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Giant reed (*Arundo donax* L.) from ornamental plant to dedicated bioenergy species: review of economic prospects of biomass production and utilization

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Summary: Giant reed (*Arundo donax* L.) is a perennial, herbaceous grass, it has been spread all over the world from continent to tropical conditions by human activities. In continental climate, especially Hungary, it has been considered as ornamental species, due to its decorative appearance, striped variants' colour of leaves, long growing season and low maintenance requirements. It does not produced viable seeds, so it can be propagated vegetative ways by rhizomes or stem cuttings and by *in vitro* biotechnology methods. Because of its growth habits and good adaptation capability, it has been considered invasive weed primarily in coastal regions in warmer climate areas. In the previous century, giant reed produced for paper/cellulose/viscose production, woodwind musical instruments, stakes for plants or fishing rods etc. Over the last few decades, it has been produced for bioenergy purposes (bioethanol, biogas, direct combustion) or utilize as chemical basic compounds or construction materials. It has been considered a dedicated promising biomass crops thanks to high biomass production, high energy balance of cultivation and adaptability of different kind of soils and conditions. The objective of the present paper is to overview the most significance literature data on giant reed production and utilization, compare to own experimental data and economic calculations and to determine some critical factors, advantages and disadvantages of giant reed production compare to other biomass species.

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Key words: giant reed, biomass production, biomass utilization, economic benefits

Introduction

The energy consumption of the global population is still depends on fossil fuels, in spite of the rapidly increasing role of renewable energies, environmental problems and climate policies. The biomass is the greatest renewable resources, with almost 73% share of global renewable energy supply (IEA, 2017). The annual rate of biomass utilization is less than other renewable resources (especially sun or wind), so it should be used the biological resources more effectively to ensure food and energy demands of a growing population (WBA, 2017).

The world is already moving towards to the "bio-based society", confirmed many practical examples (optimized production system with less waste generation, recycling, bio-based production instead of fossil-based products, protein-rich animal feed, healthy food ingredients, circulation of nutrients to the soil etc.). However, globally the biomass resources utilize as heat or electricity production, it has been produced biofuels for transportation, bioplastic and biobased chemicals etc. The most optimized way of using biomass to utilize its nutritional values, structural building blocks, not only energy contents. Cellulose, hemicellulose, lignin and leaf proteins are valuable components of green biomass to produce higher value added new products such as feed and food ingredients, medicine and health promoters (Lange & Lindeman, 2016). Nowadays, the soybean is one of the most important protein sources of animal husbandry, but by fractionation of green biomass leaves can be produce also valuable leaf protein concentrate. The production of fractioned green leaf is not a new concept, because in the beginning of last century, Karoly Ereky, the "father" of term biotechnology, has already used the fractional technique to produce fodder to feed. The fractioned green biomass techniques were developed over the previous decades, but its application did not spread widely (Popp & Fári, 2016). Nevertheless, there are many biological, ecological, economical and technological problem with biomass plant production and utilization. One of the most promising opportunities to produce perennial species in marginal lands. Dedicated plants with large root system can restore the quality of soils and result more environmentally friendly production, because of less soil cultivation intervention contribute the reduction of CO_2 emission (Fári et al., 2014).

University of Debrecen has been carrying out biological, genetical, agronomic and biotechnological researches on perennial, primarily herbaceous plant species suitable for bioindustrial processing that can be grown on marginal areas. The objective of the present paper is to overview the most significance literature data on giant reed production and utilization, compare with own experimental data and economic calculations and other biomass species' data.

Materials and methods

Within the framework of the University of South Carolina (USA) and the University of Debrecen, MÉK, Department of Plant Biotechnology (Hungary) joint research program, has been developed in vitro propagation techniques of dedicated perennial species, giant reed (*Arundo donax* L.) and miscanthus (*Miscanthus x gigantheus*) based on methods of Márton & Czakó (2002a, b, 2007a, b). From in vitro propagation of two different giant reed ecotypes uses somatic embryogenesis were propagated and acclimatized seedlings were planted in the Experimental Garden of Future Biomass Crops at University of Debrecen. Resulting of joint researches, from 2010 in several places in Hungary and other countries in the world (USA, Italy, Spain, China, Romania, Ukraine and Slovakia) has been started to establish biotechnologically propagated giant reed plantations. I have been collecting production and utilization data of giant reed plantation in Hungary from 2013 until 2018 (based on plantations of University of Debrecen), used for cost-benefit analyses of giant reed production. I compared the results with significant literature data to introduce and overview the most relevant properties of giant reed in aspects of production and different utilization methods by economical, ecological and biological advantages and disadvantages of giant reed compare with other biomass species. In case of higher value added products from giant reed and other species from Experimental Garden of Future Biomass Crops at University of Debrecen could produce leaf protein concentrate (LPC) based on Ereky's process (Fári & Popp, 2016) and combined with the coagulation technique was related to patent application. Department of Agricultural Botany, Plant Physiology and Plant Biotechnology, MÉK, University of Debrecen were measured physical and chemical parameters from the LPCs and the by-products (brown juice, green fiber) from different species supported by the GINOP-2.2.1-15-2017-00051 project, is co-financed by the European Union and the European Regional Development Fund. Based on these results and data, I evaluated the efficiency and perspectives of LPC production and available protein content per unit from giant reed compared to a dedicated forage crop, alfalfa (*Medicago sativa* L.).

Results

Importance of giant reed researches

The growing importance and interest of giant reed can be obviously characterized by literature databases. Based on the Google Scholar database, the total number of publications is over 17 400 (Until 12.11.2017), from which in 1 340 paper's title contain the plant's scientific name (Arundo donax or giant reed). Over the last 50 years, the number of publications about giant reed has been increasing, between 1997 and 2001 it almost doubled, which was typical of the later periods (Figure 1). Over the past 10 years, more than 13 000 scientific papers were published which are related to the plant, and annually, almost 100 publications appeared with giant reed or Arundo donax names in the title of publications. In those papers, the term of "biomass" and "energy" 5 600, the "biorefinery" 1 080, the "biofuel" 2 620, the "biogas" 1 270, the "musical" 612, the "invasive" 4 040 and the "phytoremediation" 956 pieces of publication contained. It is interesting that the word "propagation" and "in vitro" same 1 560 publications can be found in Google Scholar's search base (Until 12.11.2017) (*Figure 1*).

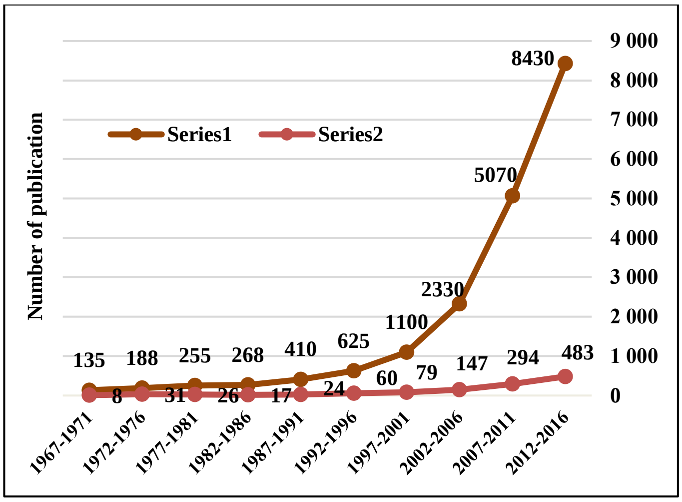

Figure 1: Number of publications related to "giant reed" or "Arundo donax" in Google Scholar's database (between 1967-2016)

Source: author's composition based on a Google Scholar database. Series 1) Number of publications containing the plant's scientific name. Series 2) Number of publications containing the plant's scientific name in the title.

Chemical composition and valuable properties from view of production

The physical and chemical composition of giant reed was reported in several publications, such as a lignocellulose plant. The ratio of cellulose and hemicellulose is approximately 55-60% with higher cellulose content (30-39%), and the amount of lignin (20-24%) and ash (4-6%) are also relatively high (Corno et al., 2014). Some authors (Neto et al., 1997; Shatalov & Pereira, 2002a,b; Ververis et al., 2004) determined the chemical composition of the various segments of the plant, which shows that the chemical content of internodium, nodes and leaf are diverse (*Figure 2*). The internodium contains average 34.61% cellulose, 26.58% hemicellulose, 19.58% lignin and 4.38% ash. The percentage of cellulose content of internodium with nodes is less (30.80%), hemicellulose content is higher (28.62%), but the lignin (18.97%) and ash content (4.38%) is almost same than internodium. According to Neto et al. (1997), the leaves of plant contain 35.1% cellulose, 25.60% hemicellulose, 16.80% lignin and 5.80% ash (*Figure 2*).

It also increases the plant's biological value that it is able to adapt to different type of soils, marginal, periodically flooded or saline territories (Pilu *et al.*, 2012). Numerous authors is reported that giant reed can accumulate heavy metals (cadmium, nickel, lead, chromium, arsenic, mercury, copper etc.) (Mlinarics *et al.*, 2009; Alshaal *et al.*, 2013; 2014; Elhawat *et al.*, 2014; 2015), because of its expanded root system and vigorous ground biomass. Therefore, as phytoremediation plants can restore the soil ecosystem (Alshaal *et al.*, 2013; 2015) from sewage and from different pollutants (Simon *et al.*, 2012; Elhawat *et al.*, 2013a; 2015). Giant reed can grow on red mud, high pH or EC, heavy metal polluted soils (Alshaal, 2013). In addition Domokos-Szabolcsy *et al.* (2014) and El-Ramady *et al.* (2015) reported its tolerance of different selenium forms and according to Williams *et al.* (2008) and Elhawat *et al.* (2013b) giant reed can be adapt to salty soil.

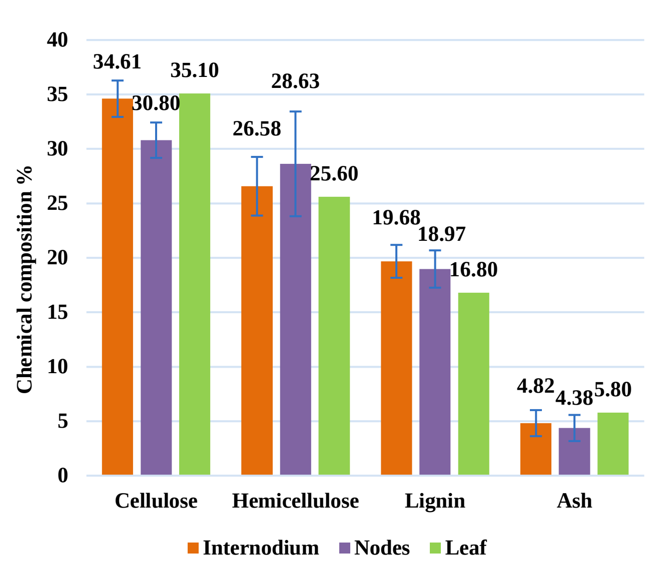

Figure 2. Chemical composition of different segments of giant reed

Source: Neto et al. (1997); Shatalov & Pereira (2002a,b); Ververis et al. (2004)

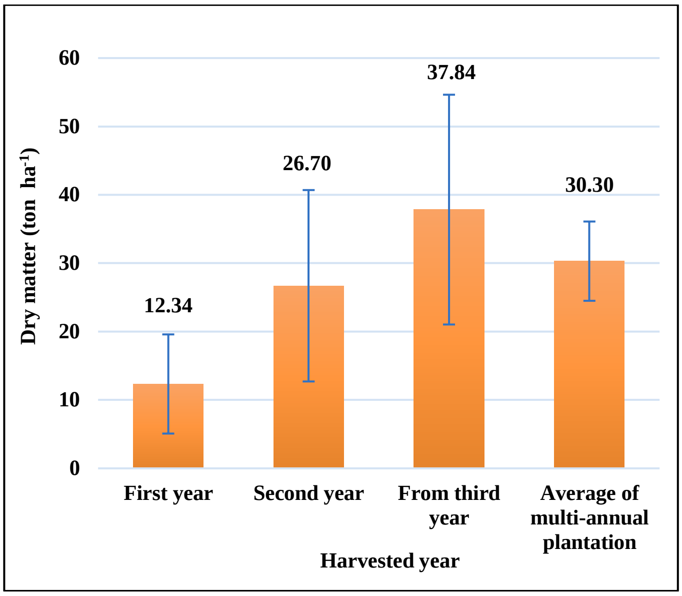

Figure 3: Biomass yield of giant reed plantations in the Mediterranean environment

Source: Christou et al. (2003); Angelini et al. (2005; 2009); Cosentino et al. (2006; 2008); Mantineo et al. (2009); Ceotto & Di Candilo (2010); Roncucci et al. (2012); Nassi o Di Nasso et al. (2011a, b, 2013a, b); Ceotto et al. (2015); Dragoni et al. (2015, 2016)

Biomass yields and production cost depending on cultivation elements

Giant reed can produce different biomass yield in different climate and cultivation conditions. Based on numerous significant reports, the biomass yield of multi-annual giant reed plantation can reach 30 tons dry matter per hectare (t DM ha^{-1}) per year in Mediterranean environment (*Figure 3*). The annual quality and quantity of biomass production are influenced by a lot of factors (microclimate, soil, agronomic techniques, harvest time and method etc.), therefore biomass yields show large standard deviations. The average values of the *Figure 3* represent warmer condition's data than continental climate, such as Hungary.

Contrary to the large number of foreign literatures, there are very few Hungarian publications which are dealing with the properties and cultivation of giant reed, and they are largely referring to the results of foreign sources. Hungarian literatures estimated an average 20 t DM ha^{-1} in Hungary with annual precipitation of 650-800 mm. According to Fogarassy (2001), the annual biomass yield of the plant is between 20-30 t DM ha^{-1} on average soils without irrigation. As reported Gyulai (2009) and Csete (2008a, b, c) biomass production of giant reed can be achieved 20 t DM ha^{-1}, but with adequate irrigation and fertilization can be reached 35 t DM ha^{-1}.

Based on the field experiment in Debrecen, giant reed ecotype from the subtropical climate could produce average 16.37 t DM ha^{-1} under six cultivation year, on calcareous chernozem soil without irrigation and fertilization, because of the frost damage in 2012. While ecotype from Hungary could produce average 18.05 t DM ha^{-1} at the end of winter harvest time under six cultivation year. It can be concluded that in 1x1 meter plant spacing (10 000 plants per hectare) is enough to establish giant reed plantation. Based on our field experiment, in more dense plant spacing (13 334 or 20 000 plant per hectare) the biomass productions did not increase, but the establishment costs are greatly influenced (Antal, 2018).

In experiments of Cavallaro et al. (2014), in the first year with previous autumn establishment 12.1 t DM ha^{-1}, with the early spring establishment 20 t DM ha^{-1} biomass produced in Northern Italy. The average biomass yield of micropropagated derived giant reed plantation in a warmer climate in the 3-4 years could produce approximately 22 t DM ha^{-1} (Roncucci et al., 2012; Nassi o Di Nasso et al., 2013a; 2013b; Corno et al., 2014), which above 4-6 t DM yields than measured in Debrecen (Hungary).

The production of perennial plants differs from annual arable plant cultivation. In the viewpoint of economic calculation, the life cycle of perennial plant production lasts from the propagation of propagules until the elimination of the plantation. Based on own research activity and literature data, giant reed production can be feasible in continental climates, also in Hungary. Harvest time is depending on the utilization method, but for the sustainable, low cost cultivation in a continental climate, the end of the winter season could be the optimal harvest time of giant reed (Antal, 2018). During estimated 15-20 years of giant reed production, the cost of establishment, the price of propagules is one of the most expensive direct cost besides the harvest and transportation costs (Pilu et al., 2012). Calculation of Pilu et al. (2012), in North Italy, the annual cost of cultivation without irrigation (apart from the first year) reaching at least 700 euro ha^{-1} (can be 1000 euro ha^{-1}), if the propagules are derived from the rhizomes (0,5 euro/propagules). During 15 years old cultivation, cost of propagules is 11,90%, tillage and rhizomes transplantation is 6,67%, weeding and irrigation is 5,24%, fertilization is 24,29% and harvesting is 51,43% in giant reed production (Pilu et al., 2012). It can be reduced the cost of propagules used by biotechnology-propagated plants, it can be less than 3 000 euro ha^{-1} depending on propagation technology (Corno et al. 2014, Antal, 2018). In Hungary, the consumption of the household sector (pellet, briquette etc.) is not significant, therefore biomass power plants can be greatest market of the plant. The prices of absolutely dry giant reed chops decreased to 8 000 HUF from 16 000 HUF in the last years (2014-2018). Based on our calculation, average direct cost of cultivation of giant reed is between 7 200-7 500 HUF per dry tons in Hungary (without agricultural financial support), if are using biotechnologically propagated plants (Antal, 2018). The current low prices of energy and absence of the domestic processing industry are not contributed the profitable production.

Based on economic calculations carried out in similar years by Arundo Italia Ltd. (Italy), total cost of giant reed production exceeded the Hungarian data, but the costs of harvest and transportation are not significant, due to the proximity of the market outlets. The Italian company establishes giant reed plantations, particularly for biogas and bioethanol production with the suitable facilities. Currently, purpose of global giant reed production is biogas or bioethanol production, but other forms of its utilization were also reported.

Utilization of giant reed compared to other biomass species

The high heating value of giant reed is between 17-20 MJ kg^{-1}, that is similar to other energy plants such as poplar, miscanthus, switchgrass etc. (Rabemanolontsoa & Saka, 2013; Molari et al., 2014; Saikia et al., 2015). Giant reed has high ash and silicon content, such as switchgrass, which substances accumulate mainly in the leaves (Coulson & Bridgwater, 2004; Monti et al., 2008). During combustion, this silicon-content with high potassium or chlorine elements may cause fouling or corrosion problem and rise amount of volatile particles (Monti et al., 2008). In experiment of Nassi o Di Nasso et al. (2010) confirmed that it can be improved the quality of biomass and heating value with the application of appropriate agronomy techniques (autumn-winter harvest and convenient fertilization).

In agronomy, environment and economic researches of Nassi o Di Nasso et al. (2010; 2011a; 2013a) and Angelini et al. (2009) compared the productivity and efficiency of giant reed production and utilization to miscanthus, short-rotation poplar or annual agricultural crops (sugar-beet, durum wheat, sorghum, sunflower). From the energy production of plants, energy input of cultivation of giant reed and miscanthus were close to equal per hectare (13 GJ), but in case of annual agricultural crops were more than 20 GJ ha^{-1} and 3 yearly harvested poplar were 5 GJ ha^{-1}. Maximum annual net energy yield can be reached with giant reed production (~600 GJ), the values of miscanthus (~450 GJ), poplar (~300 GJ) or agricultural crops (~110 GJ) are less. The annual emission of greenhouse gases can be calculated 1400 kg CO_2 equivalent in production of agricultural plants, and short-rotation poplar is less (460 kg) than giant reed or miscanthus (800 kg).

According to Schievano et al. (2012), giant reed has lower biogas productivity per dry matter than other traditional energy plants (corn, sorghum, triticale etc.). Due to its high biomass production, 7 170-11 280 Nm^3 CH_4 production per hectare can be reached in one harvested process per year, so biomethane production of giant reed per unit area higher than other biomass plants. In the calculation of Ragaglini et al. (2014) with two moving per year can be rise with 20-35% bio-methane production per year. With one harvesting 9 580 Nm^3 CH_4, two harvesting 11 585-12 981 Nm^3 CH_4 biogas yield measured per one year in same cultivation area. Based on Corno et al. (2014), 3-year-old giant reed plantation with one harvesting an optimal period of a year (October) can be resulted much more biogas yield per hectare (19 440 Nm^3 CH_4), than two harvesting in the same year and area (9 930 Nm^3 CH_4 per moving). Based on the calculation of Arundo Italia Ltd. (Italy), the unit biogas yield of giant reed (16 000 m^3) is one and half times exceeds the corns' (11 000 m^3), despite corn has higher biogas production per dry matter. Under 15 cultivation year, the total direct cost of giant reed production for biogas utilization is one third (11 850 euro) than corn (40 727 euro) per hectare (Corno et al., 2014; 2015; 2016). Furthermore, based on Di Girolamo et al. (2013) and Adani et al. (2010), with adequate pretreatment can be rise 12-60% the biogas yield from giant reed. The problem is the presence of volatile elements (especially silicon-containing compounds) which during digestion of the raw material can transform into silicon (Monti et al., 2008; Nassi o Di Nasso et al., 2010).

The processing method of bioethanol production of giant reed as a potential second generation lignocellulosic plants, is more complex and diverse from first generation bioethanol plants (cereals). In comparison with other bioethanol plants (cereals, sugar cane, miscanthus, sorghum etc.), giant reed produced generally 20, even 50% higher bioethanol per hectare (11 000-15 000 litre), because of high biomass production and chemical components (Williams et al., 2008; Corno et al., 2014). In 2013, Mossi & Ghisolfi Group (in Crescentino, Italy) was building a second gerenation bioethanol pilot plant with a capacity of 60 thousand tons per year supported by the European Union's Research and Innovation funding program (FP7-239204) with cooperation other consortium partner (Biochemtex, WIP Renewable Energy, Novozymes, ENEA, Agroconsulting, Italian Bio Products etc.). This pilot demonstration bioethanol plant can utilize 270 000 dry tons plant material, such as agricultural residues and second generation bioethanol plants (miscanthus, sorghum, switchgrass and giant reed). Thanks to the developed Proesa technology, can be made efficiently the cellulose digestion and solved the utilization of lignin as electric energy (13 MW). Based on their economic profitability, annual total cost of bioethanol production from giant reed or agricultural residues (wheat straw) is less than 500 euro, which is cheaper than production from sorghum (600 euro) in case of capacity of 100 000 tons material processing per year. Beside wheat straw, giant reed has been considered one of the most perspective raw materials. From giant reed can be produced 5 tons bioethanol per hectare with average 20 dry matter biomass yield and with cultivation of giant reed can reduce GHG emission with average 8 tons per year (Chiaramonti et al., 2013).

Due to the chemical structure of giant reed (cellulose, hemicellulose, lignin, protein etc.), it can be produced for bio-compound of plastic (Fiore et al., 2014), green construction (Carneiro et al., 2016) and leaf protein concentrate (LPC) for feed ingredients (Molnár et al., 2015), not only bioenergy purposes. Based on own and Varga (2014) calculation, in case of recommended harvesting time (end of May), from 3-4 tons fresh matter giant reed biomass yield can be produced 190-300 kg ha^{-1} fresh leaf protein concentrate with 15-38% available crude protein content. The protein yield per hectare from giant reed is 58-74% less than measured from alfalfa, but there are no data from digestible or essential amino-acid content of LPC from giant reed or from other treated species. The protein yield is depending on harvesting time, chemical composition of ecotypes and applied technologies. During the process, large amounts of green fiber and brown juice are generated as by-products, which can be used for varied purposes (as nutrition resources and medium for biological fermentation, as raw material for enzymes, biodegradable plastics, amino acids, vitamins, alcohol production etc.) (Bákonyi et al., 2018). Because of the high biomass yield of giant reed and growing demand for higher protein content products, it can be perspective to following researches in field of leaf protein concentrate production from giant reed.

Discussion

Based on above described numerous literature data and own field experiments, it can be determined some critical factors of giant reed production. Giant reed can be cultivated on different kind of soil and climate, but the cold is a limiting factor in production. For these reasons, can be concluded that in the production of the giant reed needs to utilize climate-adapted varieties or ecotypes to maintain the profitability. As phytoremediation plant can be cultivated also in marginal or heavy metal polluted lands. It cannot produce viable seeds and its rhizomes not creeping such as bamboo, but it can be invasive in wetland or coastal regions, so it is not suitable to establish a plantation next to the waterside. It can be propagated only by vegetative methods (rhizomes, stem cuttings, *in vitro* propagation) and the most of propagation methods are inefficient with higher propagation costs. As perennial plant, lesser number of cultivation elements of production resulted reducing in production costs, energy consumption and GHG emissions. Resulted that the direct production cost is lower compared to woody plants or one-year energy crops, because of significantly less fertilizer, pesticide and herbicide needs to produce high biomass yield. But the investment cost is higher, because of the establishment and propagules costs. Without irrigation it can be produced 20 DM ton ha^{-1} in continental climate and 25-37 DM ton ha^{-1} in a warmer climate, but high water content at harvesting (over 40%), which increases the transport and processing costs. Although from giant reed can be produced for different kind of purposes (combustion, biogas, bioethanol and basic components for higher value added products such as bioplastic, fodder or other compounds), the processing cost of lignocellulose-based biomass can be higher. Despite of numerous environmental, economic and social benefits, due to the lack of manufacturing industry, cannot be declared that the todays the biomass-based technologies can be replaced or supplemented fossil energy-based technologies.

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