Lignocellulosic Waste Treatment in Biogas Biorefinery with Reduced CO_2 Production: A Techno-Economic Study

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The paper presents a techno-economic study of a biogas plant in biorefinery concept with reduced CO_2 production. Such a biorefinery proposal treating lignocellulosic waste produces a portfolio of products with higher added value and a reduced amount of produced CO_2 by 47 vol. % for model materials in the comparison with a conventional biogas plant. Economic analysis also shows an attractiveness of the technology with conventional payback period without any subsidies that is strongly dependent on product demand and waste politics.

1. Introduction

Lignocellulosic wastes like wastes from agriculture, wood processing industries, food industry, wastewater sludge, green urban waste or separately collected municipal biodegradable waste from households and gardens represent the most energy-rich and unused renewable raw materials. The traditional way of modern energy recycling of lignocellulosic wastes can be found at biogas plant, where anaerobic microorganisms convert waste to biogas, i.e. to mixture of methane and carbon dioxide, which is nowadays dominantly used as a decentralized energy source. Nevertheless, such a conventional biogas plant is not efficient in waste treatment and it is also not economically feasible as a waste treatment technology. Generally known, the energy potential of waste is unused because the biodegradability of untreated lignocellulosic waste is not higher than 20 wt. % (Al Seady, 2008), carbon dioxide is produced by the process and during methane combustion, a large amount of waste heat is generated without any use, and finally conventionally operating biogas plant is not economically feasible without subsidies.

Nowadays, there is a trend of mutual material and energy recycling of wastes known as biorefinery concept (Jong and Jungmeier, 2015). The biorefinery is a flexible multi-technology in which waste is transformed to biomaterials, biochemicals, and biofuels as primary products and to electricity or heat generation in parallel as secondary products. A portfolio of various products with higher and lower economic values are therefore generated. Biorefinery concept has a potential of intensive waste reduction, amount of produced sludge can be decreased, amount of produced exhausts can be decreased as well. There is therefore a potential to reach environmentally friendly and economic feasible waste treatment independent on subsidies. Generally known, lignocellulosic waste is composed of cellulosic fibres, hemicellulose and lignin. Cellulosic fibres represent a product with high potential for applicability, e.g. as insulation material, as a biodegradable reinforcing element in bioplastics or nanocomposites. Based on the purity of cellulosic fibres, their potential can be also found in furniture production technologies, automotive, pharmacy, electronics, cosmetics or in chemical and food processing technologies like membrane component (Yang and Reddy, 2009).

There is plenty of research and studies of biogas biorefinery that deal e.g. with mutual biogas and bioethanol production (Yahmed et al., 2016), with integrated biodiesel production (Prieto et al., 2017), with protein extraction (Santamaría-Fernández et al., 2018), or mutual nutrients and liquid biofuels production (Jin et al., 2018). Nevertheless, an information about engineering studies are still missing. The novelty of this paper is that demonstrates a techno-economic potential of mutual material and energy recycling using lignocellulosic waste treatment at a biogas plant in biorefinery concept with emphasis to operate economically feasible with reduced carbon dioxide production.

2. Methods

Presented biorefinery proposal of lignocellulosic waste treatment, see Fig. 1, is based on cellulosic fibre separation, their drying and usage as a biodegradable material for various application mentioned in the introduction. Sorted lignocellulosic waste that is free of stones, metals, plastics and another impurity, is firstly defibered. Hydrothermal pretreatment, i.e. boiling of waste in pressurized liquid water with subsequent rapid batch decompression as an environmentally friendly technology, is used to dissolve lignocellulosic matrix. Wet cellulosic fibres are separated in fibre separation unit. Fibres are going to the dryer. The liquid residue that is rich in dissolved organic compounds from waste, is anaerobically fermented to produce biogas. Biogas is combusted in cogeneration unit with combined electricity and heat production. Electricity is used to cover electric energy demand of the biorefinery and heat is used as a heat source to preheat drying air. Products of such biorefinery concept are cellulosic fibres as the primary one, electricity and heat that are recovered in the biorefinery, sludge from anaerobic fermentation and flue gases from cellulosic fibre drying, as secondary ones.
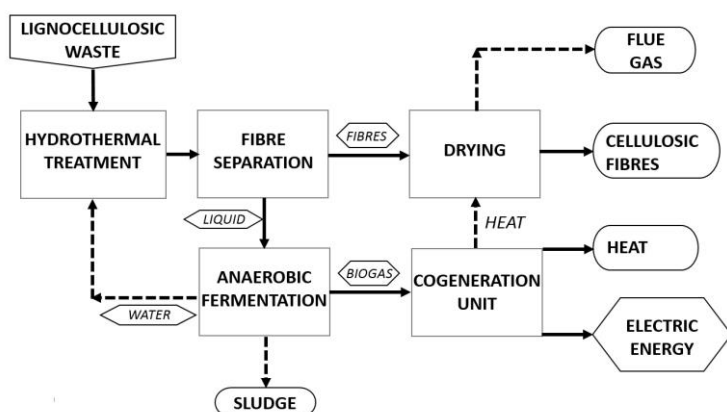

Figure 1: Block diagram of biogas biorefinery.

2.1 Mass and energy balances

Wood chips with flowrate 500 kg h^{-1} of total solids containing 47 wt. % of cellulosic fibres were used as the model material. Mass and energy balances were calculated using the law of mass conservation respecting no mass losses in the system, and the law of energy conservation respecting no heat loses in the system, fermenter excluded. Heat loss of fermenter 15 W m^{-3} (Deublein and Steinhauser, 2011) was taken into account. Biogas yield 100 Nm^3 t^{-1}, concentrations of methane to carbon dioxide in volumetric ratio 1:1 and methane lower heating value 9.94 kWh Nm^{-3} were used in calculations (Al Seadi, 2008). Electric efficiency 40 % and heat efficiency 52 % of combined heat and power unit were used to calculate its powers.

2.2 Economic analysis

Capital investment cost (CAPEX) and operating expenses (OPEX) were evaluated to be able to predict payback time of biogas biorefinery. Estimation of CAPEX was based on "The factorial method of cost estimating" described by Towler and Sinnot (2013). CAPEX was set as the sum of ISBL, OSBL, DE and EeE multiplied by design factor. The crucial step was to evaluate investment cost of installed machines and apparatuses. Based on detail analysis and knowledge of characteristic process parameters for individual equipment like flowrate, volume, mass transfer surface, heat transfer surface, heat power etc., their investment price ISBL was estimated. OSBL represent the investment cost of installation, pipeline system, measurement and control, energy distribution systems, construction, supporting elements, protection and coatings. OSBL level 40 % of ISBL costs was used as an initial estimation. DE abbreviation represented the investment costs for all engineering works, i.e. the projection of technology, construction of equipment, legislation, and its estimation was as 0.1×(ISBL+OSBL). EeE was a reserve for price fluctuations of materials and labor, its value was defined as 0.1×ISBL. Design factor takes into account present knowledge about realization, operating and control of such a technology. The value of 1.15 was used for new and unproven processes. The error of determining the total investment cost was ± 15-30% of the total amount.

Operational expenses were calculated as the sum of profit from fibre purchase, direct operational costs, indirect operational costs and distributional costs with recommended initial estimations given by Towler and Sinnott (2013). The selling price of cellulosic fibres 2.2 $ kg^{-1} was used for model set-up, the average buying price of wooden chips 20 $ t^{-1}. Operating cost of raw materials was 0.04 $ kg^{-1} with the cost of transport being 2 % of

the raw material price. The economic model includes eight employees with average Brutto wage 768 $ per month, supervision being 5 % of personal cost, maintenance being 4 % of CAPEX, material cost for maintenance 100 % of maintenance cost, consumables 0.5 % of CAPEX, energy cost according to demand with 0.05 $MJ^{-1}, reserve as 1 % of direct operational cost, insurance as 1 % of CAPEX, corporate directions as sum of personal and supervision cost and 50 % of maintenance cost.

3. Results and discussion

Based on the concept presented in Figure 1, process flow diagram of the biorefinery was designed (Figure 2) to be able to determine mass and energy balances through individual streams, machines and apparatuses with the emphasis to energy recovery in the technology, and to define the biorefinery model that performed economic and sensitivity analysis.
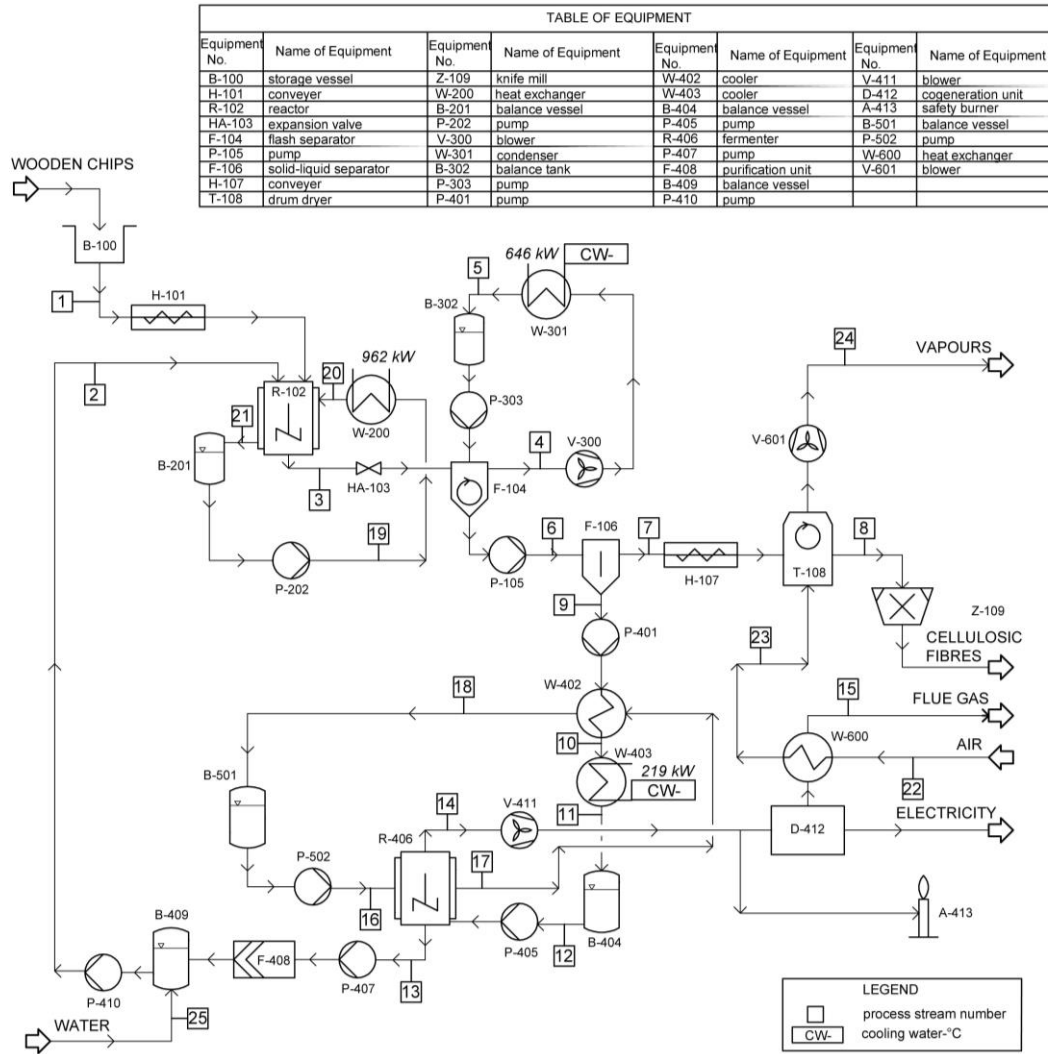
TABLE OF EQUIPMENT

Equipment No.	Name of Equipment	Equipment No.	Name of Equipment	Equipment No.	Name of Equipment	Equipment No.	Name of Equipment
B-100	storage vessel	Z-109	knife mill	W-402	cooler	V-411	blower
H-101	conveyer	W-200	heat exchanger	W-403	cooler	D-412	cogeneration unit
R-102	reactor	B-201	balance vessel	B-404	balance vessel	A-413	safety burner
HA-103	expansion valve	P-202	pump	P-405	pump	B-501	balance vessel
F-104	flash separator	V-300	blower	R-406	fermenter	P-502	pump
P-105	pump	W-301	condenser	P-407	pump	W-600	heat exchanger
F-106	solid-liquid separator	B-302	balance tank	F-408	purification unit	V-601	blower
H-107	conveyer	P-303	pump	B-409	balance vessel		
T-108	drum dryer	P-401	pump	P-410	pump		

TABLE OF STREAMS

		1	2	3	4	5	6	7	8	9	10	11	12
TOTAL FLOWRATE	(kg/h)	500	4500	5000	1056	1056	5000	825	235	4175	4175	4175	4175
WATER	(kg/h)	-	4500	4765	1056	1056	4765	590	-	4175	4175	4175	4175
TOTAL SOLIDS	(kg/h)	500	-	235	-	-	235	235	235	-	-	-	-
TEMPERATURE	(°C)	20	35	25	100	100	100	100	80	100	80	35	35

TABLE OF STREAMS

		13	14	15	16	17	18	19	20	21	22	23	24	25
TOTAL FLOWRATE	(kg/h)	3895	280	400	1800	1800	1800	1540	1540	1540	1096	1096	1686	605
WATER	(kg/h)	3895	15	-	1800	1800	1800	1540	1540	1540	-	-	-	-
SOLIDS	(kg/h)	-	-	-	-	-	-	-	-	-	-	-	-	-
TEMPERATURE	(°C)	35	35	385	60	40	60	210	210	210	20	80	80	20

Figure 2: Process flow diagram of the biogas biorefinery

Table 1: Investment cost of the technology

Individual investment costs			Process characteristics	Estimated price ($)
ISBL	B-100	storage vessel	volume 32 m^3, conical bottom, ventilation	6,400
	H-101	screw conveyor	flowrate 500 kg h^{-1}	8,000
	R-102	reactor	parallel set of 6x 20m^3, double jacket, mixed	453,500
	HA-103	expansion valve	flowrate 1.388 kg s^{-1}	6,300
	F-104	cyclone separator	volume 2.9 m^3	7,200
	P-105	screw pump	flowrate 1.388 kg s^{-1}	4,200
	F-106	drum separator	flowrate 1.388 kg s^{-1}	20,000
	H-107	conveyer	flowrate 825 kg h^{-1}	3,000
	T-108	belt dryer	heat transfer surface 13 m^2, flowrate 825 kg h^{-1}	100,000
	Z-109	grinder	flowrate 235 kg h^{-1}	3,200
	W-200	steam generator	steam power 962 kW	150,000
	B-201	balance vessel	volume 0.160 m^3	5,900
	P-202	liquid pump	flowrate 0.428 kg s^{-1}	3,400
	V-300	blower	flowrate 1328 m^3 h^{-1}	6,600
	W-301	condenser	cooling power	280,900
	B-302	balance vessel	volume 0.210 m^3	6,000
	P-303	liquid pump	flowrate 0.293 kg s^{-1}	3,400
	P-401	screw pump	flowrate 1.160 kg s^{-1}	4,200
	W-402	heat exchanger	heat transfer surface 17.85 m^2	1,100
	W-403	cooler	cooling power 219 kW	166,600
	B-404	storage vessel	volume 2510 m^3	14,900
	P-405	screw pump	flowrate 1.160 kg s^{-1}	4,200
	R-406	fermenter	volume 2510 m^3	301,300
	P-407	liquid pump	flowrate 1.082 kg s^{-1}	3,400
	F-408	filter	filtration cloth surface 20 m^2	92,600
	B-409	balance vessel	volume 2.25 m^3	7,000
	P-410	liquid pump	flowrate 1.25 kg s^{-1}	3,400
	V-411	blower	flowrate 13.25 Nm^3 h^{-1}	4,500
	D-412	cogeneration unit	electric power 53 kW, safety burner 132 kW	63,300
	A-413	burner	burning power 132 kW	9,000
	B-501	balance vessel	volume 1 m^3	6,400
	P-502	liquid pump	flowrate 0.5 kg s^{-1}	3,400
	W-600	heat exchanger	heat transfer surface 26.4 m^2	23,600
	V-601	blower	flowrate 1096 m^3 h^{-1}	4,300
	Total ISBL plant costs			1,781,200
OSBL	Offsite costs			713,000
DE	Engineering costs			499,000
EaE	Contingency charges			250,000
	sum of individual investments			3,243,200
			design factor	1.15
CAPEX	Total investment costs of technology			3,730,000

Wooden chips are according to PFD scheme in Fig.2 dosed from storage vessel B-100 to pretreatment reactor R-102 by screw conveyor H-101. An aqueous suspension containing 10 wt. % of wood chips is prepared in pretreatment reactor and it is treated under recommended processing temperature 200°C for a residence of 40 min. 47 wt. % of wooden chips´ organic solids is solubilized to water during processing. As processing time is over, the batch rapidly expands from pressurized pretreatment reactor R-102 to atmospheric separator F-104. Solid-liquid residue and vapours are generated there. Vapours are led by blower V-300 to heat exchanger W-301, where they condense. Condensate is stored in a balance vessel B-302, from which is sprayed by pump P-303 and spraying system to separator F-104 to wash its internal surface. The solid-liquid content of separator F-104 is pumped by pump P-105 to drum separator F-106, where the solid and liquid phase is separated. Solid phase, i.e. wet cellulosic fibres are dosed by screw conveyor H-107 to dryer T-108, where they are dried by drying air that is preheated in heat exchanger W-600 by exhaust gases from cogeneration unit D-412. Dried cellulosic fibres to initial moisture content after treatment was 1.00:2.47 (Krátký and Jirout, 2015). Size reduction of dryer cellulosic fibres follows in knife mill Z-109 to prepare their size for demanded quality. Liquid residue rich for dissolved organic solids is pumped from drum separator F-106 by pump P-401 through a set of heat exchangers W-402 and W-403 to balance vessel B-404 to be cooled to fermentation temperature being at mesophilic conditions 35 °C. Such a substrate is dosed by pump P-405 to the anaerobic fermentor. Organic content is transformed by anaerobic bacteria to biogas, residence time 25 days is respected in the design. The

fermented residue is pumped by pump P-407 through purification unit F-408 to storage vessel B-409, from which liquid is pumped by pump P-410 back to the beginning of the technology. Generated biogas is led by blower V-411 to cogeneration unit D-412, where it is combusted to produce electricity and heat. Exhaust gases are not cooled directly in cogeneration unit D-412 as standard heat recovery, but they are going through heat exchanger W-600 to heat the air from drying of cellulosic fibres. Blower V-601 provides drying air flow both heat exchanger W-600 and dryer T-108 operating in the under-pressure regime. Safety burner A-413 is installed for direct biogas combustion due to a possibility that cogeneration unit D-412 is disconnected out of the technology. Heat is partially regenerated using tempering system for fermenter R-406 that runs with pump P-502 and balance vessel B-501. Heating water is pumped through heat exchanger W-402 where it takes heat from the liquid substrate for fermentation. No other heat recovery is considered for such a biogas biorefinery to have it easy to operate.

Table 2: Operating expenses, revenues, profits, income taxes

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Cellulosic fibre production – *8000 working hours per year*	1,880,000	kg y^{-1}
Cellulosic fibre purchase cost	2.2	$ kg^{-1}
Profit from fibre purchase	4,042,000	$ y^{-1}
Operating costs excluding depreciation and interests (OPEX)	3,765,000	$ y^{-1}
Direct operating costs	2,068,000	$ y^{-1}
Raw materials	174,000	$ y^{-1}
Personal costs of employees	150,000	$ y^{-1}
Supervision	8,000	$ y^{-1}
Maintenance	126,000	$ y^{-1}
Consumables	16,000	$ y^{-1}
Energy cost	1,575,000	$ y^{-1}
Reserve	21,000	$ y^{-1}
Indirect operating costs	98,000	$ y^{-1}
Insurance	32,000	$ y^{-1}
Corporate directions	66,000	$ y^{-1}
Distributional costs	1,600,000	$ y^{-1}
Transport	1,600,000	$ y^{-1}
Taxable income	278,000	$ y^{-1}
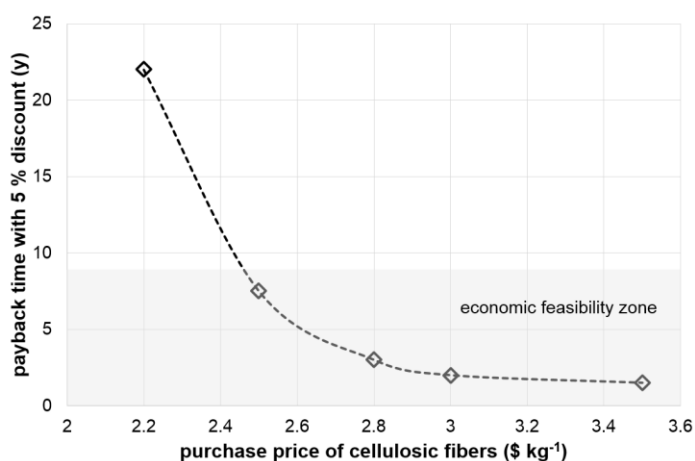
Figure 3: Discounted payback time dependence on the purchase price of cellulosic fibres.

CAPEX cost for such a biogas biorefinery proposal was estimated to be 3 730 000 $, see Tab. 1. OPEX expenses were 3 765 000 $ y^{-1}, see Tab. 2. CAPEX level is based on nowadays pricing of individual equipment. There is only a potential to decrease CAPEX by a price reduction of pretreatment technology, i.e. to intensify processes, treatment under higher solid loading, heat recovery using a heat pump, where all that can lead to a decrease of its investment cost and CAPEX. Biogas technology and drying are conventional methods, there is no potential to decrease CAPEX. As for OPEX, its set up is based on actual energy prices, actual percentage pricing of individual items, there is no potential to be decreased. Based on sensitivity analysis, it was found that economic feasibility of the process is strongly dependent on profit from cellulosic fibre purchase. Discounted

payback time was evaluated in dependence on the purchase price of cellulosic fibres and depreciation rate 5 %, see Fig. 3. Period of interest rate 10 years and lifetime of the project 30 years is expected. The minimum purchase price of cellulosic fibres 2.5 $ kg^{-1} generates a profit of the technology with common payback time being the 6-8 year (Towler and Sinnott, 2013).

Such a biogas biorefinery has two dominant environmental benefits, i.e. intensive waste treatment in material-energy recycling and carbon dioxide reduction.

- If wooden chips are directly combusted, there is production of 1080 kg$_{CO_2}$ from each ton of wood chips (Yliopisto, 2017). If wooden chips are digested in a conventional biogas plant, 220 Nm^3 of biogas yield per ton of wooden biomass can be expected (Al Seadi, 2008) and 110 Nm^3 of CO_2 per ton of wood chips is produced if volumetric ratio methane to carbon dioxide 1:1 being typical for polysaccharide substrates. Carbon dioxide production by wood chips treatment in conventional biogas plant is roughly 10 times lower than direct combustion.
- The biorefinery concept assumed that wooden chips contain 47 wt. % of cellulosic fibres that are removed before anaerobic fermentation. Only 53 wt. % of wooden chips´ organic solids are available for anaerobic fermentation for the biorefinery set-up. 58 Nm^3 of CO_2 per ton of wood chips is produced respecting previous assumptions. Carbon dioxide production of biogas biorefinery is roughly 2 times lower in comparison with conventional biogas plant.

4. Conclusion

Cellulosic fibre rich lignocellulosic waste treatment in the biogas biorefinery showed benefits of waste material-energy recycling. There is a potential of environmentally friendly treatment of waste using economically feasible technology with reduced carbon dioxide production. Nevertheless, the techno-economic study proved that its economic feasibility is strongly dependent on operating expenses and purchase price of cellulosic fibres especially. Such a waste treatment technology and its industrial set-up is therefore strongly dependent on industrial demand to the product in relation to its quality and also on government rules and policy for waste treatment technologies in mutual material and energy recycling mode.

Acknowledgments

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