million m^3 of non-conifers annually [13]. Beech represents approximately 33% of growing stock in Slovenia [24]; therefore, it is a dominant species. Its density at 12-15% moisture content is 710 kg/m3 [25]. With these data available, the weight of unharvested potential of hardwood could be calculated by Equation 1.

$$m = \rho V \tag{1}$$

From the weight of biomass available for gasification, the sum of electric energy yield can be determined by equation 2.

$$E = \eta m \tag{2}$$

However, the precise data for energy yield η weren't available directly for the data used for this study, which is why it had to be determined before proceeding with Equation 2. The first step for calculating the energy yield was determining the low heating value of 1 kg of wood used. The biomass LHV describes the energy density of the forestry residues, and determines the maximum amount of energy that can be extracted in the gasification process. This property depends on the type of wood, and mainly on the moisture content [26]. LHV can be determined as [27]:

$$LHV = HHV(1 - MC) - 2.447MC \tag{3}$$

In Equation 3 HHV represents the high heat value of the dry biomass based on [26], **and** the values range between 17 MJ/kg and 21 MJ/kg for dry wood. The average 19 MJ/kg was used. MC is the moisture content, which based on [28], in commercial plants, usually only allowed up to 15%. For this study, 12% MC was used.

The LHV = 16.42636 MJ/kg was determined after inserting these properties in Equation 3. Indirectly relevant to producing electric energy in a biomass gasification power plant is the energy of syngas, which can be determined from the LHV of the biomass using the value of cold gas efficiency, which measures how effectively a gasification process converts solid fuel (biomass) into combustible gases by comparing the energy in the produced gas (syngas) to the energy in the initial solid feedstock. The average cold gas efficiency is 70% [29], which means that LHV = 16.42636 MJ/kg has to be multiplied by a factor of 0.7, resulting in the energy of syngas roughly 11.5 MJ/kg. Finally, generator efficiency should be taken into consideration. Based on [30] the generator efficiency ($MJ_{electricity}/MJ_{syngas}$) ranges from 20-35%, and the average factor 0.275 was used for this study. After multiplying the energy of syngas (11.498452 MJ/kg) by the generator efficiency, we are left with an energy yield of round $\eta = 3.16$ MJ/kg.

Now $\eta = 3.16$ MJ/kg can finally be used in Equation 2.

$$E = \eta m \tag{2}$$

resulting in total energy of 5 837 189 157.8 MJ or 1 621 441 432.7 kWh from 1 846 000 000 kg unharvested hardwood potential.

The last step is converting the power (kWh) to kilometers. Equation 4 respects the fact that, for 100 km of driving with an electric passenger car, 20 kWh are necessary based on [31], where it is stated that an electricity consumption of up to 20 kWh/100 km should be realistic for a European mid-size car moving in urban areas or extra-urban at limited speeds.

$$d = E\,\frac{100\ km}{20\ \mathrm{kWh}} \tag{4}$$

For better transparency, all the data used are shown in Table 2.

Table 2: Data used for calculations

	Data
Low heating value of biomass at 12% MC	16.42636 MJ/kg
Generator efficiency ($MJ_{electricity}/MJ_{syngas}$)	0.275
Cold gas efficiency	70%
Energy yield	3.1620743 MJ/kg

3 Results and analysis

Table 3 shows all the calculation results based on an initial input of 1 ton of biomass at 12% MC. In Table 4, the results are based on all the unharvested hardwood potential in Slovenia at the same moisture content.

Table 3: Results for 1 ton

	Value
Mass of wood at 12% MC	1000 kg
Total energy content of biomass	16 430 MJ
Energy yield	878.55 kWh
Number of kilometres	4392.75 km

Table 4: Results for all unharvested hardwood potential

	Value
Mass of unharvested hardwood potential at 12% MC	1 846 000 000 kg
Total energy content of biomass	30 329 780 000 MJ
Produced electric	1 621 803 736.1 kWh
Number of kilometres	8 107 207 163.6 km

Table 4 shows that, from the gasification of 1,846,000,000 kg of unharvested hardwood, enough electric energy would be generated for approximately 8.1 billion kilometers made by passenger vehicles. This is 94.27% of all the kilometers made by national and foreign vehicles on Slovenian motorways and highways (for the year 2024), which are, as already mentioned above, an essential part of the TEN-T core road network. Furthermore, the calculated number of kilometers that could be made in the future with electric vehicles with electricity produced from the biomass gasification process is equal to 45.04% of all the kilometers made by national passenger vehicles on Slovenian and foreign road territories in 2024.

Integrating biomass gasification power plants near the highways and motorways would be the most effective way to install charging stations at highway rest stops, complying with European Regulations. It is important to highlight that optimal locations should be considered, which means the best areas would be the ones that are near the sources of biomass (forests), and also not too far from potential charging spots, to minimize additional carbon emissions due to the transportation of biomass and practically cancel out the electric energy losses for distribution.

4 Discussion and conclusion

With one of the highest forest coverages in Europe, Slovenia has a great potential for implementing the biomass gasification process as a source for electricity production. Not only would that lower carbon and NO_x emissions that are heating our planet, but a mixture of other valuable and important chemical components would be synthesized. As the traffic sector is known to be the most significant pollutant in Slovenia, the study focused on how implementing such power plants could reduce the number of kilometers driven by non-electric passenger vehicles. It is important to highlight that data, especially energy yield, depend on the type of gasifier, the type of biomass, its moisture content, and cold gas efficiency. The study used the average of these values; therefore, more detailed calculations should be made based on the previously stated data for a concrete example of a biomass gasification power plant. This paper also didn't consider charging stations and battery charging efficiency. In all cases, even if the energy yield would be somewhat lower, this strategy would still be efficient for Slovenia's green transition in the transport sector via e-mobility. To conclude, it was proved by the calculations in the study that biomass gasification technology has a great potential to become the primary source of electric energy for transport sector in Slovenia – it could cover roughly 94% of the kilometers made on highways and motorways, in other words, 45% of all the kilometers that were made by national passenger vehicles on Slovenian and foreign road territories in 2024. Biomass could, in the future, serve as an important complementary source to existing renewable energy systems, enabling synergies such as with hydrogen technologies and combined heat and power generation. Furthermore, additional research is needed, including pilot projects along highway corridors and comparisons of different biomass share scenarios in the energy mix, in order to assess its long-term role realistically in Slovenia's green transition. This potential not only supports Slovenia's energy independence, but also aligns with the European Union's broader goals for decarbonization and sustainable transport solutions [32].

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Nomenclature

Symbol	Meaning
m	mass
ρ	density
V	volume
E	energy
η	energy yield
HHV	High heating value
LHV	Low heating value
MC	Moisture content
d	distance

Povzetek v slovenskem jeziku

Uplinjanje biomase za zeleni prehod Slovenije: e-mobilnost. Skoraj polovica vseh s potniškimi avtomobili prevoženih kilometrov v Sloveniji je bila v letu 2024 prevožena z dizelskimi avtomobili, kar nakazuje na odvisnost transporta od fosilnih goriv, ki zaradi emisij toplogrednih plinov med drugim prispevajo k globalnemu segrevanju. Raziskave prav tako potrjujejo, da tudi v letu 2024 transportni sektor ostaja največji vir emisij toplogrednih plinov v državi. Kot izjemno sredstvo zelenemu prehodu Slovenije v transportnem sektorju preko e-mobilnosti se zaradi obdanosti Slovenije z gozdnimi viri uplinjanje biomase ponuja kot trajnosten in okolju prijazen vir energije, ki bi lahko Slovenijo posredno pripeljal do želenih okoljskih ciljev s poudarkom na krožnem gospodarstvu.