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Research Paper

Energy intensity and energy ratio in producing willow chips as feedstock for an integrated biorefinery

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This study examined the production of willow at a commercial plantation with an area of 10.5 ha, situated in north-eastern Poland. Its aim was to evaluate the energy intensity and energy ratio of the production of chips of new willow cultivars as feedstock for an integrated biorefinery. This study emphasises the key importance of the selection of a willow cultivar for the production of willow chips and the transport distance to a biorefinery for the energy intensity of the production process and the energy ratio of the supplied biomass. The lowest energy intensity for willow chip production was achieved for the plantation of the highest-yielding cultivar (UWM 006). When the yield exceeded 86 t ha^{-1} of fresh biomass, the energy intensity was 0.35 GJ t^{-1} of fresh matter (f.m.). The energy ratio for the product at the farm gate varied depending on the cultivar and ranged from 23.9 to 10.2, for UWM 006 and UWM 155 cultivars, respectively. The distance of biomass transport to a biorefinery significantly affected the energy ratio. When chips were transported for 25 km, the energy intensity for the production of 1 t of chips increased by 3–7% compared to its value at the farm gate. The energy intensity for the longest of the analysed transport distances increased by 23–53%. The energy ratio for each cultivar decreased significantly by 3–35% with increasing transport distance. The values of energy intensity and energy ratio for UWM 006 and UWM 043 were better than those achieved in other studies.

1. Introduction

Bio-based industry and renewable energy are one of the new research and development directions supported in Europe by the European Commission and by other countries around the world (Bridge 2020, 2014; European Commission, 2012). Until recently, biomass was perceived as feedstock mainly for heat and power production, while its use for other purposes was regarded as a niche activity. A huge part of the energy and

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chemical industry base their production on fossil feedstock (non-renewable). The continuous increase in consumption of fossil feedstocks has led to their depletion and to price increases. Moreover, their mining and consumption is accompanied by the emission of greenhouse gases and, in consequence, an escalation of the greenhouse effect (IEA, 2012; IPCC, 2013). As a result, the status of biomass may change from the "fuel of the poor" to a component of many biorefinery industry products.

Willow biomass is used in the production of heat, power and biofuels (Carroll & Finnan, 2013, 2012; Stolarski, Krzyzaniak, et al., 2013; Stolarski, Szczukowski, Tworkowski, & Klasa, 2013; Wang, Dunn, & Wang, 2012). However, ultimately, willow biomass can be one of the potential lignocellulose feedstocks for integrated multi-product biorefineries. The EuroBioRef project will develop a new highly-integrated and diversified concept, including multiple feedstocks (including lignocellulosic biomass), multiple processes (chemical, biochemical, thermochemical) and multiple products (aviation fuels and chemicals). A flexible approach will widen bio-refinery implementation to the full geographical range of Europe and will offer opportunities to export biorefinery technology packages to more local markets and feedstock hotspots. The ambitious objectives of the EuroBioRef project seek a decrease in energy consumption by 30% for a final product and at least 10% lower raw material consumption (EuroBioRef, 2013). Willow, as a lignocellulose biomass, is proposed as the feedstock in two value chains: VC 3 – alcohols to fuels and VC 5 – syngas-based products.

Perennial energy crops, including willow, should be characterised by high productivity and the biomass produced from them should have high calorific value. This would produce considerable amounts of energy and would result in a high energy ratio of biomass production. Only if this is achieved will further stages of biomass conversion to secondary energy carriers and bioproducts be justified as an environmentally-friendly and sustainable solution. Short-rotation willow output achieved in experiments conducted in Poland has reached 30 t dry matter (d.m.) ha^{-1} $year^{-1}$. The average yield has usually ranged from 10 to 12 t d.m. ha^{-1} $year^{-1}$ (Stolarski, Szczukowski, Tworkowski, & Klasa, 2008; Stolarski, Szczukowski, Tworkowski, Wroblewska, & Krzyzaniak, 2011; Tworkowski, Szczukowski, & Stolarski, 2006). On the other hand, the willow yield on large (70–300 ha) commercial plantations was usually much lower than that in experiments and typically amounted to 4–10 t d.m. ha^{-1} $year^{-1}$. Such a low yield was achieved on commercial plantations because of difficulties with the right choice and preparation of the field, errors in setting up plantations, ineffective weed control, wrong fertilisation and using clones with low efficiency (Tworkowski, Kuś, Szczukowski, & Stolarski, 2010). Therefore, it is very important from a practical point of view that the yield obtained in experiments should be verified in professional commercial production. Further development of this type of production requires an analysis of the relationship between the effectiveness of different cultivars and clones of willow on commercial plantations and environmental and agrotechnical procedures. An evaluation of the energy intensity (the ratio of the total energy use per t of fresh matter yield) and energy ratio (the energy value of yield divided by the total energy input) in willow chip production for industrial or energy feedstock is also necessary.

Similar studies on energy yield and energy ratio of biomass production can be found in scientific literature. For instance, Boehmel, Lewandowski, and Claupein (2008) compare energy yield and primary net energy yield (the difference between the primary energy yield and the energy consumption) of perennial (SRC willow, miscanthus) and annual (maize, rape) plants. Vande Walle, Van Camp, Van de Casteele, Verheyen, and Lemeur (2007) studied the utilisation potential of birch, maple, poplar and willow as feedstock for the production of renewable power in Flanders (Belgium). On the other hand, Matthews (2001) modelled the energy and carbon budgets of wood fuel coppice systems, to study the energy and carbon budgets of biofuel production systems. The above-mentioned studies, as well as those recently conducted in Italy with poplar cultivated in a 6-year harvest cycle (Manzone, Bergante, & Facciotto, 2014), prove the high energy ratio of both the cultivation and acquisition of perennial plants.

The advantage of the present study was the possibility of using varieties offering the lowest willow chip production energy intensity. This further reduced this indicator for the final product in the biorefinery. Therefore, the aim of this study was to evaluate the energy intensity and energy ratio of the production of chips of seven new willow cultivars harvested in a three-year rotation as feedstock for an integrated biorefinery, depending on the transport distance.

2. Materials

This study was conducted on a commercial willow plantation with an area of 10.5 ha, set up in mid-April 2010 at the Didactic and Research Station in Łężany, owned by the University of Warmia and Mazury in Olsztyn. It is located in the north-east of Poland, on land of the village of Samławki (53°59′ N, 21°05′ E). The area on which the plantation was situated is undulating and very diverse in elevation. Low quality soil (mainly on soil created from slightly loamy sand and light loamy sand) that was of limited use for typical annual crops was selected for the plantation. Generally, the land in the elevated areas had a groundwater level far below 1.50 m so the soil was permanently dry. By selecting a relatively poor soil site it was possible to evaluate the willow yield potential in areas of little use for food or feed crops. Three cultivars and four clones of willow were planted on the plantation; for this study they were regarded as cultivars and all had been bred at the Department of Plant Breeding and Seed Production of the University of Warmia and Mazury in Olsztyn. Start, Tur, Turbo, UWM 006, UWM 043 were of the species *Salix viminalis*, UWM 035 was of the species *Salix pentandra* and UWM 155 was of the species *Salix dasyclados*.

Willows were planted at a density of 18×10^3 ha^{-1}. Willow cuttings were planted in strips, with two rows in a strip spaced every 0.75 m, with 1.5 m of space separating the next 2 rows in a strip with 0.75 m space between them, etc., with plants in a row spaced every 0.5 m.

Triticale was sown as the previous crop. The following procedures were carried out in order to prepare the site: spraying with glyphosate to eliminate weeds (Roundup