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THE ENERGY EFFICIENCY OF WILLOW BIOMASS PRODUCTION IN POLAND – A COMPARATIVE STUDY

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ABSTRACT: Field experiments with willow (*Salix* L.) coppice cultivation and Eko-Salix systems have been conducted at the University of Warmia and Mazury since 1992. In that wider context, the aim of the work described here was to compare energy inputs involved in setting up a plantation and producing biomass, and to assess the efficiency of willow-chips production under the coppice and Eko-Salix systems. The energy gain determined in the experiments was several to more than twenty times as great as the inputs needed to operate the plantation and to harvest willow biomass, this leaving both systems of willow cultivation under study attractive where setting up short-rotation coppices is concerned.

KEY WORDS: willow, cultivation systems, energy input, efficiency of chips production, biomass.

INTRODUCTION

Field experiments with coppice cultivation of willow (*Salix* L.) involving a **S**hort-**R**otation **W**oody **C**rops (SRWC) system (of 3–4-year rotation), or else the Eko-Salix systems (5-year rotation) have been conducted by the University of Warmia and Mazury since 1992, at the four experimental facilities of Bałdy, Łężany, Obory and Tomaszkowo. At the same time, a programme has been pursued to develop new willow cultivars for the two cultivation systems. This cultivation work puts great emphasis on increased productivity, resistance to pests and diseases and the selection of cultivars to match different types of soil. The genetic and breeding work has produced the Start, Sprint Turbo, Monotur, Kortur, Oltur, Tur, Żubr and Ekotur cultivars of willow, over which the breeder (UWM in Olsztyn) acquired exclusive rights by virtue of a decision of the Head of the Research Centre for Cultivar Testing with the Patent Office of the Republic of Poland granting patent P No. 213441 – for the establishment of a willow plantation. In addition, field experiments on short (3–6-year) rotations of poplar (*Populus* L.) and black locust (*Robinia pseudoacacia* L.) have also been conducted at the UWM in Olsztyn (Stolarski *et al.* 2014b).

Plantations of willow to be used as energy feedstock are established on agricultural land using cuttings 18–25 cm long, planted in two rows. The distance between rows is 0.75 m, with 1.5 m between belts. The usual spacing is of 0.5 m in a row, equating to 18 000 cuttings per ha. Cuttings are planted with a planter in the spring, the site having been prepared in the preceding year. To facilitate the growth of young willows, mechanical and chemical weed control measures are taken during the first year of cultivation, after cuttings have been planted in carefully prepared soil. Willows are harvested every three years for about 20 years. Plantations of this kind should be located on agricultural soil prepared in the same manner as for other agricultural crops (Szczukowski *et al.* 2012, Stolarski *et al.* 2014a,c).

Recently, the setting-up of plantations using the Eko-Salix method has been proposed for land which is not suitable for edible crops, as an alternative option in biomass production (Stolarski *et al.* 2011a, Szczukowski *et al.* 2011, Tworkowski *et al.* 2010). Establishment of plantations under the Eko-Salix system involves using 2.00–2.50 m un-rooted, woody cutting live stakes obtained from three-year willow shoots. Such long cuttings are planted at a depth of 0.4–0.6 m, with rows spaced every 2.00–3.00 m and with plants spaced every 1.00–1.50 m in a row. Long cuttings are planted in unploughed soil. During the first year of growth, weeds could be mown in inter-rows (Stolarski *et al.* 2011b, Tworkowski *et al.* 2011). This method of planting long cuttings (live stakes) of willow (Eko-Salix) makes the preparation of the site easier compared with the traditional method of setting up SRWC plantations on agricultural land using short cuttings. The need for ploughing is also eliminated, while the costs of nurturing and treatment with fertiliser are reduced, and the farmer's interference at the site minimised (Stolarski *et al.* 2011a). In future, the founding of short-rotation willow coppice systems (especially of the Eko-Salix type) over considerable areas of marginal land and partial wasteland could reduce the clearing of forests for wood intended for industrial purposes considerably.

It is stressed *in litt.* that the yield of willow biomass obtained with different cultivation systems is only one of the criteria used to evaluate utility for industrial purposes. It is also important to assess the amounts of materials and energy expended on obtaining willow biomass, the amount of energy in it and the consequent energy ratio. Meeting those conditions is necessary to make further stages of biomass conversion to secondary energy carriers justifiable energetically and economically (Heller *et al.* 2003). However, willow cultivation is also favourable from the environmental point of view. Research by Krzyżaniak *et al.* (2013) shows that greenhouse gas emissions from the combustion of willow are less than one-fifteenth of those due to coal.

The aim of the work described here was thus to compare the energy inputs associated with the establishment of a plantation and production of biomass, as well as to assess and compare the efficiency of willow-chips production using the SRWC or Eko-Salix systems.

MATERIALS AND METHODS

Experiments with willows cultivated under the SRWC system on a 3-year rotation were conducted at the Didactic and Research Station in Łężany: at the Łężany facility (53˚58' N, 21˚8' E). Those involving the Eko-Salix system were in turn run at the Łężany-Kocibórz facility (54˚00', 21˚10'). The station is owned by the University of Warmia and Mazury in Olsztyn.

The experiment at the Łężany facility was conducted in the years 2008–2011 on typical proper, incomplete brown soil formed from medium loam on loamy, light, silty sand. This is classified as Class IVa arable land, defective wheat complex. The water table level was located more than 1.5 m below the surface, and water relations were appropriate. Willow cultivars and clones were grown at 25 000 cuttings ha^{-1}, and harvested every 3 years.

Willows were grown at the Łężany-Kocibórz facility under the Eko-Salix system in the years 2006–2010 and on peat-muck soil (Ł-MtII cb). The water table level was found at 0.1–0.3 m. Six cultivars and clones of willow were examined at a long-cutting planting density of 5 200 ha^{-1}.

The energy ratio for the production of chips from the willow cultivars under study was analysed based on the fresh biomass average yield obtained with the production systems under study.

It was assumed that a one-stage willow harvest would be conducted on a 3-year cycle with a Claus Jaguar 830 combine harvester and in a two-stage harvest with a chainsaw and grinding wood chipper on a 5-year cycle. Transport loco plantation was taken into account in each method of biomass harvesting.

The total input was divided into stages. The first stage involved establishment of the plantation and the second stage its operation. The material and energy inputs required to set up and operate a plantation in the first year of growth, as well as those needed to liquidate it at some later point was presented overall, and then divided into the 19-year period of operation under the SRWC system, or else the 20-year period characterising the Eko-Salix system.

The accumulated material and energy input in the growing of willow and production of chips were determined using standard methodology (Anuszewski 1987, Szeptycki and Wójcicki 2003, Wójcicki 2005, 2007). The analysis of the materials and energy incurred to set up the plantation and produce willow chips, encompassed separate streams of energy: direct energy carriers (diesel fuel); wear on fixed assets and materials used to repair them (tractors, machines, tools); consumption of mineral fertilisers and agrochemicals, consumption of plant materials (cuttings) and human labour. The energy input associated with direct energy carriers, mineral fertilisers, agrochemicals, and the use of tractors, machines and human labour was calculated on the basis of accumulated energy intensity indexes (Szeptycki and Wójcicki 2003, Wójcicki 2007).

The energy ratio for the production of chips from the willow cultivars was analysed by reference to the average yield of fresh biomass obtained with the production systems under study. The yield energy value was then calculated by multiplying the net calorific value of fresh biomass by its yield per ha. Assessment of the willow-cultivation system and chips production on a plantation in terms of its energy efficiency involved: the cumulative energy gain, which was the difference between the energy value of the yield and the total input used to obtain it; as well as the energy ratio for chips production, which was calculated as the ratio of the energy value of the biomass yield and the cumulative material and energy input required to achieve it.

RESULTS AND DISCUSSION

The cumulative material and energy inputs involved in setting up and operating a 1 ha willow plantation were found to be greater during the first year of growth under the Eko-Salix system than the SRWC system, and amounted to 48 235 and 23 461 MJ ha^{-1}, respectively (Tab. 1). The inputs per year of plantation use amounted to 2 412 and 1 235 MJ ha^{-1}. The higher material and energy inputs in the Eko-Salix system as compared with the SRWC system resulted from the high energy inputs necessary to make long cuttings (25 536 MJ ha^{-1}) and to plant them manually (17 973 MJ ha^{-1}). This therefore makes clear the urgent need for the plantation planting of long cuttings to be mechanised.

Table 1. Cumulative material-energy inputs incurred in the establishing and running of willow plantations based on the **S**hort-**R**otation **W**oody **C**rops (SRWC) or Eko-Salix systems

Specification	**Cultivation system**	
	SRWC Łężany Site: planting density 25 000 cuttings ha^{-1}, harvest every 3 years	**Eko-Salix Łężany-Kocibórz Site: planting density 5 200 long cuttings ha^{-1}, harvest every 5 years**
Total inputs (MJ ha^{-1})	23 461	48 235
Per year of plantation activity 1/19	1 235	–
Per year of plantation activity 1/20	–	2 412

Cumulative material and energy inputs for the production of chips varied with the system of cultivation (Fig. 1); being greater with the Eko-Salix system and when plants were harvested on a 5-year rotation, as opposed to with the SRWC system and a 3-year harvest rotation. Inputs of direct energy carriers and human labour accounted for most of the energy streams under the Eko-Salix system, whereas inputs of direct energy carriers and the consumption of mineral fertilisers and pesticides accounted for most of such streams with the SWRC system.

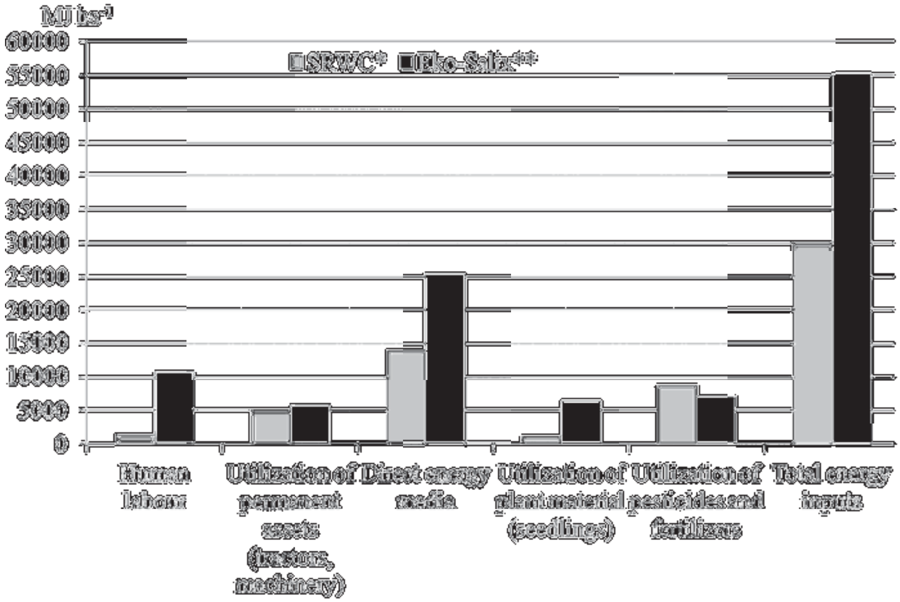

Figure 1. Cumulative material-energy inputs incurred by the technologies producing willow chips within the framework of the SRWC or Eko-Salix systems (MJ ha^{-1})

SRWC* – Łężany Site: planting density 25 000 cuttings ha^{-1}, harvest every 3 years;

Eko-Salix** – Łężany-Kocibórz Site: planting density 5 200 long cuttings ha^{-1}, harvest every 5 years.

The cumulative material and energy inputs in the Eko-Salix and SRWC systems (expressed per ha and per year) were similar, and amounted to 11.0 and 9.9 GJ ha^{-1} $year^{-1}$ (Tab. 2). At 209.9 GJ ha^{-1} $year^{-1}$, the energy value of the willow biomass yield under the SRWC system (with willows planted at a density of 25 000 cuttings ha^{-1} and harvesting taking place every 3 years) was significantly greater than the 128.0 GJ ha^{-1} $year^{-1}$ ascribable to the Eko-Salix system, with its density of 5 200 long cuttings per ha and biomass harvesting on a 5-year rotation.

Kwaśniewski (2010) reported that the energy value of willow biomass under the SRWC system, obtained on a three-year harvest rotation, amounted to 226 GJ ha^{-1} $year^{-1}$. According to Börjesson and Berndes (2006), the energy value of yield from plantations under the SRWC system can be close to 200 GJ ha^{-1} $year^{-1}$. On the other hand, Stolarski (2009) found that the energy value of willow biomass harvested every 3 years ranged from 188 to 349 GJ ha^{-1} $year^{-1}$ where humus-rich alluvial soil under optimum agrotechnical conditions was used. In another experiment conducted using the Eko-Salix system on the same soil (Stolarski *et al.* 2011b), the willow biomass yield energy value was shown to range from 162 to 220 GJ ha^{-1} $year^{-1}$.

Table 2. Energy efficiency of the production of willow chips using the **S**hort-**R**otation **W**oody **C**rops (SRWC) and Eko-Salix systems

Specification	**Cultivation system**	
	SRWC Łężany Site: planting density 25 000 cuttings ha^{-1}, harvest every 3 years	**Eko-Salix Łężany-Kocibórz Site: planting density 5200 long cuttings ha^{-1}, harvest every 5 years**
Energy inputs (GJ ha^{-1} $year^{-1}$)	9.9	11.0
Energetic value of yield (GJ ha^{-1} $year^{-1}$)	209.9	128.0
Energy gain (GJ ha^{-1} $year^{-1}$)	200.0	117.0
Unit energy consumption in wood-chips production (MJ t^{-1})	406.0	690.0
Index of energy efficiency of chips production	21.2	11.6

The cumulative energy gain with the SRWC system was higher by 83 GJ ha^{-1} $year^{-1}$ than that under the Eko-Salix system (Tab. 2). The energy intensity index per unit output of willow chips in the SRWC system was thus more favourable (at 406 MJ t^{-1}) than the values of 690 MJ t^{-1} obtained for the Eko-Salix system. The energy ratio for willow-chips production (the energy value of the yield as set against the energy input needed for its production) was in turn higher with the SRWC system, at a density of 25 000 plants ha^{-1} and a three-year harvest rotation, than with the Eko-Salix system, in which willows were planted at a density of 5 200 plants ha^{-1} and harvested every 5 years.

Stolarski *et al.* (2011b) reported energy ratios of 14.3 and 14.8 respectively, for willow production with the Eko-Salix system on alluvial soil unusable for consumer crops, on a 3-year rotation and with densities of either 5 200 or 7 400 long cuttings ha^{-1}. Kwaśniewski (2010) in turn found that the energy ratio for willow biomass production under an SRWC system harvested every 3 years could vary widely (from 15.4 to 40.7), in relation to the facilities under analysis.

According to Heller *et al.* (2003), Matthews (2001) and Pisker (2008), factors having a significant effect on energy ratio are: the method of site preparation and soil type, the density of planting of cuttings in the plantation, the amounts of mineral fertilisers used, the use of plant-protection products, agrotechnical measures and – especially – the method used to harvest willows.

SUMMARY

By growing willow using the SRWC and Eko-Salix systems, it is possible to obtain considerable amounts of biomass, although it is necessary to ensure the right choice of species and cultivar, as well as appropriate operation of the plantation.

The energy value of willow biomass yield under the SRWC system at a density of 25 000 cuttings per ha and biomass harvested on a 3-year rotation was significantly higher than in the Eko-Salix system, with its density of 5 200 long cuttings per ha and a biomass harvest on a 5-year rotation (209.9 GJ ha^{-1} $year^{-1}$ and 128.0 GJ ha^{-1} $year^{-1}$, respectively).

The energy gain in the experiments was between several and over twenty times greater than the inputs needed to operate the plantation and to harvest willow biomass, which makes both systems of willow cultivation under study attractive where the establishment of short-rotation coppices.

REFERENCES

Anuszewski R., 1987, *Metoda oceny energochłonności produktów rolniczych*, (*Method of evaluating the energy intensity of agricultural products*), Zagadnienia Ekonomiki Rolnictwa, 4, 16–26.

Börjesson P., Berndes G., 2006, *The prospects for willow plantations for wastewater treatment in Sweden,* Biomass and Bioenergy, 30, 428–438.

Heller M.C., Keoleian G.A., Volk T.A., 2003, *Life cycle assessment of a willow bioenergy cropping system*, Biomass and Bioenergy, 25, 147–165.

Krzyżaniak M., Stolarski M.J., Szczukowski S., Tworkowski J., 2013, *Life cycle assessment of willow produced in short-rotation coppices for energy purposes*, Journal of Biobased Materials and Bioenergy, 7, 5, 566–578.

Kwaśniewski D., 2010, *Efektywność energetyczna produkcji biomasy z trzyletniej wierzby*, (*Energy efficiency of biomass production from a 3-year old willow*), Inżynieria Rolnicza, 5, 123, 113–119.

Matthews R.W., 2001, *Modelling of energy and carbon budgets of wood fuel coppice systems,* Biomass and Bioenergy, 21, 1–19.

Piskier T., 2008, *Efektywność energetyczna uprawy wierzby w różnych warunkach glebowych*, (*Energy efficiency of willow cultivation under various soil conditions*), Inżynieria Rolnicza, 2, 100, 215–220.

Stolarski M., 2009, *Agrotechniczne i ekonomiczne aspekty produkcji biomasy wierzby krzewiastej (Salix spp.) jako surowca energetycznego*, (*Agrotechnical and economic aspects of biomass production from willow coppice Salix spp. as an energy source*), Rozprawy i Monografie, 148, UWM Olsztyn, 145 pp.

Stolarski M., Szczukowski S., Tworkowski J., Klasa A., 2011a, *Willow biomass production under conditions of low-input agriculture on marginal soils*, Forest Ecology and Management, 262, 1558–1566.

Stolarski M., Szczukowski S., Tworkowski J., 2011b, *Efektywność energetyczna produkcji biomasy wierzby w systemie Eko-Salix*, (*Energy efficiency of willow biomass production in the Eko-Salix system*), Fragmenta Agronomica, 1, 28, 62–69.

Stolarski M.J., Krzyżaniak M., Szczukowski S., Tworkowski J., 2014a, *Efektywność energetyczna produkcji biomasy wierzby w jednorocznym i trzyletnim cyklu zbioru*, (*Energy efficiency of willow biomass production in one or three-year harvest cycles*), Fragmenta Agronomica, 31, 2, 88–95.

Stolarski M.J., Krzyżaniak M., Szczukowski S., Tworkowski J., Bieniek A., 2014b, *Short-rotation woody crops grown on marginal soil for biomass energy,* Polish Journal of Environmental Studies, 23, 5, 1727–1739.

Stolarski M.J., Krzyżaniak M. Tworkowski J., Szczukowski S., Gołaszewski J., 2014c, *Energy intensity and energy ratio in producing willow chips as feedstock for an integrated biorefinery,* Biosystems Engineering, 123, 19–28.

Szczukowski S., Stolarski M., Tworkowski J., 2011, *Plon biomasy wierzby produkowanej systemem Eko-Salix*, (*Yield of willow biomass produced in the Eko-Salix system*), Fragmenta Agronomica, 28, 4, 104–115.

Szczukowski S., Tworkowski J., Stolarski M., Kwiatkowski J., Krzyżaniak M., Lajszner W., Graban Ł, 2012, *Wieloletnie rośliny energetyczne*, (*Perennial energy plants*), Warszawa, Oficyna Wydawnicza Mulico, 156 pp.

Szeptycki A., Wójcicki Z., 2003, *Postęp technologiczny i nakłady energetyczne w rolnictwie do 2020 r.*, (*Technological development and energy inputs in agriculture up to the year 2020*), IBMER, Warszawa, 242 pp.

Tworkowski J., Szczukowski S., Stolarski M., 2010, *Plonowanie oraz cechy morfologiczne wierzby uprawianej w systemie Eko-Salix*, (*Yield and morphological features of willow cultivated using the Eko-Salix system*), Fragmenta Agronomica, 27, 4, 135–146.

Tworkowski J., Stolarski M., Szczukowski S., 2011, *Efektywność energetyczna produkcji biomasy wierzby systemem Eko-Salix,* (*Energy efficiency of willow biomass production in the Eko-Salix system*), Fragmenta Agronomica, 28, 4, 123–130.

Wójcicki Z., 2005, *Metodyczne problemy badania energochłonności produkcji rolniczej,* (*Methodological question at investigation of energy inputs in agricultural production*), Problemy Inżynierii Rolniczej, 1, 5–12.

Wójcicki Z., 2007, *Poszanowanie energii i środowiska w rolnictwie i na obszarach wiejskich,* (*Saving energy and the environment in agriculture and in rural areas*), Infrastruktura i Ekologia Terenów Wiejskich, 2, 1, 33–48.