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Biomass Production of Selected Energy Plants: Economic Analysis and Logistic Strategies

Abstract

The objective of this article is the conducting of an analysis of the production of selected energy plants that are already a basic source of agrobiomass in Poland. The analysis looks at environmental aspects and production conditions for biomass designated for energy for the Virginia mallow (Sida hermaphrodita), common osier (Salix viminalis), silver–grass (Miscanthus x giganteus), and switchgrass (Panicum virgatum). What is presented is an economic analysis of the production of selected energy plants, taking into account the costs of establishing plantations and their cost effectiveness. Moreover, logistic strategies for the delivery of biomass intended to secure continuous production of renewable energy as a part of sustainable development is signaled.

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1. Introduction

Energy efficiency is one of the central objectives for 2020. It is also key to achieving the long-term energy and climate goals and the most cost-effective way to reduce emissions, improve energy security and competitiveness and keep energy costs down. The action plan presented by the European Commission aims to reduce the insecurity of investors by evaluating the physical and economic availability of different biomass types, including wood and wood residues, waste and agricultural crops, and by determining priorities regarding the biomass types in use and ways of developing them, as well as by pointing out measures to be taken in order to enhance this. The action plan is also connected with consumer information campaigns about the benefits of biomass and bioenergy[1].

Second generation energy plants—perennial forage plants—are considered the future of bioenergy and are subject to intensive study for this reason. Compared with plants of the first generation—annual bearing fruits of the caryopsis type—they produce more energy at significantly less input and have a more favorable GHG emission balance (Sanderson and Adler 2008). Among the many plants currently grown for energy biomass, the Virginia mallow, willow, miscanthus, and switchgrass have a good chance of development, assuming that their profitability will be higher than in the case of plants grown for consumption.

2. Environmental and economic conditions for agrobiomass production in the case of selected plants for energy biomass

2.1. Virginia Mallow

The Virginia mallow (*Sida hermaphrodita*) is a perennial plant originating from North America. The species has been known in Poland for over fifty years, which is when the Agricultural Academy of Lublin (presently the University of Life Sciences) launched studies on the possibility of its cultivation and use as fodder. It is a honey plant with a honey output of 110–315 kg ha^{-1} (Borkowska and Styk 2006).

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[1] "DEVELOPMENT PLAN 2007−2013 FOR ENHANCING THE USE OF BIOMASS AND BIOENERGY", http://ec.europa.eu/energy/res/biomass_action_plan/doc/nbap/information/estonia_en.pdf

Fresh unimproved seeds that are the source of the plants have a very low germination rate, which is on a level of 5–15%. The highest germination capacity is achieved after a one or two year period of storage (Antonowicz 2005). By using appropriate hydro–priming methods it is possible to increase it to over 50% (Grzesik et al. 2001). The Virginia mallow also reproduces through rooted cuttings planted at densities of 10,000–20,000 per hectare. Biomass harvests are made, depending on region, in the months of February, March, and April or at the time of first frosts in November and December. The moisture content of harvested biomass under natural conditions decreases from approximately 40% in November to approximately 20% in January. This allows its direct designation for palletizing (Borkowska and Styk 2006). A plantation may be effectively exploited for fifteen to twenty years (Antonowicz 2005).

The Virginia mallow, due to its low soil requirements, which are significantly lower than the common osier and *Miscanthus giganteus*, may be used to develop poorer soils, including all types of Grade V soils all the way up to sandy soils. This property of the mallow is especially significant in the case of use for the recultivation of degraded and polluted soils, where subject to unfavorable conditions it can produce 11 t d.m. ha^{-1} $annum^{-1}$. In practice, it may be cultivated in soils of Grade IVb and V poor Secale Complex with a water table at a depth of over two meters. In establishing plantations by way of sexual reproduction (using seeds), catchment area soils with tendencies for encrusting should not be used. Under favorable cultivation conditions, on Grade III soils, harvests may achieve 17 t d.m. ha^{-1} $annum^{-1}$. The harvesting of biomass should take place in the winter season (I–III) when the humidity is lower. The biomass may be compressed into bales or used in the production of briquettes and pellets.

The mallow is less sensitive to lack of mineral fertilizer when compared with the miscanthus. From an economic point of view, what is important is that the fertilizer needs of the mallow are very low in the year of the establishing of the plantation. Starting with the second year, recommended dosages of N–P–K per hectare are 90 kg N, 30–90 kg P_2O_5, and 80–150 kg K_2O. Nitrogen dosages amounting to 200 kg ha^{-1} do not have an impact on the number of shoots. However, increasing phosphorous fertilization from 39 to 53 kg ha^{-1} increases the number of shoots by an average of one per square meter, which give approximately 20,000 additional shoots per hectare (Borkowska et al. 2009). Studies have indicated that the use of treated sewage sludge, which is very inexpensive, increases biomass yields and facilitates its acquisition on very poor soils (Romanowska–Duda et al. 2009; Kacprzak et al. 2010). The mallow also demonstrates small sensitivity to soils with pH=6. This property is especially useful in the Voivodeship of Łódź, where the acidity of the soil is a universal problem. At the same time, the mallow takes up fewer nutrient elements from the soil than the willow or miscanthus (Łabętowicz and Stępień 2010). In the case of mallow harvests, only small amounts of fertilizer components are removed from the field because as the shoots dry, nutrients are moved to the rootstock or are retuned to the soil through falling leaves. Mallow biomass collected at the right time is characterized by low ash content and relatively few mineral components such as nitrogen, potassium, and chlorine—hence, the small outtake of fertilizer components with the harvest (Kuś and Matyka 2010).

The results of studies conducted to date indicate large lignocellulosic biomass harvests as compared with other energy plants. Moreover, heat of combustion is large—an average of 18.4 MJ kg^{-1}—and a lower heating value of 16.6 MJ kg^{-1} (Szyszlak et al. 2006; Borkowska and Styk 2006). The lower heating value and heat of combustion are dependent on the thickness of the mallow stem, which is strictly tied with planting density per 1 m^2. The highest heat of combustion and lower heating value amounting to 19.2 MJ kg^{-1} and 17.4 MJ kg^{-1}, respectively, were received from sprouts of a thickness in the 10 mm to 13 mm range (thickness achieved at a planting density of 23 sprouts per m^2) (Szyszlak et al. 2006). Biomass harvests with a moisture content of 20%–24% amount to 20 to 25 tons per ha^{-1} (Denisiuk 2006), with a theoretically assumed germination capacity of 100% and planting density amounting to 64,000 seeds per hectare, the biomass harvest may amount to 120 t ha^{-1}. Mallow stems on an appropriately dense plantation are easily crushed and compressed (Denisiuk 2006). Mallow harvests on land classified as clayey amount to 15–20 t d.m. ha^{-1} (Borkowska 2007), while in the case of difficult conditions using sewage sludge the amount to from 9 to 11 t d.m. ha^{-1} (Borkowska 2003). Similar or higher harvests as in the case of using sewage sludge are possible in the case of cultivation on light soils. Cultivation on soils classified as light silty–clay, depending on the dosage of nitrogen and phosphorous fertilizer, can amount to 6.71–9,54 t d.m. ha^{-1} in the second year and 10.29–11.75 t d.m. ha^{-1} in the third and fourth years. At the same time, it should be noted that with each year of the experiment, there were significant deficits of precipitation and droughts during June and July, periods of the greatest demand for water (Borkowska et al. 2009). Water shortages are also tied with the properties of light soils. Research conducted in the year 2005 on light soils gave a dry matter yield of 20.5 t d.m. ha^{-1} due to significant precipitation in July (Kuś and Matyka 2010). Appropriate irrigation systems should be considered in the event of cultivation on such soils. Studies conducted on various types of soils indicate that cultivation achieves full production potential in the third and fourth years. Virginia mallow harvests are decidedly dependent on planting density (Faber et al. 2007; Kuś and Matyka 2010). The mallow provides a low harvest when at a density of 10,000 per ha^{-1}, regardless of soil. In the case of sites with such a planting density on soils of Complexes 8 and 4, the harvest amounted to approximately 9 t ha^{-1} dry matter and was 20% lower than for light soils (Complex 5), where the planting density amounted to 20,000 ha^{-1}. However, good harvests were achieved when planting density was increased to 20,000 ha^{-1}. At the same time, harvests amounting to approximately 12 t d.m. ha^{-1} received on light soils should be considered interesting (Faber et al. 2007; Kuś and Matyka 2010).

The Virginia mallow was considered to be a plant free of agrophages (Borkowska and Styk 2006). However, according to the Poznań Institute for Plant Protection (IOR), approximately 30% of the plants on a plantation may be infested with spider mites and aphids. Bearing in mind the size of the mallow, their harmfulness is small and does not require the application of costly and environmentally undesirable plant protecting operations. Mallow plants were also infested with numerous omnivorous hemiptera such as the dock bug (*Coreus marginatus* L.) and the lygus bug (*Lygus* spp). The growing quantities of these insects suggests that in the case of multi–year plantations they, as well as butterfly caterpillars, may be a threat (Mrówczyński et al. 2007; Remlein–Starosta and Nijak 2007). The mallow is also susceptible to fungus infections of the *Fusarium*, *Sclerotinia sclerotiorum*, and *Botritis cinerea* type, causing fusariosis, *Sclerotinia sclerotiorum* mold, and noble rot (Grzesik et al. 2011).

2.2. Common osier

About 450 species of trees and shrubs throughout the world belong to the *Salix* genus. Among other things, willows are utilized to minimize the negative impact of Man on the ecosystem, including for the renovation, stabilization, and recultivation of disrupted areas, phytoremediation, the control and prevention of erosion, and the production of biomass (Kuzovkina and Quigley 2005). For economic reasons, in addition to the poplar and switchgrass, the willow is a promising energy plant for cultivation in United States regions with a moderate climate. The State University of New York developed a program for reproducing the willow whose effect is hybrids designated for the production of biomass and dendroremediation (Kopp et al. 2001). However, willow cultivation is of greatest importance in Sweden, the home of many varieties of willow that are also cultivated in Poland (Aronsson and Perttu 2001). A very useful feature in its cultivation is adaptation to growth at locations with very limited access to basic nutrient components. One of the reasons why this is possible is thanks to mycorrhizas, which guarantee additional sources of nutrients such as nitrogen and phosphorous. The colonization of disturbed areas by the willow marks a start, accelerating recultivation and bringing about increased biodiversity in such areas. Among changes that take place following the establishing of the willow in an area are the creation of humus, an improvement in soil structure and in the quantity of nutrient ingredient, shading, etc. The willow is also relatively resistant to salt (Highshoe 1988) and pollution, such as by heavy metals (cadmium, copper, zinc, lead) and radionuclide (cesium) (Kuzovkina and Quigley 2005). There are also reports of significant resistance to air pollution (Zvereva et al. 1997). Research into using the willow *Salix dasyclados*, that under defined conditions gives higher dry matter yields, are also underway (Tworkowski et al. 2010).

The common osier, with its favorable qualities as an energy crop, is a perennial plant with a plantation service life of fifteen–twenty years. The primary benefit of its cultivation is inexpensive and easy to independently prepare cuttings. The cultivation of only a single variety of willow on a plantation with a large area is a venture encumbered by significant risk. It is much safer to use several varieties, which should restrict the spreading of disease. In the case of cultivation for energy purposes, harvesting the willow once every three years is the best solution, as it is then that a bigger harvest per year is achieved, where additionally the wood has a higher energy value than in the case of an annual harvest. However, cultivation in a three–year cycle requires specialized and costly machines for the harvesting of biomass. The quick growth of biomass and its related intensive ion exchange between the roots and components of the polluted soil make this species particularly useful in its biological use in phytoremediation.

Both Swedish and English studies indicate that subject to moist condition the planting of willows at a density of 10,000–13,000 ha^{-1} is beneficial (Ericsson et al. 2009). Willows are harvested during the autumn–winter period when soils are usually very moist, which may impede or even make impossible the use of certain machines.

Willow may be cultivated on non–wetland, moist Grades IVa and IVb soils of the weak cereal–fodder Complex. It may be cultivated on Grade IVb or V soils made up of sands and included in the good Secale Complex, bearing in mind the fact that groundwater in such soils should occur no deeper than 250 cm. In the case of energy crops, there is the possibility of using weaker soils of lower quality grades, but only in the case of intensive fertilization and irrigation during dry periods. Willow plantations may be established on soils excluded from agricultural production for food purposes due to their salt content. In the case of dry soils, during seasons with low precipitation, the harvest are up to 30% lower than on moist soils This makes the cultivation of willow uneconomical.

Many factors have an impact on willow harvest. They include soil and hydrological conditions, the selected and used variety, and fertilization

(Kalembasa et al. 2006a; Rockwood et al. 2004; Stolarski et al. 2007; Kalembasa et al. 2009; Labrecque et al. 1993, 1994, 1997). Willow shrubs cultivated in Poland are estimated at approximately 15 t d.m. ha $^{-1}$ annum^{-1} (Stolarski 2003; Szczukowski and Stolarski 2005; Szczukowski et al. 2005a, b). At a planting density of 40,000 per hectare and fertilization at a rate of 75 kg ha^{-1} N, 50 kg ha^{-1} P_2O_5, and 75 kg ha^{-1} K_2O on Complex 8 soils (heavy black soil) with annual harvest cycles, the yield in the first year of cultivation amounts to 10.8 tons d.m. ha^{-1} (maple 1054), 17.2 tons d.m. ha^{-1} (maple 1052), 14.1 tons d.m. ha^{-1} (maple 1047), and 16.6 tons d.m. ha^{-1} (maple 1023). In the second and third years the harvest amounted to 12.4 and 11.5 tons d.m. ha^{-1} (maple 1054), 13.7 and 10.1 ton d.m. ha^{-1} (maple 1052), 12.7 and 12.8 ton d.m. ha^{-1} (maple 1047), and 12.6 and 10.0 ton d.m. ha^{-1} (maple 1023). At the same planting density and fertilization on medium soil of Complex 4, three successive years of cultivation yielded harvests amounting to 14.0, 12.1, and 12.7 tons d.m. ha^{-1} (maple 1054), 13.1, 10.8, and 10.8 tons d.m. ha^{-1} (maple 1052), 12.7, 9.4, and 11.2 tons d.m. ha^{-1} (maple 1047), and 13.4, 11.0, and 11.2 tons d.m. ha^{-1} (maple 1023) (Faber et al., 2007). In the case of harvests every three years on Complex 8 soils (heavy black soil), harvests amounted to 11.7 tons d.m. ha^{-1} annum^{-1} (maple 1054), 16.0 tons d.m. ha^{-1} annum^{-1} (maple 1052), 15.8 tons d.m. ha^{-1} annum^{-1} (maple 1047), and 18.3 tons d.m. ha^{-1} annum^{-1} (maple 1023), while on medium Complex 4 soils the yield was 15.2 tons d.m. ha^{-1} annum^{-1} (maple 1054), 13.4 tons d.m. ha^{-1} annum^{-1} (maple 1052), 15.2 tons d.m. ha^{-1} annum^{-1} (maple 1047), and 13.6 tons d.m. ha^{-1} annum^{-1} (maple 1023) (Faber et al. 2007). In the case of all other examined maples cultivated, harvest every three years gave larger yields than in the case of annual harvests.

Mineral, organic, and inexpensive sewage sludge, filtered effluent from waste dumps, and water from secondary treatment of sewage may be used in the fertilization of willow shrub plantations as the plant uses contained nutrients efficiently (Romanowska–Duda 2009; Kuś and Matyka 2010). The recommended quantities of fertilizer may be decreased by 10%–20% in the third and further years of cultivation because the plants reuse a part of the nutrient components found in falling leaves (Szczukowski et al. 2004). An absence of mineral fertilization results in a drastic 42% to 60% fall in harvests. The willow is significantly more sensitive to an absence of mineral fertilization than the miscanthus. Lack of potassium fertilization lowers willow yields by an average of 7%. This indicates a lower sensitivity to shortages of this element than in the case of the Virginia mallow. However, an absence of phosphorus fertilization lowered harvests by 22%. The role of phosphorus fertilization in the cultivation of the miscanthus and Virginia mallow is significantly lower. The willow also indicates a relatively small sensitivity to soil acidity. Cultivation on pH=4.2 soil lowered yields by just over 7% with respect to pH=6 soils (Łabętowicz and Stępień 2010).

Both diseases and pests are a threat to willow plantations. Diseases caused by fungus include rust (*Melampsora* sp.), leaf and shoot spotting (*Trichometasphaeria* sp.), blight (*Venturia* sp.), and anthracnose (*Aureobasidium* sp.). Also threatening are *Venturia chlorospora*, *Physalospora miyabeana*, and *Rhytisma salicinum* (Błażej 2007). The presence of phytophages during the first year of growth or on one–year basal shoots may cause a significant fall in the quantity and quality of the willow harvest. It is for this reason that it is particularly important to apply costly protection for young plantations (Czerniakowski 2005).

2.3. Miscanthus giganteus

The *Miscanthus* x *giganteus* is a perennial grass of southeast Asian origin. It is one of twenty species of miscanthus developed as a result of the cross breeding of Chinese silver grass (*Miscanthus siniensis*) and Amur silver grass (*Miscanthus sacchariflorus*). It has a strongly developed system of rhizomes and the expansive root system reaching over 2.5 m into the earth. Such an underground structure may be used to prevent erosion (Wersocki 2008). This plant uses C_4 carbon fixation (photosynthesis). This is in contrast to C_3 carbon fixation that is used by most plants in the Polish climate. In it there is no respiration during CO_2 assimilation in which 1/5 to 1/3 of the gas is released into the atmosphere (Osińsko 1996). The lack of CO_2 losses results in more rapid biomass increase and a higher carbon content in the plant tissue (Wersocki 2008). This grass forms large clumps made up of thick blades filled with a spongy core, where over 200 may make up a single plant. Miscanthus achieves a height of 200–450 cm. It has been cultivated in Europe for over eighty years. Initially it was an ornamental plant, but for over eighteen years it has been grown on energy plantations. Various studies have been conducted in Great Britain since 1990 on miscanthus biomass production subject to various conditions of temperature, solar insolation, water availability, and various soil conditions (Bullard et al. 1995; Nixon 2001; Ozimek 2009; Kuś and Matyka 2010). The plant is characterized by quick growth, high harvest yields per unit area, and resistance to low temperatures (Bullard et al. 1995; Nixon et al. 2001b).

In the first year of cultivation the harvest amounts to approximately 8 t d.m. ha^{-1}, while in the second it reaches 25–45 t d.m. ha^{-1} (Scurlock 1999; Danalatos 2007). This is at least ten times more than can be achieved by cultivating one hectare of forest (Uniśko 1996; Wersocki 2008). Annual harvests subject to the climatic conditions of Great Britain amount to 12–16 t d.m. ha^{-1}, Denmark 15–25 t d.m. ha^{-1}, and Austria 22 t d.m. ha^{-1} (Nixon and Bullard 1997; Scurlock 1999). In Poland the output of a several year old plantation reaches 20 t d.m. ha^{-1}. The service life of a miscanthus plantation is from ten to twenty–five years (Bullard and Metcalfe 2001; Wersocki 2008).

It has been confirmed that the *Miscanthus giganteus* has a broad scope of tolerance with respect to soils and pH (Nixon 2001). Subject to Polish climatic conditions, the cultivation of this plant should be concentrated on Grade IVb soils of a good Secale Complex. The structure of the root system makes possible the cultivation of the miscanthus on moderately cohesive Grade IVa and IVb soils with a low level of ground water (Kolowca et al. 2009). According to simulations conducted for Eastern Europe, in the case of very good soils subject to such conditions it is possible to achieve 17.7–21.8 t d.m. ha^{-1}, and 12.9–17.1 t d.m. ha^{-1} on good soils (Fischer et al. 2005). However, German experience demonstrates that on good soils it is possible to achieve up to 24 t d.m. ha^{-1}, but only 2–10 t d.m. ha^{-1} on poor soils (Surlock 1999). Applying a planting density of 15,000 (*Miscanthus* x *giganteus*) per hectare and fertilization amounting to 75 kg ha^{-1} N, 50 kg ha^{-1} P_2O_5, and 75 kg ha^{-1} K_2O on Complex 8 soil (heavy black soil), the yield achieved over three successive years was 9.0, 21.7, and 18.0 t d.m. ha^{-1}. With the same planting density and fertilization on Complex 4 medium soil, three successive annual harvests gave 10.4, 19.2, and 14.9 t d.m. ha^{-1} (Faber et al. 2007; Kuś et al. 2008). Harvests of miscanthus and willow dry matter on heavy black soil were similar in a three–year cycle. However, on medium soil the miscanthus gave a yield significantly better than that of the willow. During a very dry third year of cultivation, the harvest for miscanthus was approximately 50% greater than that of the one year basal shoots of the willow shrub (Faber et al. 2007).

Miscanthus plantings using seedlings produced in laboratories *in vitro* should amount to 10,000 to 12,000 plants per hectare with rows every 75–100 cm and distances between plants in the rows of 60–100 cm. Fifty to 100 cuttings may be received from one well–developed rootstock after three to four years of cultivation. Plants developing from such cuttings are already more deeply rooted in their first year. Because of this they are more resistant to damage caused by low temperatures than seedling produced using the *in vitro* method. Miscanthus biomass may be harvested during the period from November to December when its moisture content amounts to 35%–45%, or from March to April when water content falls to 25%–30% and elements unfavorable from the point of view of energy—chlorine, potassium, and sodium—are also lower. The negative aspect of the later date is lower yields due to the falling of leaves. Losses reach 15%–20% with respect to the late–autumn harvest.

The miscanthus' fertilization needs in the year of the establishing of the plantation are small. A total of 30 kg ha^{-1} N, 20 kg ha^{-1} P_2O_5, and 40 kg ha^{-1} K_2O are sufficient. A larger dosage of N–P–K is recommended starting with the second year—90 kg ha^{-1} N, 30 kg ha^{-1} P_2O_5, and 80 kg ha^{-1} K_2O. During the drying of plant shoots, large quantities of nutritional ingredients move to the rootstock, while through falling leaves, a part of them return to the soil. Thanks to this only small quantities of fertilizer components are removed from the field with the biomass harvest. Studies have demonstrated that applying N–P–K fertilizer at the recommended ratio of 2:1:1 did not significantly change the ash content (~3%). However, application of sewage sludge at a rate of 20 t ha^{-1}, which has a favorable impact on yield, decreased the quantity of ash after burning to approximately 2.5% with respect to the unfertilized control sample (3%). Sewage sludge applied at a rate of 10 and 40 t ha^{-1} increased ash quantities to 4% and 5%, respectively (Kacprzak et al. 2010).

Lack of mineral fertilization in the first year of cultivation resulted in a lowering of the harvest by approximately 25%. The role of mineral fertilization over successive years of cultivation is significantly smaller. It resulted in a fall in harvest yields by 10%–13% as compared with a full dosage of Ca–N–P–K. Miscanthus is significantly less sensitive to a lack of mineral fertilization than the willow. Study results show that the miscanthus is best adapted to utilize natural soil nutrient component resources subject to conditions of sandy soils (soils with a clay–sand granulometric make up). Absence of nitrogen while maintaining dosages of the remaining component lowered the harvest by a total of 43.5%, while an absence of N–P–K fertilization resulted in a fall of only 15.8%. Cultivation of soils with pH=4.2 lowered harvest yields by just over 7% as compared with soils of pH=6 (Łabętowicz and Stępień 2010).

Up to now, disease and pests were not a significant threat to miscanthus cultivation. Only a single viral disease is known that results in inhibited growth and chlorosis. However, it does not spread from plant to plant. Its source is infected seedlings (Wersocki 2008). Plantations existing in Poland have noted damage to miscanthus stems caused by the feeding of fly larvae as well as leaf damage characteristic of the feeding of the corn ground beetle (*Zabrus tenebroides* Goeze). In a longer timeframe, with an increase in the area of cultivations, this beetle from the ground beetle family may prove a major pest because miscanthus plantations provide it with potential for development. This will force the application of costly plant protection efforts (Mrówczyński et al. 2007).

In the case of the cultivation of miscanthus on good Secale Complex soils of Grade Iva quality that are acidic (pH=4.1), both the application of inexpensive sewage sludge (63 t ha^{-1}) and N–P–K fertilization at a dosage of 90:70:90 kg ha^{-1} as well as half that dosage had an impact on improving plant growth. N–P–K mineral fertilization using a full dosage resulted in an increase in plant height as well as mass by 44.4% and 96.1%, respectively, sewage sludge by 24.7% and 81.3%, respectively, and a half N–P–K dosage by 27.1% and 60.4%, respectively (Lisowski and Porwisiak 2010).

2.4. Switchgrass

Panicum virgatum has been grown in the United States as protection of the soil against erosion as well as animal fodder for the past fifty years. Studies conducted as of the nineteen–thirties have provided valuable data and led to the creation of many varieties designated for soil protection and as animal feed (Vogel 2000; Vogel and Jung 2001). As of the nineteen–nineties, the plant has been used by the United States Department of Energy as a model herbaceous energy plant for the production of bioethanol and electricity (Lemus et al. 2002; Schmer et al. 2006; Mulkey et al. 2006; 2008; Tober et al. 2007).

In Canada, the Resource Efficient Agricultural Production (REAP) organization has been working on the use of the *Panicum virgatum* for the production of biomass for energy purposes, bioethanol, and pulp for the production of paper since 1991. Intense research into the *Panicum* has resulted in an increase in the harvest yields of this pant, while most recent filed tests have shown that the cost of cultivation in the United States is a mere USD 46.00 per ton (Bals et al. 2010). A recent economic study in Nebraska, South Dakota, and North Dakota indicated that producers can grow switchgrass at a farm gate cost of USD 60/ton (Perrin et al. 2008). Producers with experience in growing switchgrass had five–year average costs of USD 43/ton, and one producer grew switchgrass for USD 38/ton. These costs include all expenses plus land costs and labor at USD 10/hour. Each ton of switchgrass represents 80 gallons (302.8 l), with a farm gate cost of USD 0.75/gallon at USD 60/ton. This research indicates that growing switchgrass for cellulosic ethanol is economically feasible in the central and northern Great Plains. It should be noted that fuel and land prices have increased since this study, so the cost increases for those inputs need to be considered when determining switchgrass production costs. (Perrin et al. 2008; Mitchel et al. 2012). Until recently, the *Panicum virgatum* was only known as an ornamental grass in Europe (Elbersen et al. 2000).

According to studies and simulations conducted in central Canada, switchgrass is a more promising energy plant than willow for those climatic and soil conditions. This is mainly due to the significantly lower overall costs of production of one ton of dry matter and better adaptation to hydrological and soil conditions (Girouard et al. 1995).

Studies conducted on a large scale (cultivation on fields with an area of three to nine hectares) have demonstrated that the cultivation of *Panicum virgatum* as an energy plant designated for biomass produces over 500% more renewable energy than it uses. Moreover, total greenhouse gas emissions resulting from the production of bioethanol using *Panicum virgatum* is 94% lower than in the case of gasoline (Schmer et al. 2008).

Among the benefits of cultivating switchgrass are:

- Large net energy production per hectare,
- Low costs of cultivation,
- Small nutrient requirements,
- Low ash content,
- Efficient water use,
- Adaptation to various geographical latitudes,
- Cultivation easy to start from seeds,
- Potential for adapting the plant to grow on non–agricultural soils that are too weak and degraded, and
- Capability of biological capture and storage of carbon dioxide.

Studies have demonstrated that the cultivation of switchgrass in Europe may be conducted on land significantly more to the north than is the case in North America. This is a result of climatic conditions, which are more moderate due to the presence of oceans.

Switchgrass is a C_4 type plant that has additional mechanisms for tying CO_2 through anatomical and physiological mechanisms, which makes possible an increased concentration of CO_2 in the cells (Gołaszewski 2011). The effect is that such plants have a quicker photosynthesis and greater biomass efficiency with a relatively small demand for water. They account for less than 5% of the world's flora. From an energy point of view, they are the most sought after plants. Apart from switchgrass (*Panicum virgatum* L.) they include common corn (*Zea mays* L.), miscanthus (Amur silver grass, Chinese silver grass, *Miscanthus giganteus*—*Miscanthus* sp.), sorghum (*Sorghum* sp.), and sugar cane (*Saccharum officinarum* L.) (Gołaszewski 2011).

Switchgrass is more resistant to drought than miscanthus and has achieved better harvests per hectare subject to unfavorable hydrological conditions.

Switchgrass may grow on many types of soil. It has a deep and very developed root system. Thanks to the phenomenon of mycorrhiza it can efficiently take up phosphorus. It can be cultivated on shallow and rocky soils, subject to erosion and with little water capacity as well as occasional flooding. *Panicum* cultivated on soils with a low pH give significantly higher harvests than other grasses in a moderate climate or than energy plants such as the common osier (*Salix viminalis*) (Elbersen et al. 2004).

The primary difficulty in cultivating this plant is fighting weeds, which are particularly threatening to energy plants that are slow growers in their first year (Elbersen et al. 2004; Bendfeldt et al. 2001; Shrestha and Lal 2006).

Panicum virgatum harvests are dependent on the soil and climate conditions of the site of cultivation and may range from 6 t d.m. ha^{-1} in the case of poorly fertile soils in northern Europe to over 25 t d.m. ha^{-1} in fertile soils found in the southern zone (Elbersen et al. 2004). Harvests achieved on Upper Great Plans United States farms range from 5.2 to 11.1 tons ha^{-1} and deliver 60 GJ of energy per annum (Schmer et al. 2008). In the case of proper cultivation it is possible to achieve long–term production stability lasting over fifteen years.

Subject to long–term drought and during pre–winter drying, perennial high prairie grasses such as switchgrass and cordgrass are capable of the translocation of 30% of the nitrogen found in their above–grade parts into their roots and rhizomes (Chołuj et al. 2008; Elbersen et al. 2004).

It has been demonstrated that switchgrass cultivated subject to northeastern European conditions has sufficient nitrogen resources from the soil, remobilized from the roots, and deposited from the atmosphere. In the case of very infertile soils and irrigation, nitrogen fertilizer may be unnecessary. Up till now diseases have not been a problem in the cultivation of *Panicum* in Europe, which does not require plant protection operations.

Depending on the type of soil, optimum production is achieved in the 2–3 year for light soils and the 4–5 year for heavy soils. The first–year harvest is small and may be uneconomical in northern areas. The second–year harvest amounts to 8–10 tons of dry matter per hectare and increases further in the third year. Early frosts and drought may delay the full harvest potential (Elbersen et al. 2004; Fike et al. 2006; Monti et al. 2001; Parrish and Fike 2005).

Switchgrass has a total lignin content of approximately 17.6%, cellulose 31.0%, and hemicellulose 24.4% (USDE). Cellulose and lignin content in biomass is important in biochemical processing by way of methane or alcohol fermentation. The conversion of lignocellulosic biomass into ethanol is an environmentally–friendly alternative to petroleum (Bals et al. 2010). The biodegradability of cellulose is higher than that of lignin, which means that biomass with low lignin content is more useful for fermentation processes.

Moreover, the spatially mutual placement of lignin and cellulose in biomass has an enormous impact on possibilities of utilizing cellulose as raw material for fermentation (Pulaski et al. 2010). *Panicum* biomass is receptive to preliminary processing and hydrolysis. According to research by Balsa et al. (2010), there is an over 90% conversion of the hydrocarbon cell walls into simple sugars. The energy value for cellulose may change slightly depending on the quality of the raw material, where the average heat of combustion amounts to 17.4 MJ kg^{-1} while that for lignin is 21.2 MJ kg^{-1}. The lower heat of combustion for cellulose is caused by its higher level of oxidation (Podlaski et al. 2010).

3. Economic analysis of the production of selected energy plants

Growth in interest in perennial energy plants on the part of potential planters, including increase in increasing cultivated area, is dependent on the profitability of production. It should be assumed that such profitability must be higher than the profitability of cereal or rape production for consumption. It is only then will farmers be interested in such cultivation. In the event of just slightly higher or lower production profitability, compared with growing annual farming plants, there will be no increase in area for energy cultivation on agricultural land. This stems from the fact that multiyear energy crop plantations are established once every ten to twenty–five years, where initial costs are high and there is no return until after several years—longer than in the case of annual crops. Moreover, the cultivation of such plants is, from the point of view of the farmer, encumbered by significantly higher risk than one–year cultivations (Stuczyński et al. 2008; Kwaśniewski 2011).

Discussions underway in the scientific community as well as public opinion see the risk of an increase in the prices of plant products resulting from the appearance of new sources of demand from the energy sector that will compete for space with demand for plant products as generated by the food sector. These concerns are also justified by reports by international organizations such as those of the FAO and OECD. They point to forced demand for biofuels, which may lead to growth in competition for agricultural space and an increase in food process (OECD–FAO, 2007). Newer studies project a fall in the prices of cereals by 2020, which will make investments in energy crop plantations more profitable (OECD–FAO, 2011). The development of second–generation biofuels will work to decrease the use of raw materials derived from annual plants serving the production of first–generation biofuels in the energy industry. Second–generation plants may be cultivated with relatively large efficiency on soils that are not suitable for food–oriented cultivation. In their turn, the development of third–generation biofuels may lead to a complete independence of production from soil quality and hydrological conditions, where only solar insolation and temperature will be determinants. Bearing in mind these factors and applying an appropriate policy of agricultural spatial management, the risk of increased price for food due to energy biomass production will fall.

Estimating plantation costs is rather difficult due to the very large number of variables with an effect on it, the continuous development of agricultural technology, the specifics of individual countries or even regions, and the incomplete data available in literature. This may result in both over– and under–estimation. Growth in the number of commercial plantations will lead to the optimizing of planting and harvesting processes as well as improved management. In its turn, this will play a role in continued falling prices. On the other hand, increases in energy costs will result in higher fertilizer and transportation costs (Faasch and Patenaude 2012).

The three most frequently cultivated energy plants in Poland are the common osier, the Virginia mallow, and the *Miscanthus giganteus*. Production profitability, understood as the relation of the value of achieved production to costs incurred to produce it, is different for each of those species. In light of the specifics of cultivating perennial energy plants, significant costs must be borne when establishing the plantation. It is necessary to take into account the readying of the fields (soil analysis, machine and tool use, materials such as fertilizer, herbicides, etc., and labor costs), the procurement or production of seedlings, inclusive of transportation, planting (use of machines and tools, labor costs), and tending throughout the growing season (use of machines and tools, materials such as fertilizers, pesticides, etc., labor costs). The costs incurred will vary significantly depending on plant species and the scale of the venture (manual or machine effort). From among the most frequently cultivated species in Poland, the decidedly highest costs of establishing a plantation are incurred in the case of the miscanthus. This is due to the high costs of procuring cuttings (this plant does not produce seeds). Depending on their quality (number of basal shoots and possible damage), type (root cuttings received from an existing plantation or reproduced using the *in vitro* method), and the volume of the order, prices may range from PLN 0.35 all the way up to approximately PLN 1.50. The planting density ranges from 10,000 to 18,000 plants ha^{-1}. This gives an average of PLN 15,250 (PLN 3,500 to PLN 27,000) for planting material necessary to establish one hectare of plantation. What is most often done in practice is a planting density of 12,000 plants ha^{-1}, where cuttings of good quality may be purchased at PLN 0.70. Such a price is offered in the case of the purchase of quantities as needed to plant up to 50 ha, which gives PLN 8,400/ha. In the case of large areas of approximately 100 ha, the price may fall to PLN 0.50, which generates a cost of PLN 6,000/ha. The costs of establishing one hectare of miscanthus plantation in 2008 (Matyka 2008) were calculated at PLN 21,871, while a 2009 analysis assuming complete mechanization as conducted on Vattenfall (by Bio Energia) stated a price of PLN 20,640 (Vattenfall 2009). The cost of establishing one hectare of willow plantation in 2008, depending on planting method, amounted to PLN 8,732–9,231 in 2008 (40%–43% of the costs of establishing a miscanthus plantation) and PLN 6,575 in 2009 (31.8% of the costs of a miscanthus plantation). However, in the case of the Virginia mallow, the costs amounted to PLN 9,721–11,349 (44%–53% of the costs of establishing a miscanthus plantation) and PLN 7,775 (36.7% of the costs of establishing a miscanthus plantation).

Analysis of the costs of existing plantations performed in 2011 (Kwaśniewski 2011) defines the average cost of establishing a plantation at PLN 5,328.7 ha^{-1}. Smaller plantations (up to 5 ha) had decidedly higher costs (PLN 6,481.4 ha^{-1}), while for larger plantations (over 5 ha) they amounted to PLN 4,176.1 ha^{-1}. The highest share in tangible costs was for seedlings. On average, they amounted to PLN 2,688 ha^{-1} (92.7% of tangible costs) for the group of plantations up to 5 ha, while for the group of plantations over 5 ha these costs amounted to PLN 1,152 ha^{-1} (75.5% of tangible costs). For all examined plantations the assessed costs are PLN 1,920 ha^{-1} and their share in the cost structure is 84%. In the case of larger plantations of the second group, in three out of five cases, owners used seedlings from what are known as mother plantations, which had a significant impact on the lowering of the costs of planting material. It is also for this reason that the costs were significantly lower in the second group. Harvesting and harvested matter transportation costs were decidedly dominant in production costs. They amounted to from PLN 3,110.1 ha^{-1} on plantations where harvesting was conducted using combustion engine brushcutters to PLN 7,833.6 ha^{-1} for plantations where Mengele self–propelled forage harvesters (this was the only plantation where biomass was harvested in the form of chips). The annual depreciation costs related to the establishing of a plantation were in the PLN 327/7 to PLN 1,048.9 ha^{-1} range. Total biomass production costs amounted to from PLN 3,942 ha^{-1} for plantations using disc mowers to PLN 8,435 ha^{-1} for plantations with self–propelled harvesters.

Differentiation in the costs of establishing a plantation is linked with the method of planting and is highest in the case of mallow. The most expensive method of establishing a plantation is using hand–planted rooted cuttings, while the least expensive is direct sowing of seeds into the soil (Matyka 2008). In each case a significant share in the cost structure is made up of plant material that, in the case of the miscanthus planted using a transplanter, amounts to 71% of the costs of establishing a plantation and 24% of overall costs. In the biomass production process using energy willow, in addition to the costs of establishing and operating the plantation, it is necessary to take into account the costs of its liquidation. Stolarski et al. (2008) put them at PLN 2,075 ha^{-1}, while in other studies they were calculated at PLN 1,129 ha^{-1} (Matyka 2008) and PLN 1,078 ha^{-1} (Vattenfall 2009).

Calculations performed in 2008 (Matyka, 2008) point to a very interesting phenomenon. A comparison of the cost and revenue parts in calculations demonstrated that in the case of all energy plants encompassed by analysis, revenues from such production did not cover costs. Analysis indicated that the main source of revenues for farmers managing energy–oriented plantations is the value of production (82%) and direct subsidies (13%). The calculations conducted by the authors took into account subsidies then in effect on the cultivation of energy plants (5% of revenues). Presently, such subsidies are no longer available. However, subsidies have been introduced for short–rotation forest tree groves, which include the willow.

According to calculations conducted in Germany, the preparing of the field (mechanical and chemical operations) for willow and poplar cultivation amount to EUR 281.8 ha^{-1} on average. On average, the cost of machine planting of plants is EUR 0.04 per plant. The costs of seedlings (cuttings) of the poplar and willow amount to EUR 0.20 and EUR 0.08, respectively, when the reproductive material is bought on the open market, and EUR 0.15 and EUR 0.04 for reproductive material produced in–house. In the case of willow plantations the planting density amounts to from 18,000 to 32,000 plants ha^{-1}, while in the case of the poplar it is approximately 12,000 plants ha^{-1}. The costs of fertilization amount to EUR 155.5 ha^{-1} annum^{-1}. Harvesting, drying, and transporting biomass was estimated at EUR 40.8 t^{-1} d.m. Assuming an average yield at a level of 11.6 t d.m. ha^{-1} annum^{-1} (Germany), this works out to be EUR 473.28 ha^{-1} annum^{-1}. Liquidation of the plantation costs EUR 1,023 ha^{-1}, which in the case of a twenty–year cultivation gives EUR 51.15 ha^{-1} annum^{-1}. An interesting conclusion stemming from the analysis is that SRC production is more profitable in Germany than in Poland or Northern Ireland, which is the result of the significantly lower costs of chips in those countries (Faasch and Patenaude 2012).

Of the ten plantations encompassed by analysis in 2011 (Kwaśniewski 2011), only in the case of two can biomass production be profitable at an assumed price of PLN 120 t^{-1}. In the case of a successive two, such production will generate profits at a price greater than PLN 150 t^{-1}, with four assuming a price of PLN 170 t^{-1}. Achieving such a high price for the sale of fresh, unprocessed biomass in the nearest future is highly improbable. The extremely diverse profitability indicators for biomass production (at assumed prices) confirm the suggestions of many authors that the production of biomass using energy willow in the current macro–economic conditions in southern Poland is not profitable.

4. Logistic strategies for biomass deliveries

Criteria for sustainable development with respect to biofuels and bioliquids have been defined in order to implement the requirements of Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. These criteria detail the restriction of greenhouse gas emissions by at least 35%, where it is assumed that there will be an increased reduction in the emission of these gasses by 50% up to the year 2017 and by 60% as of January 2018. Calculations of gas emissions should be provide in **life cycle assessments** (**LCA**), which is intended to assess potential threats to the environment. The essence of this method is estimating and assessing the consequences of the entire technological process as well as management strategies for it with respect to the natural environment. The analysis should encompass the entire system, from raw material production to the final product, including the impact of biomass transportation on energy, economic, and environmental efficiency.

As to national energy policy, the basic document that is in effect is "Energy Policy Up to the Year 2030" (in Polish) as approved by the Council of Ministers on January 4, 2010, which includes energy safety and respect for environmental protection (Ministry of the Economy 2010). Developed logistic operations should provide for interdisciplinary engineering of the systems and encompass services for the entity (the plant biomass producer), demand projections, information flow, stock monitoring, the rational storage of plant biomass, contracting and the supply of production plants in agrobiomass, and the organization and management of delivery transportation. Logistic systems should take into account planned optimum costs during performance of operations. In order to increase energy production using renewable sources, it is vital to optimize the logistics of deliveries of raw material and the development of public awareness relating to aspects of business management. To date, many works have appeared on the design of biomass supply strategies and management systems aimed at generating energy from second–generation biomass (Brouglieri and Liberti 2008; Dunnett et al. 2008). Sokhansanj et al. (2006) described the dynamic model of consolidated logistics with the biomass load. This model facilitates the simulation of the entire process from raw material sourcing, storage and warehousing all the way to biomass transportation. Bearing in mind the low level of biomass production in certain regions of Poland, individual system modeling is necessary. Also worthwhile is continued interdisciplinary development that will take into account the individual needs of the country's regions for efficient and stable biomass supply.

5. Conclusions

Appropriate policy of agricultural spatial management, will decrease the risk of increased price for food due to energy biomass production. Profitability of energetic plants cultivation must be higher than the profitability of cereal or rape production for consumption. In the event of just slightly higher or lower production profitability, compared with growing annual farming plants, there will be no increase in area for energy cultivation on agricultural land. The development of second–generation biofuels will work to decrease the use of raw materials derived from annual plants serving the production of first–generation biofuels in the energy industry. Choosing the right energy plant species adapted to the habitat, and to create a local market of biomass are the two most important determinants of profitability of the investment.

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Streszczenie

ANALIZA EKONOMICZNA I STRATEGIE LOGISTYCZNE PRODUKCJI BIOMASY WYBRANYCH ROŚLIN ENERGETYCZNYCH

Celem nieniejszego artykułu było przeprowadzenie analizy produkcji wybranych roślin energetycznych, które w Polsce są już podstawowym źródłem agrobiomasy. W treści analiza zawierała aspekty środowiskowe i uwarunkowania produkcji biomasy na cele energetyczne dla ślazowca pensylwańskiego (Sida hermaphrodita), wierzby wiciowej z rodzaju Salix,i miskanta olbrzymiego (Miscanthus x giganteus) i prosa rózgowatego (Panicum virgatum). Przedstawiono analizę ekonomiczną produkcji wybranych roślin energetycznych z uwzględnieniem kosztów plantacji i ich opłacalności oraz zasygnalizowano strategie logistyczne dla dostaw biomasy w celu zabezpieczenia stałej produkcji energii odnawialnej w zrównoważonym rozwoju.