Willow Biomass Energy Generation Efficiency and Greenhouse Gas Reduction Potential

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Abstract

This study evaluates the efficiency of energy generation from willow chips and analyses the potential to reduce GHG emissions depending on the biomass transport distance to a conversion facility. The potential amount of electrical energy ranged from 59.2 GJ·ha^{-1} to 136.8 GJ·ha^{-1} when produced using combustion and co-combustion, respectively. The total energy in CHP generation ranged from 295.9 GJ·ha^{-1} to 321.8 GJ·ha^{-1} for gasification and co-combustion, respectively. It should be stressed that the largest amount of energy was produced using combustion in a heat-only boiler station.

Total GHG emissions from willow chips production and transport of 25 km was 73.0 kgCO$_2$ eq.·Mg^{-1} d.m. Increasing the transport distance to 50, 100, and 200 km resulted in the growth of GHG emissions by 6%, 17%, and 39%, respectively. The highest potential for reducing GHG emissions (62.5 MgCO$_2$ eq.·ha^{-1}) was achieved in a heat-only boiler station with the shortest transport distance. The index was 3-11% lower when energy was generated in CHP systems. The lowest potential for the reduction of GHG emissions was achieved in biomass conversion to electrical energy in the combustion process.

Keywords: biomass, willow, energy input, energy intensity, energy ratio, greenhouse gases

Introduction

Consumption of primary energy in Poland in 2013 amounted to 4,464.7 PJ. Hard coal was the most important energy carrier and its consumption accounted for 41% of the total. Crude oil accounted for 23%, natural gas for 14%, brown coal for 12%, and other carriers for 9%. The consumption structure of energy carriers has been slightly – but steadily – changing in recent years. The proportion of hard coal has been decreasing, whereas the proportion of crude oil and renewable energy sources has been increasing [1]. The generation of energy from renewable sources in Poland

increased from 5.4% to 11.7% between 2004 and 2012, which accounted for 6.7 % and 7.2% of final energy consumption. Solid biomass has been the main and dominant renewable energy source in Poland for many years; it accounted for 82.4% of all the renewable energy sources in 2012 [2].

Nevertheless, hard coal and brown coal are still the dominant energy sources in professional power generation; in 2012 they accounted for 55.1% and 34.8%, respectively. Natural gas accounted for 3.9% and biomass and biogas for 6.1%. However, it must be emphasized that, compared to 2007, consumption of biomass (in energy units) in Poland in 2012 increased by nearly 400%, and biomass replaced approx. 7 million tons of medium-quality coal [3].

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Coal fuels dominate in the structure of fuel consumption for heat generation in licensed heat-generation facilities. In 2013, coal fuels accounted for 76.6%, gas fuels for 7.9%, fuel oil for 4.0%, renewable energy sources for 6.9%, and the other fuels for 4.6%. However, it must be emphasised that the portion of heat generated by burning natural gas and biomass has been growing steadily by 4.0 and 4.1 percentage points, respectively. Generation of heat from biomass has increased more than two-fold since 2002 (from 11.5 PJ to 26.0 PJ) [4].

Currently, consumption of biomass in the co-combustion process dominates in Poland, which is frequently conducted in obsolete installations of low efficiency. Large power plants in Poland are interested in using biomass for co-combustion in the process of electrical energy generation mainly due to considerable financial support. It has been reported that 51 out of 55 Polish power plants are licensed to conduct co-combustion [5]. This has resulted in a high consumption of biomass (8.4 million tons in electrical energy generation in 2011 with 5.1 million tons used in co-combustion). It is a challenge to supply such large amounts of biomass. Wood biomass is acquired from forests, the wood industry, and as a by-product of municipal vegetation nurturing procedures.

It must be emphasised that, in the future, demand for biomass other than that from forests (i.e. mainly from agriculture and food industry) in Poland is likely to increase steadily. This is a consequence of national legislation, because the weight share of biomass from energy crops or agricultural waste and food industry (as well as grain that fails to meet the quality requirements, as well as part of other biodegradable waste except waste from forest and wood industry in the total biomass supplied to power sources with power output exceeding 5 MW) in which biomass is co-combusted with other fuels, should not be lower than 80% in 2015. This percentage is projected to increase in consecutive years, reaching 85% in 2018. However, the weight share of non-forest biomass in hybrid units and those that will burn only biomass (in systems with electric power output exceeding 20 MW) is to be 20% in 2015 and will increase to 50% in 2019 [6].

Perennial energy crops, including willow, should have high productivity and the biomass produced should have a high calorific value to produce considerable amounts of energy from 1 ha and a high energy-biomass production ratio. Only if this is achieved will further stages of biomass conversion to secondary energy carriers be justified as an environmentally friendly and sustainable solution. Willow biomass is used in the production of heat, electrical energy, and biofuels [7]. In Poland, willow is used to generate heat in both small household installations [8, 9] and in large facilities producing heat and electrical energy [10].

Willow (*Salix*) is a naturally-growing plant in Poland. It is generally characterized by high yield potential, easy reproduction, and it shoots after harvest cycles; therefore, it is preferred for growing as a short-rotation woody crop (SRWC). Fourteen willow cultivars are registered in the national crop register, including nine bred at the University of Warmia and Mazury in Olsztyn. Moreover, there is also a large base of 130 clones of different willow species, which provides ample opportunity for generating new, more productive cultivars. Admittedly, willow plantations currently occupy rather a symbolic area of approx. 7.5 thousand ha. It is estimated that in 2020 the area of such plantations in Poland could occupy 0.5 million ha without conflicting with food or fodder production [11]. However, today many barriers in Poland hinder the development of perennial energy crops, including policy restrictions that include lack of stable and predictable policy, and priorities regarding RES. Famers are not interested in setting up perennial plantations and biomass production, which is caused mainly by economic, market, agrotechnical, mental, and social factors.

Therefore, in the future considerable amounts of biomass should be supplied by plantations as SWRCs (willow, poplar, black locust) [12]. However, if there is still no support for biomass production in commercial SRWC plantations or no criteria of sustainability in its production, the import of considerable quantities of biomass may be necessary. This will be disadvantageous for the energy ratio and the environmental effectiveness of using biomass in energy generation. A wide range of feedstock is currently imported from more than 50 countries, which must travel thousands of kilometres and leave a visible "carbon footprint" along the way – a clear contradiction in the concept of green energy [5].

Therefore, new methods are being sought to reduce emissions to the atmosphere, mainly CO_2 produced in fuel combustion processes. The most significant source of carbon dioxide emissions in Poland and other countries is electrical energy generation [5, 13, 14]. One trend is carbon dioxide capture and storage which, however, has not yet been fully applied on an industrial scale. The emission of CO_2 can be reduced by applying more efficient systems of energy generation than those used to date [13]. On the other hand, using biomass for energy generation is regarded as CO_2-neutral, although this is a misconception as all processes emit CO_2 as fossil fuels and materials are used in the construction of bio-energy plants and in subsequent crop recovery. No system is truly CO_2 neutral, but it can have substantially lower emissions compared to fossil fuel energy generation [15, 16]. Reducing CO_2 emissions depends on many factors: the choice of fuel, the biomass conversion technology selected, and the biomass transport distance to the conversion facility. Therefore, the carbon neutrality of biomass used as an energy feedstock may not always be achieved [17-20]. For example, a change in land use, cutting down forests, and biomass transport over great distances may result in higher GHG emissions compared to fossil fuels. Drastic examples include oil palm plantations set up in place of rainforests. In biodiesel production, a change in land use has resulted in an increase in emission of CO_2 equivalent from 8 to 21 times compared to a fossil fuel [21].

Therefore, a field study was conducted in production and harvesting willow biomass in a commodity plantation in a three-year harvest cycle in northeastern Poland. The amount of energy spent on the production and transport

Table 1. Energy conversion and GHG emission factors used for calculations [24].

Item	Energy conversion factor	Unit	GHG emission factor	Unit
Diesel fuel	43.1	MJ·kg^{-1}	87.64	g CO$_2$ eq.·MJ^{-1}
Nitrogen fertilisers	48.99	MJ·kg^{-1} N	5,880.6	g CO$_2$ eq.·kg^{-1} N
Phosphorus fertilisers	15.23	MJ·kg^{-1} P$_2$O$_5$	1,010.7	g CO$_2$ eq.·kg^{-1} P$_2$O$_5$
Potassium fertilisers	9.68	MJ·kg^{-1} K$_2$O	576.1	g CO$_2$ eq.·kg^{-1} K$_2$O
Other fertilisers, e.g. PRP sol	15.23	MJ·kg^{-1} fertiliser	1,010.7	g CO$_2$ eq.·kg^{-1} fertiliser
Pesticides	268.4	MJ·kg^{-1} kg of active substance	10,971.3	g CO$_2$ eq.·kg^{-1} of active substance

of chips as well as the energy value of the yield as feedstock for energy generation was established. Subsequently, analyses of energy generation and GHG emission reduction potential were conducted. This study seeks to evaluate the efficiency of energy generation from willow chips and to assess the potential to reduce GHG emissions depending on the biomass transport distance to a conversion facility.

Materials and Methods

Field Experiment

The basis of analysis was a commercial willow plantation (53º59′ N, 21º05′ E) owned by the University of Warmia and Mazury in Olsztyn. No top dressing was applied in the first year of willow vegetation. However, before the beginning of the second year of vegetation, mineral fertilizers were applied at: N – 90 kg·ha^{-1}, P$_2$O$_5$ – 30 kg·ha^{-1}, and K$_2$O – 60 kg·ha^{-1}.

After the third year willow was harvested with a Claas Jaguar 830 harvester. Chips were collected from the harvester with three units, each one consisting of a tractor and a transport trailer. Subsequently, the trailers with chips produced at the plantation were weighed and the average yield of fresh biomass in tons per ha was determined. The moisture content in the willow biomass was 50.66%. Further analyses took into account the vehicle transport of chips to a biomass conversion facility, in four distance variants: 25, 50, 100, and 200 km. Empty trucks returning, covering the same distance, were also taken into account. The biomass transport was conducted with 80 m^3 containers, which totalled 25 Mg of fresh chips per run. The parameters of transport distance and container capacity stem from the practical aspects of biomass trade in northeastern Poland.

As an energy crop, willow is usually harvested in three-year rotations in commodity plantations. The life cycle of a plantation ranges from 20 to 30 years, depending on habitat conditions and agrotechnical factors. Therefore, it was assumed in the study that the life cycle of a plantation is 21 years so that seven consecutive harvest cycles in three-year rotations would be possible and could be done under production conditions.

Energy Intensity and Energy Ratio of the Processes

The energy intensity and energy ratio of chips production processes were analysed based on the average fresh yield obtained from seven willow cultivars in the first three-year harvest cycle. It must be emphasized that willow biomass yield may be diverse in successive harvest rotations. Heller et al. [22] report that subsequent harvest rotations of willow biomass will give a higher yield by up to 30-40% compared to the first harvest. Volk et al. [23] also report that the yield of four commercial clones increased by 23.0% from the first to second rotations, and by 30.8% from the first to fourth rotations. However, willow yield in consecutive harvest rotations is not always higher than in the first rotation. Production by the fourth rotation of 17 of the clones increased, while 13 decreased. Changes in the production of individual clones ranged from a decrease of 65% to an increase of 99% [23]. Furthermore, our multi-year studies have shown that the productivity of willows in consecutive rotations depends on multiple factors and, in agricultural practice, an increase in yield is indeed achieved in the second and third rotations of willow harvest. However, the yield may decrease in subsequent (4-7) harvest rotations due to an accumulation of diseases, pests, and plant loss, etc. Therefore, an increase is not always achieved in subsequent willow harvest rotations. In consequence, it was assumed in this study that mean biomass yield in subsequent harvest rotations would be similar to the first harvest rotation, which is achievable in agricultural practice.

The energy inputs used to produce the willow chips were analysed, including several energy sources: direct energy carriers (diesel fuel), exploitation of fixed assets (tractors, machines, equipment), consumption of materials (mineral fertilisers, agrochemicals, willow cuttings), and human labour. The total energy input for willow cultivation, production, and transport of chips to a biomass conversion facility was calculated based on the unit consumption of materials and the energy intensity of their production. The energy conversion and GHG emission coefficients used for calculations were based on the indexes presented by Neeft et al. [24] (Table 1). The energy input for the use of tractors (125 MJ·kg^{-1}), machines (110 MJ·kg^{-1}), and

human labour (60 MJ·hour⁻¹) in the production process has been calculated with the coefficients provided in the literature plus data provided in materials published by manufacturers of tractors and machines [25, 26]. The energy input for 1 kg of cuttings was 3.04 MJ [27].

The yield energy value at the farm gate was calculated as the product of fresh biomass yield (f.m.) per ha and its lower heating value (1):

$$Y_{ev} = Y_b \times Q_i^r \qquad (1)$$

...where: Y_{ev} is biomass yield energy value at the farm gate (GJ·ha⁻¹), Y_b is biomass yield (Mg·ha⁻¹ f.m.), Q_i^r is biomass lower heating value (GJ·Mg⁻¹).

Accumulated energy gain at the farm gate was the difference between the yield energy value and the total input for its production at the farm gate (2):

$$E_{g\,fg} = Y_{ev} - E_{i\,farm} \qquad (2)$$

...where: $E_{g\,fg}$ is accumulated energy gain at the farm gate (GJ·ha⁻¹), Y_{ev} is biomass yield energy value at the farm gate (GJ·ha⁻¹), $E_{i\,farm}$ is total energy input at the farm gate (GJ·ha⁻¹).

Energy intensity at the farm gate was energy consumption per 1 Mg of fresh or dry chips (f.m. or d.m.); it was the ratio of total energy input at the farm gate to the yield (3):

$$EI_{fg} = E_{i\,farm}/Y_b \qquad (3)$$

...where: EI_{fg} is energy intensity at the farm gate (GJ·Mg⁻¹ f.m. or d.m.), $E_{i\,farm}$ is energy input at the farm gate (GJ·ha⁻¹), Y_b is biomass yield (Mg·ha⁻¹ f.m. or d.m.).

Diesel fuel consumption at the farm gate per 1 Mg of fresh or dry willow chips was the ratio of diesel fuel consumption to willow yield (4):

$$C_D' = C_D/Y_b \qquad (4)$$

...where: C_D' is diesel fuel consumption at the farm gate (kg·Mg⁻¹ f.m. or d.m.), C_D is diesel fuel consumption (kg·ha⁻¹), Y_b is biomass yield (Mg·ha⁻¹ f.m. or d.m).

The energy ratio of willow chips production at the farm gate was the ratio of the yield energy value (energy output) to energy input for its production (5):

$$ER_{fg} = Y_{ev}/E_{i\,farm} \qquad (5)$$

...where: ER_{fg} is the energy ratio of willow chips production at the farm gate, Y_{ev} is the biomass yield energy value at the farm gate (GJ·ha⁻¹), $E_{i\,farm}$ is energy input at the farm gate (GJ·ha⁻¹).

The study also included determination of energy intensity (6) and energy ratio (7) for willow chips production at a conversion facility:

$$EI_{cf} = (E_{i\,farm} + E_{i\,trans})/Y_b \qquad (6)$$

$$ER_{cf} = Y_{ev}/(E_{i\,farm} + E_{i\,trans}) \qquad (7)$$

...where: EI_{cf} is energy intensity at a conversion facility (GJ·Mg⁻¹ f.m. or d.m.), $E_{i\,farm}$ is energy input at the farm gate (GJ·ha⁻¹), $E_{i\,trans}$ is energy input for chips transport to the conversion facility (GJ·ha⁻¹), Y_b is biomass yield (Mg·ha⁻¹ f.m. or d.m.), ER_{cf} is the energy ratio of willow chips production at a conversion facility, Y_{ev} is the biomass yield energy value at the farm gate (GJ·ha⁻¹).

To determine the energy ratio of energy production from willow biomass that can be sold directly to consumers as heat or electrical energy, it was assumed that biomass would be transformed into energy using co-combustion, combustion, and gasification. The efficiency of biomass conversion to combined electrical energy and heat was adopted as: for co-combustion 0.37 and 0.50, for combustion 0.16 and 0.69, and for gasification 0.27 and 0.53, respectively [18]. The efficiency of producing heat in a heat-only boiler station was 0.90. These assumptions were used to determine the amount of electrical energy and heat produced by willow biomass conversion. The amount of electrical energy that can be generated from biomass was calculated as the product of the efficiency of conversion to electrical energy and the yield energy value at the farm gate (8):

$$E_e = CE_e \times Y_{ev} \qquad (8)$$

...where: E_e is electrical energy that can be generated from biomass (GJ·ha⁻¹), CE_e is efficiency of conversion to electrical energy, Y_{ev} is biomass yield energy value at the farm gate (GJ·ha⁻¹).

The amount of heat that can be generated from biomass has been calculated as the product of conversion-to-heat efficiency and the yield energy value at the farm gate (9):

$$E_h = CE_h \times Y_{ev} \qquad (9)$$

...where: E_h is heat energy that can be generated from biomass (GJ·ha⁻¹), CE_h is efficiency of conversion to heat energy, Y_{ev} is biomass yield energy value at the farm gate (GJ·ha⁻¹).

The combined electrical and heat energy was calculated as (10):

$$E_{CHP} = E_e + E_h \qquad (10)$$

...where: E_{CHP} is combined electrical and heat energy that can be generated from biomass (GJ·ha⁻¹), E_e is electrical energy that can be generated from biomass (GJ·ha⁻¹), E_h is heat energy that can be generated from biomass (GJ·ha⁻¹).

The next stage of analysis involved determining energy input for transporting the biomass to the conversion facility (11):

$$E_{i\,trans} = Y_b \times T \times d \qquad (11)$$

...where: $E_{i\,trans}$ is energy input for chips transport to the conversion facility (GJ·ha⁻¹), Y_b is biomass yield (Mg·ha⁻¹ d.m.), T is energy input for biomass transport (0.00094

GJ·Mg^{-1}·km^{-1}) [24], d is transport distance (km; empty trucks returning, covering the same distance, were also taken into account).

The energy used for the needs of conversion plants (parasitic energy losses) for co-combustion, combustion, and gasification were 7%, 5%, and 5% of the yield energy value at farm gate, respectively [18]. The energy used for producing heat in a heat-only boiler station was 2.5%. It was calculated as (12):

$$E_{i\,conv} = Y_{ev} \times PEL/100 \qquad (12)$$

...where: $E_{i\,conv}$ is energy input for the conversion process (GJ·ha^{-1}), Y_{ev} is biomass yield energy value at the farm gate (GJ·ha^{-1}), PEL is parasitic energy losses (%).

The total energy input in a simulated model of bioenergy production in a conversion facility was calculated as the total energy input for chips production at the farm gate, transport, and biomass conversion process (13).

$$E_{i\,total} = E_{i\,farm} + E_{i\,trans} + E_{i\,conv} \qquad (13)$$

...where: $E_{i\,total}$ is total energy input for bioenergy production in a conversion facility (GJ·ha^{-1}), $E_{i\,farm}$ is energy input for chips production at the farm gate (GJ·ha^{-1}), $E_{i\,trans}$ is energy input for chips transport to the conversion facility (GJ·ha^{-1}), $E_{i\,conv}$ is energy input for the conversion process (GJ·ha^{-1}).

The energy ratio of biomass conversion to energy using a specific conversion process was calculated as the ratio of the energy produced in the process and total energy input (14).

$$ER_{BC} = E_n/E_{i\,total} \qquad (14)$$

...where: ER_{BC} is energy ratio of biomass conversion to energy using a specific conversion process, E_n is electrical (E_e) or heat (E_h) or combined electrical and heat (E_{CHP}) energy, which can be generated from biomass (GJ·ha^{-1}), $E_{i\,total}$ is total energy input for bioenergy production in a conversion facility (GJ·ha^{-1}).

Analysis of GHG Emissions and Potential for Its Reduction

Combustion of biomass from an SRWC plantation is regarded as a carbon-dioxide-neutral process because the CO_2 released in the process of combustion is subsequently assimilated by plants during the next rotation [17]. Nevertheless, the processes of setting up a plantation, plant cultivation, harvesting the biomass, and its transport and conversion is accompanied by a release to the atmosphere of CO_2 produced by the combustion of fossil fuels. On the other hand, only part of the biomass of SRWC is harvested, because some of it (such as rootstock, roots, and fallen leaves) is left behind. The carbon compounds in the biomass slowly decompose and become part of the soil organic matter. Therefore, it has been reported that carbon influx

to the soil can be comparable to the amount of carbon released to the atmosphere during its cultivation and transport, i.e. willow biomass can be regarded as neutral for GHG emissions for the entire production cycle [18, 28-30]. According to other studies, this assumption is not necessarily true in all cases because of GHG emissions associated with the production of willow, logistical operations, and biomass transport [31, 32]. On the other hand, the amount of carbon sequestrated in soil in the process of willow cultivation is estimated by various authors to range from 0.33 to 3.04 MgCO$_2$ eq.·ha·year^{-1} [33-37]. The above-mentioned studies show that the total emission of greenhouse gas emitted in the process of willow cultivation, including logistics and transport, could be higher than carbon sequestration in soil.

However, using willow biomass for the production of bioenergy as a substitute for energy produced from fossil fuels has a positive GHG balance and it reduces the greenhouse effect [18, 38, 39]. Therefore, an attempt has been made to estimate the reduction of GHG emissions by replacing coal with biomass produced on 1 ha of willow cultivation in generating combined heat and electricity. It was assumed in the analysis that the total GHG emissions in the process of mining and burning the hard coal, converted to 1 GJ of energy contained in the fuel, amounts to 0.11128 MgCO$_2$ eq.·GJ^{-1} [24], and the average efficiency levels of hard coal conversion to electricity, electricity and heat (CHP), and heat alone in OECD countries are 41%, 60%, and 90%, respectively [40]. Therefore, the GHG emission factors converted to electricity and/or heat will be: 0.27141, 0.18547, and 0.12364 MgCO$_2$ eq.·GJ^{-1}, respectively. These data are comparable with those provided for other facilities [41, 42].

The total greenhouse gas emissions associated with willow chips production, logistics, and transport were calculated using the following formulas (15-17):

$$EM_w = C_D'' \times EF_D + C_N \times EF_N + C_P \times EF_P + C_K \times EF_K + C_{OF} \times EF_{OF} + C_{PS} \times EF_{PS} \qquad (15)$$

$$EM_w' = EM_w/Y_b \qquad (16)$$

$$EM_w'' = EM_w/Y_{ev} \qquad (17)$$

...where: EM_w, EM_w', and EM_w'' are the total GHG emissions associated with willow chips production, logistics, and transport calculated per 1 ha of plantation (kgCO$_2$ eq.·ha^{-1}), 1 Mg d.m. of biomass yield (kgCO$_2$ eq.·Mg^{-1} d.m.), and 1 GJ of biomass yield energy value (kgCO$_2$ eq.·GJ^{-1}), respectively; C_D'', C_N, C_P, C_K, C_{OF}, and C_{PS} are actual consumption of fuel (MJ·ha^{-1}), N-, P-, K-, and other fertilisers and pesticides (kg·ha^{-1}) in this experiment, respectively; EF_D, EF_N, EF_P, EF_K, EF_{OF}, and EF_{PS} are GHG emission factors for the consumption of fuel (kgCO$_2$ eq.·GJ^{-1}), plus fertilisers and pesticides (kgCO$_2$ eq.·kg^{-1}) as reported by Neeft et al. [24] (Table 1); Y_b is biomass yield (Mg·ha^{-1} d.m.); Y_{ev} is biomass yield energy value at the farm gate (GJ·ha^{-1}).

Table 2. Energy input for setting up and running a willow plantation during the first year of vegetation and its re-establishment [27].

Operation	Labour	Machinery	Tractors	Diesel	Materials	Total
	MJ·ha⁻¹					
Spraying (Roundup)	18.0	46.4	11.4	87.8	386.50	550.07
Disking (2x)	96.0	111.7	79.7	774.1	-	1,061.4
Winter ploughing	102.0	154.0	111.7	1,262.9	-	1,630.6
Fertilisation with PRP Sol	30.0	9.1	22.8	175.5	4,569.0	4,806.4
Harrowing (2x)	72.0	34.3	56.9	482.7	-	645.9
Mechanical planting of cuttings	312.0	235.5	74.0	741.6	1,026.0	2,389.1
Spraying (soil-applied herbicide)	18.0	46.4	11.4	87.8	617.3	780.9
Weeding (2x)	132.0	74.8	91.9	605.9	-	904.6
Spraying with a herbicide against monocotyledon weeds	18.0	46.4	11.4	87.8	33.55	197.12
Re-establishment of the plantation	372.0	1,531.2	446.9	5,051.6	-	7,401.7
Total	1,170.0	2,289.8	918.0	9,357.6	6,632.37	20,367.8
Per year of plantation use 1/21 Σ	55.71	109.04	43.72	445.60	315.83	969.9

Mean carbon sequestration in soil for willow cultivation in Poland was assumed to be 0.79 $MgCO_2$ eq.·ha⁻¹·year⁻¹ (i.e. 2.37 $MgCO_2$ eq.·ha⁻¹ in a three-year cycle) [37].

The potential for GHG reduction by replacing coal with willow biomass produced at a plantation in the process of energy generation was calculated as the product of the energy produced from biomass in a conversion process, and the amount of GHG emitted in the process of energy production from hard coal. The amount of carbon sequestered in soil was then added to it and the amount of GHG emitted in the process of willow biomass production, logistics, and transport was deducted from it (18):

$$R_{GHG} = E_n \times EF_C + S - EM_w \qquad (18)$$

...where: R_{GHG} is the potential for GHG reduction by replacing coal with willow biomass ($MgCO_2$ eq.·ha⁻¹), E_n is electrical (E_e) or heat (E_h) or combined electrical and heat (E_{CHP}) energy generated from biomass (GJ·ha⁻¹), EF_C is the GHG emission factor for the process of energy production from hard coal ($MgCO_2$ eq.·GJ⁻¹), S is the amount of carbon sequestered in soil ($MgCO_2$·ha⁻¹), EM_w is the amount of GHG emitted in the process of willow biomass production, logistics, and transport ($MgCO_2$ eq.·ha⁻¹).

Results and Discussion

Energy Intensity and Energy Ratios in Willow Chips Production at the Farm Gate

The energy inputs for setting up and running 1 ha of a willow coppice plantation during the first year of vegetation and its re-establishment after exploitation totalled 20,367.8 MJ·ha⁻¹ (Table 2). Converted to one year of plantation cultivation (assuming that the plantation will be used for 21 years), it amounts to 969.9 MJ·ha⁻¹. Detailed information concerning willow farm establishment and incurred energy outlays are described by Stolarski et al. [27].

The energy input for producing willow chips in a three-year harvest cycle, including setting up and re-establishing a plantation, NPK fertilization, and the application of a herbicide against monocotyledons, harvesting the plants, and transporting the chips, amounted to 20,088.3 MJ·ha⁻¹ (Table 3).

The largest amounts of energy were consumed by harvesting the plants (34.1%), followed by mineral fertilisation (30.9%). The leading energy inputs involved the consumption of diesel (48.5%), followed by materials (32.0%) and fertilisers (approx. 30%). In a previous study conducted by these authors, the leading energy input in willow chips production was for mineral fertilisation and fuels [43]. Moreover, Heller et al. [22] reported that the structure of energy carriers in willow biomass production was dominated by fuels (46%), followed by fertilisation (37%). Therefore, replacement of mineral fertilisation by sludge from local wastewater treatment stations and introducing liquid renewable fuels, such as biodiesel, to the willow biomass production process could reduce the energy input, resulting in an increase in the energy ratio of energy production by up to 40% [22, 42]. Nitrogen fertilisation was also a significant element of energy consumption in willow and miscanthus biomass production (17-45%), while this value was even higher (41-64%) in the production of biomass from annuals. In willow production, the highest energy input was required at the stage of biomass harvest and transportation [44].

Table 3. Energy input for producing willow chips in a three-year harvest cycle at the farm gate.

Operation	Labour	Machinery	Tractors	Diesel	Materials	Total	Structure
	MJ·ha⁻¹						%
Setting up and re-establishment of plantation	167.1	327.1	131.1	1,336.8	947.5	2,909.7	14.5
NPK fertilisation	90.0	29.4	74.0	570.5	5,446.8	6,210.7	30.9
Spraying with a herbicide against monocotyledon weeds	18.0	46.4	11.4	87.8	33.6	197.1	1.0
Harvest	132.5	1,868.1	-	4,852.4	-	6,853.0	34.1
Field transport	397.5	235.7	377.18	2,907.48	-	3,917.9	19.5
Total	805.2	2,506.7	593.7	9,754.9	6,427.8	20,088.3	100.0
Structure (%)	4.0	12.5	3.0	48.5	32.0	100.0	

Table 4. Select efficiency indexes for willow chips production in a three-year harvest cycle at the farm gate.

Item	Unit	Value
Energy inputs		20.1
Energy value of yield	GJ·ha⁻¹	369.9
Energy gain		349.8
Diesel consumption	kg·Mg⁻¹ f.m.	5.1
Diesel consumption	kg·Mg⁻¹ d.m.	10.4
Energy intensity	MJ·Mg⁻¹ f.m.	455
Energy intensity	MJ·Mg⁻¹ d.m.	923
Energy ratio	-	18.4

Since the yield of fresh willow chips averaged 44.17 Mg·ha⁻¹ (while their lower heating value averaged 8.374 GJ·Mg⁻¹) the yield energy value at the farm gate was 369.9 GJ·ha⁻¹ (Table 4). Considering the energy input for producing the yield, the energy gain in a three-year cycle amounted to 349.8 GJ·ha⁻¹. This result was lower compared to the mean net energy from willow plantations in Sweden (170 GJ·ha⁻¹·year⁻¹) [45]. It is also estimated that this can be increased in Sweden to over 200 GJ·ha⁻¹·year⁻¹ by using wastewater for the irrigation of a plantation of willow [46]. In a study conducted in Canada, the energy value of the yield obtained in a two-year harvest cycle in *Salix viminalis* with a sludge dose of 300 kgN·ha⁻¹ was higher than the non-fertilisation plantation (by 580 GJ·ha⁻¹ and 146 GJ·ha⁻¹, respectively) [47]. In a different study conducted in Poland on an experimental plantation of willow with a three-year harvest rotation depending on agrotechnical factors, the energy value yield at the farm gate ranged from 564 to 1,047 GJ·ha⁻¹ [43, 48]. High primary net energy yields from willow (243-263 GJ·ha⁻¹·year⁻¹) and miscanthus (224-277 GJ·ha⁻¹·year⁻¹) were obtained in Germany [44]. Tuomisto et al. [49] also confirm that miscanthus had the highest net energy production.

It was found that the consumption of diesel fuel for the production of 1 Mg of fresh chips at the farm gate was 5.1 kg. Low fuel consumption (3.0 l·Mg⁻¹ of willow chips) was achieved by Goglio and Owende [50]. It was higher in studies conducted by Heller et al. [22] and by González-García et al. [51] (3.6 and 4.1 l·Mg⁻¹, respectively). On the other hand, the consumption of fuel in the production of poplar trees ranged from 6.4 to 7.5 l·Mg⁻¹ [7].

The energy intensity was 455 MJ·Mg⁻¹ f.m. and the energy ratio in willow chips production at the farm gate was 18.4 (Table 4). The energy ratio of willow production found in other studies, depending on agrotechnical and logistical factors, varied widely — from about 12 to more than 50 [22, 29, 43]. In other studies, willow production without nitrogen application had the highest energy use efficiency (99 GJ energy output per GJ fossil energy input). Among all the energy crops tested in a study reported by Boehmel et al. [44] for this specific site, perennial lignocellulosic crops (willow and miscanthus) provide the best combination of high biomass and energy yields with high land and energy use efficiency, nitrogen fertiliser use, and environmentally-friendly production methods.

Energy Intensity and Energy Ratio in Producing Energy in a Conversion Facility

The efficiency indexes for the production of willow chips at a conversion facility depended heavily on the distance between the plantation and the conversion facility (Table 5). The total energy input at a conversion facility ranged from 21.1 to 28.3 GJ·ha⁻¹ when the transport distance was 25 and 200 km, respectively. An increase in the transport distance resulted in an increase in the energy intensity of chips from 478 to 640 MJ·Mg⁻¹ f.m.

Furthermore, the energy ratio decreased with an increasing transport distance. When chips were transported to the shortest of the distances, the energy ratio decreased by 4.8% compared to its value at the farm gate. The transport of the chips for 50, 100, and 200 km reduced the index by 9.2%, 17%, and 29%, respectively. A decrease in the

Table 5. Select efficiency indexes for willow chips production in a three-year harvest cycle at a conversion facility.

Item	Transport distance (km)	Value
Energy input (GJ·ha⁻¹)	25	21.1
	50	22.1
	100	24.2
	200	28.3
Energy intensity (MJ·Mg⁻¹ f.m.)	25	478
	50	501
	100	547
	200	640
Energy intensity (MJ·Mg⁻¹ d.m.)	25	970
	50	1,017
	100	1,111
	200	1,299
Energy ratio	25	17.5
	50	16.7
	100	15.3
	200	13.1

energy ratio with increasing transport distance was also found in other studies [50, 52]. Those authors showed that when chips were transported up to 38 km, the energy ratio decreased by less than 8.3%, and when the distance exceeded 38 km the decrease rate was 25.9%.

Table 6 shows the yield energy value at farm gate and energy generated from biomass, which potentially can be obtained in various processes of conversion. The potential amount of electrical energy ranged from 59.2 GJ·ha⁻¹ to

Table 6. Yield energy value at farm gate and energy generated from biomass.

Conversion process	Type of energy	Yield energy value (GJ·ha⁻¹)	Energy generated from biomass (GJ·ha⁻¹)
Co-combustion (CHP)	Electrical		136.8
	Heat		184.9
	Total		321.8
Combustion (CHP)	Electrical		59.2
	Heat		255.2
	Total	369.9	314.4
Gasification (CHP)	Electrical		99.9
	Heat		196.0
	Total		295.9
Combustion (Heat)	Heat only		332.9

136.8 GJ·ha⁻¹ when produced in the process of combustion and co-combustion, respectively. On the other hand, the total energy in CHP generation ranged from 295.9 GJ·ha⁻¹ to 321.8 GJ·ha⁻¹ for the processes of gasification and co-combustion, respectively. It should be stressed that the largest amount of energy was produced in the process of combustion in a heat-only boiler station (332.9 GJ·ha⁻¹).

The total energy input in a conversion facility ranged from 30.4 GJ·ha⁻¹ with the shortest transport distance and combustion in a heat-only boiler station, to 54.2 GJ·ha⁻¹ with the longest distance in the process of co-combustion in a CHP station (Table 7). It increased 1.5-2.3-fold in processes of combustion and gasification to nearly three-fold in co-combustion compared to its level at the farm gate. The highest energy ratio of biomass conversion to energy (9-11) was achieved in the heat generation process in a heat-only boiler station. Furthermore, the energy ratio in CHP generation was lower (by 24-38%) depending on the process and transport distance, compared to heat generation in a heat-only boiler station. Moreover, it was lower by 28-46% compared to the highest value of the index in a heat-only boiler station. It ranged from 6.3 in the process of gasification with the longest transport distance to 7.9 in combustion with the shortest transport distance. The energy ratio of biomass conversion to heat in CHP stations was also lower, ranging from 3.4 to 6.4. The lowest energy ratio was achieved in the conversion of biomass to electrical energy only (1.3-2.9). It was several times lower than the highest index value in a heat-only boiler station. The energy ratio achieved for a heat-only boiler station was 1.7-2.1 times lower than at the farm gate. On the other hand, the ratio was 7-, 8-, and 17-fold lower for co-combustion, gasification, and combustion, respectively, compared to at the farm gate.

These ratios confirm that the best way of using biomass and its optimum use in terms of conversion efficiency was for generating heat in local heat-only boiler stations. This was followed by using biomass to generate heat and electrical energy in CHP systems. The generation of electrical energy only has proven to be the least efficient.

The energy ratio of willow biomass conversion to electricity and heat, depending on the analysed factors found in other studies conducted by these authors, ranged from 4.6 to 7.6 [43]. Furthermore, Keoleian and Volk [42] reported that the energy ratio of producing electrical energy from willow biomass by its direct combustion or gasification was higher and ranged from 10 to 13. According to other findings, 11 units of electrical energy can be produced from willow biomass, with one unit of energy from fossil fuels consumed [22]. Meanwhile, Vande Walle et al. [18] conducted extensive cultivation of willow at low yield energy value (67.3 GJ·ha⁻¹·year⁻¹) and achieved a high energy ratio of energy production in a CHP system (7.0-8.1), depending on the process of conversion. These values should be regarded as high compared to the energy ratio of producing first-generation liquid fuels. For producing ethanol from grain, the index ranges 0.77-1.3 [53, 54]. The ratio is better for producing second-generation fuels (ethanol) from lignocellulosic material, where the energy ratio ranges from 2.0 to 36.0, depending on the biofuel production technology [54].

Table 7. Total energy input for the production of willow chips in a three-year harvest cycle, transport, and process conversion and energy ratio of biomass conversion to energy.

Conversion process	Transport distance (km)	Total energy inputs (GJ·ha⁻¹)	Energy ratio of biomass conversion to:		
			electrical energy	heat energy	CHP
Co-combustion (CHP)	25	47.0	2.9	3.9	6.8
	50	48.0	2.8	3.9	6.7
	100	50.1	2.7	3.7	6.4
	200	54.2	2.5	3.4	5.9
Combustion (CHP)	25	39.6	1.5	6.4	7.9
	50	40.6	1.5	6.3	7.7
	100	42.7	1.4	6.0	7.4
	200	46.8	1.3	5.5	6.7
Gasification (CHP)	25	39.6	2.5	4.9	7.5
	50	40.6	2.5	4.8	7.3
	100	42.7	2.3	4.6	6.9
	200	46.8	2.1	4.2	6.3
Combustion (Heat)	25	30.4	-	11.0	-
	50	31.4	-	10.6	-
	100	33.4	-	10.0	-
	200	37.5	-	8.9	-

Potential for Reducing GHG Emissions by Replacing Coal with Biomass

GHG emissions associated with growing willow, harvest, and field transport of chips (plus their loading) amounted to 1,499.8 $kgCO_2$ eq.·ha⁻¹ (68.9 $kgCO_2$ eq.·Mg⁻¹ d.m. and 4.05 $kgCO_2$ eq.·GJ⁻¹) (Table 8). Transport of chips to a conversion plant 25 km away caused GHG emissions of 89.6 $kgCO_2$ eq.·ha⁻¹. Increasing the transport distance to 50, 100, and 200 km resulted in further increases in GHG emissions. Therefore, the total GHG emissions associated with willow chips transport for 25 km amounted to 1,589.4 $kgCO_2$ eq.·ha⁻¹, which was equivalent to 73.0 $kgCO_2$ eq.·Mg⁻¹ d.m. and 4.30 $kgCO_2$ eq.·GJ⁻¹. Increasing the transport distance to 50, 100, and 200 km resulted in the growth of GHG emissions by 6%, 17%, and 39%, respectively.

Similar levels of GHG emissions (84.0 $kgCO_2$ eq.·Mg⁻¹ d.m. and 4.48 $kgCO_2$ eq.·GJ⁻¹) were recorded in the process of biomass production from mixed prairie grasses and an average one-way transport distance of 141 km [55]. On the other hand, GHG emissions for corn stover in the study referred to above were nearly twice higher than for mixed prairie grasses, despite a much shorter transport distance (44 km) for corn stover. The results in this experiment also indicate that GHG emissions associated with production and transport of willow chips, when converted to 1 GJ biomass, were 2.7-3.8 times lower than the GHG emissions

associated with hard coal provision. Giuntoli et al. [56] report that the average European (EU coal mix) emission factor for the supply of hard coal is 16.2 $kgCO_2$ eq.·GJ⁻¹.

Fertilisation and pesticides were responsible for the largest portion (35.1-41.1%) of the GHG emissions when willow chips are transported for 25 km, 50 km, and 100 km. However, when chips were transported for 200 km, transport was responsible for the largest portion (32.3%) of GHG emissions, followed by fertilisation and pesticides, responsible for 29.5% of the emissions (Fig. 1). The contribution of transport to GHG emissions decreased considerably to 19.3%, 10.7%, and 5.6% with the transport distance decreasing to 100 km, 50 km, and 25 km, respectively. The crop harvest was responsible for a considerable portion of the GHG emissions. It was responsible for the second largest portion – 26.8% – in transporting willow chips for 25 km, and the third largest (19.2%) when chips were transported for 200 km.

The outcome of analysis of the potential for reduction of GHG emissions by replacing hard coal with willow biomass in energy production depended on the biomass yield energy value. A simulation showed that the highest potential for reduction of GHG emissions (62.5 $MgCO_2$ eq.·ha⁻¹) was achieved in the production of heat in a heat-only boiler station with the shortest transport distance (Table 9). The index was 3-11% lower when heat and electrical energy were generated in CHP systems. Furthermore, the potential for reducing GHG emissions in biomass conversion to

Table 8. GHG emissions associated with willow chips production in a three-year cycle and delivery to a conversion facility.

Item	GHG emissions		
	(kgCO$_2$ eq.·ha^{-1})	(kgCO$_2$ eq.·M^{g-1} d.m.)	(kgCO$_2$ eq.·GJ^{-1})
Establishment and re-establishment of the plantation	166.5	7.7	0.45
Spraying (Roundup)	3.4	0.2	0.01
Disking (2x)	9.7	0.4	0.03
Winter ploughing	15.8	0.7	0.04
Fertilisation with PRP Sol	45.5	2.1	0.12
Harrowing (2x)	6.0	0.3	0.02
Mechanical planting of cuttings	9.3	0.4	0.03
Spraying (soil-applied herbicide)	4.7	0.2	0.01
Weeding (2x)	7.6	0.3	0.02
Spraying (herbicide against monocotyledon weeds)	1.3	0.1	0.00
Re-establishment of the plantation	63.2	2.9	0.17
Fertilisers, pesticides	653.2	30.0	1.77
NPK fertilisation	644.1	29.6	1.74
Spraying (herbicide against monocotyledon weeds)	9.1	0.4	0.02
Harvest	425.3	19.5	1.15
Field transport and loading	254.8	11.7	0.69
Total on the field	1,499.8	68.9	4.05
Transportation 25 km	89.6	4.1	0.24
Transportation 50 km	179.3	8.2	0.48
Transportation 100 km	358.6	16.5	0.97
Transportation 200 km	717.1	33.0	1.94
Total 25 km	1,589.4	73.0	4.30
Total 50 km	1,679.1	77.2	4.54
Total 100 km	1,858.4	85.4	5.02
Total 200 km	2,216.9	101.9	5.99

heat in CHP plants was lower by 48-63% compared to its highest value. On the other hand, the lowest potential for the reduction of GHG emissions was achieved in biomass conversion to electrical energy in the combustion process. An increase in transport distance resulted in a decrease in the potential for reduction of GHG in each of the analysed technologies of biomass conversion.

Apart from its value per 1 ha of a plantation, the potential to reduce GHG emission depends on the plantation area. In order to illustrate the capacity for the reduction of GHG emissions, it was assumed that the area of willow plantations for energy production in a region have an area of 10,000 ha. Assuming a transport distance of 25 km from a conversion point, it can be calculated that it is an area of 196,250 ha. The area of the agricultural land in Poland amounts to 18.7 million ha, which accounts for approx.

60% of the country area [57]. Therefore, the area of agricultural land in a circle with a radius of 25 km is 117,750 ha. In consequence, willow plantations with an area of 10,000 ha would account for about 8.5% of the area. With longer transport distances of 50 km, 100 km, and 200 km, such plantations would account for 2.1%, 0.5%, and 0.1% of agricultural land within a specific area, respectively. Obviously, the actual proportion of willow plantations in the structure of agricultural land of an area will depend on the specificity of a region, that is, geographic, climatic, and soil conditions, location of biomass conversion plants, and economy of biomass production to farmers.

The potential reduction of GHG in the production of heat in a heat-only boiler station and with biomass transport for 25 km in such a variant would be up to 208,000 tons per year. In CHP, depending on the conversion technology and

Table 9. Potential for reduction of GHG emissions ($MgCO_2$ eq.·ha^{-1}) through replacement of hard coal with willow biomass for energy production (in a three-year harvest cycle).

Conversion process	Transport distance (km)	Biomass conversion to electricity	Biomass conversion to heat	Biomass conversion to electricity and heat
Co-combustion (CHP)	25	37.9	23.6	60.5
	50	37.8	23.6	60.4
	100	37.7	23.4	60.2
	200	37.3	23.0	59.8
Combustion (CHP)	25	16.8	32.3	59.1
	50	16.8	32.2	59.0
	100	16.6	32.1	58.8
	200	16.2	31.7	58.5
Gasification (CHP)	25	27.9	25.0	55.7
	50	27.8	24.9	55.6
	100	27.6	24.7	55.4
	200	27.3	24.4	55.0
Combustion (Heat)	25	-	62.5	-
	50	-	62.4	-
	100	-	62.2	-
	200	-	61.9	-

the transport distance, the potential for GHG reduction was lower – from 183,000 to 201,000 tons per year. The value of the index for generating electrical energy only was the lowest in the process of combustion and lay within an interval of from 54,000 to 56,000 tons per year. Therefore, it is the best option in terms of the potential to reduce CO_2 emissions to use willow chips to produce heat in a heat-only boiler station. However, environmental benefits can also be gained by using biomass as a solid fuel in other energy generation processes. For example, according to Heller et al. [58], the addition of 10% of biomass in the process of its co-combustion resulted in an increase in energy generation efficiency by 8.9% and reduced its contribution to the greenhouse effect by 7-10% compared to coal.
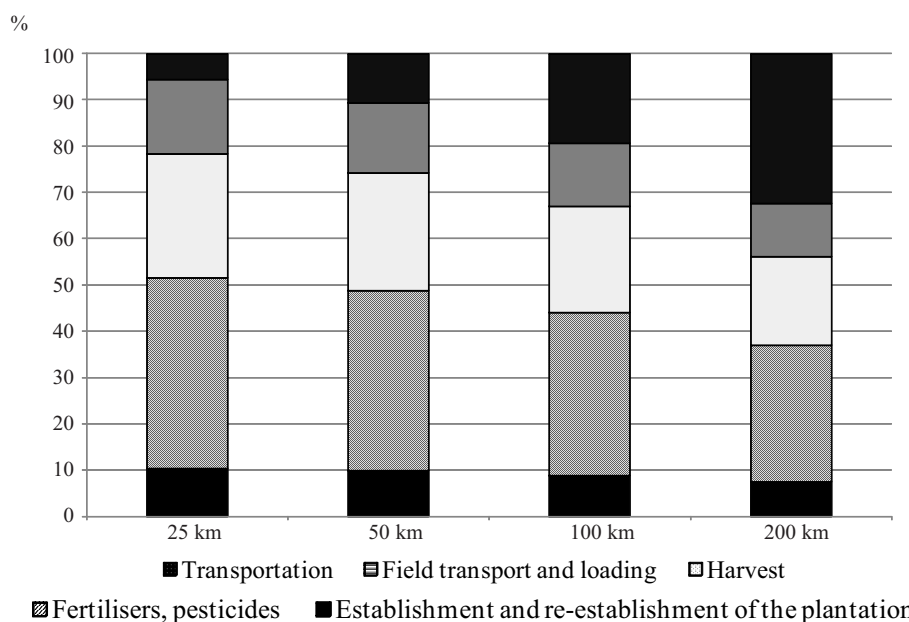

Fig. 1. Structure of GHG emissions associated with willow chips production in a three-year cycle and delivery to a conversion facility.

Conclusions

This study has shown that the production of energy from willow biomass can be beneficial in terms of energy efficiency, which can contribute to reduced fossil fuel consumption. In analysing the energy ratio of willow chips production, the generation of heat in a heat-only boiler station proved to be the best option. The total accumulated energy input at a conversion facility rose with increasing distances of chips transport from 1.5-2.3-fold for gasification and combustion to nearly 3-fold in the process of co-combustion compared to their values at the farm gate. The highest energy ratio (9-11) was achieved in the heat generation process in a heat-only boiler station. Furthermore, the values of this index in CHP generation were lower by 24-38% and in the conversion of biomass to electrical energy they were several times lower compared to heat generation in a heat-only boiler station.

Total GHG emissions from production of willow chips and their transport for 25 km amounted to 73.0 kgCO$_2$ eq.·Mg^{-1} d.m. Increasing the transport distance to 50 km, 100 km, and 200 km resulted in a growth of GHG emissions by 6%, 17%, and 39%, respectively. The contribution of fertilisers and pesticides dominated in the structure of GHG emissions when willow chips were transported for 25 km, 50 km, and 100 km; when the transport distance increased to 200 km, contribution of transport was the largest. The highest potential for the reduction of GHG emissions (62.5 MgCO$_2$ eq.·ha^{-1}) was achieved in the production of heat in a heat-only boiler station with the shortest transport distance. It has been shown in a simulation for this variant that when willow is produced for energy feedstock in an area of 10,000 ha, the GHG could be reduced by up to 208,000 tons per year.

Acknowledgements

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