Chapter 7

Energy Return on Investment (EROI) of Different Wood Products

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Additional information is available at the end of the chapter

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Abstract

Energy cannot be produced without consumption of some part of the energy, and the proportions in which this occurs are a key indicator of the efficiency of the production process. Energy return on investment (EROI) of energy production shows the relationship between obtained and invested energy in the production process. This relationship is a key factor in sustainable global energy supply. Wood chips and one-metre firewood are used to produce thermal energy. Amount of energy obtained by burning depends on the moisture content and the features of the energy plant. This chapter deals with the issue of the amount of energy required to produce in the process of wood chips and one-metre firewood production and its transport to the heating plant. When calculating the energy balance, it is important to include as many input parameters as possible (parameters of energy consumption), which represents an almost impossible task because one parameter directly binds several others. According to several authors, the relationship between obtained and invested energy or EROI for energy wood is 30:1 which is a better ratio than the production of oil, for which relationship between obtained and invested energy is about 20:1. The results of study show that most of the energy during the production and supply of energy wood products from final felling of oak stands is used for fuel for machinery and vehicles in the production process. Ultimately, the relationship between obtained and invested energy is approximately 25:1 in the case of moisture content in the wood chips in the limit (market) value of 35% and the mean distance truck transportation of wood chips of 50 km. The relationship of obtained and invested energy used for one-metre firewood is bigger than 25:1 because of less invested energy which does not include machines like wood chipper. This is a satisfactory relationship, but it decreases with a greater transport distance. Such is the case when chips manufactured in Croatia, due to the lack of heat plants, are transported over long distances to neighbouring countries.

Keywords: EROI, input energy, output energy, wood chips, one-metre firewood

1. Introduction

Energy return on investment (EROI) is the ratio between energy obtained from energy production process and energy consumption during separation, growth, etc., into new forms of energy. EROI is most often applied in energy ratios needed for oil exploration and production of petroleum distillates or in the process of generating and processing biomass (corn, sugarcane, etc.) as well as in biofuel production [1].

The ratio of inputs and outputs in the process of energy production is a key factor of sustainable global energy supply. According to the laws of physics, energy cannot be produced without a portion of it being consumed, and those values are a key indicator of the efficiency of the production process [2].

The term EROI should not be mistaken for conversion utility, which is often found in the literature, for example production (conversion) of one type of fuel to another (production of gasoline from oil, or electricity from diesel fuel). EROI is commonly referred to as an *estimate of the energy gain, energy balance* or *net energy analysis*.

The authors [1] emphasize the importance of obtained energy as a necessary criterion for survival, development and growth of many species including man. It is believed that the survival, military efficiency, wealth, art and even civilization itself are the products of energy gain because without it people through history would not be able to build cities and civilizations and still spend huge amounts of energy on wars.

Plants and trees also generate energy necessary for growth and reproduction. For example, oak as a heliophilous species does not tolerate shade for long and after a few years will die due to lack of sunlight. Also, the trees in open areas have lower green branches distributed on the trunk in relation to those that grow in dense stands. Branches that grow low in the trunk (in dense stands) do not get enough sunlight needed to produce energy throughout photosynthesis, while the energy consumed in assimilation apparatus continues and becomes greater than the energy produced by photosynthesis. Such branches first discard leaves and eventually die off due to the energy loss [3].

Every living creature that wants to survive must satisfy the law of *energy balance evolution* that says that for survival an individual must use more energy than it was required to receive that same energy. Reproduction needs more energy than it is necessary for metabolism processes, while in the process of evolution yet higher energy gain is necessary because energy losses of the majority of individuals in a population that are non-resistant need to be compensated. In other words, each individual (species) that wants to survive must adapt the method of gaining more energy than was invested in obtaining that same energy and as such is successful in evolutionary terms. Only individuals with excess of energy have the ability to spread, progress and develop.

People have eventually learned how to increase control over energy with the help of technology, although, thousands of years for energy production they used human and animal energy as well as processed solar energy (with plant help) for food production. Another, throughout history, very important source of energy for people was the energy from wood. However, energy from wood is still an important source of energy for humans, and more recently due to the trend of increasing use of renewable energy sources at the expense of using fossil fuels, energy from wood is gaining more and more attention. Ultimately, all the energy we use on Earth, either directly or indirectly as accumulated energy in the form of fossil fuels, wood, food, etc., was created with the help of solar energy. Solar energy is the basis and starting point for life on Earth.

Proponents of EROI believe that *net energy analysis* offers a realistic consideration of the advantages and disadvantages of production of a certain type of fuel, and provides guidance for the possibilities of production and energy market in the future. Also it is noted that EROI itself is not a sufficient criterion for judgement, even though it has the favour of the majority, especially when one energy source has much higher or lower EROI compared to another. In addition, it is important to take into account the current and future potential need for certain energy source and possible EROI change in case of increased demand for a specific energy source.

EROI can easily be calculated using the following expression [4]:

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

The numerator and denominator are usually in the same measuring unit, so the result is dimensionless, e.g. 30:1, which is expressed as ‘thirty to one’. This means that, for example, the process of wood chips production that has energy value of 30 J requires only 1 J of energy input, starting with the energy required for the production of machines used in the process of obtaining wood chips, fuel for those machines and, of course, manpower invested in the whole process.

The general criterion used in the current debate on EROI and energy production is the question whether energy that returns as fuel is greater than the energy invested in the process of production of that fuel, i.e. whether the EROI is greater than 1.0:1.0. If the energy output is greater than the input then this is the main argument in favour of such production project and vice versa, if the energy input is higher than that the output the project should be rejected. Thus, [5] from comprehensive studies suggests that energy surplus or EROI code for production of ethanol from corn is in the range between 1.2 and 1.6 units obtained for each unit of energy invested. Further, in such production, all the energy output is not contained only in bio-ethanol but also in by-products of that process that can be used as fodder. On the other hand, input energy does not contain depletion of soil nutrients in maize production. Therefore, there is an opinion that most EROI values, including this particular example, currently have a higher ratio between energy inputs and outputs, but when all the parameters of this relationship would be taken into account, ratio reduction would appear [1].

The same authors state that there are several different EROI values from a different data collecting scope and for different energy sources. There is an opinion that for many energy calculations, EROI is too simplified or shallow with the aim of reducing the value of competitive fuel and as such should not be the main criterion for decision making. Many EROI analyses were based with the aim of promoting or protecting certain energy source. The size and significance of the total EROI value should be investigated in terms of getting the total sum of the energy of a nation or society and all energy costs of obtaining it. This is the so-called societal EROI (EROI_{soc}):

$$EROI = \frac{Summation\ of\ the\ energy\ content\ of\ all\ fuels\ delivered}{Summation\ of\ all\ the\ energy\ \cos ts\ of\ getting\ those\ fuels}$$

The new way of calculating EROI includes the input parameters as the energy required to transport energy (oil, wood) from the processing point to the end user, while the output parameter is the amount of transported energy. This is the next step of calculating EROI and it is called EROI at 'point of use' (EROI_{pou}):

$$EROI_{POU} = \frac{Energy\ returned\ to\ society}{Energy\ required\ to\ get,\ deliver\ and\ use\ that\ energy}$$

Furthermore, the concept of calculating EROI includes not only the energy needed to obtain certain energy-generating product, but also the energy needed to use it (energy needed for building and maintaining infrastructure). Such EROI is called the extended EROI (EROI_{ext}):

$$EROI_{\mathrm{ext}} = \frac{Energy\ returned\ to\ society}{Energy\ required\ to\ get,\ deliver\ and\ use\ that\ energy}$$

As it is obvious from expressions presented earlier, there are several ways of calculating EROI, some of which take into account all input and output parameters, while some exclude certain parameters.

According to the last expression for calculating EROI_{ext}, for input parameters it includes not only the energy consumption needed, e.g. for the discovery and production of oil, but also the energy needed for oil supply, which means that the calculation should include energy consumption for:

1. Construction and maintenance of vehicles
2. Construction and maintenance of used roads
3. Calculation must contain vehicle amortization
4. Calculation must contain costs of insurance, etc.

In future, EROI_{ext} will probably expand with energy of man and the economic activity that are either directly or indirectly involved in all processes of obtaining energy. Approximately 10%

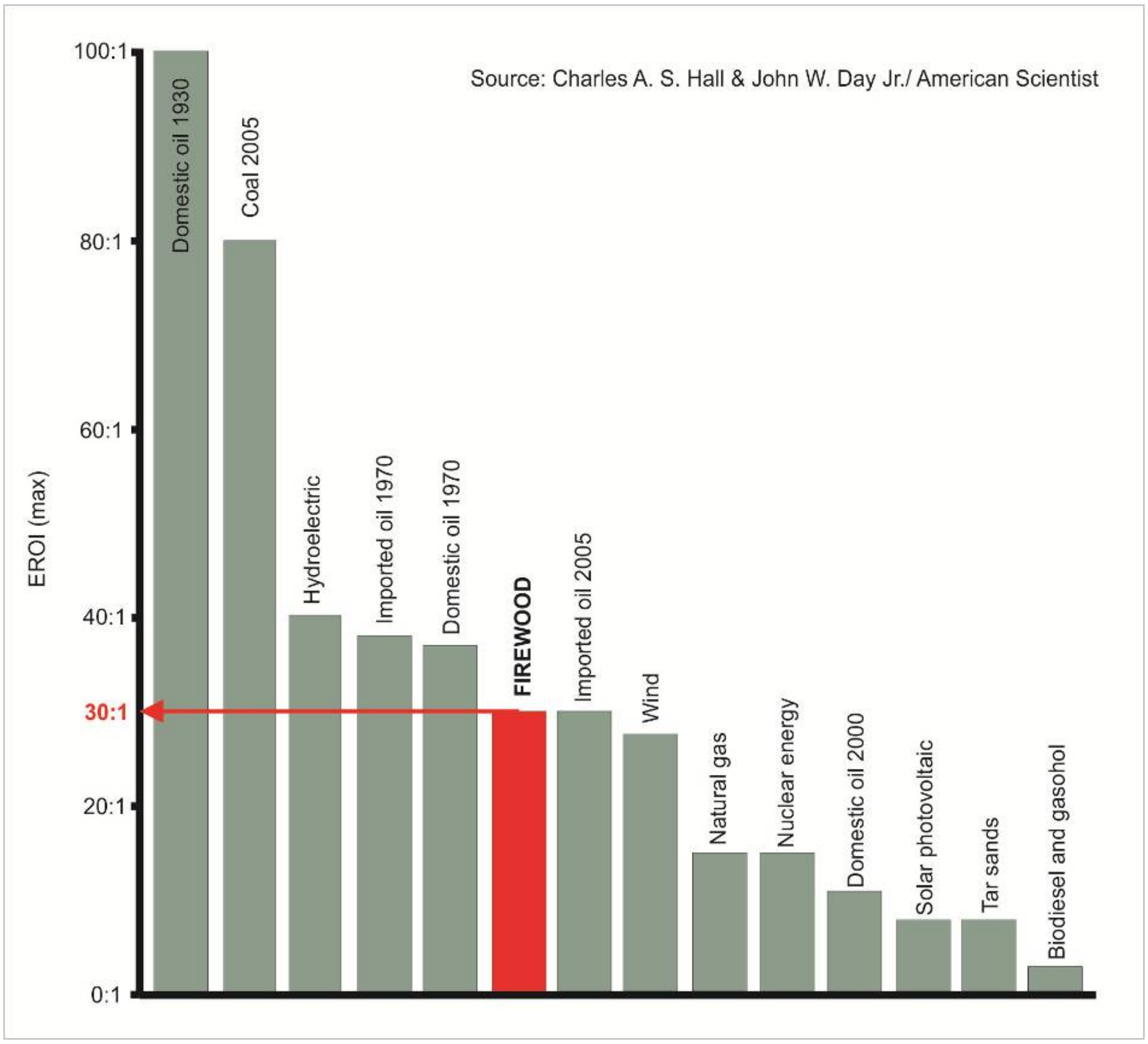

Figure 1. Values of EROI for some energy production processes

of the entire economy is included in the process of obtaining energy, which means that farmers who produce food for workers who produce machines for the transport of oil and so on. In this case, one could say that the denominator when calculating $EROI_{ext}$ contains 10% of the total used energy [1].

The same authors state that in the United States today energy gained from fossil fuels is 80:1 for coal and up to 11–18:1 for gas and oil derived from domestic sites. At the global level, this relationship for oil and gas is 20:1 which means that 1 L of oil is required to obtain 20 L of oil supplied to the society (e.g. petrol stations). Such an energy gain of 20:1 is sufficient for human civilization progress and great industrial expansion. Part of this gained energy is used to further obtain the same energy and other part is used in agriculture which results in huge energy outputs in the form of food transported to the society. It enables people and capital to produce energy outside the energy sector, and such a huge energy gain enables the development of our civilization with both good and bad points of view. The bad news is that the lack of oil began after its first discovery and use while that same oil needed more than 100 million years for formation. Due to decreasing oil reserves, its price began to grow and more and more oil is spent on the search of new bores. Thus its energy gain reduces and the society is looking for new technologies that can replace it, so it can be said that the lack of oil and the development of new technologies is the constant race against time. EROI for oil in the United States during the 1930s was 100:1, in 1970 was 30:1, in 2000 was 11–18:1, and for the rest of the world it is around 20:1.

Referring to figure 1, the ratio of obtained and consumed energy for energy wood is 30:1, which means that 1 L of oil is necessary to produce amount of energy equivalent to 30 L of oil from energy wood (biomass). But if the CO_2 emission is added, whereby it is considered that during the combustion of biomass CO_2 emission is zero because biomass during its growth binds CO_2 in the process of photosynthesis, energy wood is favourable in relation to fossil fuels [6].

The author [7] explores the energy consumption based on fuel consumption in the production chain of wood energy in the form of trunk, thin logs and brushwood and finds that the proportion of energy consumed in fuel is 3.2% for the trunk, 2.8% for thin logs and 2.5% for brushwood in relation to the wood energy value. The largest fuel consumption refers to timber and chip transportation.

The authors [8], on the basis of several studies from Germany, Switzerland and Sweden, offer data on the unit energy consumption. For silvicultural procedures of cutting, bucking and timber extraction, 62 to 135 MJ/m^3 energy is consumed, while for the long distance transport, an additional 92 to 125 MJ/m^3 energy is used (transport distances of 50 km). The overall unit energy consumption is in the range from 180 to 230 MJ/m^3. The same authors report that in 1997 the share of secondary transport amounts between 53% and 57% of the total energy consumption at the level of Sweden.

The author [9] states that for silvicultural procedures, felling and extraction consume 60–270 MJ/m^3, and for secondary transportation 90–223 MJ/m^3, the total energy consumption is 180–395 MJ/m^3.

This chapter presents a detailed calculation of the energy consumption for all machinery and vehicles that were used in the area of Forest Administration (FA) Vinkovci in 2012 with the calculation of EROI for wood chips and one-metre firewood. The total area of the FA is 72,203.27 ha, of which 68,392.48 ha is forest. The total growing stock amounts to 19,717,000 m^3, where common oak participates with 68%, ash with 12%, hornbeam with 10% and other species with 10%.

2. Methods and results of research

All presented data (data on productivity, number of machines, consumptions of fuel, lubricants and tyres as well as consumptions of chains, guidebars and sprockets of chainsaws and quantity of pesticides) were obtained (calculated) by the Department for Production of FA Vinkovci (table 1).

	Forwarders[1]	Tractor assemblies	Silvicultural tractor[2]	Farm tractor with trailer[3]	Total
			m^3		
Logs	142,203	70,124	437		212,764
Long firewood	32,239	19,380	796		52,415
Energy wood	14,396				14,396
One-metre firewood				135,139	135,139
Total	188,838	89,504	1,233	135,139	**414,714**

Source: Original data.

[1] Forwarder extraction includes use of forwarders from other FA's and private contractors.

[2] Silvicultural tractors when not involved in cleaning procedures are equipped with winches and used for timber extraction.

[3] Amount of one-metre firewood includes the amount produced by FA workers (20,693 m^3), while the remaining amount (114,446 m^3) was produced by the local community and private contractors.

Table 1. Share of wood products (m^3) for the period from 1.1.2012 to 31.12.2012 in FA Vinkovci and use of vehicles for timber extraction

When calculating EROI, it is important to include as many input parameters, or in this case the energy required to build all the machines and tools used in forest harvesting operations, construction and maintenance of forest roads, the energy of fuels and lubricants used by machines and vehicles, the energy required to build supplies, such as tyres, chains, guidebars and sprockets of chainsaws, the energy required for the production of pesticides used in cases concerning the forests protection, human energy, etc.

All the energy used in this calculation is expressed in relation MJ/m^3 at the level of year 2012 as well as the energy output, which includes:

- Energy of forest residues that are chipped and transported by trucks to heating facilities
- Energy of one-metre firewood

The final result is the ratio of obtained and consumed energy – EROI.

Output parameter in the calculation is the energy value of wood chips taken from the *Biofuel Handbook* [10] (hereinafter Handbook). Energy value of the energy wood with a moisture content in the amount of 35% according to this Handbook is 11.17 GJ/t, and calculated by the density of oak wood chips at the same moisture (852 kg/m^3) is 9.51 GJ/m^3.

Input parameters for the EROI calculation are distributed to the direct and indirect energy consumptions.

Energy value of one-metre firewood according to the same Handbook is 9.71 GJ/t with the moisture content in the amount of 42% and calculated by the density of oak one-metre firewood at the same moisture (967.3 kg/m^3) is 9.31 GJ/m^3.

Input parameters for the EROI calculation are distributed to the direct and indirect energy consumptions.

Indirect energy consumptions include:

- *Energy required for production of machines and vehicles*

In this the energy included is the energy required for the production of materials for machinery, the energy invested in manufacturing parts and transport of new machinery from place of production to the customer and the energy required for the recycling of waste machines (after amortization period).

In calculation, the energy invested in machinery and vehicles is assumed to be 66 MJ/kg [11, 12].

The author [13] states that the energy required for the production of material embedded in vehicles amounts to average 24 MJ/kg, while manufacturing and assembly of vehicles additionally consumes energy in the amount of 11 MJ/kg for tractors, 9.1 MJ/kg for harvesters, 6.3 MJ/kg for plough, etc. The authors [14] recorded similar results where the calculation for agriculture tractor amounted to 26.04 MJ/kg consumed energy. The authors [15] in their paper provide an analysis of the raw materials used in the forestry equipment and energy needed for production of each of the materials. According to their analysis, based on the vehicles mass, the total energy used in production of materials used in forwarder Valmet 840.2 amounts to 26.79 MJ/kg, respectively, for forwarder Valmet 860.4 is 26.79 MJ/kg and for the agricultural tractor John Deere 8430 amounts to 26.56 MJ/kg.

The energy invested for production of motor cars is calculated according to [16] who used model from [17] and concluded that energy required for production of motor cars is 33.4 MJ/kg.

Masses of machines/vehicles were taken from technical data of manufacturers (forwarders, dump truck, grader, chainsaws, chipper, agricultural tractors) and drivers/owners of vehicles (trucks for transport of wood chips, motor cars), or were determined by direct measuring of axle loads (forwarders) (table 2).

The productivity of each machine/vehicle is presented on an annual basis. Because all the input energy is reduced to unit MJ/m^3 (unit energy consumption), it is also necessary to express energy invested in the production of machine/vehicle on the same way. The total energy input for the production of material, construction and delivery of the machinery/vehicles divided into the depreciation of the machine/vehicle, and the result at the end, is also divided with an annual productivity of the machine/vehicle. For this reason it is necessary to know the depreciation of life of any machine/vehicle, which is 7 years for forwarders and chippers, 10 years for agricultural tractors, graders, trucks, trucks with trailers and semi-trailers, 8 years for tractors with semi-trailers, 7 years for chainsaws and 5 years for motor cars.

For the machines like grader and dump truck for transportation of stone, and the farming tractors and motor cars indirectly linked to the productivity of FA Vinkovci for the year 2012, 414,714 m^3 is the annual productivity of each of these categories of vehicles identified with the total productivity of FA Vinkovci.

Machine/Vehicle	No.	Total weight	Energy	Total energy	Period of amortization	Productivity	Energy consumption
		kg	MJ/kg	GJ	years	m^3/year	MJ/m^3
Chainsaws[1]	405	3,124	66	375.66	5	285,872[1]	**0.26**
Forwarders[2]	8	117,920		7,782.72	7	146,171[2]	**7.61**
Tractor assemblies	22	121,803		8,038.99	8	89,504	**11.23**
Silvicultural tractors	21	126,000		8,316	8	414,714	**2.5**
Truck units[3]	7	141,796		9,358.54	10	51,034[3]	**18.34**
Grader	1	16,200		1,069.2	10	414,714	**0.26**
Dump truck	1	13,350		881.1	10	414,714	**0.21**
Hauling truck	1	16,500		1,089	10	28,380	**3.84**
Farm tractor[4]	1	11,260		743.16	10	40,000[4]	**1.86**
Chipper	1	10,600		699.6	7	40,000[4]	**2.5**
Motor cars	122	146,400		4,889.76	5	414,714	**2.36**

Source: Original data.

[1] Chainsaw productivity does not include 114,446 m^3 (one-metre firewood was produced by the local community and private contractors) and14,396 m^3 forest biomass.

[2] Only timber extracted by FA Vinkovci forwarders.

[3] Only timber transported by FA Vinkovci truck units.

[4] Productivity of farm tractor driven by chipper was calculated based on hour productivity 25 m^3/h (according to: http://www.northernwoodheat.net/htm/Publications/FinnishInfoCard9.pdf), 8 working hours/day and 200 working hours/year.

Table 2. Energy consumption for vehicle and machine production

- *Energy required for production of pesticides*

The energy invested for production of pesticides was calculated according to [13] who estimated average energy consumption of 120 MJ for production of 1 kg of pesticide.

The total energy contained in pesticides was calculated on the basis of four different types of pesticides which were used for forest protection during 2012 on area of FA Vinkovci (table 3).

Direct energy consumptions include:

- *Fuel and lubricant consumptions*

Low heating value H_d is heat (energy) gained from the process of fuel combustion, without additional use of heat from condensing water vapour. Low heating value or the amount of energy gained by combustion of diesel fuel is 41.9 MJ/kg and of gasoline is 42.7 MJ/kg [18]. The amount of energy contained in oil is 35.87 MJ/l [15]. However, with energy contained in fuel and lubricants the energy used to produce them should be included. The author [19] according to [20] states that the total energy contained in mineral oil is 83.5 MJ/l (38.5 MJ/l energy value of oil, 45 MJ/l energy required for the production of mineral oil) or according to [21–23] the total energy contained in diesel fuel is 40.64 MJ/l (36.14 MJ/l energy value and the energy required to produce it is 4.5 MJ/I).

Type of pesticide	Productivity	Quantity	Density[1]	Quantity	Energy	Total energy	Total energy
	m^3/year	L	kg/cm^3	kg	MJ/kg	GJ	MJ/m^3
Artea plus	**414,714**	1,568	1.128	1,768.7	120	212.24	
Match		449.2	0.94	422.25		50.67	
Glifosat		2,110	1.172	2,472.92		296.75	
Difencanum–Sarexa cebo		–	–	11,091.6		1,330.99	
Total				15,755.47	120	1,890.65	**4.56**

Source: Original data.

[1] Pesticides amount in litres was converted to kilograms using density values given by manufacturers.

Table 3. Energy consumption for production of used quantities of pesticides

The values for calculation of total energetic value of fuels and lubricants were taken from [11, 24] which determined values of 55.3 MJ/kg for chainsaw fuel, 51.5 MJ/kg for diesel fuel and 83.7 MJ/kg for lubricants.

Since the energy content of the fuel is mainly expressed in kg/m^3, and fuel and lubricant consumption is measured in L/m^3, all quantities of fuels and lubricants are calculated in kg/m^3 based on density fuel specified by [18]. Density of gasoline is 0.72 kg/L, diesel 0.875 kg/L and lubricant (oil) 0.832 kg/L at 80°C.

The concrete values of consumption in 2011 at the FA Vinkovci were taken to calculate the fuel and lubricant consumptions for the chainsaws. 59,404 L of fuel and 22,798 L of lubricant were spent for the production of technical roundwood and stacked wood in the amount of 282,772 m^3. This means that on the average value 0.21 L/m^3 (0.1512 kg/m^3) of fuel and 0.08 L/m^3 (0.06656 kg/m^3) of lubricant calculated were spent.

The total amount of spent fuel and lubricants was obtained from the database of the production department of FA Vinkovci for forwarders, farming tractors, grader, dump truck and motor cars and chainsaws.

The direct energy consumptions should be allocated per unit energy consumption of fuel, oil and tyres of vehicles that indirectly affect the production. These are the following machines: farming tractors, graders, dump truck and motor cars.

Table 4 shows chainsaw fuel and lubricant consumption for the productivity in 2012. Consumption was calculated based on unit consumption for 2011 that was already explained.

Machine/ Vehicle	Productivity	Fuel	Fuel energy (55.3 MJ/kg)	Fuel energy expenditure	Lubricant	Lubricant energy (83.7 MJ/kg)	Lubricant energy expenditure
	m³/year	kg	GJ	MJ/m³	kg	GJ	MJ/m³
Chainsaw	414,714	62,705	3,467.59	**8.36**	27,603	2,310.37	**5.57**

Source: Original data.

Table 4. Chainsaw fuel and lubricant consumption

Fuel consumption of the agricultural tractor that drives chippers was obtained by direct survey in the field, and the fuel consumption for hauling truck for the transportation of wood chips was gained from conversation with the owner of the truck (table 5).

Machine/Vehicle	Productivity	Fuel	Fuel energy (51.5 MJ/kg)	Fuel energy expenditure	Lubricant	Lubricant energy (83.7 MJ/kg)	Lubricant energy expenditure
	m³/year	kg	GJ	MJ/m³	kg	GJ	MJ/m³
Forwarders[1]	146,171	149,617	7,705.28	**52.71**	7,954	665.71	**4.55**
Tractor assembly	89,504	71,659	3,690.45	**41.23**	6,654	389.56	**4.35**
Silvicultural tractor	414,714	114,340.63	5,888.54	**14.2**	3,627.52	303.62	**0.73**
Truck unit[2]	51,034	161,327.25	8,308.35	**162.8**	1,861.18	155.78	**3.052**
Farm tractor + Chipper[3]	40,000	131,680	6,781.52	**169.54**	100	8.37	**0.21**
Grader	414,714	25,351.38	1,305.6	**3.15**	–	–	–
Dump truck	414,714	40,730	2,097.59	**5.06**	495	41.43	**0.1**
Hauling truck[4]	28,380	32,375	1,667.31	**58.74**	133	11.13	**0.39**
Cars and vans	414,714	217,846.4	11,219.09	**27.05**	1,080.43	90.43	**0.22**

Source: Original data.

[1] Only forwarders owned by FA Vinkovci.

[2] Only truck units owned by FA Vinkovci.

[3] Productivity was calculated according to: http://www.northernwoodheat.net/htm/Publications/FinnishInfoCard9.pdf where it is stated that chipper productivity of 25 m³/h, 200 working days and 8 working hour per day, on year basis amounts to 40,000 m³. Fuel consumption was gained by direct field measurements and was 3.29 kg/m³. Oil consumption was estimated on base of engine capacity and need for oil change every 500 working hours – 100 L/year.

[4] Fuel and lubricant consumption was determined based on conversations with hauling truck owner Mr. D. Benšak (UTPR Benšak), and productivity was calculated based on average year transporting distance (100,000 km) and average transporting distance (50 km).

Table 5. Machine/vehicle fuel and lubricant consumption

- *Expenditure of tyres*

Quantity of energy invested in production of tyres was calculated based on values described by [15] according to [25] and [26] and the value is 94.448 MJ/kg of tyre. Mass of some tyre was measured by mobile scales while for the others the mass was taken for technical data of manufacturers (table 6).

Machine/Vehicle	No.	Productivity	Weight of tyres	Energy invested in production of tyres (94.448 MJ/kg)	Tyres energy expenditure
		m^3/year	kg/year	GJ	MJ/m^3
Forwarders	8	146,171	1,458	137.7	**0.94**
Tractor assembles	22	89,504	2,160	204	**2.28**
Silvicultural tractor	21	414,714	780	73.67	**0.18**
Truck unit	7	51,034	4,875	460.43	**9.022**
Farm tractor + chipper	1	40,000	–	–	–
Grader	1	414,714	–	–	–
Dump truck	1	414,714	1,033	97.56	**0.24**
Hauling truck	1	28,380[1] (100 km)	975	92.09	**3.24**
Cars and vans	122	414,714	1,731.42	163.53	**0.39**

Source: Original data.

[1] Productivity was calculated based on average year transporting distance (100,000 km), average transporting distance (50 km) and average load volume (28.38 m^3 of roundwood – calculated based on trailer volume capacity – 90 m^3, truck payload – 23,500 kg and common oak density 828 kg/m^3 with 30% moisture content).

Table 6. Energy consumption during production of pneumatic tyres based on consumption for each type of vehicle

Annual consumption of tyres for 2012 was taken for database of Production Department of FA Vinkovci for forwarders, agricultural tractors and motor cars. Durability of tyres on hauling trucks for wood chips transport is in average 80,000 km, while truck exceeds an average of 100,000 km/year.

- *Expenditure of spare parts of chainsaws (chain, guidebar, sprocket)*

Consumptions of spare parts of chainsaws were taken from Production Department of FA Vinkovci for 2012. All components are made from steel and energy required for production of steel is 19,742 MJ/kg [15, 25, 26]. It was assumed the mass of guidebar of chainsaw is 1.1 kg, mass of chain is 0.3 kg and mass of sprocket is 0.1 kg in calculation of total invested energy (table 7).

	Productivity	Expenditure				Energy invested in production of steel (19.742 MJ/kg)	Energy expenditure
	m³/year	No./m³	No./year	kg/No.	kg/year	GJ	MJ/m³
Guidebar	414,714	0.00163	676	1.1	743.6	14.68	**0.035**
Chain		0.00934	3,873.4	0.3	1,162.02	22.94	**0.055**
Sprocket		0.00152	630.4	0.1	63.04	1.24	**0.003**
Total					1,968.66	38.86	**0.094**

Source: Original data.

Table 7. Energy consumption for production spare parts of chainsaws

When cutting one-metre firewood, chainsaw fuel consumption is 0.34 L/m^3, lubricant consumption 0.17 L/m^3, guidebar and sprocket 0.0025 unit/m^3 and chain 0.005 unit/m^3 [27]. Based on these values, unit energy consumption of chainsaws during cutting one-metre firewood was calculated (table 8).

Chainsaw	Productivity[1]	Fuel	Lubricant	Guidebar	Chain	Sprocket	Total
	MJ/m³						
Energy consumption	0.26	13.54	11.84	0.0543	0.0296	0.00493	**25.73**

Source: Original data.

[1] Energy consumption was taken form table 2.

Table 8. Unit energy consumption of chainsaws during cutting one-metre firewood

Table 9 shows unit energy consumption (MJ/m^3) for all machines and vehicles used directly and indirectly in the production of wood products in 2012 in the area of FA Vinkovci. The table also shows energy consumption of each component (production, fuel, lubricants, etc.) for each machine/vehicle specifically.

Figure 2 shows the percentage of unit energy consumption for individual components used in production process (directly or indirectly) in the area of FA Vinkovci in 2012. According to this figure, it is obvious that the largest share of energy input goes on fuel for machines and vehicles in the amount of 86%. Lubricants participate in the amount of 3%, tyres 2%, while the share of energy input for the production of chainsaws spare parts is less than 1%. Amount of energy input for the production of machines, vehicles and pesticides accounts to 9% of the total unit energy consumption.

Energy	**Chainsaw**	**Forwarder**	**Tractor assembly**	**Silvicultural tractor**	**Truck unit**	**Grader**	**Dump truck**	**Hauling truck**	**Farm tractor + chipper**	**Cars and vans**	**Pesticides**	**Total**
						MJ/m³						
Production	0.26	7.61	11.23	2.5	18.34	0.26	0.21	3.84	4.36	2.36	4.56	**55.53**
Fuel	8.36	52.71	41.23	14.2	162.8	3.15	5.06	58.74	169.54	27.05	–	**542.84**
Lubricant	5.57	4.55	4.35	0.73	3.05	–	0.1	0.39	0.21	0.22	–	**19.17**
Tyres	–	0.94	2.28	0.18	9.02	–	0.24	3.24	–	0.39	–	**16.29**
Guidebar	0.035	–	–	–	–	–	–	–	–	–	–	**0.035**
Chain	0.055	–	–	–	–	–	–	–	–	–	–	**0.055**
Sprocket	0.003	–	–	–	–	–	–	–	–	–	–	**0.003**
Total	**14.28**	**65.81**	**59.09**	**17.61**	**193.21**	**3.41**	**5.61**	**66.21**	**174.11**	**30.02**	**4.56**	633.92

Source: Original data.

Table 9. Energy consumption for each machine/vehicle separately and by each component of direct/indirect energy consumption

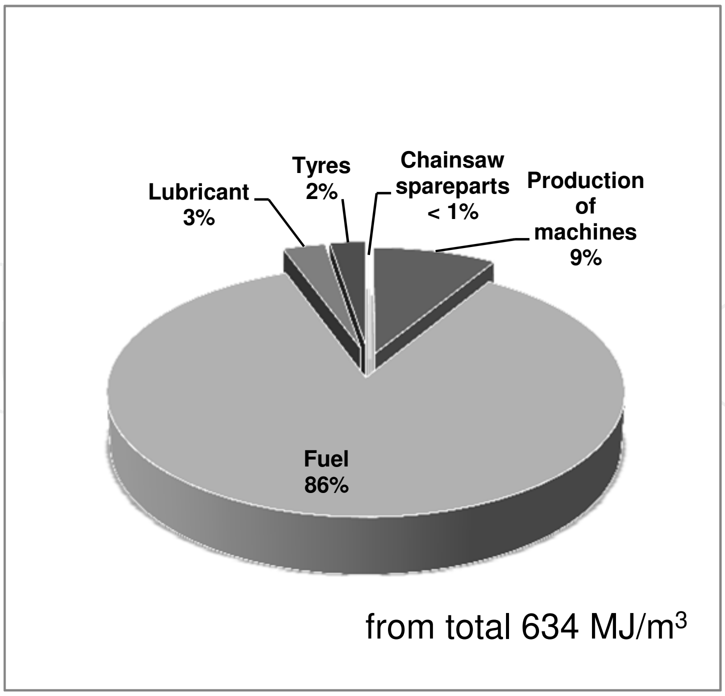

Figure 2. Proportion of unit energy consumption by components (Source: Original data)

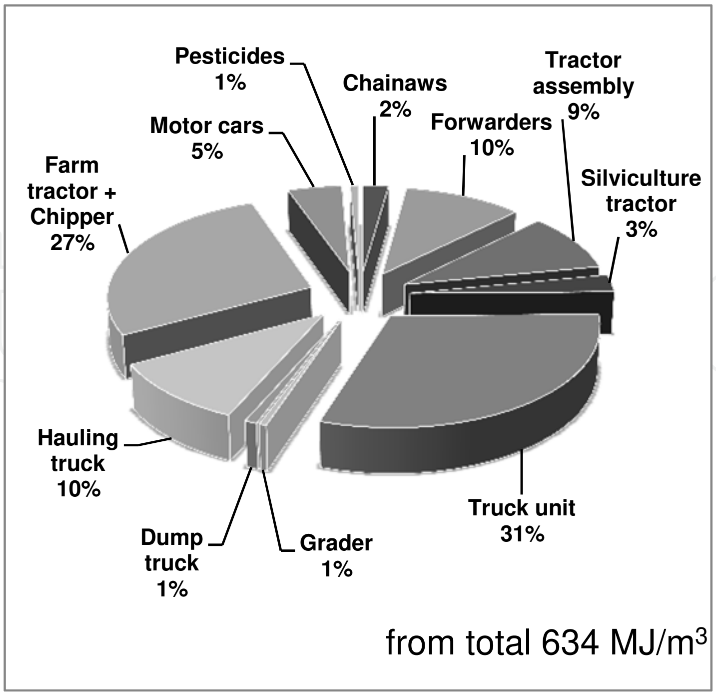

Figure 3. Proportion of unit energy consumption by each machine/vehicle included indirect energy consumption (Source: Original data)

According to figure 3, it can be concluded that the largest unit consumption (in relation to the total unit energy consumption) has truck units during assortment and long firewood transport in the amount of 31%. Chipper driven by farm tractor follows in the amount of 27%. According to table 9, it is visible that these two vehicles also have the highest fuel energy consumption. Fuel energy amounts to a great deal of energy consumption for other vehicles as well.

Average transport distance for wood chips (50 km) was chosen randomly and is in accordance with recommendations of [28], which states that it is the turning point of truck transport of energy wood costs.

Output parameters in this calculation are energy values of different wood products shown in table 10. The energy value of wood for different moisture contents is taken from the Manual of fuels from biomass [10].

Table 10 shows the amount of EROI. This amount was gained based on the relationship of obtained and consumed energy in the process of obtaining that energy. The minimal EROI is 24.97 for production of wood chips, while the maximal EROI is 64.3 for production of one-metre firewood. When calculating the energy consumption for the production of one-metre firewood, transportation to the end user should be included.

The calculated value of EROI in the process of producing wood chips (24.97) is close to values reported by [29] according to figure 1 and [4]. According to [30], mean EROI for wood is 25.

Throughout this process of calculating EROI, energy of workers, which is spent in the production process, is not included, nor is the energy of employees directly involved in the

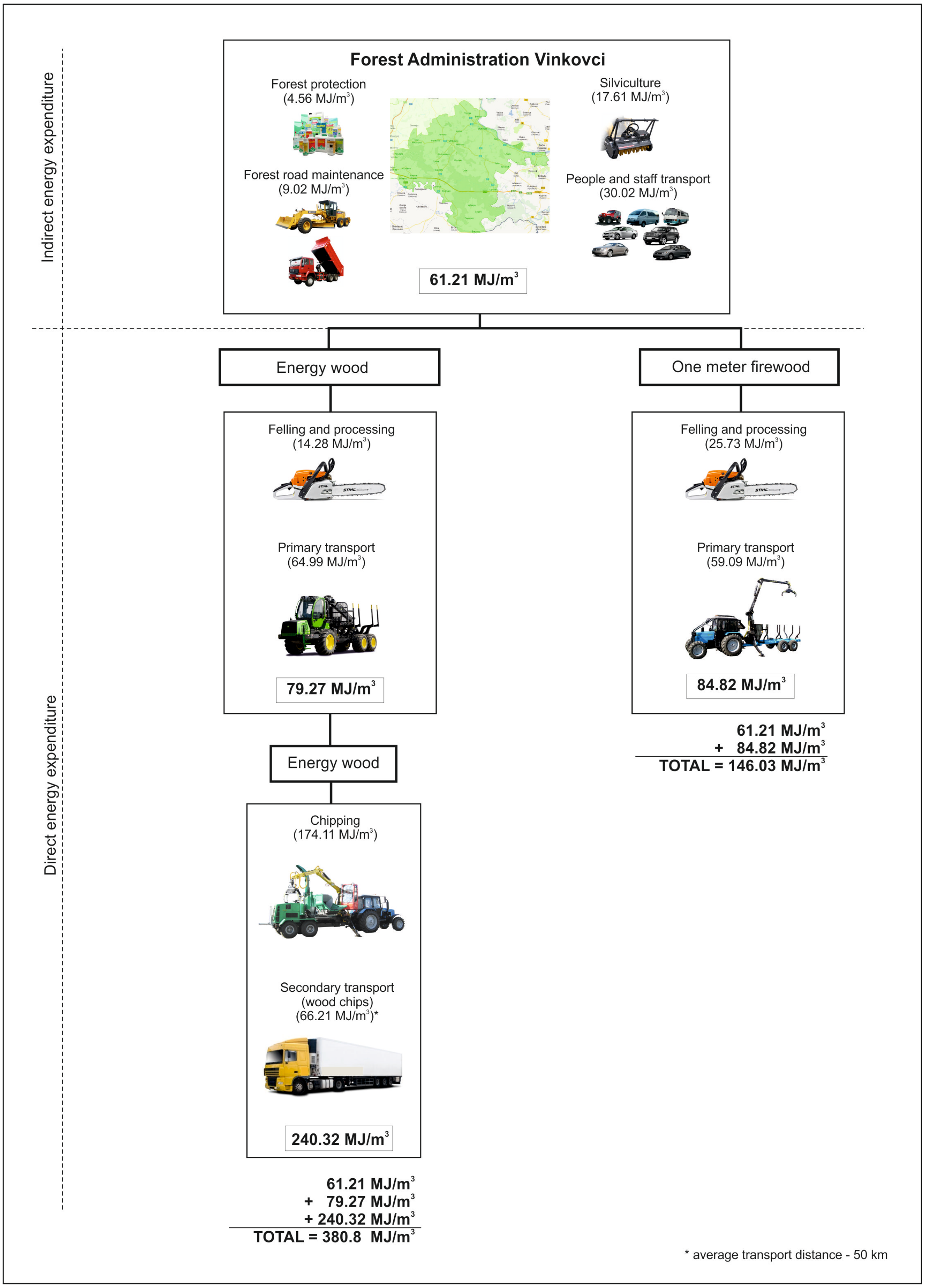

Figure 4. Components of unit energy consumption for both wood products (Source: Original data)

production process. The calculation does not include either the energy spent for maintenance and overhead of buildings of FA, or the energy that is consumed for their arrival and departure from work (does not include company cars). It is impossible to collect all the data on the energy consumed in the production of these wood products, and that energy would not significantly reduce the estimated amount of EROI.

Wood product	Energetic value			EROI
	Obtained		Invested	
	GJ/t[(2)]	GJ/m^3	MJ/m^3	
Wood chip (35% moisture. ρ_{oak} = 852 kg/m^3)(1)	11.17	**9.51**	**380.8**	**24.97**
One-metre firewood (42% moisture. ρ_{oak} = 967.3 kg/m^3)(3)	9.71	**9.39**	**146.03**	**64.3**

Source: Original data.

[1] Limit value of water in chips (35%) that is requested by market.

[2,3] Manual of fuels from biomass [10].

Table 10. EROI of wood chips and one-metre firewood

Energy consumption in the production of energy wood shows that energy balance of energy wood is not zero, because in its production process a certain amount of energy is consumed (380.8 MJ/m^3 – figure 4). Given the amount of energy that is obtained from energy wood (9510 MJ/m^3 oak with 35% moisture content), the amount of spent energy is acceptable (EROI = 24.6).

3. Conclusions

The highest energy consumption in the production and delivery of wood chips is based on the consumption of fuels and in the amount of 86%. In doing so, the biggest consumer of energy (fuel) is an agricultural tractor that drives chipper. The production of wood chips should strive to chippers with larger production capacity, and such chippers are generally self-propelled (e.g. Silvator 2000), whose hourly fuel consumption is slightly higher, but productivity is at least more than twice higher in comparison with other chippers, which leads to a significantly smaller unit fuel consumption.

The next solution is transport of energy wood to the stationary chipper which mainly uses electricity as power, and electricity is, from the energy and economic points of view, a better fuel than diesel. When using this method of production of wood chips, the problem occurs with reduced utilization of cargo space of transport means (trucks) because the density of energy wood is very low. But there is a technical solution in the form of bundler machine that compresses energy wood into a round bale. The use of mentioned machine will increase the mass yield of means of transport, but it also leads to increasing energy consumption in the whole process of production and delivery of wood chips.

Wood is a renewable energy source, but it is not completely neutral in terms of CO_2 emissions, because during its production and supply, a certain amount of energy, mostly from fossil fuels, is used. Energy value of wood chips is about 25 times higher (EROI of wood chips in this study was 24.6) of the energy used for its production, and it is considered as an environmentally acceptable energy source.

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