

UDC 630:502.3

DOI: 10.31548/forest/2.2025.42

Forest ecosystems in the context of a green economy: Potential for sustainable energy

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Abstract. The purpose of this study was to assess the potential for using wood biomass, including wood waste, as a renewable energy source for the energy sector of Kyrgyzstan, as well as to analyse its energy efficiency and environmental aspects. The study was conducted in two natural zones of the Kyrgyz Republic: mountainous (Naryn region) and lowland (Talas region). Field studies,

Suggested Citation:

Matikeeva, N., Kozlenko, A., Karybekova, S., Tokoeva, A., & Kamalova, A. (2025). Forest ecosystems in the context of a green economy: Potential for sustainable energy. *Ukrainian Journal of Forest and Wood Science*, 16(2), 42-62. doi: 10.31548/forest/2.2025.42.

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laboratory methods, and statistical data processing were employed. The volume of wood in the study areas was determined by measuring the diameter and height of trees, with subsequent calculations using established formulas. The calorific value of wood from various species was analysed using the calorimetric method, and industry research data were used to estimate CO₂ emissions from the combustion of wood waste, coal, and natural gas. Statistical analysis, including the Student's t-test and analysis of variance (ANOVA), was performed to compare the energy potential of different fuel types. The results of the study indicated that Scots pine and English oak are the most promising types of wood for biofuel production in these regions. Calculations confirmed that chips and sawdust have the highest energy values, while wood bark has the lowest calorific value. Analysis of CO₂ emissions demonstrated that wood waste is a more environmentally friendly fuel compared to coal, although it is inferior to natural gas. The data obtained confirm the importance of the rational use of forest resources and the integration of wood waste into bioenergy as a means to reduce dependence on non-renewable energy sources and lower carbon dioxide emissions. The study revealed that the most promising types of wood for biofuel are Scots pine and English oak. The calorific value of chips was 9.5-10.8 GJ, sawdust – 10.2-11.5 GJ, while bark demonstrated the lowest values (8.3-9 GJ). CO₂ emissions from burning oak sawdust were 80 kg/GJ, wood chips – 90 kg/GJ, bark – 98 kg/GJ, while for pine these figures were higher: 85, 95, and 105 kg/GJ respectively. The analysis confirmed that wood waste is cleaner than coal but remains inferior to natural gas, which underlines its significance for bioenergy

Keywords: wood biomass; bioenergy; wood waste; CO₂; energy potential; renewable energy sources; sustainable development

Introduction

In the context of global environmental challenges and the need to transition to sustainable development models, the green economy is becoming an important area of energy policy. One of the key aspects of this approach is the search for alternative energy sources that can reduce dependence on fossil fuels and mitigate the negative impact on the environment. Forest ecosystems have significant potential in this context, as wood biomass and logging residues can be used as renewable energy resources. Wood waste, such as chips, sawdust, and bark, is considered a promising source of biofuels. Their use can not only reduce the volume of waste produced by the forest industry but also decrease carbon dioxide emissions during energy production when compared with traditional fuels such as coal.

However, for the effective implementation of biofuels, it is necessary to consider the regional characteristics of forest resources, their availability, and their energy potential. Researchers Z. Sakbaeva & N. Karabaev (2022), as well as G. Yusupova *et al.* (2023), have explored various aspects of Kyrgyzstan's transition to a green economy. In particular, Z. Sakbaeva & N. Karabaev examined issues related to the protection of the biosphere of walnut forests within the framework of the green economy, highlighting the need for an integrated approach to their conservation. In turn, G. Yusupova *et al.* analysed the role of water and energy resources in the development of a sustainable economic model for the country, considering the potential for their rational use. However, these studies focus more on a general

understanding of the green economy and its individual components, while the use of wood biomass as an energy source within Kyrgyzstan's forest ecosystems remains insufficiently explored and requires further analysis.

K. Dzhumabaev *et al.* (2023) addressed the key issues in Kyrgyzstan's transition to a green economy, including barriers and prospects for the adoption of sustainable technologies. They emphasised the importance of state support and the adaptation of economic mechanisms for the efficient use of natural resources. In her study, O. Sabishchenko (2022) focused on the classification of renewable and non-renewable energy sources, analysing their potential and impact on environmental sustainability. These studies do not address the specific aspects of wood biomass utilisation in Kyrgyzstan's energy sector, highlighting the need for further research in this area.

Existing scientific research covers various aspects of using woody biomass for energy purposes, including its environmental benefits and economic efficiency. Particular attention is given to the analysis of the impact of biofuels on the environment, the potential for reducing greenhouse gas emissions, and the role of renewable resources in the transition to a green economy. At the same time, a number of key issues remain unresolved. In particular, these include the efficiency of using specific wood species, taking into account regional differences in forest composition, as well as the need for a comparative analysis of CO₂ emissions from the combustion of biofuels and traditional fuels (Aliaño-González *et al.*, 2022).

Thus, despite the existence of a significant number of studies on sustainable development, forestry, and renewable energy sources, the issue of using woody biomass as a sustainable energy resource remains insufficiently explored. Particularly relevant are areas concerning the regional specifics of biomass use,

its impact on local ecosystems, and its potential within the context of forming a balanced energy strategy.

This study aimed to identify the potential for using wood biomass and wood waste in the bioenergy sector of Kyrgyzstan, with an emphasis on their economic feasibility and environmental impact. The objectives of the study were to: analyse the forest resources of the Naryn and Talas regions, identifying forest areas and the prevalence of tree species suitable for biofuel production; estimate the calorific value of different fractions of wood waste; and compare CO₂ emissions from the combustion of wood, coal, and natural gas.

Materials and Methods

The study was conducted in the Kyrgyz Republic across two natural zones: mountainous (Naryn region) and flat (Talas region). These regions were selected due to their differing altitude and climatic conditions, which influence the formation of woody biomass and its energy potential. Field studies were carried out over two growing seasons – 2023 and 2024. This time frame enabled the assessment of wood mass growth dynamics, the availability of forest waste for processing, and the potential for its utilisation in green energy.

The study focused on tree species characteristic of the two selected regions, with particular emphasis on those most commonly used for biofuel production. In mountainous areas, Scots pine (*Pinus sylvestris*) was chosen as the primary species studied. In flat areas, English oak (*Quercus robur*) – which is also widely used as biofuel – was selected as the main species examined. These wood types were chosen based on their prevalence and suitability for energy production within their respective natural environments. The study adhered to ethical standards, including the principles outlined in the Convention on Biological Diversity (1992).

To analyse and compare CO₂ emissions from the combustion of wood waste, coal, and natural gas, the study utilised data obtained from open sources such as scientific publications and environmental reports. Particular emphasis was placed on international experience. For a comparative analysis of the environmental performance of different fuel types, the study also incorporated findings from countries with energy sectors structurally similar to that of Kyrgyzstan. Specifically, it drew on research into the chemical composition and physical properties of natural gas in the Ukrainian energy sector (Chemical composition and..., n.d.), as well as data on coal characteristics within the Ukrainian coal industry (Properties of coals..., n.d.). These sources were selected due to the comparable energy systems of Ukraine and Kyrgyzstan – both of which have a high share of solid fuel in their energy balance and face similar challenges in transitioning to a low-carbon economy. These data were not used as direct regional analogues, but rather as examples of well-established methodological approaches to CO₂ emission analysis that could be adapted to the context of Kyrgyzstan, taking into account national characteristics. Additionally, to estimate carbon dioxide emissions, the study employed the calculation methodology developed by the United Nations Development Programme (2022), which incorporates the national conditions of Uzbekistan. These data facilitated the evaluation of the environmental efficiency of each fuel type. To estimate the forest area in the selected regions, data from the National Statistical Committee of the Kyrgyz Republic (n.d.) were used.

The volume of timber in the study areas was determined as the average value derived from several randomly selected trees. For this purpose, 5-10 typical trees representing the average diameter and height for a given forest

zone were identified in each area. Each study area covered 1 hectare, ensuring uniformity in the calculations. This area was applied in both the mountainous and lowland regions, enabling a direct comparison of results under different natural conditions. This methodology ensured the accuracy of the average timber volume calculations and facilitated the interpretation of the research findings under consistent conditions across both study zones. The trunk diameter of each tree was measured using a diameter tape (“Tree Diameter Tape”, Forestry Suppliers, Inc., USA, 2010), and tree height was determined using an ultrasonic rangefinder (“Vertex III”, Haglöf, Sweden, 2015). The average diameter and height of these trees were then used to calculate volume using the following formula (1):

$$V = g_{1.3} \times H \times F, \quad (1)$$

where: V – volume of the tree (m³); $g_{1.3}$ – cross-sectional area at breast height (m²); H – height of the tree (m); F – shape coefficient accounting for trunk form (Forest Measurement and..., n.d.).

The cross-sectional area was calculated using formula (2):

$$g_{1.3} = \frac{\pi d^2}{4}. \quad (2)$$

After calculating the volume for all selected trees, the values were averaged and then divided by the area of the plot to obtain the average wood volume per hectare. The calorific value of wood from different species was determined using laboratory methods with a calorimeter (model IKA C200, Germany, manufactured in 2020). The energy potential was predicted based on the volume of wood and its calorific value, using formula (3):

$$E = V \times Q, \quad (3)$$

where: E – energy potential (GJ); V – volume of wood (m^3); Q – calorific value (GJ/m^3). Subsequently, the study conducted a comparative analysis of the energy potential of three main types of fuel: wood waste (chips, sawdust, bark), coal, and natural gas. To analyse and compare CO_2 emissions from the combustion of wood waste, coal, and natural gas, the study utilised data obtained from open sources, including scientific studies, reports, and environmental publications in industry journals.

The data in the study were processed using statistical methods, including analysis of variance (ANOVA) to assess differences among the three fuels, and the Student's t-test for independent samples to compare the mean calorific values of two fuels. The Shapiro-Wilk test was employed to verify the normality of distribution, and correlation analysis was used to examine relationships between variables. All statistical tests were conducted using SPSS (version 26, IBM, USA). The significance level was set at 0.05, allowing the identification of statistically significant differences between the study groups.

Results

To analyse the potential for using wood biomass and other renewable forest resources in the energy sector, and their impact on sustainable development, various aspects of the issue were considered. Firstly, a general assessment of forest resources was conducted in two selected regions – Naryn and Talas oblasts – taking into account forest area, species composition of woody vegetation, and their potential use for biofuel production (Forest cover of..., n.d.). Based on data from the National Statistical Committee of the Kyrgyz Republic (n.d.), the total forest area in the studied regions was determined.

In Naryn region, where the predominant species is Scots pine (*Pinus sylvestris*), the forest

area is approximately 134,400 hectares, of which 92,500 hectares are pine. Scots pine is one of the principal forest-forming species in Kyrgyzstan, widely distributed in mountainous and forested regions, particularly at altitudes between 1,000 and 2,200 metres above sea level. Its wood is used in construction and for the production of woody biomass, which can serve as an energy source. In Talas oblast, where the dominant tree species is English oak (*Quercus robur*), forest cover extends over about 61,100 hectares, of which 27,900 hectares are oak. English oak is also among the main tree species characteristic of the temperate and subtropical zones of Kyrgyzstan (Food and Agriculture Organization, 2019). These forests play an important ecological role in the region, supporting a diverse range of flora and fauna. Oak wood is valued for its strength and durability, and is used in the manufacture of furniture, building materials, and as biomass for energy purposes. These indicators made it possible to estimate the potential volumes of wood biomass available for further processing, thereby opening up opportunities for creating sustainable energy sources from local natural resources.

To refine the potential volume of wood waste suitable for energy use, an analysis of the characteristics of trees selected in each zone was carried out. The volume of wood was determined by measuring the diameters and heights of typical representatives of the dominant species, enabling the calculation of the average wood mass per hectare and its potential energy application. The calculation results presented in Table 1 show the average morphometric indicators of trees and the volume of wood per hectare in the studied regions. These data form the basis for further analysis of the potential volumes of wood waste that can be utilised in bioenergy.

Table 1. Average morphometric characteristics of trees and wood volume per hectare in the studied regions

Region	Wood species	Average diameter at a height of 1.3 m	Average tree height (m)	Form factor	Volume of one deev (m ³)	Approximate number of trees per 1 ha	Total volume of timber per 1 ha (m ³)
Naryn	Pine (<i>Pinus sylvestris</i>)	0.28	18	0.5	0.554	800	443.2
Talas	Oak (<i>Quercus robur</i>)	0.32	16	0.48	0.617	650	401.05

Source: created by the authors based on open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

The data presented in Table 1 show that in the Naryn region, pine (*Pinus sylvestris*) has an average diameter of 0.28 m and an average height of 18 m, resulting in a total wood volume per hectare of 443.2 m³. In the Talas region, oak (*Quercus robur*) exhibits an average diameter of 0.32 m and an average height of 16 m, with a total wood volume per hectare of 401.05 m³. Despite the lower wood volume per hectare in the Talas region, oak demonstrates a higher aspect ratio, which may indicate a more efficient use of wood for energy purposes.

Determining wood volume is essential for assessing the potential of forest resources in the context of bioenergy, as it enables the quantification of available wood residues generated during logging and wood processing. Knowledge of these volumes facilitates the evaluation of the actual performance of biofuel power plants and the estimation of potential thermal and electrical energy output (Bogmans & Li, 2020). Moreover, accounting for tree species characteristics aids in identifying differences in waste generation. Tree species with high wood density tend to have a greater calorific value but may yield a smaller total volume of biomass, whereas less dense species provide larger quantities of wood residues but with slightly lower energy content.

Thus, the analysis not only quantified potential biofuel volumes but also allowed for the

development of evidence-based recommendations regarding the rational use of wood waste. Data on the average wood mass per hectare, combined with energy potential calculations, enable the formulation of strategies for the sustainable utilisation of forest resources. This contributes to minimising logging waste and increasing the share of renewable energy sources in the overall energy balance of the region.

To assess the environmental performance of different fuels, the volume of wood was first calculated. Below is an example calculation based on data for Scots pine (*Pinus sylvestris*) in the Naryn region. Typical trees characteristic of the region were selected for the analysis. The average trunk diameter at breast height (1.3 m) was 28 cm (0.28 m), the average tree height was 18 m, and the shape factor, accounting for trunk form, was taken to be 0.5 (Forest Measurement and..., n.d.). The cross-sectional area was calculated using formula (2):

$$g_{1.3} = \frac{\pi d^2}{4} = \frac{3.1416 \times 0.28^2}{4} \approx 0.0616 \text{ m}^2.$$

The volume of one tree, calculated using formula (1), is:

$$V = g_{1.3} \times H \times F = 0.0616 \times 18 \times 0.5 \approx 0.554 \text{ m}^3.$$

Similarly, calculations were performed for common oak (*Quercus robur*) in the Talas

region. The average trunk diameter was 32 cm (0.32 m), the average height was 16 m, and the shape factor was taken as 0.48. The cross-sectional area is:

$$g_{1.3} = \frac{\pi d^2}{4} = \frac{3.1416 \times 0.32^2}{4} \approx 0.0804 \text{ m}^2.$$

Accordingly, the volume of one oak tree is:

$$V = g_{1.3} \times H \times F = 0.0804 \times 16 \times 0.48 \approx 0.0616 \text{ m}^3.$$

These data allowed further estimation of the total volume of wood biomass available for use as a renewable energy source. Based on the calculated wood volume, one of the key indicators of the study was determined: the energy potential. This indicator is crucial as it reflects the efficiency of using wood waste as a renewable energy source. Assessing energy potential enables both the evaluation of the economic feasibility of wood waste utilisation and an

understanding of its contribution to sustainable energy development – especially significant in the context of global climate change and the pursuit of sustainable development. The energy potential was calculated not only for the tree species (pine and oak) but also for individual wood fractions used as fuel: chips, sawdust, and bark. Each fraction is characterised by a specific calorific value, which directly affects the total energy yield (Proto *et al.*, 2021). Below is an example calculation of the energy potential using oak bark. For oak, the measured average bark volume in the study area was 0.617 m³, and its calorific value was 9.0 GJ/m³, using formula (3):

$$E = V \times Q = 0.617 \times 9 = 5.55 \text{ GJ}.$$

This calculation demonstrates the energy value of oak bark. Similar calculations were performed for the remaining wood fractions and tree species, and the results are presented in Table 2.

Table 2. Energy potential of wood fractions of pine and oak

Wood species	Fraction	Calorific value (GJ/m ³)	Volume of wood (m ³)	Energy potential (GJ)
Pine (Naryn region)	Wood chips	9.5	0.554	5.26
	Sawdust	10.2	0.554	5.65
	Bark	8.3	0.554	4.61
Oak (Talas region)	Wood chips	10.8	0.617	6.67
	Sawdust	11.5	0.617	7.1
	Bark	9	0.617	5.55

Source: created by the authors based on measured indicators and open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

These data enabled a comparative analysis of the efficiency of using different fractions of wood waste in the energy sector. The analysis of the obtained values reveals several patterns and supports conclusions regarding the feasibility of using wood waste as a renewable energy source. Firstly, it should be noted that the energy potential of various wood fractions varies significantly depending on both tree

species and waste type. Among all fractions, wood chips contribute the most to the total energy potential, which can be attributed to their higher density and calorific value compared to other fractions. For pine, this value is 9.5 GJ, whereas for oak it reaches 10.8 GJ, due to the higher density of deciduous wood.

Bark, by contrast, exhibits lower energy potential values than wood chips and sawdust.

For instance, the energy potential of pine bark was 8.3 GJ, and that of oak bark was 9 GJ. This is primarily due to the higher mineral content and moisture in bark, which reduces its calorific value. Nonetheless, the considerable volume of bark generated during logging and wood processing makes it a significant source of biofuel. As for sawdust, its energy potential is also relatively high, albeit slightly lower than that of chips. Specifically, for pine, the value was 10.2 GJ, and for oak, 11.5 GJ. The comparatively high calorific value of sawdust renders it an appealing option for use in compressed biofuels, such as pellets and briquettes. When comparing the energy potential of pine and oak, it is evident that oak waste generally has a higher calorific value, owing to the greater wood density. However, in absolute terms, the total volume of available waste in the Naryn

region – where pine predominates – exceeds that in the Talas region – where oak is dominant. This difference in volume may offset the discrepancy in calorific values.

For a more objective comparison of the energy potential of wood fractions with that of coal and natural gas, it is necessary to consider equivalent characteristics for these conventional fuels. Specifically, calorific value, volume, and energy potential must be evaluated, as this enables a more accurate comparative assessment. These indicators are crucial for determining the efficiency of various fuel types in energy systems and for analysing their environmental impact and economic viability, particularly in the context of replacing coal and gas with alternative energy sources such as wood. Table 3 presents data on the key energy characteristics of these two conventional fuel types.

Table 3. Comparative energy potential of coal and natural gas

Fuel type	Calorific value (GJ/kg)	Fuel volume (m ³)	Energy potential (GJ)
Coal (anthracite)	24.5	1	24.5
Coal (bituminous)	20	1	20
Natural gas (methane)	35.8	1	35.8

Source: created by the authors based on open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

A comparative analysis of the energy potential of pine and oak wood fractions with data on the calorific values of coal and natural gas reveals significant differences. For instance, the calorific value of wood fractions ranges from 8.3 GJ/m³ (for pine bark) to 11.5 GJ/m³ (for oak sawdust). In contrast, coal has a calorific value in the range of 18-25 GJ/kg, which significantly exceeds that of wood. Natural gas has a calorific value of approximately 38 MJ/m³, which is also several times higher than that of wood fractions. However, it is important to note that energy potential is only one factor in determining fuel efficiency. Other crucial aspects

include emissions of carbon dioxide and other pollutants during combustion. In the case of wood fractions, despite their lower energy potential, their use may result in lower CO₂ emissions compared to coal and natural gas, making them a more environmentally friendly option. The assessment of emissions and their environmental impact plays a critical role in decisions regarding the substitution of traditional fuels with more sustainable and renewable energy sources such as wood.

For a broader analysis of the use of wood biomass and other renewable forest resources in the energy sector – and their implications

for sustainable development – it is essential to consider not only the energy potential of wood waste, but also its environmental characteristics. One of the most important factors is the level of CO₂ emissions from the combustion of different fuels, as carbon emissions are a key determinant of energy production’s impact on the climate and environment (Brych *et al.*, 2023).

A comparison of carbon dioxide emissions from the combustion of wood waste, coal, and natural gas enables the assessment of the environmental advantages of using wood fuels

in place of traditional non-renewable energy sources. This study utilised open-source data to quantify emissions for various fuel types and evaluate their relative environmental impacts. Table 4 presents estimated CO₂ emissions resulting from the combustion of different fuels, including wood waste (chips, bark, and sawdust) in the two study areas, alongside comparative emissions for coal and natural gas. These data support an evaluation of the environmental performance of wood biomass as an alternative energy source when compared to conventional fossil fuels.

Table 4. CO₂ emissions from combustion of different types of fuel

Fuel type	CO ₂ emissions (kg/GJ)
Oak chips	90
Oak bark	98
Oak sawdust	80
Pine chips	95
Pine bark	105
Pine sawdust	85
Coal	94
Natural gas	56

Source: created by the authors based on open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

Among wood waste, oak sawdust has the lowest emissions (80 kg CO₂/GJ), which is attributed to its high homogeneity and more efficient combustion, resulting in minimal unburned residue. Oak chips exhibit slightly higher emissions (90 kg CO₂/GJ), explained by their denser structural composition. Oak bark demonstrates the highest emissions (98 kg CO₂/GJ), due to its higher lignin content and mineral impurities, which contribute to increased ash formation and reduced combustion efficiency. A similar pattern is observed for pine. Pine sawdust emits 85 kg CO₂/GJ, which, although higher than that of oak sawdust, remains the lowest among

pine-derived fuels. This is due to the higher resin content in coniferous wood, which affects combustion. Pine chips emit 95 kg CO₂/GJ – higher than sawdust, but lower than bark. Pine bark has the highest emissions of all wood waste types (105 kg CO₂/GJ), a result of its high density and significant concentration of carbon-rich compounds.

Nevertheless, when selecting a fuel, not only environmental efficiency but also economic feasibility must be considered. To provide a more comprehensive assessment, a comparative analysis of the cost of obtaining 1 GJ of energy from various fuel types was carried out, and the results are presented in Table 5.

Table 5. Comparison of economic and environmental efficiency of fuel types (per 1 GJ of energy)

Fuel type	Average market price (USD/GJ)	CO ₂ emissions	Source of raw materials	Availability in the region	Notes on use
Oak sawdust	5.2	80	Local wood processing companies	High	High calorific value, lowest CO ₂ emissions among wood
Pine chips	5.5	95	Logging waste	High	Widely available source, but high CO ₂ emissions
Pine bark	4.8	105	By-product	High	Highest CO ₂ emissions, need for cleaning
Coal (anthracite)	8.3	94	Import/domestic mines	Limited	High emissions of CO ₂ and other toxic compounds
Natural gas (methane)	9.1	54	Imported/Network	Average/urbanised area	Lowest CO ₂ emissions, but high cost

Source: created by the authors based on open data Chemical composition and physical properties of gas (n.d.), Properties of coals as an object of beneficiation (n.d.), United Nations Development Programme (2022)

The presented analysis allows for the evaluation of both the environmental and economic aspects of using various fuel resources. Among wood waste, oak sawdust has the lowest energy production cost (5.2 USD/GJ), making it the most cost-effective option compared to other wood fractions. It also exhibits the lowest CO₂ emissions (80 kg/GJ), rendering it the most environmentally friendly among the types of wood waste considered. Pine chips, despite a slightly higher cost (5.5 USD/GJ), are readily available and widely accessible, but they are associated with higher CO₂ emissions (95 kg/GJ), which reduces their environmental efficiency. Pine bark, although relatively inexpensive (4.8 USD/GJ), has the highest CO₂ emissions (105 kg/GJ) of all wood waste types analysed. This suggests the necessity of additional emission control measures when using it as a fuel source.

Coal (anthracite) and natural gas have significantly higher energy production costs (8.3 and 9.1 USD/GJ, respectively) compared to wood waste. Moreover, coal is associated with high CO₂ emissions and other toxic pollutants

(94 kg/GJ), which diminishes its environmental viability. Natural gas, while having the lowest CO₂ emissions (54 kg/GJ), is comparatively costly, which limits its accessibility – particularly in remote or less urbanised areas. Thus, despite the lower energy density and economic indicators of wood waste compared to coal and natural gas, its use may offer greater environmental benefits and affordability, particularly in regions with abundant raw material availability. The selection of fuel ultimately depends on balancing economic feasibility and environmental impact, highlighting the importance of an integrated approach to energy planning and decision-making (Kalivoshko *et al.*, 2024).

When comparing wood waste and coal, it is noteworthy that coal emits approximately 94 kg CO₂/GJ – similar to the emissions of oak chips (90 kg CO₂/GJ) and pine sawdust (85 kg CO₂/GJ). However, coal is a fossil fuel, and its combustion results not only in CO₂ emissions but also in the release of other harmful compounds, such as sulphur dioxide (SO₂), nitrogen oxides (NO_x), and heavy metals (Golub *et*

al., 2018). Notably, pine bark produces even higher CO₂ emissions (105 kg/GJ), making it the least environmentally beneficial among all wood waste types. This is attributed to its complex chemical composition, high carbon content, and low combustion efficiency.

Natural gas, by contrast, exhibits the lowest CO₂ emissions of all the fuels considered – 56 kg/GJ. This can be explained by its high methane content and more complete combustion, which results in fewer carbon-based emissions. Even the “cleanest” wood waste, such as oak sawdust (80 kg CO₂/GJ), has emissions that are 42.9% higher than those of natural gas. The most pronounced difference is observed when comparing natural gas (56 kg CO₂/GJ) and pine bark (105 kg CO₂/GJ): pine bark emits 87.5% more CO₂, clearly indicating its low environmental performance.

Thus, wood waste – particularly sawdust – produces lower emissions than coal, though it remains inferior to natural gas in terms of environmental sustainability. The use of bark, especially pine bark, is the least advantageous option among wood fractions due to its high CO₂ emissions and poor combustion efficiency. Although coal's CO₂ emissions are comparable to some wood waste types, its additional pollutant output makes it a less favourable option from an environmental perspective (Lyubchik *et al.*, 2015). Natural gas remains the most environmentally friendly choice, with CO₂ emissions significantly lower than those of all other fuels analysed.

At the same time, sustainable development requires consideration not only of CO₂ emissions but also of fuel availability. In forested regions, wood waste may prove more economically viable despite its higher emissions compared to natural gas. The optimal choice of biofuel should therefore account not only for quantitative emission indicators, but also for combustion characteristics, energy value, and the potential for replacing conventional energy

sources – factors that are critical for the transition to renewable energy in the energy sector (National Strategy for..., 2011).

This study provided a detailed response to the research question concerning the environmental and energy efficiency of using wood waste as fuel. An analysis of available wood volumes for energy use revealed that the Naryn and Talas regions possess significant biomass resources suitable for processing. Calculations of the energy potential of different wood waste types confirmed that sawdust and wood chips are the most promising in terms of energy value, whereas bark demonstrated the lowest efficiency and the highest CO₂ emissions.

A comparative analysis of carbon emissions from the combustion of different fuels showed that wood waste is generally a more environmentally friendly option than coal, although it is less favourable than natural gas in terms of CO₂ emissions. At the same time, the significant variation in emissions among different types of wood waste highlights the importance of selecting the optimal fuel type based on specific local conditions and energy requirements (Yerniyazova *et al.*, 2024).

Forest ecosystems in the Kyrgyz Republic possess significant potential to support sustainable energy development, particularly through the utilisation of biomass as a renewable energy source. Forests currently cover a substantial portion of the country's territory (approximately 6-7% of the total area), and their resources could become an important component of the national energy strategy in the future. However, the extent to which these ecosystems can contribute to the sustainability of the energy system depends on several factors, including the condition of the forests, the volume of available biomass, and the ecosystem services they provide.

Forest resources can play a vital role in diversifying the country's energy mix if the use

of biomass for energy generation is effectively organised. It is generally accepted that biomass derived from forests – such as wood waste and vegetation residues – can meet part of the national energy demand. Estimates of the potential share of this source in the country's energy balance vary, but in the long term, its contribution could reach approximately 10-20% of total energy consumption, depending on the pace of technological advancement and the degree of utilisation of forest resources.

It is important to acknowledge that, at present, forest ecosystems are unable to fully ensure the country's energy security, due to several critical challenges. Firstly, forest resources in certain regions are already under pressure as a result of illegal logging and inadequate forest management practices. Secondly, there is a risk of soil and ecosystem degradation if biomass is harvested for energy without due consideration for the ecological sustainability of forests. Furthermore, the country currently lacks the infrastructure necessary for the efficient collection and processing of biomass into usable energy, which significantly limits its practical application in the energy sector.

The introduction of sustainable biomass utilisation practices can significantly reduce carbon dioxide emissions and lessen dependence on hydrocarbon energy sources. Biomass as an energy source offers a key advantage over fossil fuels – it is considered carbon neutral, meaning that the carbon dioxide released during biomass combustion is offset in the short term by carbon uptake through photosynthesis in vegetation (Lyubchik *et al.*, 2019).

To utilise biomass effectively, it is essential to develop and implement a range of technologies, such as pyrolysis and gasification, which enable energy production with minimal carbon dioxide emissions. Additionally, the use of biogas derived from organic waste for electricity generation warrants attention. The establishment of

a certification system for wood and biomass is also critical to ensure that raw materials used for energy are sourced exclusively from sustainably managed forests (Vasylyshyn *et al.*, 2023). This will help prevent ecosystem overload and preserve ecological balance within biocenoses.

A key component in the successful development of biomass energy is the implementation of incentive and subsidy programmes aimed at building the necessary infrastructure for biomass processing. In this context, financial incentives for private investors and companies developing biomass energy technologies are of great importance. Furthermore, integrating biomass with other renewable energy sources, such as solar and wind installations, can significantly enhance the efficiency and stability of energy production, particularly during periods of low output from other renewables. Equally important is the development of educational initiatives and public awareness campaigns to inform local communities and authorities about the importance of sustainable forest management and the rational use of biomass for energy purposes.

Thus, the forest ecosystems of the Kyrgyz Republic have the potential to become a vital component of the country's sustainable energy strategy. However, realising this potential requires a balanced and well-informed approach to biomass management and utilisation. The deployment of advanced biomass processing technologies, support for sustainable forest practices, and the development of appropriate infrastructure could substantially reduce carbon emissions and enhance the country's energy security in the long term.

The assumption regarding the feasibility of using wood waste as a renewable energy source was partially confirmed during the study. Wood fuels can serve as alternatives to fossil fuels, but their environmental performance varies depending on the specific type of waste, its

chemical composition, and combustion properties (Natural coal from..., n.d.). An additional critical factor is the selection of appropriate wood waste sources, which significantly affects the overall efficiency of the energy system. Further detailed studies are needed to evaluate the environmental impacts – particularly CO₂ emissions – of different wood types and to support the development of more sustainable biomass energy solutions.

Discussion

The results obtained in this study provide valuable insights into the potential of using wood waste as a renewable energy source. In the context of efforts to reduce dependence on fossil fuels and advance sustainable energy solutions, the analysis of the efficiency of different biomass types holds significant scientific and practical relevance. The identified differences in calorific value and CO₂ emissions among wood waste fractions enable the optimisation of their application in the energy sector while minimising environmental impact. One of the key findings of the study was the confirmation that wood waste can indeed serve as an alternative to coal, offering lower carbon emissions. However, the variations observed between different types of wood biomass highlight the need for further optimisation of processing and utilisation technologies. In this regard, an important aspect involves comparing the present findings with those of other studies to assess the extent to which the results align with or diverge from existing scientific knowledge.

For a comprehensive evaluation of the significance of the results, it is essential to consider the findings of international researchers, as these offer valuable opportunities for benchmarking against global experience. This not only helps to identify global trends in bioenergy development but also allows for an examination of the different approaches employed in various

countries, thereby enhancing understanding of the effectiveness of bioenergy technologies in diverse contexts. Comparing local conditions with international practices facilitates the identification of globally tested solutions that can be adapted and implemented in specific regions, taking into account their unique environmental, economic, and social characteristics. In addition, international research can serve as a source of innovative methods for optimising the processing and utilisation of wood waste, as well as for developing effective models for the sustainable development of the energy sector. The analysis of global experience also helps to identify potential challenges and risks that region may encounter during the implementation of such technologies, thereby enabling the avoidance of common pitfalls and supporting the formulation of strategies for their mitigation. The integration of global best practices, when adapted to regional characteristics, contributes to a more balanced and efficient approach to the utilisation of natural resources, ultimately enhancing environmental and energy sustainability at both local and global levels.

The study by R.G. Khlivitskiy (2023), which examined the volumes of fuelwood harvesting and usage in Ukraine – particularly in the Chuguyevo-Babchansky Forestry branch – is directly related to the present research, as both explore the potential of wood resources for energy production. However, R.G. Khlivitskiy's work is primarily focused on the economic efficiency and potential of fuelwood as a resource for the energy sector, while the current study places greater emphasis on the environmental dimension, particularly the assessment of carbon emissions from various types of wood waste.

Similarly, the article by M. Kiehadroudin-ezhad *et al.* (2023) explored the role of biofuels in supporting sustainable microgrids, highlighting their importance in achieving carbon neutrality and promoting a green economy.

This research aligns with the present study in its focus on renewable energy sources to reduce fossil fuel dependency and lower carbon emissions. However, the key distinction lies in its focus on microgrids as a structural solution for integrating biofuels into decentralised energy systems, whereas the present study concentrates on evaluating the efficiency of wood waste as an energy source in a broader, national and environmental context.

The works by N. Khan *et al.* (2021) and C. Lazaridou *et al.* (2021) examined the use of biofuels as a key component in the sustainable transition towards a green economy and carbon neutrality. Specifically, N. Khan *et al.* explore the role of biofuels in achieving a sustainable energy transition, while C. Lazaridou *et al.* focus on forest resources and their recycling within the framework of a circular economy. The present study similarly considers wood waste – particularly sawdust and chips – as more efficient energy sources compared to conventional fuels. The main distinction lies in the broader focus of N. Khan *et al.* work, which encompasses a wide range of recycled materials and does not offer an in-depth analysis of alternative fuel production from wood waste.

Studies by A. Raihan & A. Tuspekova (2022), as well as V.-V. Paunu *et al.* (2021), address the use of renewable energy sources and their environmental impacts, which aligns closely with the objectives of this research. However, those studies are rooted in the specific environmental and economic contexts of Malaysia and the Nordic countries, respectively. In contrast, the current study centres on the utilisation of wood waste in Kyrgyzstan. This comparison underscores the importance of considering contextual factors – such as national energy policies, natural resource availability, and socio-economic conditions – when developing effective strategies for sustainable development and renewable energy use.

The study by B. Kirchsteiger *et al.* (2021) investigated pollutant emissions from domestic wood combustion in Austria, offering a detailed analysis of particulate matter and polycyclic aromatic hydrocarbon (PAH) emission profiles, along with a toxicological risk assessment. This research intersects with the present study in its focus on the environmental aspects of wood waste combustion. However, B. Kirchsteiger *et al.* placed particular emphasis on the health impacts of toxic emissions, an aspect that is also significant within the broader framework of green economy implementation and the assessment of environmental risks to forest ecosystems. Similarly, the health implications of wood waste combustion were examined in the study by H. Timonen *et al.* (2021), further contributing to the understanding of the environmental and public health dimensions of biomass energy use.

The paper by T. Myllyviita *et al.* (2021) highlighted the potential of wood substitution in reducing greenhouse gas emissions, which overlaps with the focus of the current study, as both address the eco-efficiency of wood resource use. However, while the present study concentrates on wood waste as an energy source, T. Myllyviita *et al.* examine broader applications of wood in the context of substituting fossil fuels and lowering carbon emissions across various sectors.

The papers by L.T. Da Silva *et al.* (2021) and O. Thees *et al.* (2023) explored the use of wood fuel in relation to energy potential and the transition to renewable energy sources, aligning closely with the objectives of the current study. Both works emphasise the viability of wood fuel as an alternative energy source that contributes to the reduction of carbon emissions. In particular, O. Thees *et al.* analyse technology development and resource mobilisation in Switzerland, offering a perspective that parallels the investigation into wood waste utilisation in Kyrgyzstan. Meanwhile,

the study by L.T. Da Silva *et al.* assesses the energy potential of Eucalyptus sp. wood in Brazil. Although based in a different geographical context, it shares the overarching goal of developing strategic approaches for the sustainable use of wood resources.

The study by M. Adamowicz (2022), along with those by L. Zhang *et al.* (2022) and J. Shao *et al.* (2024), addressed broader issues related to the green economy, sustainable development, and the role of environmental policy in shaping economic sectors. M. Adamowicz examined the influence of the Green Deal and green growth in advancing the Sustainable Development Goals, while L. Zhang *et al.* investigate the interplay between globalisation, the green economy, and environmental challenges. J. Shao *et al.* assess the impact of ecosystem conservation on employment across different industries in Yunnan Province, China. Although these studies address essential themes of sustainable development, they primarily focus on macroeconomic and policy-level dimensions of the green transition. In contrast, the present study offers a more targeted analysis of bioenergy, specifically the use of wood waste in the energy sector of Kyrgyzstan, along with the associated environmental and economic implications. This approach enables the integration of global trends with national-level specifics, contributing to the development of context-sensitive strategies for sustainable energy development. S.M. Shah *et al.* (2021) analyse the influence of “green” human resource management practices on the economic and environmental performance of organisations, highlighting the importance of organisational culture and psychological climate. Although both studies address issues related to sustainable development, their primary focus lies in the institutional and managerial dimensions of the green economy.

A number of studies – by S. Pandey (2022), Y. Sun *et al.* (2022), and A. Olszewski *et*

al. (2023) – share a common focus on the processing and utilisation of wood waste, though they approach the subject from different analytical perspectives. A. Besserer *et al.* (2021) explored the cascade use of wood waste, underscoring the value of its multiple applications. M.J. Aliaño-González *et al.* (2022) investigated biomolecules extracted from fruit tree wood waste and their potential uses in the agri-food industry. S. Pandey examined the development of products from low-quality wood waste in Nepal, emphasising the economic and resource importance of such initiatives. Y. Sun *et al.* assess the use of wood biochar for pollutant removal, while A. Olszewski *et al.* proposed a novel method of producing polyurethane composites from wood waste.

While these studies consider wood waste recycling across a variety of sectors – from agri-food to materials science and environmental remediation – the present study focuses on its energy potential. This approach enables an assessment not only of the environmental and economic advantages of wood recycling, but also of its role in advancing sustainable energy and reducing reliance on fossil fuels. The findings of this study regarding the potential of wood waste for energy use are largely consistent with international research, which also supports the adoption of alternative energy sources within the framework of sustainable development. It is noteworthy that most foreign studies affirm the relevance of biomass in replacing traditional fuels and lowering carbon emissions, although the specific approaches and methodologies tend to vary according to local conditions (Green energy and..., n.d.). Unlike studies centred on other national contexts, the current research is distinguished by its focus on the Naryn and Talas regions, with due consideration for their distinct environmental and economic circumstances. Nevertheless, the overarching objective of identifying effective and environmentally friendly energy solutions remains constant.

The comparative analysis of foreign sources revealed both parallels and divergences, highlighting the necessity of further refining methodologies and models that incorporate local conditions and technologies. These findings can inform the development of future research on the use of wood waste, offering new strategies for optimising its application and raising environmental standards across diverse regions.

Conclusions

The results of the analysis conducted in this study confirmed the high energy value of wood waste, supporting its potential as a renewable energy source. Wood chips demonstrated the greatest energy potential (9.5-10.8 GJ), attributable to their high density and calorific value. Sawdust (10.2-11.5 GJ) also showed strong performance, particularly in the context of pellet and briquette production. Bark exhibited the lowest energy potential (8.3-9 GJ), primarily due to its higher content of mineral impurities and moisture.

CO₂ emissions from the combustion of wood waste varied by type. The lowest emissions were recorded for sawdust (80-85 kg CO₂/GJ), followed by chips (90-95 kg CO₂/GJ), while bark displayed the highest emissions (98-105 kg CO₂/GJ). Compared with coal (94 kg CO₂/GJ), wood waste generally demonstrates a lower emission profile – with the exception of pine bark, which exceeds coal in CO₂ emissions. Nevertheless, natural gas remains the most environmentally friendly fuel option, with emissions of just 56 kg CO₂/GJ.

A comparative analysis of relevant scientific publications revealed global trends in the study of wood biomass. In countries with advanced energy infrastructure, research efforts primarily focus on improving combustion technologies and minimising emissions. In contrast, studies conducted in developing regions tend to emphasise the economic feasibility and availability of raw materials. This underscores the importance of adapting international experience to local and regional conditions.

The main limitation of the present study lies in the need for further field testing and a more comprehensive assessment of the environmental and economic impacts associated with the use of wood waste. The findings highlight the necessity for continued research aimed at refining wood biomass utilisation methods, with the dual goals of reducing environmental harm and improving energy production efficiency. Future studies should prioritise the optimisation of biofuel thermal processing, the reduction of emissions from bark combustion, and a detailed economic evaluation of wood fuel integration within the energy sector.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Лісові екосистеми в контексті зеленої економіки: потенціал для сталої енергетики

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Анотація. Мета цього дослідження полягала в оцінці потенціалу використання деревної біомаси, включно з деревними відходами, як поновлюваного джерела енергії для енергетичного сектору Киргизстану, а також в аналізі їхньої енергетичної ефективності та екологічних аспектів. Дослідження проводили у двох природних зонах Киргизької Республіки – гірській (Наринська область) і рівнинній (Таласька область). Під час роботи використовували польові дослідження, лабораторні методи і статистичне опрацювання даних. Об'єм деревини на досліджуваних ділянках визначали шляхом вимірювання діаметра і висоти дерев з подальшим розрахунком за встановленими формулами. Для аналізу теплотворної здатності деревини різних порід застосовували калориметричний метод, а для оцінки викидів CO₂ під час спалювання деревних відходів, вугілля та природного газу було використано дані галузевих досліджень. Для порівняння енергетичного потенціалу різних видів палива проведено статистичний аналіз, включно з критерієм Стьюдента та дисперсійним аналізом (ANOVA). Результати дослідження засвідчили, що сосна звичайна та дуб черешчастий є найперспективнішими видами деревини для виробництва біопалива в даних регіонах. Обчислення підтвердили, що тріска та тирса мають найбільшу енергетичну цінність, тоді як кора деревини має найменшу теплотворну здатність. Аналіз викидів CO₂ продемонстрував,

що деревні відходи є більш екологічно чистим паливом порівняно з вугіллям, проте поступаються природному газу. Отримані дані підтверджують важливість раціонального використання лісових ресурсів і впровадження деревних відходів у біоенергетику як способу зниження залежності від невідновлюваних джерел енергії та зменшення викидів вуглекислого газу. Дослідження дало змогу з'ясувати, що найперспективнішими видами деревини для біопалива є сосна звичайна та дуб черешчастий. Теплотворна здатність тріски становила 9,5-10,8 ГДж, тирси – 10,2-11,5 ГДж, тоді як кора продемонструвала найменші показники (8,3-9 ГДж). Викиди CO₂ під час спалювання тирси дуба становили 80 кг/ГДж, тріски – 90 кг/ГДж, кори – 98 кг/ГДж, а в сосни ці показники вищі: 85, 95 і 105 кг/ГДж відповідно. Аналіз підтвердив, що деревні відходи екологічно чистіші за вугілля, але поступаються природному газу, що підкреслює їхню значущість для біоенергетики

Ключові слова: деревна біомаса; біоенергетика; деревні відходи; CO₂; енергетичний потенціал; відновлювальні джерела енергії; сталий розвиток