Technology of biogas production, as a biorefinery concept

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Abstract

Nowadays, biogas production technology using lignocellulosic wastes is not that efficient, and without subsidies, the sustainability is hardly believed. Analogically to a petroleum refinery, possible success could be hidden in the application of biogas plants in a biorefinery concept. Several "green technologies" are studied (different rotations of biogas plants) and compared to the "biogas biorefinery". Resulted economic analysis clearly shows the transparency and applicability of each technology in practice.

Keywords: wheat straw, algae, biogas, biorefinery

1. Introduction

The lignocellulose is one of our life constitutes. From the earliest humans were using the fire, by burning of lignocellulose. From that time the huge energy doors were opened stepping humanity into new evolution. The utilization of lignocellulose created a heat by burning, and that heat was used for humanity needs: cooking, heating, etc. It was clear that lignocellulose source is inefficient and uneconomical, because of enough expensive technology, and huge material amounts need. However, the usage of lignocellulose is still one of the most widely used energy forms in the world. The utilization of lignocellulose is quite diverse: biogas can be commercially developed, and lignocellulose power generation and solid fuel (pellets). The bioliquid fuel and gasification is coming into the market. The high diverse utilization of lignocellulose puts a great role in the progress of society (Han, 2013).

As the progress is going the society naming the steps that were discovered or investigated. So that, until now 3 different generations are used widely. *First-generation biofuels,* taking the dominant production of either bioethanol or biodiesel because used technology is simple and well know (Jose & Bhaskar, 2015). The feedstock for first-generation biofuels are oils, sugars, and starches coming from food crops. There were a lot of debates over the actual benefit which brings the following generation. Is it really reducing greenhouse gas and CO2 emissions? It was estimated that comparing to petrol the first-generation biofuels can reduce greenhouse effect by 30% (Fyferling, 2013). However, the main issue is the influence of biofuel production into the price of food, which used as a feedstock. The more biofuel we produce the more food energy crops we consume for production. Such a demand leads to a direct increase of food prices. The *second-generation biofuels* came to overcome the bad sides of the previous generation. There are produced from non-food crops such as organic wastes, wood, food crop wastes, thus eliminating the main disadvantage of the first generation. It was estimated that the usage of second-generation biofuels for transport use, can reduce greenhouse effect from 70 to 90 % (Fyferling, 2013). All we need to do is to "harvest" them. However, the issue here is the sustainability, which implies different factors like, society, environment and economic possibilities. The *third generation biofuels* are the improvements of productivity aspects mainly. For example, algae is the perspective feedstock because the produced energy from 1 hectare can be 100 times higher than the productivity of conventional crops (Pandey, et al., 2014). Nevertheless, the combination of all three biofuel generation could provide significant leverage in terms of energy needs producing different products, which at the same time can decrease the cost of production considerably.

As the example of previously discussed diverse production, the well-known petrochemical industry could be taken. All great petrochemical companies owe their success to the fact, that each component of the complex substrate (e.g., crude oil) must be converted into different products by distillation and catalytic conversion technologies. Even the residues must find their own places (e.g., asphalt). The following approach called refining. However, with the incredible exploitation of petroproducts, we are not considering the price we can pay in the future. On the other hand, different biomass (food crops, non-food crops, organic wastes, algae etc.) seems to be a very promising substitution. Biomass has complex components, so as crude oil does. Thus, the combination of technologies and biomass conversion processes could define analogically another term, biorefinery (Chen, 2015).

1.1 Definition of biorefineries

Biorefinery concept consists of pre-treatments and preparation of biomass. Also, from the separation of biomass components, called *primary refining*, and subsequent processing/conversion steps called *secondary refining* (Schavan & Aigner, 2012). Biorefinery process chain is depicted in the Figure 1.

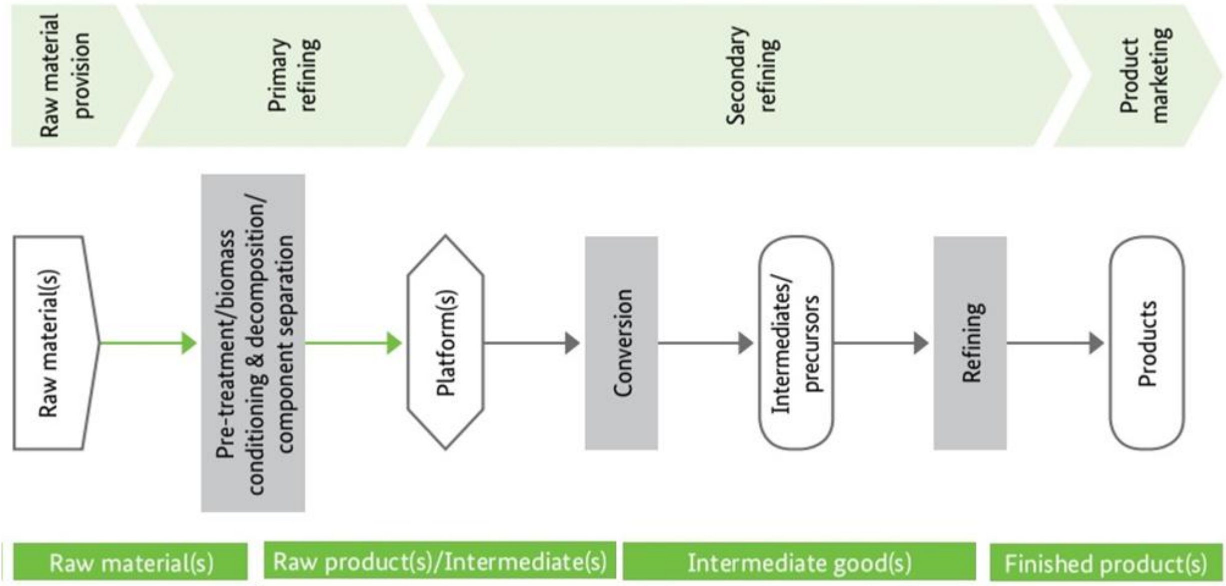

Figure 1. Biorefinery process chain (Schavan & Aigner, 2012)

Where, **primary refining** is the separation of biomass components into intermediates, such as cellulose, hemicellulose, lignin, starch, sugar, biogas, plant fibers, etc.); and it usually implies the pre-treatments and conditioning of biomass (Schavan & Aigner, 2012).

Secondary refining is further conversion and processing steps, which creates a larger number of products from intermediates taken from primary refining. Thus, in the first conversion step, intermediates are fully or partially processed into precursors, as well as into more intermediates. Further, these fully or partially refined into the products. And again, the products from biorefineries can be both finished and semi-finished, which could be transported to another plant for further processing/conversion (Schavan & Aigner, 2012).

So-called by-products, which occurs during primary/secondary refining are used for supply process energy or, where applicable or, in accordance with statutory requirements, they are processed into food or feed (Schavan & Aigner, 2012).

For a clarification the systems as follows, are not classified as biorefineries:

- Plants with biomass conversion where, no primary refining or secondary refining takes place (e.g. individual fermentation plants, starch factories with no connected processing plant).
- Systems with biomass conversion where no separation of the component. Biomass is unchanged, modified slightly, or used only minimally (e.g. wood processing mill)
- A plant where, the conversion of biomass that produces only a single major product, directly after primary refining, or where the major product substantially exceeds the quantity (e.g. biodiesel production, conventional biogas plants).

2. Materials and Methods

At first, several well-known biogas plants are examined, in order to compare practically with biorefinery concept.

Biomethane has attractive characteristics of anaerobic digestion, relatively high energy yields from organic substances, well-known technology for biogas production, low demand for substrate composition and quality, and also it has diverse application spectrum (Lindorfer & Frauz, 2015). The ratio of the substrate which is converted into biogas and residues after production can differ due to pre-treatment processes. Usually conventional plants mechanical disintegration of a substrate. In this work, highly new thermo-mechanical pre-treatment technology would examined. So called, thermal-expansionary pre-treatment has conversion ratio approximately 75:25 w.t. (Kutsay, et al., 2015). If we speak about conventional plants, then the ratio barely exceeds 60:40 w.t. (Kutsay, et al., 2015). With lesser intensive pre-treatment, the biogas production drops, thus increasing the weight of residues, or so-called digestate.

Usually, the residues are sold as agriculture fertilizers and biogas is burned in cogeneration unit to produce heat & electricity. However, there is another possibility to utilize the biogas. As the methane content in biogas can reach 70% (Deublin & Steinhauser, 2012), the idea of injecting separated methane into local grid could be another solution for profit. But the CO_2 removal is a complex and expansive process. On Table 1 you can see possible pathways of biogas processing.

Application	**Products**	**Conditioning effort/ removal**	**Degree of energy efficiency**
Burner	Heat production	None (very low – H_2O)	100%
CHP	Power	Low/H_2O, H_2S, siloxanes	34-45%
CHP	Power and heat	Low/H_2O, H_2S, siloxanes	Max.: 90%
Microgas turbine	Power and heat	Low	*Electrical:* 29-35%, *Thermal*: 65%
Direct injection	Fuel, CHP, etc.	Medium/ H_2O, H_2S, siloxanes	High
Direct fuel use	Fuel	Medium/ H_2O, H_2S, siloxanes	-
Upgrading (CH4 – 97-98% minimal demand)	Biomethane – fuel	High/ CO_2, H_2O, H_2S, siloxanes	-
	Biomethane – CHP	High/ CO_2, H_2O, H_2S, siloxanes	*Electrical:* 38-42% *Thermal:* 45-50%
	Biomethane – fuel cell	High/ O_2, CO_2 H_2O, H_2S, siloxanes	*Electrical:* 42-47% *Thermal:* 40%
	Biomethane – platform chemical	High/ CO_2, H_2O, H_2S, siloxanes	

Table 1. Utilization pathways of biogas (Lindorfer & Frauz, 2015)

Probably, the cheapest and easiest way of biogas utilization is direct combustion for the production of heat, as the only separation method to be applied is dehumidification (Lindorfer & Frauz, 2015). As only 45% of methane is necessary for combustion to occur (Deublin & Steinhauser, 2012). However, the utilization variations of heat are relatively low, comparing to electricity or liquid fuel. Some demonstration projects in Germany and Switzerland tested small biogas plants on pumping biogas, cleaned from hydrogen sulfur and other trace gasses, into the natural gas grid with 97-98% methane content, this could provide low-cost alternative to the application in cogeneration unit (Lindorfer & Frauz, 2015). Nevertheless, utilization of biogas in cogeneration unit is the most common application. The requirements for cleaning are still low, practically the same as for direct combustion. From the Table 1 it is possible to see that the power and heat generated efficiency is maximum 90 %, approximately half of it belong to power generation, and another half for heat generation.

In this work, both possibilities of cogeneration unit application, and biogas upgrading for natural gas grid would be analyzed.

As the 2nd step, the real biorefinery concept is evaluated. After studying of different biogas plants rotations, it was clear that even it is green technology and it is decreasing greenhouse gas emissions, it is still releasing high enough amounts of tail gasses, like: CO_2, vapor, H_2S. etc.; the idea to use them was to desirable. With the production of biogas the CO_2 content can reach 45% (Deublin & Steinhauser, 2012) and with the combustion in cogeneration unit the amount will increase approximately 2-3 times. Besides conversion into fuel (e.g. Sabatier methanation reaction), the CO_2 rather be used as the supply for photosynthesis, as this will not require any complicated technology. Thus, algae production was assumed to be the best alternative (Pandey, Lee, Chisti, & Soccol, 2014).

The algae were used thousands of years ago in China, Mexico. People were consuming cyanobacterium *Nostoc*, *Arthrospira* (*Spirulina*), and *Aphanizomenon* for food (Miledge, 2011). Many efforts in cultivation and commercialization of algae were done, as for biofuels aims, food etc. However, the production prices are very high comparing to conventionally used products. In recent years from around 2005, algal in deep research was resurrected. This is because of several factors: the link between climate change and increased CO_2 concentration in the atmosphere, extremely high consumption of transportation fuels, concerns about energy security owing to the huge amount of oil import (Chisti, 2007).

Until sustainable algae production for biofuel aims someday would be feasible, the high-value products for pharmacy, cosmetics and food nutrients are already withdrawn from the market.

Genus	**Production [tons y^{-1} dry weight]**	**Country**	**Application and Products**
Haematococcus	300	U.S., India, Israel	Aquaculture, astaxanthin
Aphanizomenon	500	U.S.	Human nutrition
Nostoc	600	China	Human nutrition
Dunaliella	1200	Australia, Israel, U.S., China, SA	Human nutrition, cosmetics, β-carotene
Chlorella	2000	Taiwan, Germany, Japan	Human nutrition, aquaculture, cosmetics
Spirulina	3000	China, India, Myanmar, U.S., Japan, SA	Human and animal nutrition, phycobiliproteins, cosmetics

Table 2. Commercial products from microalgae (Spolaore, et al., 2006) (Pulz & Gross, 2004) (Miledge, 2011)

Microalgae as human nutrition is restricted only to several species due to safety regulations (Pulz & Gross, 2004). From these, *Chlorella*, *Spirulina* and *Dunaliella* dominating the market. Usually, microalgae biomass is marketed as a powder or in tablets (Spolaore, et al., 2006). Some are used as animal feed supplements. Algae species like *Chlorella*, *Scenedesmus* and *Spirulina* have beneficial aspects including improved immune response, improved fertility, healthier skin and a lustrous coat (Pulz & Gross, 2004). The biorefinery concepts in this paper will include the production of especially *Chlorella Vulgaris*. Worldwide production of 2000 tones per a year of *Chlorella* was observed in the year 2003 (see Table 2).

3. Results and Discussion

Based on the previous work (Kutsay, et al., 2015), intensified biogas and non-intensified biogas plants would be taken. In this work wheat straw is used as the feedstock for anaerobic digestion in all rotations. The mass flow rate is 0.152 kg s^{-1} in every case.

Potential products of biogas plant were reviewed: heat & electricity, fermentation residue, biomethane, CO_2 emissions, other tail gasses, mineral fertilizer. Two types of biogas plant were examined: conventional biogas plant, and biogas plant with grid injection. As the biorefinery concept, biogas production was combined with the production of algae.

3.1 Intensified biogas plant: heat & electricity, digestate

To escape sophisticated process flow diagram, Figure 2 presents block diagram. Flowsheet for this concept can be found in previous studies (Kutsay, et al., 2015).

It is conventional biogas plant, except the integrated thermo-expansionary pre-treatment. Used pre-treatment is less aggressive than chemical one (Kratky & Jirout, 2014). Mass balance was constructed according to 750 kW power of CHP (Kutsay, et al., 2015). As the reference stream the biogas production was taken. With 40 days of residence time the plant produces 633±52 $Nm^3\ t^{-1}{}_{TS}$ of biogas, from which 362±43 $Nm^3\ t^{-1}{}_{TS}$ is methane (Kratky & Jirout, 2015). On Table 3 you can see mass balance for the proposed configuration. Intensified biogas production by itself regenerating energy.

On Table 4 you can see estimations of revenues and production costs.

6% of produced power used for own energy consumptions. Thus we have two key products: electricity (705 kW) and digestate. Waste streams are not counted, because the plant is producing green electricity. The consumables are not counted, even they exist the cost is negligible. The utilities are electricity, which produced by the plant itself, and water, which is cost negligible. The percentages for evaluation of fixed operating cost (labor, maintenance, land rental, etc.) were chosen in accordance with preliminary estimation. The project is not financed. The lifetime of the project is 25 years. The construction would be done within the 1^{st} year. The plant has 8000 working hours per a year. The estimated simple payback period is 30 years. Even, with 50% subsidies, which is possible to get in developed countries for renewable energy plants, biogas plant going to have around 19 years of the payback period.

Previously studied non-intensified biogas plant has the same mass flow rate (0.152 $kg\ s^{-1}$), but due to less biodegradation, it has 25% less of biogas, and 50% less methane is produced (Kutsay, Kratky, & Jirout, 2015). The technology by itself is the same, except the pretreatment. The substrate is only passing through the shredded conveyor, which is used as on-site transportation and less intensive pretreatment as a result. Such a plant has 500 kW power capacity. Even conventional technology is less effective, from a technological point of view, it has more favorable economic feasibility. In the worst case the payback period is 17 years, and including 50% subsidies it shortens to approximately 8 years.

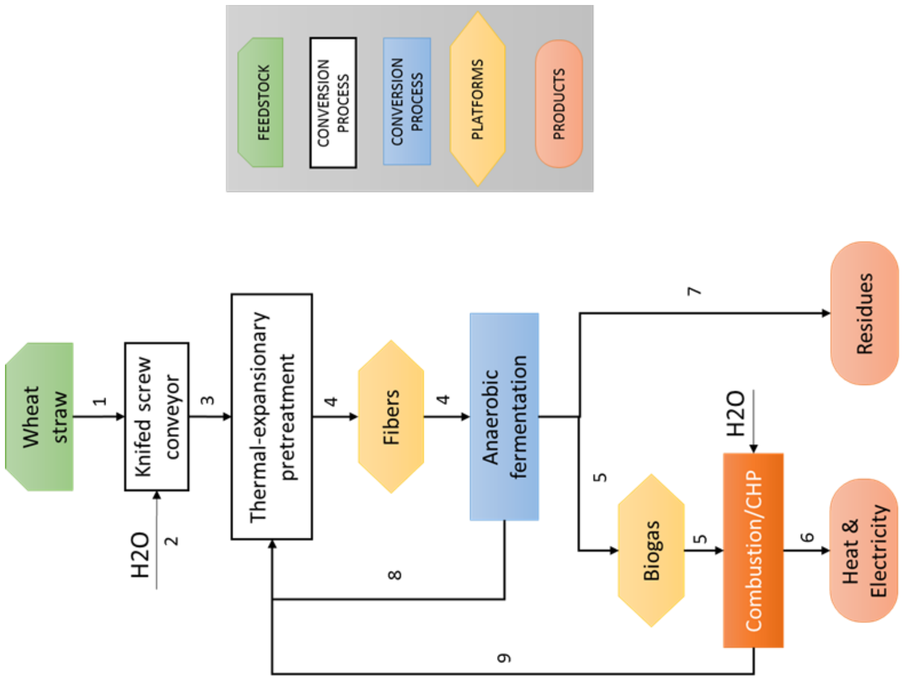

Figure 2. Block diagram: heat & electricity, digestate

Stream	Material	Mass flow [kg s^{-1}]	note
1	Wheat straw	0.152	
2	Water	0.101	
3	Wheat straw	0.152	
	Water	0.101	
4	Wheat straw	0.152	
	Water	2.888	
5	Biogas	0.113	CH_4, 0.039 kg s^{-1}
	Water vapor	0.006	
6	Recycled water	2.853	water dosage
7	Exhausts	1.000	530 ^{o}C
8	Residuals	0.068	solid, liquid mixture
9	Electricity & Heat	750 kW & hot water	

Table 3. Mass balance: heat & electricity, digestate

		Note:
ISBL Capital Cost [$MM year^{-1}]	3.816	
OSBL Capital Cost [$MM year^{-1}]	1.562	*40% of ISBL*
Engineering Cost [$MM year^{-1}]	1.068	*20% of ISBL+OSBL*
Contingency [$MM year^{-1}]	0.534	*10% of ISBL+OSBL*
Total Fixed Capital Cost [$MM year^{-1}]	**6.945**	
Variable Cost of Production [$MM year^{-1}]	0.10	*Water + own electricity*
Fixed Cost of Production [$MM year^{-1}]	0.70	*Labour, Maintenance, Land rental, Property tax, Overhead expenses*

Cash Cost of Production [$MM year^{-1}]	**0.80**	
Gross Profit [$MM year^{-1}]	0.20	*Profit-Cash cost of production*
Total Annual Capital Charge [$MM year^{-1}]	1.44	*15% Interest Rate*
Total Cost of Production [$MM year^{-1}]	2.24	*Total annual + Cash Cost of Production*
Payback period [year]	**30**	

Table 4. Preliminary economic estimations; heat & electricity, residues

3.2 Biogas plant: biomethane grid injection, digestate

As in the previous case, the basement was taken from earliest studies (Kutsay, et al., 2015). However, due to energy balance (necessity of exhausts, from cogeneration unit, for pre-treatment), conventional biogas plant was chosen (non-intensified plant). This non-intensified biogas plant can produce 280 Nm^3/h biogas, which is lower than intensified biogas plant (350 Nm^3/h). Some literature proposes to produce minimum 500 Nm^3/h of biogas in order to achieve profitability for grid injection configuration, that is due to high cost of biogas separation process (Lindorfer & Frauz, 2015).

A strong dependence of tail gasses from burning of biogas in cogeneration unit, which used after for keeping necessary temperature and pressure conditions during thermal-expansionary pre-treatment, makes the intensified technology to be not applicable for biogas upgrading plant. Thus, non-intensified technology was chosen as a reference one.

All the parameters and equipment would be the same except, instead of cogeneration unit the pressure swing adsorption would be used as a biogas upgrading technology. Figure 3 shows this concept.

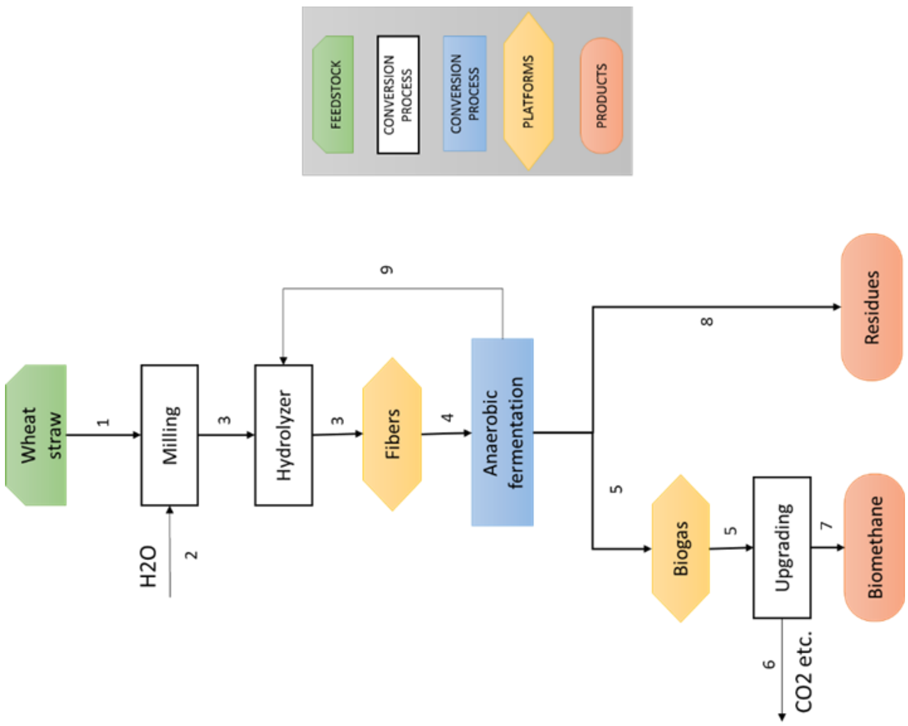

Figure 3. Block diagram: biomethane grid injection, digestate

As the reference stream the biogas production was taken. With 50 days of residence time the plant produces 509±58 $Nm^3\ t^{-1}_{TS}$ of biogas, from which 243±49 $Nm^3\ t^{-1}_{TS}$ is methane (Kratky & Jirout, 2015). Comparing to the previously discussed intensified biogas plant, the methane yield is 50% higher. On

Table 5 you can see mass balance for the proposed configuration.

Before economic analysis the total investment cost must be estimated. So, the non-intensified biogas production was updated by implementing pressure swing adsorption, and eliminating unnecessary equipment which were in use with cogeneration unit. The investments of pressure swing adsorption were calculated based on the amount of entering biogas (BIO.METHAN, 2013). On Table 6 you can see estimations of revenues and production costs.

At preliminary estimation, the price of biomethane injecting should be estimated. So, it was suggested for small biogas plants (up to 15 000 MWh per year) to have the fee range between 0.007 – 0.104 $ kWh^{-1} (RHI, 2014). For this analysis average value of 0.075 $ kWh^{-1} was chosen. Another product is digestate, which is almost profit negligible with respect to biomethane. In this concept we don’t have cogeneration unit. Thus, we need to buy electricity, equivalently 6% from 500 kW (size of reference non-intensified biogas plant) and additionally for pressure swing adsorption must be supplied. In order to be sure of fulfilling all the electricity requirements, such strategy was chosen. The other ratios for

Table 5. Mass balance: biomethane grid injection, digestate

Stream	Material	Mass flow [kg s^{-1}]	Note
1	Wheat straw	0.152	
2	Water	0.018	
3	Wheat straw	0.152	
	Water	0.018	
4	Wheat straw	0.152	
	Water	1.368	
5	Biogas	0.091	0.077 $m^3\ s^{-1}$
	Water vapor	0.002	
6	CO_2 etc.	0.064	0.037 $m^3\ s^{-1}$
7	Recycled water	1.363	Water dosage
8	Residuals	0.075	solid, liquid mixture
9	Biomethane	0.026	0.037 $m^3\ s^{-1}$

		Note:
ISBL Capital Cost [$MM $year^{-1}$]	2.59	
OSBL Capital Cost [$MM	1.04	*40% of ISBL*

year $^{-1}$]		
Engineering Cost [$MM year $^{-1}$]	0.72	*20% of ISBL+OSBL*
Contingency [$MM year $^{-1}$]	0.36	*10% of ISBL+OSBL*
Total Fixed Capital Cost [$MM year $^{-1}$]	**4.71**	
Variable Cost of Production [$MM year $^{-1}$]	0.16	*Water + own electricity*
Fixed	0.	*Labour, Main*

Cost of Production [$MM year^{-1}]	53	*tenance, Land rental, Property tax, Overhead expenses*
Cash Cost of Production [$MM year^{-1}]	**0.69**	
Gross Profit [$MM year^{-1}]	0.18	*Profit-Cash cost of production*
Total Annual Capital Charge [$MM year^{-1}]	0.98	*15% Interest Rate*
Tota	1	*Total*

l Cost of Production [$MM year^{-1}]	.66	*annual + Cash Cost of Production*
Payback period [year]	**25**	

Table 6. Preliminary economic estimation: biomethane grid injection, digestate

evaluation of fixed operating cost (labor, maintenance, land rental, etc.) was chosen in accordance with preliminary estimation. Again, the project is not financed, a lifetime of the project is 25 years, construction would be one within the 1st year, the plant has 8000 working hours per a year. Summarizing data, the simple payback period is 25 years. Including 50% subsidies, such a concept can have around 19 years of the payback period.

3.3 Biorefinery plant: heat & electricity, high-value algae powder, digestate

The production of algal biomass seems to be promising, as only water, CO_2 and light are needed for growing. Also, its applicability is quite diverse (Pandey, et al., 2014) (Brennan & Owende, 2010). Yet, it is possible to predict the same economics as for 1st and 2nd biofuel generations. Thus, an attempt in this chapter would be taken to gain another profit by producing, processing algal biomass and biogas altogether. There are several types of algae growth: one which is continuously under the sunlight (autotrophic), and another growing in dark (heterotrophic) (Pandey, et al., 2014). In this work autotrophic and mixotrophic (combination of sun and dark) would be examined as a potential.

3.3.1 In combination with autotrophic

For the production of algal the CO_2 must be supplied. If the feedstock supply would be fixed for both biogas productions (speaking about 3.1 and 3.2), then intensified biogas production will have higher amounts of released CO_2, because more biogas is produced and burned in cogeneration unit. Thus, intensified production with thermal-expansionary pre-treatment would be selected for this biorefinery concept. On Figure 4 you can see a block diagram of proposed concept.

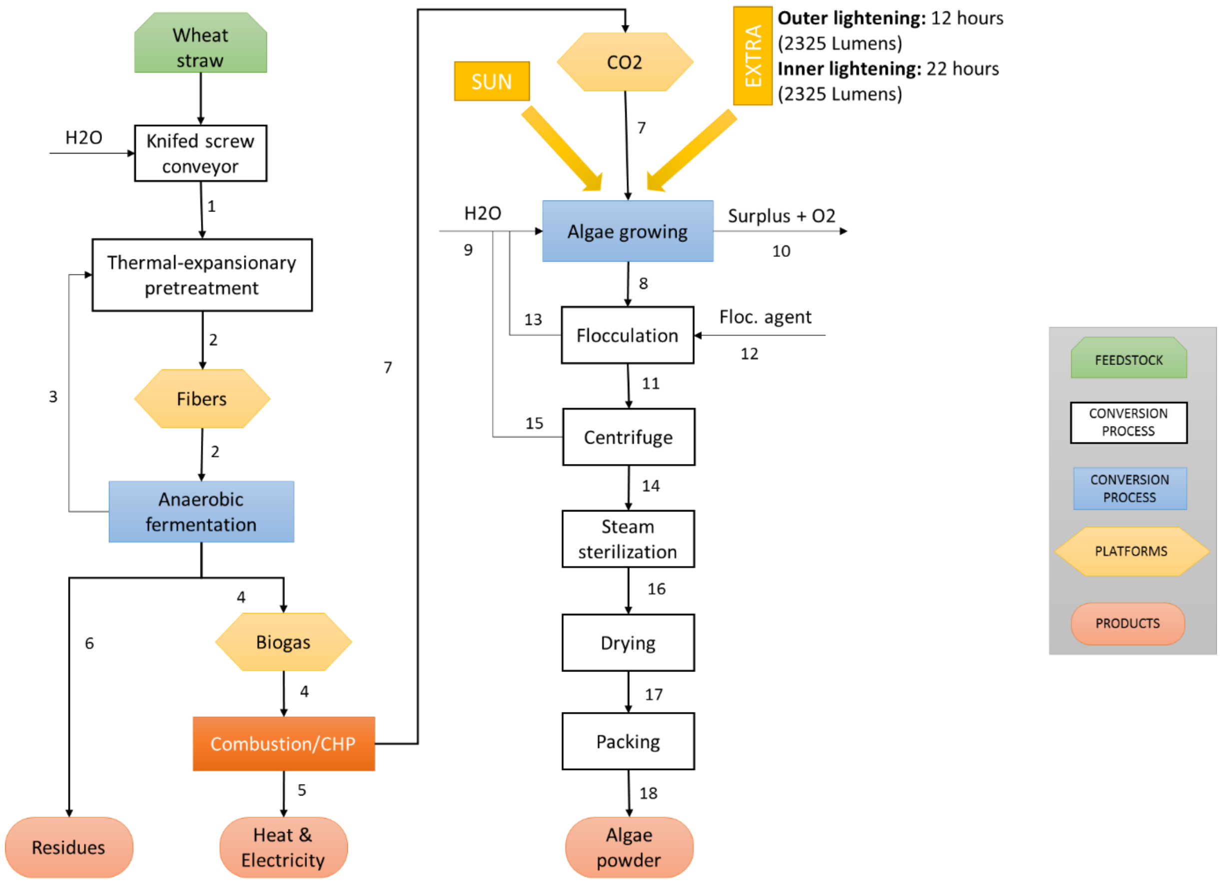

Figure 4. Biorefinery, intensified biogas plant & Algae biomass production

It was found that utilization of tail gases, directly after combustion of biogas, for cultivation of Chlorella species is allowable, because it has no negative influence on the growth of algal (Pourmovahed, et al., 2011) (Maeda, et al., 1995) (Doucha, et al., 2005). It is assumed that all the needed nutrients and CO_2, for algae cultivation, would be supplied with tail gasses. Thinking about, that such an algae biomass could be further used as a feed or nutrients would be madness. Also, the prices of different end products must differ. Thus, this work includes economic analysis for a range of algae biomass prices.

First part is exactly the same as, the production of heat & electricity and residuals in intensified biogas plant (3.1). However, at this moment the tail gasses would be also used as the feed for algal species (Figure 4). Production of any algal is the quite complicated procedure. Thus, comprehensive study showed, in order to gain higher profit from algal biomass it must be produced with small period of time, and high value of productivity per used square meter (Lindorfer & Frauz, 2015) (Pandey, et al., 2014) (Sadhukhan, et al., 2014) (Chavada, 2012) (Mokebo, 2012). So, one very interesting and progressive way of algae cultivation was chosen. Co-annular vertical photobioreactor has a simple construction and relatively high biomass productivity (Chavada, 2012). The source of light is mounted inside the submerged cylinder and surrounded outside of it, preferably from four sides. Such a construction ensures high light penetration depth through the wall, which is quite critical parameter for algae growth.

The number of photobioreactors is strictly depended on the amount of CO_2 that we have. Using a a mass balance of combustion reaction, it was found that, with the burning 0.113 kg s^{-1} of biogas, kg s^{-1} of CO_2 would be produced. Used co-annular photobioreactors are slightly reconstructed decreasing the size) to increase specific productivity, comparing to the found one (Chavada, These co-annular photobioreactors approximately 3 meters high and 0.45 meter in diameter and meters high and 0.3 meters in diameter, for outside and inside cylinder respectively. Water is the gap between small and big cylinder. The mix of air and CO_2 (9% by vol.) is supplied from the of the co-annular cylinder (Chavada, 2012). With the estimated CO_2 mass flow emissions, it is that approximately 9240 pieces of such a photobioreactors could be supplied. On

Table 7you can see mass balance.

The residence time for Chlorella Vulgaris is 10 days, and the working volume of one vertical co-annular photobioreactor is 265 liters. Found algal productivity is 0.1841 g L^{-1} d^{-1}, but in this work the productivity would be lowered to 0.15 g L^{-1} d^{-1} (Chavada, 2012). So that, one vertical co-annular photobioreactor will produce 13.25 kg of algal biomass per year, with 8000 working hours. Hence, the total possible production of all photobioreactors is around 122.5 tons per year, which is approximately 6% of worldwide production (Brennan & Owende, 2010). After algal biomass must be harvested. First the suspension is flocculated using flocculant seed of clearing nut, Strychnos potatorum (Razack, et al., 2015). Such an organic bioflocculant could be a promising substitute for expensive and hazardous chemical flocculants. Usually after flocculation the mixture has 2% of total solids (Benermann, 2013) (Saravacos & Kostaropoulos, 2002). Then, the mixture is entering to the high-speed centrifuge, after what the amount of total solids rises to 17% (Saravacos & Kostaropoulos, 2002) (Grima, et al., 2003) (Heaven, 2011) (Steiger & Wimmer, 2012). To ensure product quality the mixture must be sterilized (Pandey, et al., 2014). As the final step, the mixture is dried. After spray dryer the amount of total solids rises up to 97% (Lin, 1985) (Xingyu, 2016).

With all needed parameters the investment cost for algae plant especially is evaluated (Table 8). For the estimation of investment cost for algae production, only most expensive and critical equipment were taken into account. For estimation of whole biorefinery, intensified biogas plant must be added to algae plant (Table 9).

Table 7. Mass balance: Biorefinery, biogas plant and algae production

Stream	**Material**	**Mass flow [kg s^{-1}]**	**Note**
1	Suspension	3.04	
2	Suspension	3.04	
3	Biogas	0.113	CH_4, 0.039 kg s^{-1}
4	Water	2.853	
5	CO2 + Nutrients	0.188	
6	Electricity & Heat	750 kW	
7	Residuals	0.039	
8	Water	2.834	
9	CO2 + Nutrients	0.184	
10	Water	2.834	
	Algae biomass	0.0043	
11	Flocculant agent	0.0003	
12	Water	0.208	
	Algae biomass	0.0043	
13	Water	0.021	
	Algae biomass	0.0043	
14	Water	2.626	
15	Water	0.1875	
16	Water	0.021	
	Algae biomass	0.0043	
17	Water	0.00013	
	Algae biomass	0.0043	
18	Algae biomass	0.0043	

Reference	Name	Parameter **1**	Parameter **2**	Specific cost	Capital cost [$]

(SOLAR-COMPONENTS, 2016)	PBR outer cylinder	9240 pc.	440 L	508.3 $ m^{-3}	2 066 544
(SOLAR-COMPONENTS, 2016)	PBR inner cylinder	9240 pc.	150 L	835 $ m^{-3}	1 157 310
(HOMEDEPOT, 2016)	T12 Fluorescent bulb	147840 pc.	-	2 $ pc^{-1}	295 680
(FIXR, 2016)	Basement	13720 m^2	-	65 $ m^{-2}	891 800
(GREENHOUSEMEGASTORE, 2016)	Greenhouse Roof	1960 m^2	7 houses	170 $ m^{-2}	2 287 000
(Towler & Sinnot, 2012)	High speed Centrifuge	0.3 m	2 pc.	a, b, n tabulated values	530 000
(Mujumdar, 2014)	Spray Drier	2 m^3	1 pc.	M&S, A, D tabulated values	101 000
		ISBL [mil. $]			7.326
		OSBL [mil. $]			2.930
		Engineering Cost [mil. $]			3.077
		Contingency Charges [mil. $]			3.077
		INVESTMENT COST [mil. $]			16.411

Table 8. Fixed capital cost for algae production plant

	Intensified Biogas Plant (Kutsay, 2015)	Algae Production
ISBL [mil. $]	3.816	7.326
OSBL [mil. $]	1.526	2.930
Engineering Cost [mil. $]	1.068	3.077
Contingency Charges [mil. $]	0.534	3.077
INVESTMENT COST [mil. $]	**6.945**	**16.411**
TOTAL INVESTMENT COST [mil. $]	**23.356**	

Table 9. Total fixed capital cost of biorefinery

The price of Chlorella Vulgaris on market is around 45 $ kg^{-1} (Brennan & Owende, 2010). The following price is an average value of human nutrition, cosmetics and aquaculture applications. Among algae powder, electricity and residuals are another profits. For the flocculation strychnos potatorum must be bought, as a consumable. As for extra utilities, 10% of produced electricity is used for own equipment consumption. However, equipment like: high-speed centrifuge, spray drier and lightening, were added as an extra charge for utilities, because of high energy consumption. With help of mass balance and specific consumptions of each equipment it is possible to estimate operating costs (high-speed centrifuge, 1.4 kWh m^{-3} (Heaven, 2011), spray drier, 6 MJ kg^{-1} (Saravacos & Kostaropoulos, 2002), T12 fluorescent bulb, 40 W each). Fixed operating costs was estimated using ratios for preliminary estimations. Table 10 describes preliminary economic estimations.

		Note:
ISBL Capital Cost [$MM $year^{-1}$]	11.142	
OSBL Capital Cost [$MM $year^{-1}$]	4.457	*40% of ISBL*
Engineering Cost [$MM $year^{-1}$]	4.145	*27% of ISBL+OSBL*

Contingency [$MM year^{-1}]	3.611	*23% of ISBL+OSBL*
Total Fixed Capital Cost [$MM year^{-1}]	**23.356**	
Variable Cost of Production [$MM year^{-1}]	4.58	*Water + own electricity*
Fixed Cost of Production [$MM year^{-1}]	1.69	*Labour, Maintenance, Land rental, Property tax, Overhead expenses*
Cash Cost of Production [$MM year^{-1}]	**6.27**	
Gross Profit [$MM year^{-1}]	0.19	*Profit-Cash cost of production*
Total Annual Capital Charge [$MM year^{-1}]	4.84	*15% Interest Rate*
Total Cost of Production [$MM year^{-1}]	11.11	*Total annual + Cash Cost of Production*
Payback period [year]	**59**	

Table 10. Preliminary economic estimation: heat & electricity, high-value algae powder, digestate

The simple payback period is around 59 years. Assuming 50% subsidies, payback drops to 30 years.

3.3.2 In combination with mixotrophic growth of algae

Chlorella Vulgaris is capable of growing in both techniques, autotrophic and heterotrophic (Safi, et al., 2014). Thus, the incredibly high operating cost for lightening could be saved. However, the disadvantage of heterotrophic growth is a low price on market and availability of sugars, which compete with feedstocks for food nutrition, pharmacy etc. (Safi, et al., 2014). Hence, to assume the products of mixotrophic growth for the same price, as for autotrophic (45 \$ kg^{-1}), would be quite unfair. The price for produced algae biomass would be fully depended on its applicability. In order to understand its applicability, appropriate laboratory measurement must be done. Nevertheless, just to see the possibilities for mixotrophic growth, several assumptions would be examined.

Firstly, we set light and dark ratio to be 12:12, and we assume the same productivity. Thus, using mixotrophic conditions, we decrease variable cost (saving on lightening only) of production by 40% approximately. Next, based on the final product a few assumed prices are examined: 5 \$ kg^{-1}, 10 \$ kg^{-1}, 20 \$ kg^{-1}, 30 \$ kg^{-1}, 40 \$ kg^{-1}. All the other parameters for economic estimations would be the same as in autotrophic growth.

Price	5 \$ kg^{-1}	10 \$ kg^{-1}	20 \$ kg^{-1}	30 \$ kg^{-1}	40 \$ kg^{-1}
Average Cash flow [mil. \$ y^{-1}]	-2.11	-1.61	-0.61	0.39	1.39
Payback [years]	-	-	-	66	19
Average Cash flow [mil. \$ y^{-1}] incl. 50% subsidies	-1.69	-1.19	-0.19	0.81	1.81
Payback [years] incl. 50% subsidies	-	-	-	32	14
Notes:	*Negative values*	*Negative values*	*Negative values*		

Table 11. Feasibility analysis: heat & electricity, high-value algae powder (mixotrophic), digestate

3.4 Discussion

Studied different biogas plant rotations, both combinations have almost same payback period, including the error of preliminary estimation which is 30%. The production of electricity is good if there is a shortage of it in a district. When it comes to transportable fuel, biomethane is much more applicable, as electricity storage batteries are heavy and cannot store big amounts of energy. Also, big scale plants are more likely to have higher yields, and higher profits. Anyway, the techno-economic analysis clearly shows unsustainability of these projects, as the profitable project must have 3-5 years of paybacks. Attempts in the intensification of biogas production lead to substantial capital cost increase (approximately 50% higher comparing to non-intensified biogas plant (Kutsay, Kratky, & Jirout, 2015)), which as a result, is not justified by gained profits.

Looking into conventional (non-intensified) biogas plant (Kutsay, et al., 2015), even with 30% less biomethane productivity the payback period is sensitively shorter, comparing to intensified biogas plant. That clearly explains unworthy efforts in technology improvements. Also, conventional biogas plants are well known in today's practice, which is one of the most important factors in the selection procedure.

In the biorefinery concept, the biggest problem in the cultivation of high-value algae biomass is the expenditures for lightening. From the autotrophic growth it follows that approximately 65% of gained profit, spent for lightening only. Thus, the location of the biogas-algae biorefinery is very important, warm countries with more sunny days are in top priority. Another critical factor is a selection of photobioreactor. High productivity values are usually followed by the low production volumes (Pandey, et al., 2014). Investigated vertical co-annular photobioreactor has enhanced productivity comparing to vertical photobioreactor, due to extra from-the-inside lightening (Chavada, 2012).

Ideas about algae growing for biofuels, are almost impossible with such a petroleum prices. It has been reported, to be competitive with petroleum at 100 $ per barrel, the biomass with 40% oil content will need to be produced at 0.16 $ kg^{-1} (Chisti, 2012). As the example, the production cost of algal biodiesel ranges in 2.17-9.92 $ L^{-1}, depending on the production technology (Delrue, et al., 2012). Hence, the production cost of biodiesel production from algae exceeds minimum 13.5 times, comparing to a competitive one. Until now, mixotrophic and heterotrophic growth are closer for biodiesel production. Heterotrophic cultivation of *Chlorella zofingiensis* estimates the oil production cost of 0.9 $ L^{-1} (Liu, et al., 2010), which exceeds production cost more than 5 times in comparing with competitive one (Chisti, 2007).

Mixotrophic growth can be applied to cultivate high-value products. However, with dark ratio increase makes algae cheaper, consequently with predominant light ratio increase makes algae biomass more valuable (Safi, et al., 2014). Noticing in Table 11, the best case, when the price of biomass algae would be 40 $ kg^{-1}, the payback period is 19 years. There are no investors who would be interested in such a projects. So, for this time the only who can do something is a local state, by helping projects with subsidies.

	Name	Non-Intensified (description not included in this paper)	Intensified biogas plant	Biogas plant, grid injection	Biorefinery
PROCESS	Substrate mass flow [kg_{TS} s^{-1}]	0.152	0.152	0.152	0.152
	Biogas yield [Nm^3 t^{-1}_{TS}]	509 ± 58	633 ± 52	509 ± 58	633 ± 52
	CHP power capacity [kW]	500	750	500	750
	Products	Heat & electricity, residues	Heat & electricity, residues	Biomethane, residues	Heat & electricity, algae powder (autotrophic), residues

ECONOMIC ANALYSIS	Total Capital Cost (TCC) [mln. $]	1.90	3.82	2.59	11.14
	No. of equipment	27	37	25	-
	Fermenter volume [m^3]	6600	10500	6600	10500
	Fermenter cost [mln. $]	0.891	1.155	0.891	1.155
	Fermenter percentage of TCC [%]	46	30	35	10
	Pretreatment percentage of TCC [%]	–	35.6	-	12.2
	Total Investment Cost [mln. $]	3.46	6.96	4.71	23.36
	Specific Investment [$ kW^{-1}]	6920	9280	9420	31147
	Profit [mln. $ y^{-1}]	0.67	1	0.87	6.46
	Payback period [year]	17	30	25	59
	Payback, including subsidies [year]	8	19	19	30
	Lifetime [year]	25	25	25	25
	OLR value [kg_{vs} m^{-3} d^{-1}]	2.0	1.2	2.0	1.2

Table 12. Table of all crucial evaluations

4. Conclusion

It is obvious that fossil fuels will end one day, and renewable energy sources going to take their places. However, from the studies it is clear, that now human kind is not fully ready for such a big change. As from studied renewable energy (biogas plant) and biorefinery plants it follows, that the more sophisticated technology is, the higher probability of its unsustainability. Every time we were trying to enhance the production by implementing new equipment, or diversify the products, continuously techno-economic was only getting worse. Anyway, bad results are also results. The solution can be found only by searching, testing and simulating new processing technologies.

The biorefinery concept showed how sophisticated the technology could be in order to have multi-products. Thus, until now single production, or where major product substantially dominates the other products, is more attractive than multi-production.

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