CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

SUMMARY OF DISSERTATION

CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Mechanical Engineering
DEPARTMENT of Process Engineering

Summary of Dissertation Thesis

Technology and equipment for lignocellulosic waste conversion to biofuels and bioproducts with high added value

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Doctoral Study Program: *Mechanical Engineering*

Study Field: *Design and Process Engineering*

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Co-Supervisor: *Doc. Ing Lukáš Krátký Ph.D.*

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Title in Czech language: Technologie a zařízení pro zpracování odpadů v ušlechtilé formy chemických látek a energií.

This doctoral thesis is an outcome of a full-time doctoral study program at the Department of Process Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague.

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Title: Technology and equipment for lignocellulosic waste conversion to biofuels and bioproducts with high added value

Summary:

In technical terms, a biogas biorefinery offers a sustainable platform for material and energy recycling. The objective of this dissertation is to test the hypothesis that the design of biogas plants within the biorefinery concept can achieve economic attractiveness without being dependent on subsidized investment costs and product purchase costs. Various concepts of biogas plant and biogas biorefinery were investigated and designed, incorporating different methods of substrate pretreatment such as mechanical disintegration and hydrothermal treatment, and product processing such as biogas refining, separation of cellulose fibers, and the use of CO2 for microalgae production. Each concept is equipped with a parametric model, which enables a comparative evaluation of mass and energy balances, technical maturity, and design economics. A critical analysis reveals that, apart from biogas upgrading, all concepts are deemed unfeasible, with a negative payback period. Although biogas upgrading demonstrates a positive payback period, it is still not attractive from an investment standpoint.

Název práce: Technologie a zařízení pro zpracování odpadů v ušlechtilé formy chemických látek a energií

Souhrn:

Technologie výroby bioplynu v konceptu biorafinerie nabízí udržitelnou platformu pro recyklaci materiálů a energie. Cílem této disertační práce je ověřit hypotézu, zda návrh bioplynových stanic v konceptu biorefinerie může dosáhnout ekonomické atraktivnosti bez závislosti na dotovaných investičních nákladech a nákladech na nákup produktů. Byly zkoumány a navrženy různé koncepty bioplynových stanic a biorefinerií bioplynu, které zahrnují různé metody předúpravy substrátů (mechanická dezintegrace, hydrotermální zpracování) a zpracování produktů (čištění bioplynu, oddělení celulózových vláken, využití CO2 pro produkci mikrořas). Každý koncept je vybaven parametrickým modelem, který umožňuje srovnávací hodnocení hmotnostních a energetických bilancí, technické dospělosti a nákladů na návrh. Kritická analýza ukazuje, že všechny koncepty kromě vylepšování bioplynu jsou neuskutečnitelné s negativní dobou návratnosti. Vylepšování bioplynu ukazuje pozitivní dobou návratnosti, ale stále není atraktivní z investičního hlediska.

CONTENTS

SYMBOLS

BBM	Bold's Basal Media
BP	Biogas Plant
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
$C:N$	Carbon : Nitrogen
CO	Carbon Monoxide
CO_2	Carbon Dioxide
GHG	Green House Gas Emissions
HRT	Hydraulic Retention Time
H_2O	Water
IEA	International Energy Agency
$ISBL$	Inside Battery Limit
LCB	Lignocellulosic biomass
N	Nitrogen
NPV	Net Present Value
NO_x	Nitrogen oxide
OLR	Organic loading rate
$OSBL$	Outside Battery Limit
PFD	Process Flow Diagram
pH	Power of Hydrogen
TS	Total Solids
VS	Volatile solids

1. INTRODUCTION

The concept of biorefinery has gained popularity in recent times. A biorefinery approach promotes an economy where material waste is minimized, new biobased products are developed to substitute their fossil counterparts, greenhouse gas emissions (GHG) are significantly reduced, and innovative policies support new economic perspectives. The recent fluctuations in the prices of fossil oil and biomass raw materials, coupled with their high demand, call for robust systems that can remain competitive while offering a variety of products. An ideal economy should make innovative and cost-effective use of biomass to produce various bioproducts like algae and different types of bioenergies such as biogas or bioethanol. At the same time, it should be governed by well-developed integrated biorefining policies. This type of economy will require a considerable amount of biomass, which could lead to increased food and commodity prices and unwanted competition for the production of food, feed, wooden products, paper, and other such commodities. Programs promoting reforestation, sustainability, and conservation for the long run cannot be limited to emerging economies such as Algeria or Kenya [1], but must also be considered for deforested regions worldwide, including countries with developed economies. Biorefinery processes and their primary and secondary products are essential in improving the smart and efficient use of biomass resources, forming a flexible and robust economy in the future. The best approach is to process food-based raw materials as little as possible and instead focus on the potential of non-food resources [1].

The International Energy Agency (IEA) Bioenergy has been promoting cooperation and information exchange between countries involved in biotechnology research and development since 1978. The IEA Bioenergy's vision is to make a desirable contribution to the future global energy demand by enhancing bioenergy production with environmentally friendly applications, socially acceptable, and cost-competitive biobased products while reducing GHG emissions. IEA Bioenergy Task 42 proposes the following definition for biorefinery: "*Biorefinery is the sustainable processing of biomass into a spectrum of marketable products and energy*." [2]. The biorefinery concept is a process chain consisting of systematic divisions for pre-treatment and biomass preparation, separation of biomass parts (primary refining), and subsequent conversion/processing steps (secondary refining) [3]. Figure 1 illustrates the biorefinery process chain.

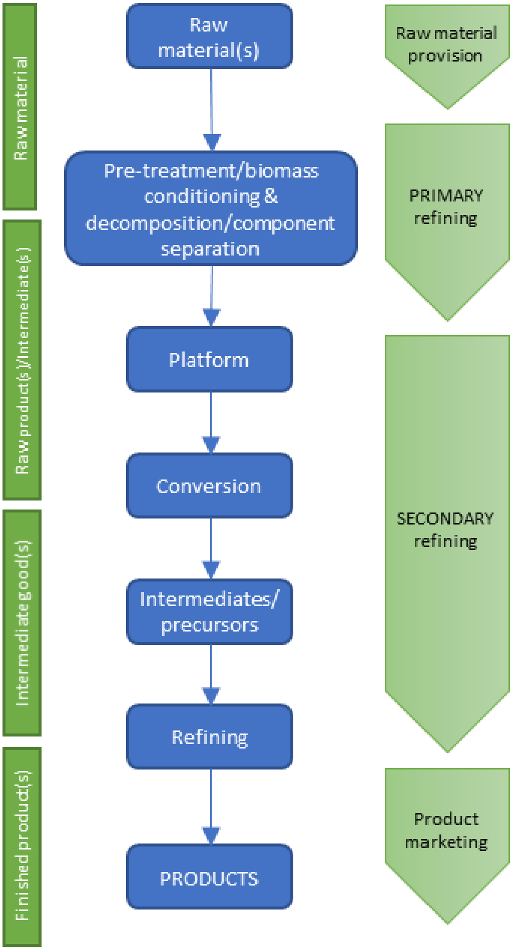

Figure 1. Scheme of biorefinery process chain [4]

2. SUMMARY OF CRITICAL REVIEW

There exist numerous types of biorefineries worldwide that produce various products such as ethanol, diesel, and biogas. Commercial biorefineries primarily focus on producing bioethanol and biodiesel, which is reasonable given that almost half of the global mineral oil consumption is utilized in the transportation sector, and approximately 20% of world energy is used for the same purpose [5]. Ethanol and biodiesel offer advantages as they can be utilized immediately in vehicles either alone or in blends, and the feedstocks required for their production are easy to obtain, despite any economic disputes. Ethanol and biodiesel have historically been considered as an alternative to food crops (first-generation biofuels) based on lignocellulosic biomass (LCB) [6]. With the increasing demand for bioethanol and biodiesel, the production of these biofuels is expected to increase substantially by 2050, with annual biofuel demand expected to reach 24-26 EJ [7].

Global liquid biofuel production in 2017 amounted to 138 billion liters, with 61.5% being bioethanol, 26.1% being biodiesel, and the remainder being other biofuels [8]. In Europe, biodiesel and bioethanol production reached 15.8 billion liters and 4.74 billion liters, respectively, in 2017. In the same year, the United States produced 13.2 billion liters of biodiesel and 74.3 billion liters of bioethanol, while Asia produced 7.18 billion liters of biodiesel and 5.8 billion liters of bioethanol [9].

One of the critical factors in the production of renewable energy sources is the feed-in tariffs, which guarantee continuous retail price support over a certain period. Feed-in tariffs can provide predictability and stability for the overall renewable energy landscape from a policy perspective, and for individual producers and investors with regard to their revenue [10]. Feed-in tariffs for different kinds of renewable energy sources such as solar, wind, hydropower, biomass, and geothermal energy, have historically tended to decrease, necessitating the improvement of technology to maintain economic feasibility.

2.1 Biogas Production as a main technology

Biogas production is a fundamental process in all evaluated biorefinery plants. Biogas is a versatile product that can be easily converted into biomethane through cleaning or upgrading. Biomethane can be injected into the grid, used as compressed natural gas (CNG), or burned directly in a combined heat and power (CHP) unit to generate heat and electricity.

Biogas production was chosen predominantly because of its conversion diversity. Despite the advantages of biogas production, biogas biorefineries are not as popular as other types of biorefineries. However, there are several biogas biorefinery plants in operation around the world. For example, in Denmark, the Billund Biorefinery is a demonstration plant that processes manure and organic agricultural waste to produce biogas and organic fertilizers [11]. In Germany, there are commercial, pilot, and demonstration plants such as Brensbach/Biowert and Sunliquid Straubig, which process grass, silage, and straw to produce energy and chemical products [11]. In Ireland, the Biorefinery Grass Demonstration plant processes grass to produce protein for animal feed, fertilizer, and biogas [11]. Finally, in Sweden, commercial and demonstration plants such as Domsjo Fabriker, ST1 Gothenburg, and Gobigas-Gothenburg process forestry raw materials and bakery residues to produce cellulose, lignin, bioethanol, animal feed, and biogas [11].

The following figure is based on a systematic supply chain perspective [12],

Substrate chain: Waste generation, collection, transportation and supply to the digestion facility and necessary pre-treatment of waste before feeding the digester.

Transformation process: Biological and chemical transformation processes of feedstock in the digester which leads to valuable products.

Product chain: Post-treatment of outflows from the digester that refines these into improved value products, and their distribution and utilization.

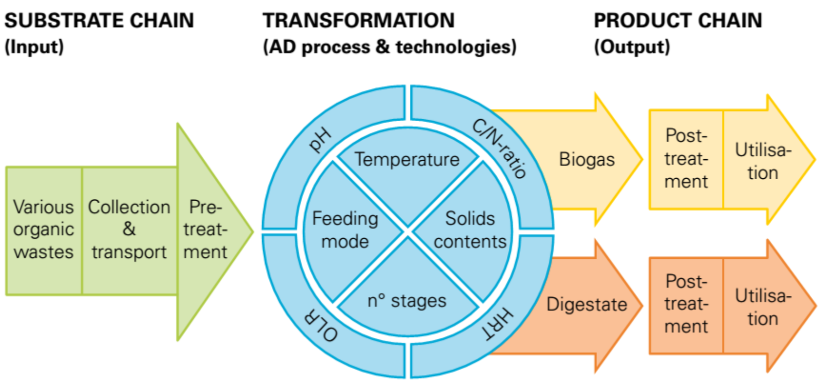

Figure 2. Process chain of anaerobic digestion [10]

3. OBJECTIVES

Hypothesis:

Lignocellulosic waste treatment in biogas biorefinery producing simultaneously green chemicals and energies can meet industrial attractivity independent on green subsidies.

The aims of the dissertation:

- To create a general parametric model of biogas biorefinery enabling a comparative evaluation of mass and energy balances, technical maturity and design economics, including sensitivity analysis.
- To investigate an innovative technological set treating lignocellulosic biomass in biorefinery concept to reach investment attractiveness without any subsidies.

4. MATERIAL AND METHODS

The original biogas biorefinery strategies are depicted in Figure 3. Based on combinatorics, following innovative biogas production technologies were proposed as presented in Table 1.

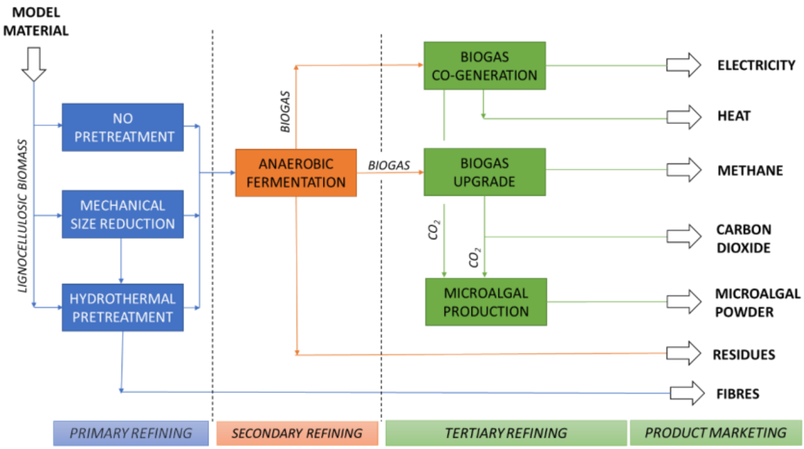

Figure 3. Biogas biorefinery strategies

There are six technologies described in the work, see Table 1 [AK1] [AK2] [AK3] [AK4] [AK6] [AK8] [AK9] [AK10].

All the plants are new, there is no revamping case.

It is assumed that all plants are parts of existing agricultural farms. Thus, the availability of substrate is constant.

	Technology	Substrate	Products
1	Conventional Biogas Plant	Wheat straw wastes	heat & electricity, residues
2	Biogas upgrade		biomethane, residues
3	Intensified Biogas Plant		heat & electricity, residues
4	Biogas-Fiber Biorefinery		fiber, heat & electricity, residues
5	Biogas-Algae Biorefinery		algae (autotrophic), heat & electricity, residues
6	Biogas-Algae Biorefinery		algae (mixotrophic), heat & electricity, residues

Table 1. Overview of technologies

4.1 Design of technology and process set-up parameters

The presented biorefinery plants have been designed with detailed mass and energy balances. These balances were constructed based on process flow diagrams (PFD) and were included in the appendices of the dissertation. The models were constructed and simulated using engineering practices and transport phenomena, along with basic software. The raw material used for all models was wheat straw waste (next only wheat straw), which was collected in storage areas. Table 2 shows the pre-treatment methods used in the different concepts.

For all models, a mesophilic, +35 °C, process was assumed with hydrolyzer and one level fermentation stages. The residence time for biodegradation in the fermenter is 40 and 50 days, intensified and non-intensified pretreatment respectively. Only Biogas-fiber biorefinery has 20 days residence time, because suspension inside the fermenter is liquid mainly. For designing it was decided not to have 65-day residence time as applied in [13], because the best engineering practice shows that, with mechanical disintegration only 50 days of residence time is sufficient [13] [14]. The fermenters are preheated with warm technological water, having minimum insulation thickness of 50mm, operated at 35 °C and designed for heat loss 12.5 W m^{-3} [14]. Fermenter and the homogenization vessel have agitators for mixing, which uniformly distribute the media inside. Electricity consumption of the agitator motors was considered for estimation of variable cost. Values of OLR, fermenter volume, CHP unit's installed electric power and the others, are presented in Table 4. Fermenters are assumed to be made of concrete with heating coils.

To maintain a constant flow of biogas, a buffer vessel was placed between the fermenter and the CHP unit. Biogas and methane yields are described in Table 2, at normal conditions 20 °C and 1 bar.

CHP unit has an electric efficiency of 38 % and a thermal efficiency of 45 %. [15]. For start-up and safe production, the surplus of biogas is burned in flares. Tail gases are cooled down in CHP, heated water is used for keeping process parameters in the other equipment.

To produce 500 kW_{el} in conventional plant it is necessary to use 0.545 t_{TS} h^{-1} or 0.152 kg_{TS} s^{-1} of wheat straw. To compare the difference of the techno-economical estimations between the concepts, it was decided to fix the calculated mass flow rate and to use it for all the concepts.

As a product of biogas combustion in CHP unit, tail gasses are released to atmosphere, but in biogas-algae biorefinery tail gases are used for cultivation. Tail gas produced by burning of biogas, consists of 66.1 % N_2, 22.3 % CO_2, 11.2 % H_2O, and traces like NO_x and CO [16] [17]. The post-rotting of the fermentation residues is not assumed, due to the carbon-poor residual solids.

For digestated fermentation residues, solid bowl decanter centrifuge was assumed to be used for liquid and solid separation process.

	Technology	Type of substrate pre-treatment	Solid concentr. in homogn. vessel [%wt.]	Biogas yield [$Nm^3t^{-1}_{TS}$]	Methane yield [$Nm^3t^{-1}_{TS}$]	Reference
1	Conventional Biogas Plant	No pre-treatment	10	509±58	243±49	[18], [AK3]
2	Biogas upgrade	No pre-treatment	10	509±58	243±49	[18], [AK2]
3	Intensified Biogas Plant	Thermal-expansionary	5	633±52	362±43	[13], [AK2]

4	Biogas-Fiber Biorefinery	Thermal-expansionary	5	100	55	[13], [AK2]
5	Biogas-Algae (autotrophic) Biorefinery	Mechanical disintegration	10	605±17	343±11	[19], [AK3]
6	Biogas-Algae (mixotrophic) Biorefinery	Mechanical disintegration	10	605±17	343±11	[19], [AK3]

Table 2. Pre-treatment methods of substrate and biogas yield

4.2 Economic evaluation technique

4.2.1 Economic evaluation

Fixed capital investment is the sum of designing, construction, commissioning, start-up and the other costs, which are necessary to build and hand over the plant. It was estimated with help of individual components: inside battery limit (ISBL) investment, outside battery limit (OSBL) investment, engineering and construction costs, contingency charges [20].

Purchased equipment costs were estimated by empiric models [20], and specific values for the equipment, which are not standard like, cogeneration unit or huge anaerobic fermenters, for which the specific cost could be found in terms of $ kW_{el}^{-1} or $ m^{-3} respectively.

Production costs were set as per percentages found in literature [20].

Net present value (NPV) was used to estimate discounted payback period, having discount cash flow rate of 5%.

4.2.2 Economic model set-up

Al the values which were used for economic model set-up are shown in Table 3.

<table>
<tr><th colspan="2"></th><th>Conventional BP</th><th>Biogas upgrade</th><th>Intensified BP</th><th>Biogas-Fiber Biorefinery</th><th>Biogas-Algae Biorefinery</th><th>Biogas-Algae Biorefinery</th></tr>
<tr><td>Raw material</td><td>Wheat straw [$ t^{-1}]</td><td colspan="6">0 (free, taken from local farm)</td></tr>
<tr><td rowspan="4">Key-product</td><td>Electricity [$ kWh^{-1}]</td><td>0.157 [21]</td><td>N/A</td><td colspan="4">0.157 [21]</td></tr>
<tr><td>Biomethane [$ kWh^{-1}]</td><td>N/A</td><td>0.108 [22]</td><td colspan="4">N/A</td></tr>
<tr><td>Fibers [$ t^{-1}]</td><td colspan="3">N/A</td><td>185 (assumed)</td><td colspan="2">N/A</td></tr>
<tr><td>High-value algae [$ kg^{-1}]</td><td colspan="4">N/A</td><td colspan="2">45 [23]</td></tr>
<tr><td rowspan="3">Consumables</td><td>Flocculant agent [$ kg^{-1}]</td><td colspan="4">N/A</td><td colspan="2">5 [24]</td></tr>
<tr><td>Nutrient BBM [$ kg^{-1}]</td><td colspan="4">N/A</td><td colspan="2">0.5 [25]</td></tr>
<tr><td>Nutrient H_2SO_4 [$ L^{-1}]</td><td colspan="4">N/A</td><td colspan="2">3.1 [26]</td></tr>
<tr><td rowspan="3">Utilities</td><td>Electricity [$ kWh^{-1}]</td><td>N/A</td><td>0.13 [27]</td><td colspan="2">N/A</td><td colspan="2">0.13 [27]</td></tr>
<tr><td>Cold water [$ m^{-3}]</td><td colspan="6">3.0 [28]</td></tr>
<tr><td>LPS [$ t^{-1}]</td><td>N/A</td><td colspan="3">13 [29]</td><td colspan="2">N/A</td></tr>
<tr><td rowspan="9">Fixed operating cost</td><td>Number of shifts X Operators per shift</td><td colspan="4">3 X 8</td><td colspan="2">3 X 20</td></tr>
<tr><td>Average salary</td><td colspan="6">15600 $ annually</td></tr>
<tr><td>Supervision [% of operating labor]</td><td colspan="6">5%</td></tr>
<tr><td>Direct overhead [% of Labor and Supervision]</td><td colspan="6">5%</td></tr>
<tr><td>Maintenance [of ISBL investment]</td><td>2%</td><td colspan="2">3%</td><td colspan="3">2%</td></tr>
<tr><td>Land rental [%of ISBL and OSBL]</td><td colspan="6">N/A</td></tr>
<tr><td>Property tax [% of ISBL and OSBL]</td><td colspan="6">0.9%</td></tr>
<tr><td>Plant overhead [% of Labor and Maintenance]</td><td colspan="6">10%</td></tr>
<tr><td>Insurance [% of ISBL and OSBL]</td><td colspan="6">0.5%</td></tr>
<tr><td rowspan="5">Economic assumption</td><td>Cost of capital</td><td colspan="6">5%</td></tr>
<tr><td>Tax rate</td><td colspan="6">19%</td></tr>
<tr><td>Depreciation method</td><td colspan="6">Straight-line</td></tr>
<tr><td>Depreciation period</td><td colspan="6">15 years</td></tr>
<tr><td>Lifetime</td><td colspan="6">15 years</td></tr>
</table>

Table 3. Economic model set-up

5. RESULTS AND DISCUSSION

In Table 4 are the main outputs related with techno-economic analysis for all concepts.

5.1 Conventional Biogas Plant

Block diagram of conventional biogas plant (BP) is shown in Figure 4 [AK2] [AK4].

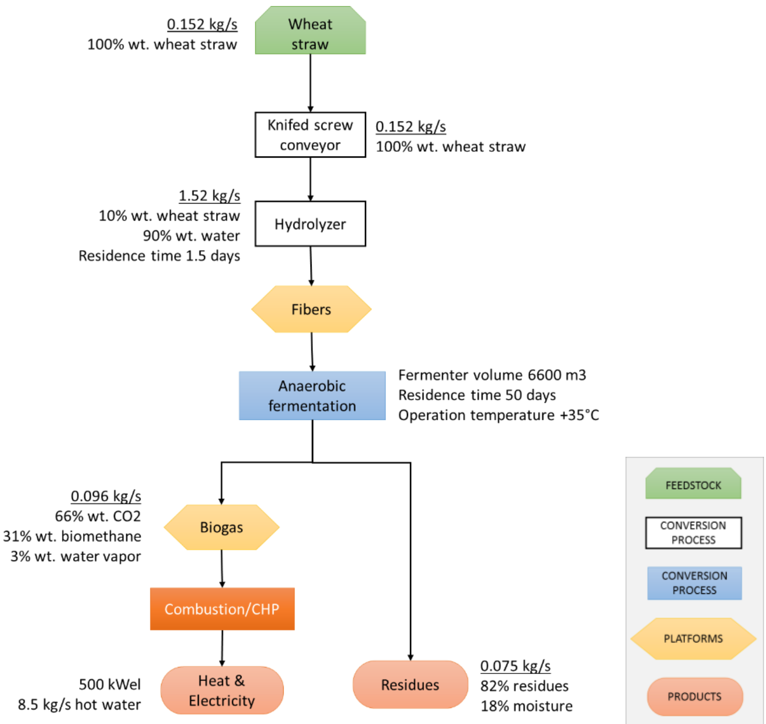

Figure 4. Block diagram, conventional BP

Wheat straw waste, an abundant residue from agriculture farms, is collected and transported to the hydrolyzing section via a knifed screw conveyor. Upon arrival, it is mixed with water and subjected to hydrolysis. The resulting suspension is then transferred to a fermenter with a capacity of 6600 m^3, where it is fermented for a period of 50 days. The produced biogas is subjected to purification to remove water content and subsequently utilized in a cogeneration unit for electricity and heat production. The residuals of the fermentation process are utilized as a nutrient-rich fertilizer for cultivation.

5.2 Biogas upgrade

Block diagram of biogas upgrade plant is shown in Figure 5 [AK2] [AK4] [AK6] [AK8].

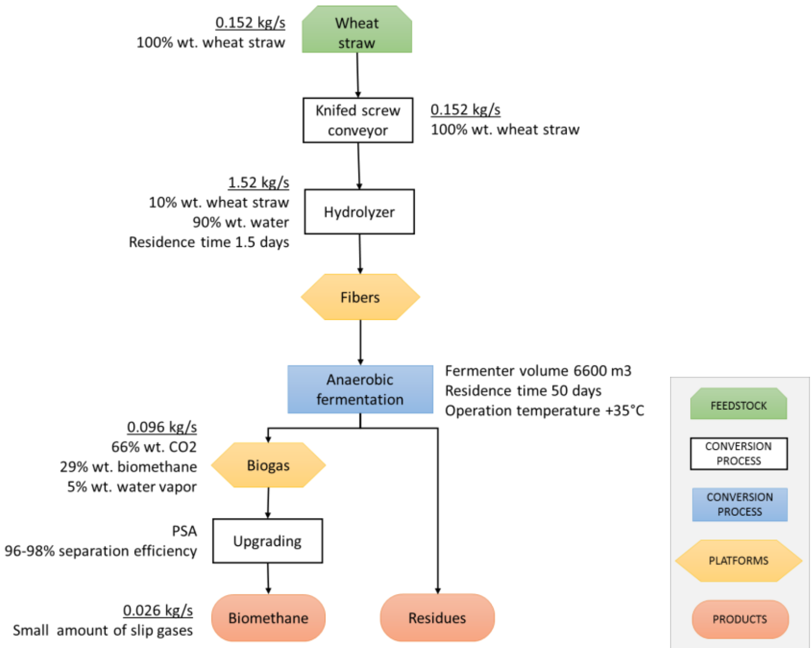

Figure 5. Block diagram, Biogas upgrade

The biogas production process in the upgraded biogas plant is similar to that of a conventional biogas plant. Once biogas is generated, it undergoes a preliminary purification step, which involves removing water vapor. The purified biogas is then directed to the upgrade section, where the CO2 component is primarily separated. The upgrade process utilizes pressure-swing adsorption columns, which play a crucial role in transforming the biogas into biomethane, which is the final product. The leftover fermentation residues are repurposed as organic fertilizers in the farm's cultivation process.

5.3 Intensified Biogas Plant

Block diagram of intensified BP is shown in Figure 6 [AK1] [AK2] [AK4] [AK5] [AK6] [AK8] [AK9] [AK10].

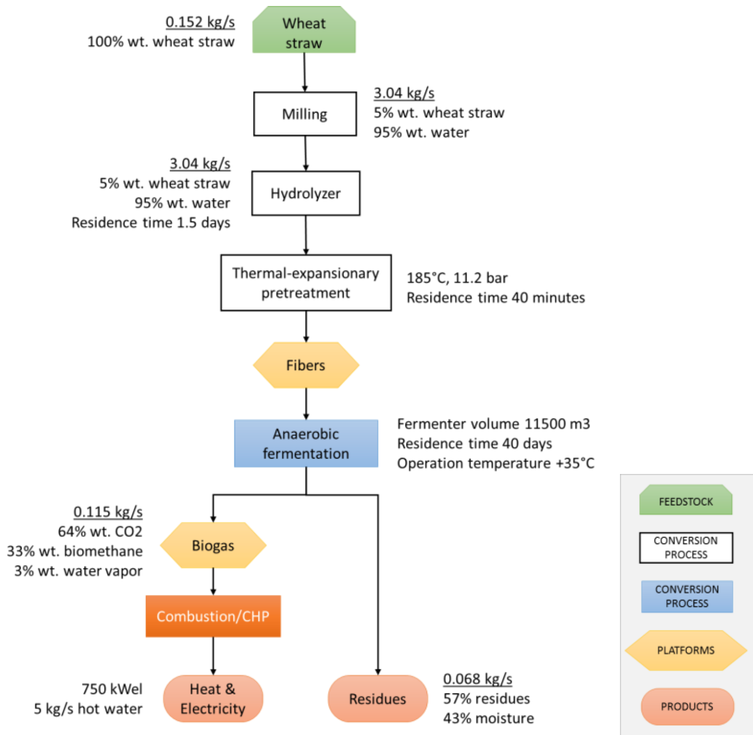

Figure 6. Block diagram, Intensified BP

Wheat straw waste is subjected to mechanical pretreatment by milling, followed by hydrolysis and thermal-expansionary pretreatment (TEP) to improve the fermentation conditions. TEP ruptures the wheat straw fibers, facilitating better digestion during the anaerobic fermentation process. The suspension is then sent to a fermenter with a residence time of 40 days, which is shorter compared to conventional biogas plants. The produced biogas is subjected to preliminary treatment and utilized in a cogeneration unit for the generation of heat and electricity.

5.4 Biogas-fiber biorefinery

Block diagram of biogas-fiber biorefinery is shown in Figure 7 [AK2] [AK4].

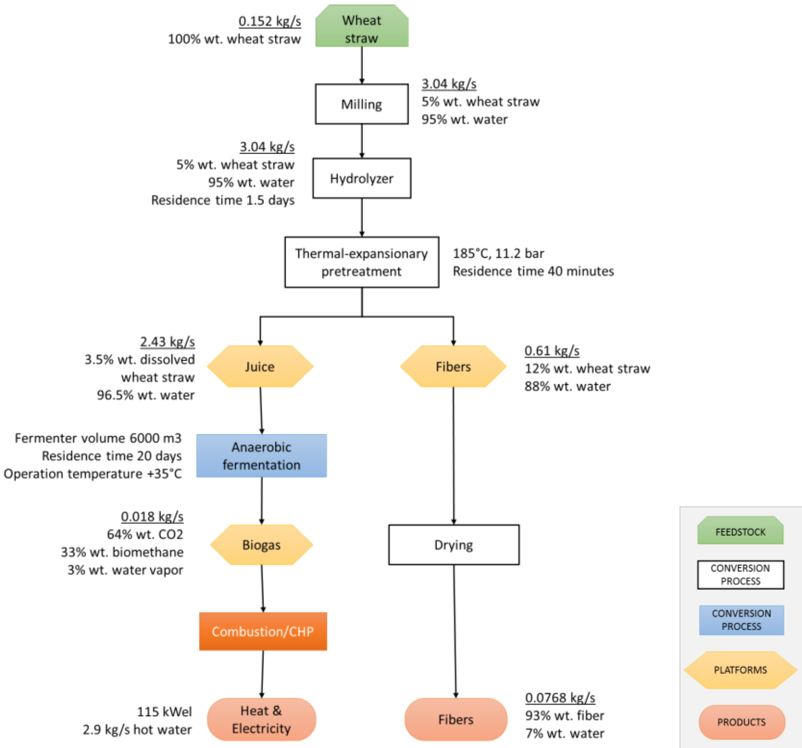

Figure 7. Block diagram, Biogas-Fiber biorefinery

In the biogas-fiber biorefinery, a thermal-expansionary pretreatment is also utilized to improve the conditions for fermentation. However, after this pretreatment, the liquid and solid phases are separated by a perforated belt conveyor. The liquid phase, which is rich in dissolved wheat straw, undergoes anaerobic fermentation with a residence time of 20 days in the fermenter. The resulting biogas is preliminarily treated and utilized for the production of heat and electricity in a cogeneration unit. On the other hand, the solid phase consists of ruptured lignocellulosic wheat straw fibers which are subsequently deeply dried. The end product is dried fibers which are packed into waterproof bags.

5.5 Biogas-Algae Biorefinery

Block diagram of biogas-algae biorefinery is shown in Figure 8 [AK3] [AK4] [AK6] [AK8].

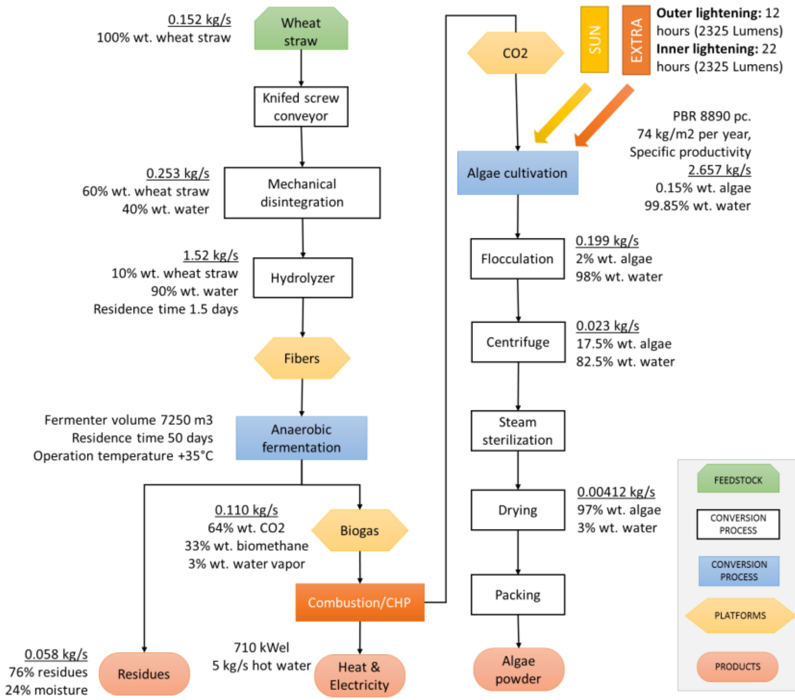

Figure 8.Block diagram, Biogas-Algae biorefinery

In biogas-algae biorefinery the only substrate pre-treatment method is mechanical disintegration. After treatment the mixture of milled wheat straw and water is entering into hydrolyzer and subsequently to the fermenter. Residence time in the fermenter is 50 days. Produced biogas is used in cogeneration unit for heat and electricity production. Produced by-product the exhaust gases are cooled to approximately 70 °C and used as one of the constituents for algae cultivation. Algae species are cultivated in co-annular photobioreactors. For algae cultivation natural and electric lightening are used. Two techniques for cultivation examined, autotrophic and mixotrophic growth. To presume autotrophic growth the light:dark ratio for internal bulbs and externals bulbs is 22:2 and 15:7, respectively. Mixotrophic growth technique includes combination of autotrophic and heterotrophic growth. Thus, algae shall receive less light. Light:dark ratio for internal and external bulbs is 12:12. For both techniques bold's basal media is used as the consumable for algae. After residence time of 10 days the mixture of water and algae is passing through flocculation, centrifuge, steam sterilization and final drying. The end product is high value algae biomass.

5.6 Discussion

The estimation of different biogas plant realizations in the absence of subsidies is an important aspect of designing economically feasible renewable energy projects. In this study, each concept was assumed to have the same mass flow of wheat straw, specifically 0.152 kg s^{-1}, with the organic loading rate varying from 1.25 to 2.50 kg_{vs} m^{-3} d^{-1}. The biogas plants with thermal-expansionary pre-treatment were found to have the highest biogas and methane yields, with the CHP unit in intensified biogas plants having the highest installed electric power at 750 kW_{el}. Additionally, biogas plants in biorefinery concepts had other key-products, such as fiber and high-value algae, which were incorporated in the analysis.

However, the results of the analysis indicated that each of the biogas plant concepts, except for biogas upgrade, had negative payback periods, meaning that the profit was negative. Although biogas upgrade showed a positive payback period of 17 years, it is still not realistic for an economically feasible project. This economic behavior could be explained by the high capital cost associated with each concept, as well as the insufficient revenues from the key-products to cover the production costs.

Despite these limitations, biogas plants can provide a reliable platform to compensate for electricity shortages during times when solar panels and windmills are not in operation. Furthermore, biogas plants can be technically combined with other types of technologies to produce different key-products, making them a versatile renewable energy source with potential for further development.

Designing economically feasible renewable energy projects requires careful consideration of several factors, including the capital cost, production costs, and revenues from key products. Although the biogas plant concepts evaluated in this study had some limitations, they demonstrated the potential for biogas to serve as a reliable and versatile renewable energy source.

	Name	Conventional Biogas Plant	Biogas upgrade	Intensified Biogas Plant	Biogas-fiber Biorefinery	Biogas-Algae Biorefinery (autotrophic growth)	Biogas-Algae Biorefinery (mixotrophic growth)
PROCESS (Biogas, fiber plant)	Substrate mass flow [kg_{TS} s^{-1}]	0.152					
	OLR value [kg_{vs} m^{-3} d^{-1}]	2.00	2.00	1.25	2.50	2.00	
	Residence time [days]	50	50	40	20	50	
	Fermenter volume [m^3]	6 600	6 600	11 500	6 000	7 223	
	Biogas yield [Nm^3 $t^{-1}{}_{TS}$]	509±58	509±58	633±52	100	605±17	
	Methane yield [Nm^3 $t^{-1}{}_{TS}$]	243±49	243±49	362±43	55	343±11	
	Annual residuals production [ton]	1 750	1 750	1 150	-	1 200	
	Annual CO_2 release [ton]	5 300	1 850	5 450	1 250	7 100	
	CHP electric power [kW_{el}]	500	-	750	110	709	709
	Products, and by-products	Heat & electricity, residue	Biomethane, residue	Heat & electricity, residue	Fiber, heat & electricity	Heat & electricity, algae, residue	
PROCESS (Algae plant)	Algae specie [-]	N/A				*Chlorella vulgaris*	
	PBR type [-]					Co-annular	
	PBR working volume [L]					258	
	PBR area occupation [m^2]					14000	
	Light:Dark ratio [-]					22:2 (internal), 15:7 (external)	12:12 (internal and external)
	Consumable					BBM + sulfuric acid, every 3 days	BBM + sulfuric acid, every 2 days
	Productivity [g L^{-1} d^{-1}]					0.15	
	Resident time [day]					10	
	Annual algae productivity [ton]					107.451	
ECONOMIC ANALYSIS	TFCC [$ mil.]	3.136	3.248	4.973	3.923	16.671	
	Fermenter percentage of ISBL	48%	47%	53%	40%	10%	
	Purchased Capital Cost, algae plant:biogas plant [%]	N/A				77%	
	Variable Operation Cost [$ mil. y^{-1}]	0.09	0.20	0.32	0.55	4.7	4.51
	Fixed Operation Cost [$ mil. y^{-1}]	056	0.60	0.67	0.58	1.681	
	Specific Investment[$(TFCC) $kW^{-1}{}_{el}$]	6 300	NA.	6 630	35 660	23 500	
	Gross Profit [$ mil. y^{-1}]	-0.07	0.33	-0.15	-0.72	-0.75	-0.52
	Discounted payback period [year]	negative	17	negative	negative	negative	negative
	NPV at the end of plant lifetime [mil. $]	-3.3	-0.2	-5.6	-9.3	-21.4	-19.5

Table 4. Summary table comprising of process, cost of production and economic analysis result

6. CONCLUSION

This doctoral thesis presents the technological design of five concepts, all of which involve biogas production as a fundamental component, and use different types of material pre-treatment, including mechanical disintegration and hydrothermal treatment. Two of these concepts are biorefinery concepts, which produce several key products such as fiber and high-value algae.

For each concept, the following steps were performed or evaluated:

- Critical literature search,
- Process flow diagram,
- Mass and energy balance,
- Original parametric model,
- Techno-economic analysis.

To ensure the accuracy of the techno-economic calculations, a conventional biogas plant was designed and evaluated based on a critical literature search and evaluated to check the results' truthiness.

The dissertation refutes the hypothesis that the design of BP in the biorefinery concept can achieve economic attractiveness without subsidized product selling prices.

The following observations were made for each concept:

- Conventional biogas plant: cannot be sustainable without subsidies due to the low electricity price, but the production process is reliable and selectable.
- Biogas upgrade: showed the best sustainability compared to other concepts, but the critical factor is the price of biomethane.
- Intensified biogas plant: cannot be sustainable even with free raw materials, and subsidies are required. The new hydrothermal pre-treatment method process cannot be completely reliable at present.
- Biogas-fiber biorefinery: showed the worst sustainability, and the value of dry fiber is low, making selling price growth uncertain.
- Biogas-algae biorefinery: both concepts were unsustainable, and the critical factor is the selling price of algae. However, the demand for biogas and algae is expected to increase in the future, making this concept promising.

The author's opinion is that conventional, intensified biogas plants, and biogas upgrade have dominance over biorefinery concepts. Having a single key product brings less process complexity, resulting in less equipment and lower capital costs.

Government and local regulations are the main drivers of renewable energy development. Subsidization is essential, as renewable energy plants are not feasible without it. A percentage of the government budget should be dedicated to renewables, with yearly increases. Countries must set targets to produce a certain amount of energy from renewables only, and renewable energy philosophy should be propagated in schools and colleges.

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