Willow Cultivation as Feedstock for Bioenergy-External Production Cost

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Abstract: Biomass remains one of the most important materials for the production of renewable energy in the European Union. Willow can be one of the sources of biomass, and its production can also be profitable on soils with low quality. A proper selection of raw material for energy production should be based not only on the cost effectiveness or crop yield, but also on the environmental impact and the cost it incurs. The aim of this work was to evaluate the external environmental costs of the production of willow chips of seven willow genotypes, produced for energy generation on marginal cropping lands. The environmental external costs of chips production were estimated against the amount of emissions calculated according to the LCA method (ReCiPe Midpoint) and its monetary value. The external environmental cost of willow chips production amounted to €212 ha⁻¹ year⁻¹, which constituted 23% of the total production cost of willow chips. The external cost of production of 1 Mg d.m. of willow chips for the best yielding variety averaged €21.5, which corresponded to 27% of the total production cost. The research demonstrated that a proper selection of an optimal variety may lead to the reduction of the external cost.

Keywords: externalities; economic analysis; willow biomass production; new varieties; sustainable production

1. Introduction

The development of renewable energy has stimulated the growing interest in biomass [1], which is its main source in both Poland and the whole EU [2]. Biomass for energy purposes is mostly obtained from forests, but also includes short-rotation coppice (SRC) [3], herbaceous crops and other streams of residues [1,4].

The need for the diversification of the material sources has led to the establishment of dedicated plantations of woody biomass, which ensure the availability of consistent quality biomass for most of the year [5]. Of all the natural perennial crops grown in Poland, willow attracts special attention [2]. The literature includes many works describing the suitability of willow as a resource for energy production [6]: electricity, heat [7–9] and biofuel [10,11]. It has been demonstrated that production of willow wood pellet, in comparison with the generation of electric power and production of biofuels, has the smallest impact in all environmental impact categories. In turn, electric power generation is the second best option in terms of environmental emissions (except for blue water consumption and particulate matter PM₂.₅) to use willow for energy purposes. Production of biofuels has the strongest...
impact in most of the environmental impact categories [12]. Finally, analysis of the production of bioethanol and biomethane from lignocellulosic biomass (straw) has proved that bioethanol production has a weaker impact on the environment than production of biomethane as co-fermentation of lignocellulosic biomass substrates leads to the production of high density biofuels, although reaching a higher CO$_2$ equivalent emission per energy unit globally [13].

The willow yield, depending on many factors such as species, variety, climatic conditions, plantation technology soil conditions and many others, may reach 34 Mg ha$^{-1}$ year$^{-1}$ d.m. under optimal conditions, although typical yields are around 8–12 Mg ha$^{-1}$ year$^{-1}$ d.m. [14]. Under certain environmental and economic conditions, willow can be grown profitably [15–18]. Considering the issue of soil competitiveness for food production and non-food production, including energy purposes, it is worth noting that willow can be grown on marginal cropping lands [2,10,19–21]. What also transpires from many relevant studies is that willow seems an appealing choice because of the limited greenhouse gas emissions caused by its production [7,11,19,22,23].

The evaluation of willow production for energy purposes is often carried out through Life Cycle Assessment (LCA) [24–27]. This method allows an evaluation of the product impact on the environment in all its phases, namely from the harvesting of raw material to the generation of a product, and even further into its disposal and recycling [28]. LCA is a holistic approach with respect to the environment, but it is not until LCA is integrated with an economic assessment that decision makers can gain full insight to evaluate the environmental and economic impact of a product. A feasibility study is part of every product’s analysis, but it overlooks a whole group of costs generated in its life cycle. These costs are the external costs related to the environmental impact of different elements/stages of production [29]. Internal costs are defined by the price paid by the consumer. External costs are mainly the costs borne by the society in the form of taxes, as well as costs of the losses to the quality of the environment and natural capital as well as costs of restoring the quality of natural resources, i.e., air, water and soil. In his review, Stern [30] indicated that climate change proves market failure, called externality in economics. The external ecological effects follow not only from the climate change, but also the changes in the air, water and soil quality; they in turn have impact on human health and environment.

The literature provides examples of methods for making an economic assessment of the environmental impact [31]. The most popular are (ExternE) [32] “External Costs of Energy,” a method of calculating external environmental cost, mainly based on the market prices, and “Willingness to pay,” which was implemented in the EcoSense model. Stepwise2006 [33,34] is a method of budget constraint. Monetary values of indicators for three damage categories are provided: Quality-Adjusted Life Years (QALYs) for impacts on human wellbeing, Biodiversity Adjusted Hectare Years (BAHYs) for impacts on ecosystems, and monetary units (EUR2003) for impacts on resource productivity [31]. Ecovalue08 [35,36] is a method which takes advantage of both contingent valuation and the market price; it is used for the monetization of the impact indicators in midpoint category. EPS [37–39] is an approach which makes use of the WTP (willingness to pay) for human health evaluated using contingent valuation (value taken from ExternE), and averting behaviour method, developed for LCIA on the endpoint level. Ecotax02 [40,41] is a method where the weight ratios come from the taxes and environmental fees in effect in Sweden. LIME 1-2 [42,43]—life cycle impact assessment method based on endpoint modelling is an approach based on the preferences determined through an experimental method in the category of human health Disability-Adjusted Life Year (DALY), social resources (jen), and bio-diversity through Expected Increase in Number of Extinct Species (EINES) and Net Primary Production (NPP). EVR [44–46] is a method of cost reduction based on the cost necessary to reduce the current pollution and resource depletion to a sustainable level.

Monetization, or an economic assessment of the environmental impact, is defined by many authors and in many approaches [46,47], although further studies in this scope are still necessary. It is important that external costs should be included in the economic assessment, i.e., internalization, as it allows one to fully evaluate the cost of production [34,48–51]. Therefore, an assessment of the external cost incurred during the production of materials is one of the aspects which should constitute a complex
evaluation of the material in the production of renewable energy [52]. Dias et al. [7] demonstrated in their research that the use of biomass for bioenergy generation could be a valuable approach to mollify climate change and it might generate economic benefits as well, although it is important to ensure that this source of energy does not entail other environmental costs. Hence, the identification and evaluation of external environmental costs belong to applied science.

An assessment of external environmental costs will not only allow one to estimate the full cost of willow chip production for energy purposes but will also make it possible to identify sources of these costs and assess costs of emission to the environment due to the implemented production stages, applied production means and other decisions affecting the entire production process. In the light of the above, the aim of this research was to make an evaluation of external environmental cost of the seven genotypes of willow chips production including cultivation, harvesting, chipping and transporting. In addition, an attempt was made to identify production stages responsible for specific external costs, and to determine which environmental impact categories generate the highest costs.

2. Materials and Methods

2.1. Field Experiment

The research was based on experimental data obtained from a willow plantation where seven genotypes were grown, including five varieties (Star, Tur, Turbo, Zubr—previously clone UWM 006, Ekotur—previously clone UWM 043 and two clones (UWM 155 and UWM 035), bred in the Department of Plant Breeding and Seed Production of the UWM in Olsztyn. All of these varieties and clones will be referred to here as varieties. A plantation of 10.5 ha was located in north-eastern Poland, in the village of Samlawki (53°59′ N, 21°05′ E), on a field of the Research Station in Łeżany, owned by the University of Warmia and Mazury in Olsztyn (UWM). The plantation was established in 2010 and run for three-year harvesting cycles. It was assumed that the plantation would be used for 21 years and later terminated. The field research included the preparation of the farmland (glyphosate spray of 1.44 kg ha\(^{-1}\) of active substance), fertilization of 300 kg of PRP Sol (a calcium and a magnesium fertilizer mixed with minerals specific to PRP technology and agglomerated by a soluble plant-based binder—lignosulphonate), harrowing and mechanical planting of cuttings with a step planter. The preparation also included spraying with a soil herbicide (1.58 kg\(^{-1}\) of active substance), mechanical weeding and spraying with a herbicide against monocotyledon weeds (0.13 kg ha\(^{-1}\) of active substance). In each cycle, fertilization was done: N—90 kg ha\(^{-1}\) (as ammonium nitrate), P\(_2\)O\(_5\)—30 kg ha\(^{-1}\) (as triple superphosphate) and K\(_2\)O—60 kg ha\(^{-1}\) (as potassium chloride). The crops were harvested every three years. Willow crops were harvested with a single stage forage harvester Claas Jaguar 830 modified for short rotation coppices. Chips were collected from the harvester with three tractors with trailers and transported to the farmstead, where they were loaded with a telescopic loader onto trucks and transported to a conversion plant. The road transport was conducted with 80 m\(^3\) containers, which totalled approximately 25 Mg of fresh chips, and transported to a conversion plant over a distance of 50 km; the same distance after biomass unloading was added. The details of the plantation management were described in the previous articles on the crop yield and its suitability as a substrate for the biorefinery [53], energy value [6], production cost and economic feasibility [18], and environmental impact of production [24].

The analyses feature the following functional units: 1 ha of the plantation, 1 Mg of dry mass and 1 GJ of energy. The system boundaries assumed for a from cradle to gate (including the transport distance of 50 km) included the plantation and harvest of the analysed varieties of willow, chipping and transport to the conversion plant.

2.2. Internal Cost

The evaluation of the internal cost [18] included the direct cost of performing all of the phases and operations, together with the use of fuel, materials and instruments for the plantation of the analysed
varieties of willow, as well as harvesting, chipping and transporting. The evaluation of the internal cost was based on the prices in effect in 2012. The analysis of the environmental external cost included the impact evaluation for year 2015, so the internal cost was adjusted to the 2015 prices, against the rate of inflation in Poland, in line with ISO recommendations [54]. The rate of inflation in Poland by the Polish Central Bank in the consecutive years (2013–2015) was 0.8%, 0.1% and −0.7% respectively.

2.3. External Cost

The external environmental cost of willow chips production of the analysed varieties was determined on the basis of the amount of emissions, according to the Life Cycle Assessment method, and with the use of the Sima Pro software, as well as the monetary value of the emissions at midpoint category, proposed in the Environmental Prices handbook of the EU 28 version [46] (Table 1).

Table 1. Monetary value (€) of impact categories.

| Impact Category                           | Unit                     | Environmental Price as External Cost |
|------------------------------------------|--------------------------|--------------------------------------|
| Climate change                           | €kg CO$_2$ eq$^{-1}$     | 0.057                                |
| Ozone depletion                          | €kg CFC-11 eq$^{-1}$     | 30.4                                 |
| Human toxicity                           | €kg 1,4-DB eq$^{-1}$     | 0.214                                |
| Photochemical oxidant formation          | €kg NMVOC eq$^{-1}$      | 2.1                                  |
| Particulate matter formation             | €kg PM$_{10}$ eq$^{-1}$  | 69                                   |
| Ionising radiation                       | €kg U$_{235}$ eq$^{-1}$  | 0.0473                               |
| Terrestrial acidification                | €kg SO$_2$ eq$^{-1}$     | 5.4                                  |
| Freshwater eutrophication                | €kg P eq$^{-1}$          | 1.9                                  |
| Marine eutrophication                    | €kg N eq$^{-1}$          | 3.11                                 |
| Terrestrial ecotoxicity                  | €kg 1,4-DB eq$^{-1}$     | 8.89                                 |
| Freshwater ecotoxicity                   | €kg 1,4-DB eq$^{-1}$     | 0.0369                               |
| Marine ecotoxicity                       | €kg 1,4-DB eq$^{-1}$     | 0.00756                              |
| Agricultural land occupation *           | €m$^2$a$^{-1}$           | 0.0261                               |
| Urban land occupation *                  | €m$^2$a$^{-1}$           | 0.0261                               |

* Value of external cost of land use was taken for the evaluation of the environmental external cost in the impact category of agricultural land occupation and urban land occupation. Source: [46].

The monetary value of the emissions reflects the social cost and the cost of polluting the natural environment. They are expressed in euro per kilogram of the pollutant. The environmental prices indicate a loss of welfare following from one additional kilogram of pollution or a decibel of noise emitted into the environment. The use of environmental prices in the life cycle assessment allows one to evaluate the environmental footprint generated by a particular product or service.

Life Cycle Assessment is a standardized method (ISO 14040-44) of a quantitative analysis of the total environmental impact of products or services in their life cycles delineated by the system boundaries, namely the life phases included in the analysis. It is based on the identified and determined amount of the used materials and energy as well as residues and other emissions entered into the environment. Subsequently, the impact of these processes on the environment is evaluated both for the utilization of resources and the emission of pollutants. The LCA analysis for the varieties of willow presented in work [24] were determined by the CML 2 baseline 2000 method; however, for the sake of this analysis, the results originating from the life cycle impact assessment of willow cultivation were determined according to ReCiPe Midpoint (H). 14 impact categories were investigated: climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionising radiation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation and urban land occupation (Table 2).
Table 2. Data from LCIA of 1 Mg d.m. willow chips taken for the analysis.

| Impact Category                  | Unit  | Start | Tur  | Turbo | Žubr  | Ekotur | UWM 035 | Average |
|----------------------------------|-------|-------|------|-------|-------|--------|---------|---------|
| Climate change                   | kg CO₂ eq | 45.26 | 74.22 | 46.55 | 27.63 | 59.92  | 31.91   | 108.44  | 44.89   |
| Ozone depletion                  | kg CFC-11 eq | 0.000012 | 0.000017 | 0.000012 | 0.000009 | 0.000014 | 0.000010 | 0.000021 | 0.000012 |
| Human toxicity                   | kg 1,4-D eq | 12.54 | 19.74 | 12.65 | 7.90  | 15.47  | 8.91    | 25.33   | 11.95   |
| Photochemical oxidant formation  | kg PM₁₀ | 0.70  | 0.87  | 0.71  | 0.57  | 0.77   | 0.60    | 1.06    | 0.68    |
| Particulate matter formation     | kg SO₂ eq | 5.41  | 7.62  | 5.49  | 3.92  | 6.31   | 4.25    | 9.57    | 5.22    |
| Ionising radiation               | kg 1,4-DB eq | 0.000012 | 0.000017 | 0.000012 | 0.000009 | 0.000014 | 0.000010 | 0.000021 | 0.000012 |
| Terrestrial acidification        | kg U₂³⁵ eq | 1.09  | 1.49  | 1.10  | 0.81  | 1.25   | 0.87    | 1.86    | 1.05    |
| Freshwater eutrophication        | kg 1,4-DB eq | 0.034 | 0.060 | 0.034 | 0.017 | 0.044  | 0.021   | 0.078   | 0.032   |
| Marine eutrophication            | kg 1,4-DB eq | 0.011 | 0.015 | 0.011 | 0.008 | 0.012  | 0.008   | 0.019   | 0.010   |
| Agricultural land occupation     | m²/a | 1.09  | 1.49  | 1.10  | 0.81  | 1.25   | 0.87    | 1.86    | 1.05    |
| Urban land occupation            | m²/a | 0.59  | 0.76  | 0.60  | 0.47  | 0.66   | 0.50    | 0.94    | 0.58    |

3. Results and Discussion

Table 3 shows the total production cost of the willow varieties. The differences in the costs, both internal and external ones, followed from the varied crop yields obtained from the plantation. The lowest production cost and yield was found for UWM 155 (sum of cost €530 ha⁻¹ year⁻¹; average of yield 3.6 Mg ha⁻¹ year⁻¹ d.m.) and Tur (sum of cost €599 ha⁻¹ year⁻¹; average 4.8 Mg ha⁻¹ year⁻¹ d.m.) [53]; the highest percentage of external cost to total cost was observed for these varieties, namely 29% and 27%, respectively. The highest yielding varieties were Žubr (average 18.5 Mg ha⁻¹ year⁻¹ d.m.) and Ekotur (15.0 Mg ha⁻¹ year⁻¹ d.m.). The different costs of harvesting and transporting resulted in significant differences in the total cost [6]. Obviously, any additional application of production means will increase the external costs in any production, which is corroborated by Notarnicola [47].

The average total cost of production per 1 Mg d.m. of willow chips was €94.0, of which €29.2 was the external cost. The average share of external cost in the total production cost of 1 Mg d.m. of willow chips was 31% (from 27% for Žubr and 28% for Ekotur to 38% for UWM 155) (Table 4). The internal cost of 1 Mg UWM 155 willow chips was 1.5 times higher than for Žubr, while the external cost was 2.5 times higher. In other research, the share of external cost in the production of 1 Mg d.m. of poplar on mineral fertilization was lower and equalled 23% [56].
Table 4. Equivalent cost of production 1 Mg d.m. depending on willow variety (€ Mg\(^{-1}\) d.m.).

| Willow Variety | Cost (€ Mg\(^{-1}\) d.m.) | Internal | External | Total |
|----------------|----------------------------|----------|----------|-------|
| Start          | 65.8                       | 30.3     | 96.1     |       |
| Tur            | 79.9                       | 43.4     | 123.3    |       |
| Turbo          | 65.8                       | 30.7     | 96.5     |       |
| Zubr           | 57.2                       | 21.5     | 78.7     |       |
| UWM 035        | 71.5                       | 35.8     | 107.3    |       |
| Ekotur         | 59.0                       | 23.5     | 82.5     |       |
| UWM 155        | 89.3                       | 55.5     | 144.8    |       |
| Average        | 64.7                       | 29.2     | 94.0     |       |

The analysis of the production of willow varieties for energy purposes indicates that both the internal and external cost were the lowest for the Zubr and Ekotur varieties, and so was the share of the external cost to the total cost. The average cost of producing 1 GJ was €5.53, of which the internal cost was €3.81, and the external €1.72 (Table 5). The differences in the calorific value [54] decreased the share of the internal cost for the variety of a calorific value and increased the share of the external cost relative to the analyses per 1 Mg d.m. Such relations were observed for Tur and UWM 035 varieties, which achieved the highest calorific values (Tur, UWM 035); in the varieties of lower calorific value, like UWM 155, Turbo and Star, the share of the external costs diminished.

Table 5. Production cost of willow variety per energy unit (€ GJ\(^{-1}\)).

| Willow Variety | Cost (€ GJ\(^{-1}\)) | Internal | External | Total |
|----------------|----------------------|----------|----------|-------|
| Start          | 3.91                 | 1.78     | 5.69     |       |
| Tur            | 4.31                 | 2.50     | 6.81     |       |
| Turbo          | 4.11                 | 1.83     | 5.94     |       |
| Zubr           | 3.41                 | 1.26     | 4.67     |       |
| UWM 035        | 4.11                 | 2.09     | 6.19     |       |
| Ekotur         | 3.51                 | 1.38     | 4.89     |       |
| UWM 155        | 5.71                 | 3.35     | 9.06     |       |
| Average        | 3.81                 | 1.72     | 5.53     |       |

The comparison of the production cost of 1 GJ from willow varieties and 1 GJ of polar chips (from our previous research) on mineral fertilization [56] indicates that the share of the external cost was similar among the highest yielding varieties, 26% for poplar and 27% for Zubr and Ekotur willow varieties. The share of the external cost for the other willow varieties was higher, 31% on average and 37% for Tur variety.

The results concerning the willow varieties indicate a relatively high average share of the total external cost in the total cost of producing 1 Mg d.m. in comparison with poplar chips presented in other research [56]. However, these values for the best yielding Zubr and Ekotur varieties were comparable. Also Panataleo et al. [49] investigated the impact of the external environmental effects of energy crops on the biomass, and calculated the external cost of forest biomass of short rotation to stand at 15%. Such significant differences may result from the lower internal costs of production than in other European countries [15] while the external cost for the EU28 is higher. In accordance with the Environmental Prices handbook the EU 28 version [46], the monetary Value Of Life Year (VOLY), or the endpoint impact category was adopted in line with the NEEDS project for the EU 15: €41,000, in 2005 prices, and then recalculated for €48,000 to correspond to the 2015 prices. In line with the calculations made by Desaigues et al. [57], the recommended VOLY value for Poland and other countries outside the EU 15 for 2015 should amount to €38,635. Following the recommendation that the VOLY values for countries outside the EU 15 should be lower by 24%, the values obtained by the authors perhaps
should have been decreased accordingly. Another solution could be to adopt the environmental prices for midpoints for the monetary evaluations in countries outside the EU 15, based on the individualist characterization perspective at a lower value rather than the central value.

The analysis of the external production cost of willow varieties relative to the production phases per 1 hectare (in the whole life cycle of the plantation) indicated that the highest external cost, depending on the variety, was incurred by harvesting (Figure 1). For example, it came up to €2800 for the Żubr variety. The cost of fertilization was also high (over €1800) and the same for all of the varieties. Transport was also expensive, for instance nearly €1250 for Żubr and over €1000 for Ekotur. Similarly, in the structure of the internal cost analysed in previous studies [18], harvesting (26% share) and fertilization (33% share) made a major contribution; according to Havličjova [58], they had the largest impact on the minimal price of the produced biomass. Soil carbon sequestration was estimated as a value that reduced the cost, and its amount did not differ much between the varieties. The value of sequestration C was between €−873 for the Żubr variety to €−502 for Tur, with the average of €−622. The external cost of over €100 per 1 ha was also incurred for plantation re-establishment, tractor transport, loading chips (only for the Żubr variety).

![Figure 1. External cost for willow chips production depending on variety per 1 ha.](image)

The analysis of the external cost of producing willow chips with reference to the agrotechnical operations per 1 Mg d.m. (Figure 2) and 1 GJ (Figure 3) suggested that nitrogen fertilization generated the highest external cost, particularly for the low yielding varieties (UWM 155—over €30 Mg⁻¹ d.m. and €1.86 GJ⁻¹, and for Tur over €23 Mg⁻¹ d.m. and €1.35 GJ⁻¹), unlike for the high yielding varieties (Żubr, Ekotur), where these values were €6 i €7 Mg⁻¹ d.m. and €0.36 and €0.44 GJ⁻¹. PK fertilization yielded a similar structure of the external cost, but the values were smaller by over €7 Mg⁻¹ d.m, €0.45 GJ⁻¹ for UWM 155 to €1.4 Mg⁻¹ d.m. and €0.32 GJ⁻¹ for Żubr.
Like the external cost per hectare, the other phases of production generating high external cost per unit of mass (Figure 2) and energy (Figure 3) were harvest and transport. The values were similar, at approximately €9 and €1.3 Mg\(^{-1}\) d.m. and €0.55 GJ\(^{-1}\) and €0.08 GJ\(^{-1}\), respectively. With regard to C sequestration, which reduced the external cost, the highest negative value was calculated for UWM 155 (€−7.56 Mg\(^{-1}\) d.m and €−0.46 GJ\(^{-1}\)) and for Tur (€−6.52 Mg\(^{-1}\) d.m; €−0.37 GJ\(^{-1}\)); the lowest was computed for Žubr (€−2.92 Mg\(^{-1}\) d.m and €−0.19 GJ\(^{-1}\)) and for Ekotur (€−3.22 Mg\(^{-1}\) d.m; €−0.17 GJ\(^{-1}\)). Also, the internal cost of biomass production increased along with the increase in yield per 1 ha. This
was due to the longer working time and the use of fuel, machines, and devices for harvest and transport. On the other hand, the cost of the establishment of plantation, fertilization, and plant protection was the same for all of the varieties, and its share in the total cost diminished as the willow yield increased. This is why the improvement in the economic effectiveness in both internal and external biomass production cost must be attained through the selection of varieties and the optimization of the willow harvesting technology [18]. Tharakan et al. [59] demonstrated that an increase in production may reduce the unit cost (per Mg d.m.) of delivering biomass to the end user by 13%. LCA analyses carried out by other authors [11] also indicated that nitrogen fertilization and diesel fuel in willow production had a significant environmental impact; in their view, the introduction of biodiesel to agriculture could reduce its negative impact on the environment.

An investigation into the categories of environmental impact of willow chips production singled out particulate matter formation as the one which involved the highest external cost. The cost in this category was between €1792 ha$^{-1}$ for UWM 155 and €3935 ha$^{-1}$ for Żubr (on average €2615 ha$^{-1}$) during the lifetime of the plantation (Figure 4). The external cost in the range of €180 ha$^{-1}$ to €600 ha$^{-1}$ followed from the categories: terrestrial acidification, human toxicity, climate change, photochemical oxidant formation, marine eutrophication. The external cost related to other impact categories in the whole period of the plantation’s use amounted to less than €50 ha$^{-1}$. In our previous research the highest external cost for the poplar on mineral fertilization was also particulate matter formation, but terrestrial acidification came close second, at €1614 ha$^{-1}$ and €1519 ha$^{-1}$ respectively [56]. In other study the analysis of the external cost of electricity production from various biomass materials indicated that emissions of PM$_{10}$, NO$_X$ i PM$_{2.5}$ were one of the most significant factors contributing to this cost, and followed from the combustion of fossil fuels in the production of fertilizers [60].

![Figure 4. External cost of willow varieties production per 1 ha depending on impact category.](image-url)

The analysis of the external cost of willow chips production per 1 Mg d.m. (Figure 5) and 1 GJ (Figure 6) also confirmed the highest cost of particulate matter formation, €17.17 Mg$^{-1}$ d.m., €1 GJ$^{-1}$ on average. The highest cost per 1 Mg d.m. and 1 GJ was generated by the lowest yielding varieties, namely UWM 155, while the lowest cost was generated by the best yielding varieties, like Żubr.
The external cost related to particulate matter formation was €13.17 Mg\(^{-1}\) d.m and €0.77 GJ\(^{-1}\) for Żubr, and €30.58 Mg\(^{-1}\) d.m. and €1.84 GJ\(^{-1}\) for UWM 155. The second group was composed of the categories: terrestrial acidification (from €2.69 Mg\(^{-1}\) d.m. to €7.93 Mg\(^{-1}\) d.m. and from €0.16 GJ\(^{-1}\) to €0.48 GJ\(^{-1}\)), and climate change and human toxicity at similar levels (from ok €1.5 Mg\(^{-1}\) d.m. to approximately €6 Mg\(^{-1}\) d.m. and from approximately €0.1 GJ\(^{-1}\) to approximately €0.35 GJ\(^{-1}\)). Emissions in the category of photochemical oxidant formation generated the cost of from €1.2 Mg\(^{-1}\) d.m. to €2.23 Mg\(^{-1}\) d.m. and from €0.07 GJ\(^{-1}\) to €0.13 GJ\(^{-1}\) for Żubr and UWM 155 varieties, respectively. Particulate matter formation was an impact category of the highest weight in the procedure suggested by Hafizan et al. [61], while the second highest category was fossil depletion. In LCA studies over willow production, the highest environmental impact was determined in the range of 51–67% in the following categories: global warming, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity [24,62]. Besides, a high impact of willow production on the environment in terms of acidification was also noted by Borzecka-Walker et al. [63].

![Figure 5](image-url). External cost of willow varieties production per 1 Mg d.m. depending on impact category.

In the analysis of the structure of external costs generated in willow chips production (Figure 7), it is noteworthy that the share of particulate matter formation exceeded half of the cost for every variety, namely from 55% for UWM 155 (a low yielding variety [53]) to 61% for Żubr (a high yielding variety [53]); the average was 59%. Another cost-intensive impact category was terrestrial acidification. The share of this cost was different, from 13% for Żubr to 14% for Tur (low yield varieties [53]). The share of the other impact categories in the cost usually did not exceed 10% (with the exception of 11% for climate change in the case of UWM 155). The other impact categories whose share in the external cost was at 8–9% were human toxicity and climate change. The share of photochemical oxidant formation and climate change was 4–5%, while the share of the remaining categories did not reach 1%. An LCA analysis [24] of the production of 1 Mg willow chips for indicated a significant contribution of mineral fertilization to global warming. Another phase of production, harvesting, also significantly contributed to global warming through its acidifying impact. The LCA also showed the positive influence of carbon sequestration in the soil under the willow plantation, mitigating global
warming. The normalization value for average yield (chips transporting distance of 25 km) indicated that freshwater toxicity had the largest impact on the environment.

![Graph showing external cost of willow varieties production per 1 GJ depending on impact category.](image)

**Figure 6.** External cost of willow varieties production per 1 GJ depending on impact category.

![Graph showing contribution to the sum of external cost of field operation depending on impact category.](image)

**Figure 7.** Contribution to the sum of external cost of field operation depending on impact category.

Both the analysis of the external environmental cost and the economic and energy research results presented in previous works [18,53] demonstrated that the selection of willow varieties is of utmost
importance. The cost of fertilizers was the dominant variable for the lowest yielding varieties, whereas for the high yielding varieties it was the cost of diesel fuel. It was determined that the cultivation of high-performance willow varieties may lead to a significantly reduced energy consumption in the willow chips production and a higher energy ratio in comparison with the varieties of lower productivity. The analysis of the energy consumption and the energy ratio in the production of chips of new willow varieties also defined the optimal transporting distance to the end user. The lowest energy consumption was noted for the Zubr variety. When the yield exceeded 86 Mg ha\(^{-1}\) of fresh biomass, the energy intensity amounted to 0.35 GJ Mg\(^{-1}\) f.m.\cite{6}. Although it is often recommended that biomass should not be transported further than 30–50 km, the LCA analysis and the profitability studies of willow chip production indicate that for high-yielding varieties, like Zubr, willow chips can be transported for up to 100 km\cite{18,53}. Transport is an important issue as the external cost they generate may reach 26–37%\cite{64}.

Woody plants of short rotation, like willow, have a lower or similar impact on the environment to other perennial energy crops. Their impact is 2- to 3-fold lower than that of annual crops, which is true for food, energy or industrial crops\cite{63}. The evaluation of the impact on the environment resulting from the production of 1 MJ thermal energy from short rotation willow (SRC) compared to fossil fuel (heating oil and gas) indicated that the direct combustion of the SRC chips reduced the global warming potential (GWP) by nearly 85% against fossil fuels, and the carbon sequestered by the SRC biomass reduced the GWP by 23%\cite{7}. Similar results related to the reduction of the GHG can be found in the literature\cite{27,65–67}. However, in comparison with fossil fuels, the energy generated from SRC had a larger share in such categories as eutrophication, due to the use of mineral fertilization in the production of biomass\cite{7}. The production of energy from fossil fuels involves three key environmental strains, and in consequence, an environmental cost. These are land use, depletion of non-renewable resources and air pollution from the emissions of CO\(_2\), CH\(_4\), N\(_2\)O, CO, NO\(_x\), SO\(_2\), VOC i PM\(_{10}\). It was determined that the environmental cost they involve constitute as much as 34% of the total production cost of conventional diesel fuel\cite{68}. An equal value of external cost, namely 33.6%, was obtained for the production of 1 dm\(^3\) of diesel fuel\cite{69}. A shift from fossil fuels to willow for the production of electricity was estimated to reduce the external cost of air pollution in the range of $0.02–0.06 kWh\(^{-1}\)\cite{70}. The study by Wang et al.\cite{71} confirms that the external cost of using coal for the production of electricity amounted to $0.072 kWh\(^{-1}\), while the same cost for the production of electricity from biomass was $0.00012 kWh\(^{-1}\). In China, the direct internal cost of energy from biomass reached CNY 0.44 per 1 kWh (approx. $0.0678 kWh\(^{-1}\)); this figure for coal was higher by 25–37%. However, due to significant emissions of the GHG and PM\(_{2.5}\) pollution during coal combustion, the external cost of coal energy is estimated at CNY 0.17 kWh\(^{-1}\) (approx. $0.0262 kWh\(^{-1}\)) and from biomass at CNY 0.06 kWh\(^{-1}\) (approx. $0.0092 kWh\(^{-1}\)), on average. What follows from estimations is that if the external environmental cost were included in the cost or electricity production, the production of electricity from biomass would be less expensive than from coal\cite{71}. Owen\cite{72} suggested that the inclusion of the external cost to the price of production of electricity would render some of the renewable technologies financially competitive against the energy generated in coal power plants.

Cultivation of crops for energy purposes, like willow, generates not only cost but also several environmental benefits. Nitrogen remains a key element in today’s agriculture\cite{73}. The positive nitrogen-binding impact of willow plantation, which eliminates fertilizer-derived nitrogen compounds from the soil of the neighbouring plantations was estimated at $1.8–37.0 kg year\(^{-1}\) N\cite{74,75}. Brink et al.\cite{76} analysed the cost of nitrogen in the environment and concluded that the annual damage resulting from the presence of nitrogen in waters and soils of the European countries varied between €70 and €320 billion (€150–750 per resident), of which 75% was related to harm to the human health and air pollution. Jongeneel et al.\cite{77} presented an analysis of the Dutch agricultural sector in terms of the cost and benefits of externalities. The authors estimated the annual external cost related to agriculture at €1857 million, while the revenue from positive externalities was estimated at €186.2 million.
Another group of environmental benefits derived from willow cultivation is the enhanced biodiversity. A well-managed SRC plantation can enrich biodiversity in a landscape dominated by agriculture [78]. It has also been found that willow plantations grown for energy purposes increase the biodiversity of earthworms and add to landscape diversity [79]. An SRC plantation has also been identified as a habitat for many microorganisms, soil organisms and insects [80].

4. Conclusions

The external cost of willow chip production varied between varieties; in other words, the value and share of the cost depended on a crop yield. The highest external cost (per 1 Mg d.m. and 1 GJ) of a willow plantation was obtained for the lowest yielding varieties, like UWM 155 and Tur, whereas the lowest cost was determined for the highest yielding varieties, such as Zubr and Ekotur. The external environmental cost of willow chip production amounted to €212 ha\(^{-1}\) year\(^{-1}\) which constituted 23% of the total production cost of willow chips. The average total cost of production per 1 Mg d.m. of willow chips was €94.0, of which €29.2 was the external cost.

Among the agrotechnical operations, nitrogen fertilization generated the highest external cost, particularly for the low yielding varieties (UWM 155—€1.86 GJ\(^{-1}\), and for Tur—€1.35 GJ\(^{-1}\)), unlike for the high yielding varieties (Zubr, Ekotur), where these values were €0.36 and €0.44 GJ\(^{-1}\). The research demonstrated that a proper selection of an optimal variety may lead to the reduction of the external cost. The highest external cost was generated in categories of particulate matter formation (from €0.77 to €1.84 per 1GJ) and terrestrial acidification (from €0.16 to €0.48 per 1GJ), which followed from the use of mineral fertilizers. Such high values of the external cost indicate the need to seek production residues, which could be used for fertilizing plants, enriching the soil, and enhancing the productivity of biomass, in particular in the areas with poorer soils. Willow harvesting also involved a significant external cost, which points at harvesting technologies, machine capacity, and energy intensity of this phase as key elements of the process.

Determination of the external environmental costs involved in the production of energy from biomass is an extremely important step in any discussion on profitability of energy generation, especially from such non-renewable resources as coal. When the price of raw material for energy generation does not include such aspects as depleting non-renewable energy sources or CO\(_2\) emission, then an image of the estimated production costs is erroneous and therefore an estimate of the energy production profitability is incorrect as well. Whenever external environmental costs are not included, the consequence is the omission of costs borne by the society, that is by consumers, who make buying decisions based on the price usually reflecting only internal costs, and neglecting the costs that need to be covered in order to restore or maintain the quality of the natural environment in at least non-deteriorated condition.

To sum up, our research has shown that a comprehensive evaluation of the economic effectiveness, beside the internal and external cost, will also require studies of the environmental benefits of willow cultivation and its cascading use for energy and industrial purposes. It is worth adding that the literature provides information about other methods and values applied to estimate the monetary value of pollutants, with results different from the ones employed in this study. Moreover, the subject raised in this paper is relatively new and submitted to ongoing investigations, therefore it cannot be excluded that results of current analyses will need to be verified in the future. Moreover, social aspects have not been discussed in this article, as they fall outside the scope of this study. The importance of social issues related to the production and use of bio-materials for renewable energy and other bio-products cannot be stressed enough, which is why these considerations will be the subject of our future research.
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