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Energy Gain and Carbon Footprint in the Production of Bioelectricity and Wood Pellets in Croatia

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Abstract: The paper presents the process of electricity and thermal energy production in a cogeneration plant and the process of wood pellet production. The aim of this study was to analyze the energy gain—EROI for energy products that are created as a product contained in electrical and thermal energy and the energy contained in wood pellets. According to the obtained results, the production of only electrical energy from wood biomass in a cogeneration plant was not sustainable from an energy point of view, since the obtained electrical energy was only 1.46 times greater than the input wood energy ($EROI_{el}$ = 1.46), while the obtained energy of the produced wood pellets was 4.82 ($EROI_{pel}$ = 4.82). According to the results of equivalent carbon emission, positive net value was achieved only with cogeneration plant and pellet plant working in synergy. Wood is a renewable source of energy, and its economic use can create a significant energy gain. However, due to the trend of using renewable energy sources and the increasing need for electricity, such a process of obtaining electricity is financially profitable, although it is not justified from the energy profitability and environmental sustainability point of view.

Keywords: EROI; CHP; cogeneration plant; pellet plant; CO_2 eq; GWP; thermal energy; electrical energy

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1. Introduction

In recent years, increasing attention has been paid to green and renewable energy sources, which should not only replace the bulk of today's energy sources but also preserve the environment, thus reducing greenhouse gas (GHG) emissions [1–4]. The main sources of energy are still non-renewable, obtained from fossil fuels—coal, oil and oil derivatives, natural gas, and nuclear energy. The basic disadvantages of non-renewable energy sources are pollution of the environment and limited quantity [5]. The most common forms of renewable sources are found in solar, wind, and water energy, with a smaller part obtained from biomass (numerous and diverse products from the plant and animal world) or residues from agricultural and forestry production [6]. Biomass is the most complex form of renewable energy. As a raw material containing both forest and agricultural biomass, biomass is generated during production processes in various industries or from waste in terms of municipal waste, water purification, and sewage sludge, and can also be grown in the form of energy plantations [7]. Biomass can serve as a renewable source for the production of electrical energy, thermal energy, and transportation fuels [8]. Increasing the use of wood waste as an energy fuel can reduce the need for imported fossil fuels, resulting in many benefits for the economy while reducing net carbon emissions [9].

The forestry profession manages a certain amount of renewable energy sources in the form of wood biomass, which can include all types and forms of energy wood according to the EN 14961-1:2010 standard [10] (wood chips, splinters, bark, bundles, wood dust, pellets, briquettes, etc.). Forest biomass is classified into roundwood production and residues, and waste generated during regular forest management [11]. The final product is made by converting forest residues through chemical or other physical processes. Forest biomass used in heating systems varies from firewood to various products obtained from wood processing and wood residues. Biomass from the wood industry (sawdust, shavings, etc.) can be used as a fuel in their own boilers or as a raw material for the production of briquettes, pellets, and the like [12]. Such biomass is much more suitable than forest biomass because it has a lower percentage of wood moisture content. From an economic point of view, it also has an advantage due to lower operating costs involved in the industry in terms of maintenance costs and waste management [13].

The development of biomass use should follow some basic principles, such as high conversion efficiency, competitiveness, and sustainability. Experience proves that the use of biomass in heat production best meets these principles. Biomass for heat production can be used in small units, such as individual houses, in heat supply projects, for district heating, and in industry. In any case, the supply of high-quality biomass, whether it is firewood, wood chips, or processed wood, is crucial for the rapid growth of this market [14]. Small-scale power generation or on-site power generation, such as cogeneration in wood product mills, could provide electricity generation from non-fossil fuel sources, resulting in reduced GHG emissions [15].

Biomass in its cycle from production to use for energy purposes results in no CO_2 production, i.e., it has a closed carbon cycle circulation. The amount of CO_2 produced during the processing of biomass for energy purposes through photosynthesis and solar energy is reabsorbed in the growth of raw materials from which biomass is formed. Energy in the raw material (plants, trees) is in chemical form and this energy is released when biomass is used for energy purposes, either during natural decay or combustion [16]. Biomass is commonly considered a CO_2-neutral fuel, but additional amounts of CO_2 are generated during its conversion in energy production. This is due to the use of fossil fuels in the process of transportation, processing, and biomass cultivation [15,17,18]. Although biomass is a CO_2-neutral fuel, the amount of GHG reduced in the atmosphere by using biomass compared to fossil fuels depends on the efficiency of the conversion process of biomass into the final energy consumed by end-users [19]. The term global warming potential (GWP) describes the emissions of different greenhouse gases into the air expressed in kg CO_2 equivalents (kg CO_2 eq). Although wood combustion is considered the most common way of obtaining bioenergy, it does not produce only CO_2, but also many pollutants with a high GWP, notably CO and volatile organic compounds (VOCs), among others [20]. Biomass combustion, or the release of thermal energy, can be used in electricity production to generate chilled water for air conditioning or refrigeration, or used directly in heating. Additionally, there is a process called gasification, in which biomass is converted into gas, which is then used directly as gas or for obtaining other forms of energy (electricity) [21].

1.1. Energy Return on Investment—EROI

Energy return on investment (EROI) is the ratio of the energy obtained from the energy production process to the energy required for extraction, growth, etc., into a new form of energy. EROI is most commonly applied in relationships between energy required for exploration and production of oil distillates or in the processes of growing and processing biomass (corn, sugarcane, etc.), as well as the production of biofuels [22]. The ratio of obtained and invested energy in the energy production process is a key factor in sustainable global energy supply. According to the laws of physics, energy cannot be produced without a certain amount of energy being expended, and the ratios in which this occurs are crucial indicators of the efficiency of the production process [23]. The concept of EROI should not be equated with the usefulness of conversion, which is often encountered in the literature, such as the production (conversion) of one type of fuel into another (production of gasoline from crude oil or production of electricity from diesel fuel). EROI is often referred to as an estimate of energy gain, energy balance, or net energy analysis. Proponents of EROI believe that net energy analysis offers the possibility of a realistic assessment of the advantages and disadvantages of producing a certain type of fuel and provides guidance for future fuel production and market possibilities. It is also noted that EROI itself is not necessarily a sufficient criterion for judgment, although it has the favor of the majority, especially in cases where one type of fuel has a much higher or lower EROI compared to another. Additionally, it is important to consider the current and future potential need for a certain fuel and possible changes in EROI in case of increased demand for a particular fuel [24].

EROI is simply calculated using the following expression [25]:

$$\text{EROI} = \frac{\text{Energy gained}}{\text{Energy required to get that energy}}$$

A general criterion used in the current discussion about EROI and energy production is whether the energy returned as fuel is greater than the energy invested in the processes of obtaining that fuel. More precisely, it refers to whether the EROI is greater than 1. If the obtained energy is greater than the invested energy, then the main argument is that such an energy production project should be carried out, or conversely, if the invested energy is greater than the obtained energy, then it should be discarded. Thus, Farrell et al. [26], in comprehensive research, state that the energy surplus, i.e., EROI in the production of ethanol from corn, ranges from 1.2 to 1.6 units obtained for each unit of energy invested. Further aspects dictate that in such production, all the obtained energy is not contained only in bioethanol but also in by-products that can be used as animal feed. On the other hand, the invested energy does not take into account soil depletion of nutrients during corn production. Therefore, there is an opinion that most of the obtained EROI values, including the example mentioned, currently have a higher ratio of obtained to invested energy, but considering all parameters, that ratio would decrease [22]. The same authors state that in the USA, the energy gain from fossil fuels is currently 80 for coal, and around 11–18 for gas and oil from domestic deposits. On a global scale, EROI for oil and gas is 20, meaning that 1 L of oil is needed to obtain 20 L delivered to society (e.g., at a gas station). Such an energy gain valued of 20 is sufficient for the functioning and progress of human civilization and significant industrial expansion. Part of this energy gain is used for further obtaining the same energy, while a certain portion is used in agriculture, resulting in a huge energy gain in the form of food delivered to society. This allows people and capitals to ensure energy gain outside the energy sector. Such a huge energy gain enables the development of our civilization from all perspectives, both good and bad. The challenging situation is that the shortage of oil began after its initial discovery and use, while the same oil took 100 million years or more to form. Due to the depletion of oil reserves, its price began to rise, and more and more oil is being consumed in the search for new deposits. Consequently, its energy gain decreases, and society seeks ways through technological development to compensate for it. Thus, it can be said that the shortage of oil and the development of new technologies are in a constant race against time. In the USA, the EROI for oil was 100 in the 1930s, 30 in the 1970s, 11–18 in the 2000s, and around 20 for the world. The ratio of obtained to invested energy for energy wood is 30:1, which means that one liter of oil is needed to obtain an amount of energy equivalent to 30 L of oil from energy wood (biomass) [27]. However, if CO_2 emissions are taken into account, assuming that during biomass combustion, the CO_2 emissions are zero because biomass absorbs CO_2 during its growth through photosynthesis, energy wood is in a more favorable position compared to fossil fuels [28].

In recent years, a new term, green EROI (EROIg), has been introduced [1,29,30]. It is a new form of EROI which includes Ecosystem Maintenance Energy (ESME) costs. Conventional EROI estimates by different researchers show large variation [31]. ESME cost estimates are even more uncertain. The prospect of accounting for ESME costs in net energy analysis leads to the possibility of an expression similar to that traditionally defined by EROI, but which addresses the production of green energy—EROIg [31]. If the EROIg is >1, then green energy generation is viable using the assessed energy generation technique.

Carbon capture by photosynthesis and biodiversity offsets have been shown to be of prime importance in improving the EROIg [1,30].

1.2. Cogeneration Plant

Cogeneration, also known as Combined Heat and Power (CHP), is the simultaneous production of two useful forms of energy (electricity and heat) in a single process [32], and it is the most cost-effective use of biomass as fuel [33]. The thermal energy that remains unused in conventional power plants (or is released into the environment with negative effects) is utilized for various production processes or, more commonly, for heating individual buildings or even entire communities. The main problem is that the construction of CHP or similar plants in relatively small regions has been encouraged without a critical review of the long-term availability and costs of preparation and supply of biomass, the type and speed of economic development, consumers of heat and economic conditions for production, transport, and energy use [33].

In the process of utilizing wood biomass for energy, wood chipping production has proven to be the most acceptable option. The increase in the use of wood chips in the EU and changes in the legal framework in Croatia have spurred the development of the energy wood market, creating a completely new economic activity that generates new jobs. The opening of new job positions and the increase in Croatia's energy independence are sufficient reasons to invest in the development and research of biomass utilization possibilities. The basic idea of projects for the construction of cogeneration plants using forest biomass (wood chips) in Croatia has been initiated due to incentive frameworks for such investments. The main purpose was the electricity production for delivery to the public electricity grid and thermal energy production for covering the needs of pellet production. This incentive framework began with the adoption of appropriate pre-legislative regulations in 2007. In the period from 2010 to 2022, the production of electricity from renewable sources (with the exception of large hydroelectric power plants) in Croatia increased by ten times, to over 3600 GWh per year. Of that amount, 20% of electricity was obtained from forest biomass that burns in CHP plants [34].

Cogeneration plants have long been developed in energy-intensive industries where there are uniform needs for thermal and electric energy. The most common cogeneration processes for such applications are traditionally steam turbine cycles that enable the use of waste steam for processing heat. Intensive development over the last two decades has enabled the development of many kinds of available equipment, so today the application of various cogeneration plants is suitable for different systems. They are, in terms of connection and operation with respect to the distribution network, the most commonly operated in parallel with the electrical distribution grid. In this way, they are meeting their own electricity needs, with possible surpluses delivered to the external grid. Cogeneration plants can also operate in a standalone mode when they exclusively meet the electricity consumption of the facility (complex). Combinations of parallel operation with the possibility of separate operation are also possible [6]. In such types of facilities, the gross electrical efficiency can reach up to 24%. The overall energy efficiency, which includes the thermal energy used in the production process, can reach up to 98%, indicating that almost all energy released from biomass is utilized in the facility. This high energy efficiency contributes to the economic viability and sustainability of such facilities. The variety, quality, moisture content, and degree of biomass processing all have a considerable influence on its energy value and, thus, on its use in the conversion of electricity and heat [33]. The challenge is to use wood resources in a sustainable way while improving the economy of society, but without a negative impact on the environment.

Given all the aforementioned, the aim of this paper is to analyze the energy gain and to determine the carbon footprints and the global warming potential (GWP) of a cogeneration plant that uses raw wood material to produce electricity for delivery to the public electricity grid, and thermal energy for covering the needs in the wood pellet production process. This study contributes to better understanding the degree of sustainability of the energy production from the ecological and economical point of view in the example of a cogeneration plant in Croatia.

2. Materials and Methods

2.1. Cogeneration Plant Lika Energo Eko Ltd.

The biomass cogeneration plant operated by Lika Energo Eko Ltd. (Udbina, Croatia) is located in Udbina, in the central part of Lika–Senj County (southwest of the central part of Croatia). The plant was constructed towards the end of 2011 and has been in full operation since May 2012. This plant holds the status of a privileged producer of electricity from renewable sources, meaning the price of the produced electricity is additionally subsidized by the state. According to founder research, the most cost-effective investment was found to be in a power plant capable of producing up to 1 MW of electrical power. In line with this finding, a decision was made to build a cogeneration plant with an electrical capacity of 0.95 MW and a thermal output of 4.1 MW, alongside a facility for wood pellet production.

In addition to the cogeneration plant, company Moderator Ltd. (Weston-super-Mare, UK) constructed a pellet production facility with a capacity of 5 tons per hour. The thermal energy from the cogeneration plant serves as the energy basis for pellet production, while the company sources its raw materials from wood assortments obtained from surrounding forests.

Both mentioned companies operate at the same location, and the annual quantity of wood mass required for production amounts to 73,000 tons. This quantity is contained in the form of long firewood, or assortments that cannot meet the standards of the sawmill industry in terms of technical quality. The types of wood used in the companies are assortments of common beech (*Fagus sylvatica* L.) and common fir/spruce (*Abies alba* Mill./*Picea abies* L.) in a ratio of 2:1.

The energy consumption for production, ultimately, of electrical energy and thermal energy for pellet production, in this case, is observed from the very beginning, i.e., the forest where the wood mass is produced. The representation of energy (invested and obtained) for all the components shown is expressed in MJ/ton.

On the plant grounds, chipping is carried out to obtain wood chips used directly as fuel in the cogeneration plant boiler, while on the opposite side, debarking of logs is performed followed by chipping. The bark obtained from debarking is used as fuel in the cogeneration plant, while the debarked logs are chipped to produce wood chips as raw material for pellet production. Such debarked wood chips are dried, further crushed, and dusted to make them suitable for pellet production.

The system of the biomass cogeneration plant consists of two main components: a wood chip-fired hot water boiler and an ORC (Organic Rankine Cycle) plant (Figure 1). The heat produced in the wood chip-fired hot water boiler is transferred to the ORC module via a thermal oil circuit. Using thermal oil as a heat transfer medium enables the boiler to operate at lower operating pressures (unlike steam boilers) and without changing the phase of the working medium (evaporation). The ORC plant generates electricity and low-temperature heat in a closed thermodynamic cycle according to the Organic Rankine Cycle (ORC) [35]. ORC technology is successfully applied in small biomass cogeneration plants with rated capacities between 200 kW and over 2 MW, proving to be an excellent solution for smaller local communities rich in biomass of any form. ORC is a variation of the Rankine cycle in which an organic fluid (oil) is used instead of water as the working medium. Due to the relatively low evaporation temperature of the organic fluid, it is possible to exploit low-enthalpy heat sources (biomass, waste heat, geothermal, and solar energy). ORC technology can convert low-temperature heat energy into electricity and can play an important role in increasing the energy efficiency of new or existing applications [36].

The design and construction of the turbogenerator installed at Lika Energo Eko d.o.o. are engineered and developed by Turboden, an Italian company. The type of the installed ORC plant is Turboden 10 CHP split with the capacity of electricity and thermal energy production in the amount of 999 kW and 4.1 MW, respectively.

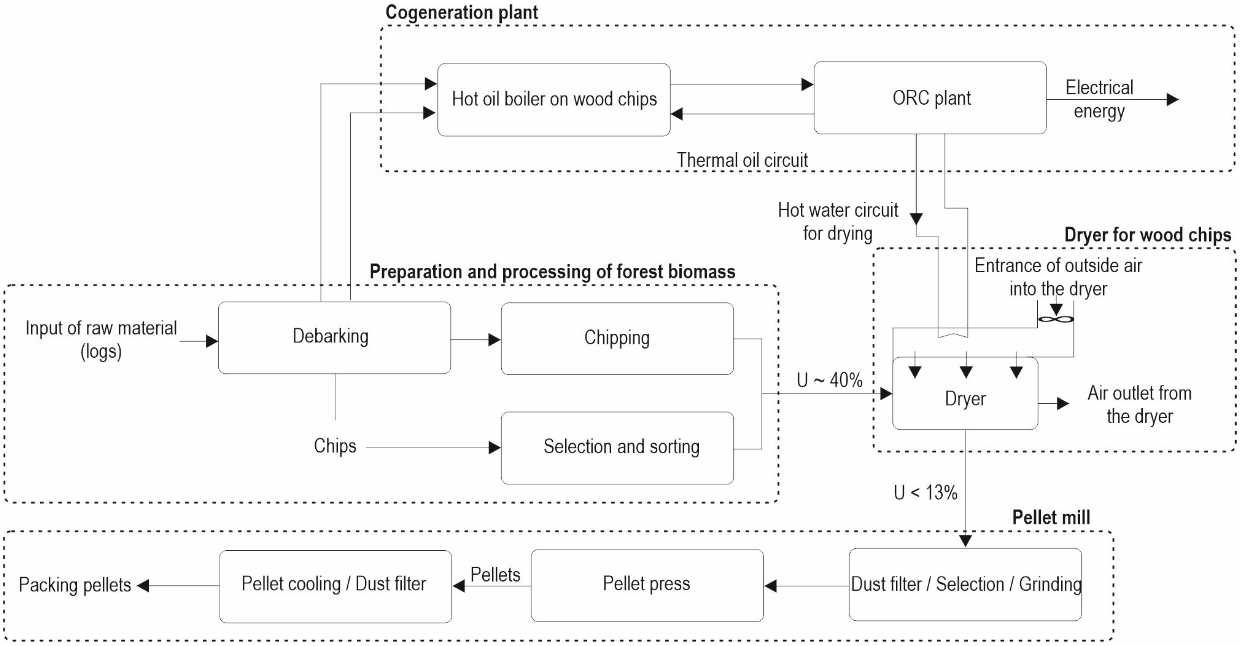


Figure 1. Simplified scheme of the process in the cogeneration plant on forest biomass (Lika Energo Eko Ltd. and Moderator Ltd. pellet production plant).

The start of wood pellet production involves the process of debarking logs to separate impurities (bark) that do not enter the composition of the pellets. Debarked logs are chipped, and the resulting wood chips are transported to the dryer. In the dryer, a portion of the heat from the cogeneration plant is used to reduce the moisture content of the wood chips from 40–60% to approximately 10%. After the drying process, the wood chips undergo further processing through fine grinding and are transported to the pellet press roller matrix. In this part of the plant, steam is added to assist the wood starch in the chips in binding the wood material together. After pressing, the resulting product, i.e., wood pellets, is again transported, this time for cooling, to begin packaging in 15 kg bags or, according to specific requirements, in 1-ton big bags.

Wood pellets are classified as renewable energy sources. A characteristic of pellets is that they burn cleaner than wood, which means a lower ash content, and they also require much less spatial volume (low moisture content), making them extremely suitable for transport and storage [37].

2.2. Data Collection and Calculation

For EROI calculation, input data or energy consumption (invested) were taken from Pandur et al. [24] for the following categories: forest management, harvesting, log transport, and chipping. In all categories, the energy invested is expressed in the unit MJ/t of the input raw material (long firewood). The forest management category includes energy expenditures for machines such as a cultivation tractor used for forest breeding work and for forest stand maintenance, grader and dump truck for the construction and maintenance of forest roads, personal vehicles for the transport of employees and goods, and also for pesticides used in the protection of forest stands. For machinery (chainsaw, forwarder) and vehicles (truck with trailer, passenger car), the energy required for their production and delivery to the place of work was taken into account, as well as the energy consumption of fuels and lubricants during their operation in the production of wood mass, while for pesticides, energy was taken into account only for their production.

The calculation of the equivalent carbon emission per ton of produced wood mass (kg CO_2 eq/ton) was performed on the basis of data presented by Pandur et al. [24], which refer to the mass of each machine and vehicle, its consumption of fuel and lubricants, and pesticides (Table 1).

Table 1. Energy consumption and equivalent emission of CO_2 eq of electric and pellet production.

	Machine/ Vehicle/ Input	Energy invested MJ/t					GWP kg CO_2 eq/t				
		(Production) [1]	(Fuel) [1]	(Oil) [1]	(Total) [1]		(Production) [2]	(Fuel) [2]	(Oil) [2]	Total	
Forest management	Cultivation tractor	2.5	14.2	0.73	17.43	60.4	0.19	0.99	0.01	1.19	4.17
	Grader	0.26	3.15	-	3.41		0.02	0.22		0.24	
	Dump truck	0.21	5.06	0.1	5.37		0.013	0.36	0.001	0.37	
	Personal vehicles	2.36	27.05	0.22	29.63		0.142 [3]	1.9	0.003	2.05	
	Pesticides	4.56			4.56		0.315 [4]				
Harvesting	Chainsaw	0.26	8.36	5.57	14.19	79.06	0.011	0.6	0.08	0.69	5.04
	Forwarder	7.61	52.71	4.55	64.87		0.58	3.7	0.065	4.35	
Log transport	Truck with trailer	18.34	162.8	3.05	184.19	184.19	1.13	11.44	0.043	12.61	12.61
Chipping	Chipper	4.36	169.54	0.21	174.11	174.11	0.39	11.91	0.003	12.3	12.3

[1] Original data from Pandur et al. [24]. [2] Calculation of GWP was performed according to Abbas and Handler [38]. [3] Calculation of GWP was performed according to Sullivan et al. [39]. [4] Calculation of GWP was performed according to Audsley et al. [40].

The calculation of the equivalent carbon emission for the manufacture and maintenance of machinery was 5.01 kg CO_2 eq per kg of produced machine [38]. Taking into account the mass of the machines, their productivity and depreciation life, equivalent carbon emissions per unit mass of wood produced were calculated.

According to Abbas and Handler [38], the equivalent carbon emission for the production and combustion of diesel fuel, gasoline fuel, and lubricants was 3.62 kg CO_2 eq, 3.97 kg CO_2 eq, and 1.19 kg CO_2 eq, respectively. Unit equivalent carbon emissions were calculated on the basis of diesel, gasoline, and lubricant consumption for all machinery and vehicles based on data from Pandur et al. [24].

For the production and maintenance of log trucks with trailer, the equivalent carbon emission was 82,400 kg CO_2 eq per unit [38]. The unit equivalent carbon emission was calculated on the basis of the productivity and depreciation life of the truck [24].

In the production of passenger cars, the equivalent carbon emission was 2.013 kg CO_2 eq per kg of produced vehicle [39]. The unit equivalent carbon emission for the purpose of this paper was calculated on the basis of data on passenger vehicles according to Pandur et al. [24].

The calculation of the unit equivalent carbon emissions for pesticide production was performed based on data on pesticide consumption per log mass produced [24] and equivalent carbon emissions in the amount of 0.069 kg CO_2 eq/MJ [40].

The equivalent carbon emission in electricity production in Croatia was on average 0.23 kg CO_2 eq/kWh [41]. The unit equivalent carbon emission in the cogeneration plant was calculated based on the produced electrical and thermal energy, while in the pellet plant, it was calculated on the basis of the energy of the produced pellets (Figure 2).

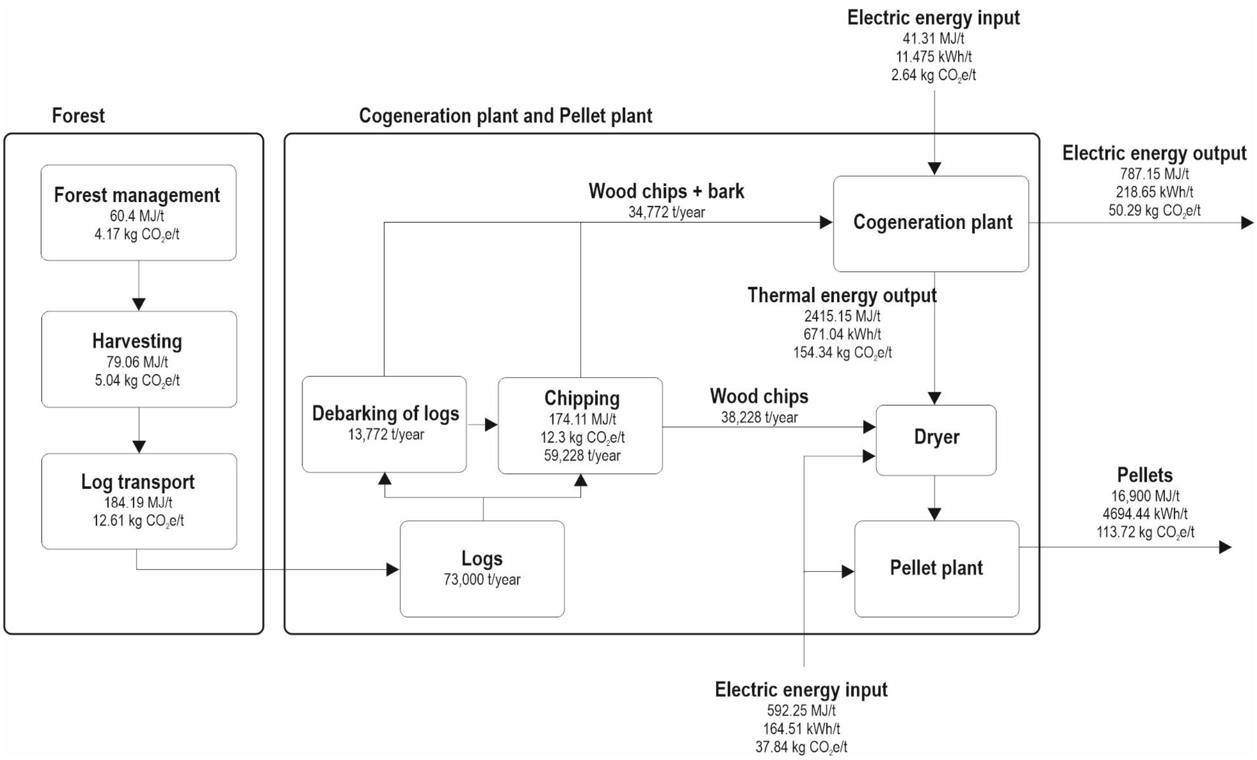


Figure 2. Schematic diagram of energy flow in the cogeneration plant Lika Energo Eko d.o.o. and the pellet plant Moderator d.o.o.

3. Results and Discussion

Based on the collected basic data on energy consumption and production related to the cogeneration plant Lika Energo Eko d.o.o. and data related to the production of wood mass as the fuel necessary for the operation of cogeneration, an analysis of energy gain in the production of electrical and thermal energy directly from cogeneration, i.e., the energy contained in the pellets produced by the company Moderator d.o.o., which purchases all the thermal energy produced by the company Lika Energo Eko d.o.o., has been conducted.

As shown in the schematic diagram in Figure 2, the calculation of invested energy included the energy consumed for forest management in the amount of 60.4 MJ/ton. This amount contains all the energy expended for standard forest management, meaning it includes the energy spent on forestry activities such as forest management operations, forest protection, construction and maintenance of forest roads, and energy from transportation vehicles (personal cars, vans). This amount was taken from research conducted by Pandur et al. [24].

According to research by the same authors, the energy consumption for harvesting (felling, processing, and extracting) was 79.06 MJ/ton, and for long-distance transport by truck with trailer (gross weight is 40 tons) within a radius of up to 50 km, it was 184.19 MJ/ton.

As mentioned earlier, the total annual quantity transported by truck with trailer to the auxiliary depot of cogeneration and pellet production was 73,000 tons. A portion of this quantity was used for debarking (as bark is not used for pellet production but is used in the cogeneration boiler). This amounted to 13,772 tons of bark annually, which was added to the quantity of chipped wood at 21,000 tons, totaling 34,772 tons annually for cogeneration energy production. The remaining quantity of 38,228 tons was used for pellet production [42].

In pellet production, debarked logs are chipped using self-propelled diesel chippers, and the chips are further ground in a mill. The ground wood mass then goes into a belt dryer, which receives all its thermal energy from the cogeneration plant. Before pressing, the dried wood mass (with a water content below 13%) undergoes dusting/selection/refinement. The produced pellets undergo cooling and dusting processes before packaging. The total amount of electrical energy used in the pellet plant operation was 592.25 MJ/ton [42]. All operational components of the pellet plant use electrical energy from the power grid, except for the chippers, which use diesel fuel for which Pandur et al. [24] indicated a unit energy consumption of 174.11 MJ/ton.

For the operation of the cogeneration boiler, bark obtained from debarking and wood assortments chipped by self-propelled diesel chippers were used. The total required quantity of wood mass on an annual basis was 34,772 tons. Cogeneration used electrical energy amounting to 41.31 MJ/ton [42].

The final products of the cogeneration plant Lika Energo Eko Ltd. are electric energy amounting to 787.15 MJ/ton, which is sold to the state-owned company Hrvatska elektroprivreda d.d. as a privileged producer, and thermal energy amounting to 2415.74 MJ/ton, sold to the company Moderator Ltd. (Table 2). The mentioned electrical and thermal energies were obtained based on the consumption of wood raw material amounting to 34,772 ton/year. The total energy required for the production of electrical and thermal energy from the cogeneration plant (invested energy) amounts to 539.07 MJ/ton (according to the scheme in Figure 2). The $EROI_{el}$ for the production of electrical energy was only 1.46, which indicates a very small energy gain. Daaboul et al. [1] found the $EROI_{el}$ to be 1.54 for electrical energy from short rotation willow coppice (SRWC). Numerous authors [22,25,26] have been suggesting that when the value is less than 2, the purpose of energy production becomes questionable.

Table 2. EROI of cogeneration plant and pellet plant.

Product	Energy Value (MJ/ton)		EROI
	Obtained	Invested	
Electric energy	787.15	539.07	1.46
Thermal energy	2415.74	539.07	4.48
Cogeneration plant (electric energy + thermal energy)	3202.89	539.07	5.94
Pellet	16,900 [1]	3505.75	4.82
Cogeneration plant + Pellet plant (electric energy + pellet)	17,687.15	3547.06	4.99

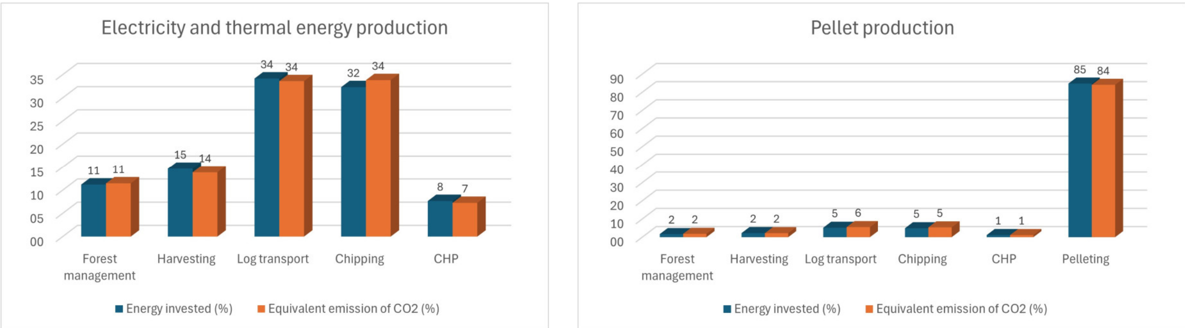
[1] According to Telmo and Lusada [43].

The $EROI_{term}$ for the production of thermal energy in the investigated cogeneration plant was 4.48, while considering both electrical and thermal energy production, the $EROI_{CHP}$ for the cogeneration plant stands at 5.94. Wang et al. [44] noted that EROI values for biomass power plant range from 2.07 to 16.48 and are significantly higher than the value of coal-fired power generation (0.34).

For pellet production, the calculated $EROI_{pel}$ was 4.82. This value approximately corresponds to the value of 4.43 reported by Danon and Furtula [45]. Furtula [46], for example, concluded that the EROI exceeded 7 in the pellet production using thermal energy from a cogeneration plant with a water content of 20% in wood chips. Similarly, Furtula et al. [47] mention a value of 1.9, emphasizing the significant role of the water content in wood chips in the final invested energy value, as a large amount of thermal energy is used for its evaporation. For both cogeneration and pellet plant, the $EROI_{tot}$ was 4.99.

Pandur [18] noted that the energy value of wood chips was about 25 times higher than the energy consumed for their production in thermal energy production. In relation to this energy return ratio, wood chips have been considered an environmentally acceptable source of energy compared to wood pellets. According to this research, the obtained EROI ratio for the production of electrical and thermal energy (combined) in the cogeneration plant was significantly lower ($EROI_{CHP}$ was 5.94), raising the question of whether such energy production is energetically profitable.

In the process of producing electricity and thermal energy in the cogeneration plant (Figure 3a), the largest share of the energy input was in the phase of log transportation by trucks and in the chipping process, 34% and 32%, respectively. For forest management and harvesting, 11% and 15% were used, respectively, while the least amount of energy was used for the operation of the cogeneration plant, at 8%. The share values and equivalent emissions of CO_2 eq are similar. The highest emissions occurred during long-distance transport and wood chipping, at 34% for both, smaller values during forest management and harvesting, at 11% and 14%, respectively, while the lowest emission was determined during the operation of the cogeneration plant, at 7%. The reason for the largest share of energy consumption and equivalent CO_2 eq emissions was the transport of wood by trucks and chippers, which is due to the large consumption of diesel fuel by those two machines. An increase in the transport distance has the highest impact on the global warming potential [11]. Pandur et al. [24] and Klvač et al. [48] found that diesel fuel accounted for 82% and 86% of total energy consumption, respectively. For this reason, the highest share of equivalent emission CO_2 eq was determined for those two machines.



(**a**) (**b**)

Figure 3. Percentage of energy consumption (invested energy) and equivalent emission of CO_2 eq: (**a**) electricity and thermal energy production in cogeneration plant; (**b**) pellet production in pellet plant.

In the production of wood pellets, the largest share of energy was consumed in the pellet mill, or in the dryer for wood chips, which used all the thermal energy produced in the cogeneration plant for its work, in the amount of 85% (Figure 3b). The pellet plant had the highest equivalent emission of CO_2 eq, at 84%. The lowest energy consumption and the lowest equivalent emission of CO_2 eq were in the cogeneration plant, in the amount of 1%. In other stages of production, the share of invested energy and equivalent emissions of CO_2 eq was up to 5%. Similar shares of consumed energy and equivalent emission of CO_2 eq were presented by Furtula et al. [47] where the greatest share was in pellet plant, at 88% and 69%, respectively.

According to Figure 4. equivalent emission of CO_2 eq per ton of invested wood at the cogeneration plant had a positive net value (+167.9 kg CO_2 eq/ton). This was primarily due to the produced thermal energy that is further used in the pellet plant, i.e., the dryer for wood chips. The pellet plant had a negative net value of CO_2 eq (−115.2 kg CO_2 eq/ton). This could be explained by a huge amount of thermal energy taken from cogeneration plant used for drying wood chips. Produced pellets had only a half equivalent emission of CO_2 eq/t (+113.7 kg CO_2 eq/ton) regarding equivalent emission of CO_2 eq per ton of consumed energy, which mostly consists of thermal energy taken from the CHP. Pergola et al. [49] found that the production of wood pellets resulted in GHG emission of 83 kg CO eq/ton when using timber directly obtained from the harvesting activities. Similar results were reported by Magelli et al. [50], 87.19 kg CO eq/ton. In some other cases, the values were higher and ranged from 100 to 1102.5 kg CO eq/ton [51]. Overall, for both CHP and pellet plant, i.e., produced electrical energy and wood pellet, the net value of the equivalent emission of CO_2 eq per ton of invested wood had a positive value (+89.4 kg CO_2 eq/t).

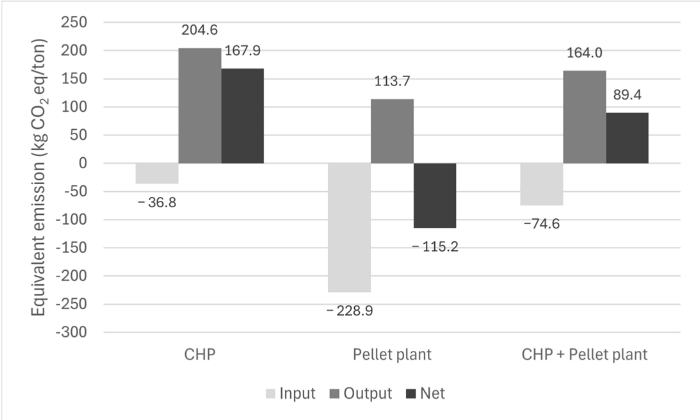


Figure 4. Input, output and net equivalent emission of CO_2 eq for cogeneration plant, pellet plant, and combined cogeneration and pellet plant.

The reduction in energy input (thermal) and equivalent emission of CO_2 eq in pellet plant is possible by using natural drying of biomass raw material. In that case, the energy gain of pellet production would also be improved. Equivalent emission of CO_2 eq could also be reduced by using a renewable source of electric energy (photovoltaic power plants). The plan in the near future is to build such a plant in line with the researched cogeneration plant, in order to reduce costs of using electrical energy from a national power grid.

In this study, the energy consumption and equivalent emission of CO_2 eq for the construction and delivery of cogeneration plant machinery (boiler with associated equipment and ORC plant with associated equipment) and pellet production plant (mill, dryer, dusting system, pressing, cooling, and packaging) was not included in the unit energy consumption (invested energy). Only the electrical energy used by these plants in production was included in the calculation.

4. Conclusions

Based on the results obtained in this research, it can be concluded that energy production (electrical and thermal) in the cogeneration plant is on the brink of energy profitability ($EROI_{CHP}$ = 5.94). The production of electricity alone, without utilizing thermal energy, was not justified ($EROI_{el}$ = 1.46), while the EROI for thermal energy was 4.48. Therefore, it confirms the thesis that the main product in the cogeneration plant is thermal energy, while electrical energy is a byproduct. The EROI ratio for pellet production was also on the verge of energy profitability ($EROI_{pel}$ = 4.82). This ratio can be increased solely by using pre-dried wood chips (with a moisture content below 20%), where minimal thermal energy is used for drying.

Equivalent emission of CO_2 eq had a positive net value for CHP in a case when the total thermal energy was used efficiently, like in the presented example for pellet production. Synergy production of CHP and pellet plant was a good combination regarding the positive net equivalent emission of CO_2 eq, but if either of these two plants operated independently, the equivalent net carbon emission would be negative.

If the energy required for the construction and delivery of cogeneration plant machinery (boiler with associated equipment and ORC plant with associated equipment) and pellet production plant (mill, dryer, dusting system, pressing, cooling, and packaging) were included in the calculation of invested energy, the obtained EROI ratio would be even lower.

Wood is a renewable source of energy, and its economical use can create significant energy gains. However, due to the trend of using renewable energy sources and the increasing demand for electricity, such a method of obtaining electrical energy is financially viable, even though it may not be justified from an energy profitability standpoint.

In the future, it is planned to investigate to what extent the use of electricity from renewable energy sources (photovoltaic power plant) affects the reduction in equivalent CO_2 eq emissions in the operation of a cogeneration plant and in the production of wood pellets using the same example.

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