

## Annotation sheet

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**Annotation - Czech:** Zpracujte rešerši zaměřenou na potenciál zpracování odpadu zplyňováním. Připravte přehled, který shrnuje aktuální poznatky o zplyňování (technický rozsah a nastavení, parametry). Provedte technicko-ekonomickou analýzu vybraných technologií, s cílem zhodnotit jeho ekonomický potenciál, tj. proudové technologické schéma, hmotnostní a energetickou bilanci, ekonomickou analýzu technologie, citlivostní analýzu. Analyzujte možnost využití syngas jako suroviny pro výrobu chemických látek, pokročilých biopaliv.

**Annotation – English:** Discuss potential of waste processing by gasification. Prepare review that scopes to summarize current knowledge about gasification (technical scale and set up, parameters). Perform techno-economical study of selected technology set up to evaluate it's economic potential , i.e. PFD, mass and energy balance, economic analysis of technology, sensitivity analysis. Discuss possibility of syngas utilization as raw material to produce chemicals, advanced biofuels.

**Keywords:** biomass, gasification, syngas, syngas utilization

**Utilization:** Design of technology

**Declaration**

I confirm that the diploma work was disposed by myself and independently, under leading of my thesis supervisor. I stated all sources of documents and literature

Prague.....

.....Name and Surname

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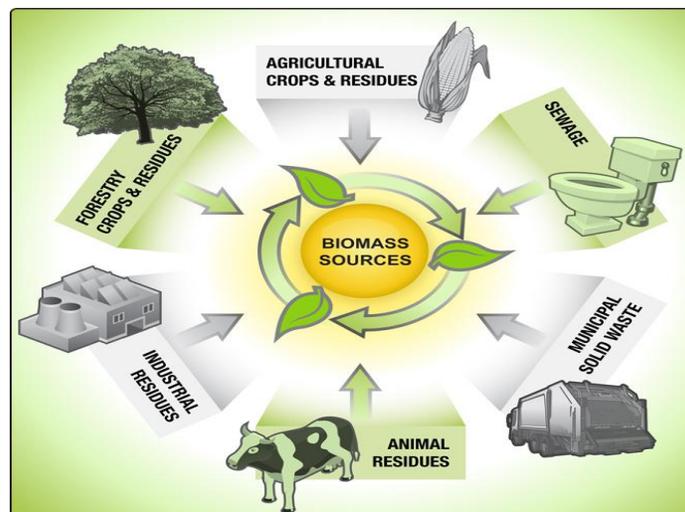
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# 1.INTRODUCTION

## 1.1.1 Biomass

The term "biomass" refers to organic matter that has stored energy through the process of photosynthesis. It exists in one form as plants and may be transferred through the food chain to animals' bodies and their wastes, all of which can be converted for everyday human use through processes such as combustion, which releases the carbon dioxide stored in the plant material. Many of the biomass fuels used today come in the form of wood products, dried vegetation, crop residues, and aquatic plants.[1] Although biomass is the oldest energy source known to mankind, its current contribution to the primary energy consumption in the Western world is small. Biomass was gradually substituted after the discovery of huge amounts of cheap fossil fuels. Coal, crude oil, and natural gas were not only cheaper, but also more convenient to use. Furthermore, the 'new' fuels allowed applications that were not possible with biomass: liquid transportation fuels from crude oil and gas for cooking. Biomass appeared to have no future as energy source.[2]



*Figure 1. Sources of Biomass [18]*

The insight that the fossil fuel reserves are limited, together with concerns over security of supply i.e. the oil crises, initiated the first upraise of interest in biomass and all other renewable energy forms in the 1970s. However, continuously low fossil energy prices and the discovery of new fossil fuel reserves impeded the development of biomass technologies. In the 1980s the concern grew that global warming and the resulting climate change were enhanced by CO<sub>2</sub> emissions resulting from fossil fuel consumption. This concern resulted in the Kyoto protocol in which objectives to reduce the anthropogenic CO<sub>2</sub> emissions are documented. To achieve the Kyoto objectives, the share of renewable energy in the primary energy consumption has to increase significantly. The interest in biomass was renewed, as biomass is considered to be one of the most important renewable energy sources for this century. Biomass has become one of

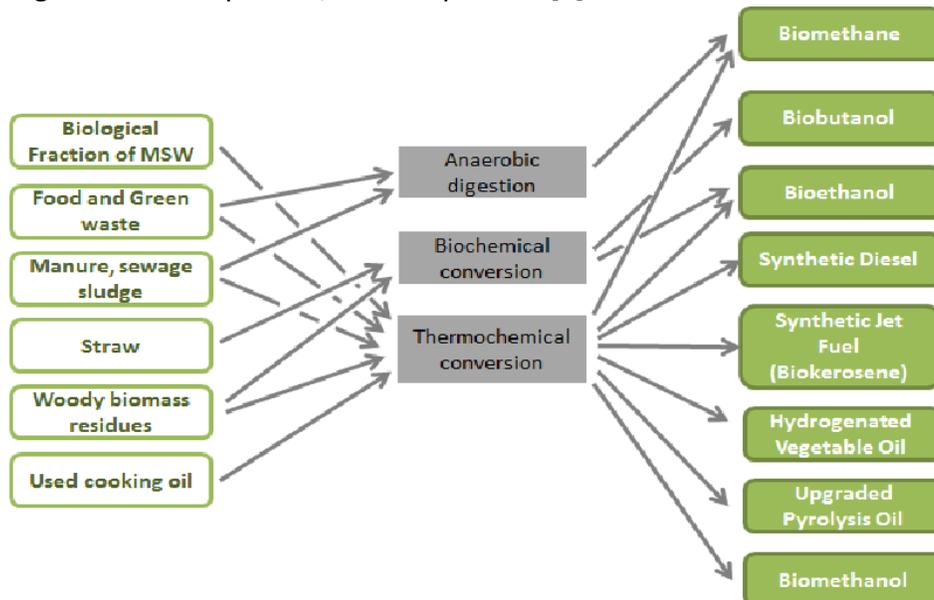
the most commonly used renewable sources of energy in the last two decades, second only to hydropower in the generation of electricity. [3]

### 1.1.2 Fuels and products of Biomass feedstock.

By definition, biomass is a renewable material, as during growth of the plants, crops, and trees, CO<sub>2</sub> is withdrawn from the atmosphere and stored in the biomass as chemical energy. The CO<sub>2</sub> cycle is closed again when the CO<sub>2</sub> is released during conversion of the biomass and the use of derived products. The renewable and CO<sub>2</sub>-neutral nature of biomass is the major motivation to use the material for the energy generation for example green electricity and heat.

The same consideration applies for the use of biomass for the production of fuels and products. To date, nearly all transportation fuels and most materials and chemicals are produced from crude oil or natural gas. At a certain moment in the future, the decreasing reserves of these fossil materials will give rise to increasing prices. Therefore, an additional motivation is that to maintain the same production levels, an alternative carbon source is required and biomass is the only carbon source that is renewable.

Waste biomass is one of the most energy-rich and unused renewable raw material not only for the production of alternative energy sources such as bio methane, biogas, bioethanol, pyrolysis oil, synthesis gas, but also for the production of valuable chemicals such as oligosaccharides, furans, polyhydric alcohols, cellulosic fibers, natural antioxidants, essential substances, oils, which find their application as petrochemical substitute, or in the production of eco-innovating materials bioplastics, bio-composites. [4]



*Figure 2. Conversion of Biomass to Liquid Fuels [18]*

More than 13 Ttons( $10^9$ ) of dry solid waste was generated in 2016 in Europe according to Eurostat, including agricultural wastes from plant and livestock production, food and processing waste, municipal waste, green waste, sludge from sewage treatment plants, biodegradable municipal solid waste from households and gardens, or waste from restaurants and canteens, mine and surface mining and energy production.

However, technologies for efficient waste transformation to biofuels or valuable chemical substances of second or higher generation are still under development. Thousands of studies have been presented to produce bio products from different wastes, both in laboratory and pilot scale. Nevertheless, there is nowadays still a large gap between projected and operated industrial technologies, mainly for economic reasons. No waste biomass to bio-product technology has been developed in industrial scale to guarantee the possibility of energy-efficient, economically profitable and environmentally friendly large-scale waste biomass transformation to biofuels and bio-products of second or higher generation. Biofuels and bio-products are therefore unable to compete with conventional fuels or petrochemicals, especially in terms of production costs. [4]

### 1.1.3 Gas from Biomass gasification

Gasification might be one of the key conversion technologies in all processes for the production of energy, fuels, and/or products from biomass. It is in each turn the highest possible thermochemical conversion of a fuel containing carbon (e.g. biomass) to combustible gases by use of gasification agents. The advantage of the gasification route is the higher overall electric efficiency compared to the alternative of direct biomass combustion.

Produced gas has following advantages:[6]

- Easy transportation
- Easy unwanted component removal possibility
- Good combustion properties
- Possibility to adapt fuel properties for certain purpose
- Possibility to be used in chemical industry
- Clean fuel

### Industrially used gasification processes

Gasification agent	Type of gas	Main components	Application
air + steam	heating gas	CO,H <sub>2</sub> ,N <sub>2</sub>	industrial heating
air + steam, pressurized	heating gas	CO,H <sub>2</sub> ,N <sub>2</sub> ,CH <sub>4</sub>	electricity generation
steam + oxygen	syngas	CO,H <sub>2</sub>	synthesis of NH <sub>3</sub> ,MetOH, H <sub>2</sub> , F-T, production of CO, ore reduction
steam + oxygen pressurized	syngas	CO,H <sub>2</sub>	“ “
	reduction gas	CO,H <sub>2</sub>	“ “
	citygas	CO,H <sub>2</sub> ,CH <sub>4</sub>	public light, cooking
	heating gas	CO,H <sub>2</sub> ,CH <sub>4</sub>	electricity
	SNG	CH <sub>4</sub>	heating

*Figure 3. Industrially used gasification processes[7]*

The subject of interest is syngas, which is also referred as synthesis gas. The general technology is relatively simple in the essence, biomass feedstock is “burned” i.e. gasified within a reactor, alongside constantly incoming certain type of gasification agent, under high temperatures and special conditions, resulting gas is good energy carrier, but requires further cleaning. More detailed explanation of the technology is described in chapter 2.

Thus, based on the general composition and the typical applications, two main types of gasification gas can be distinguished- bio syngas’ and ‘product gas’.

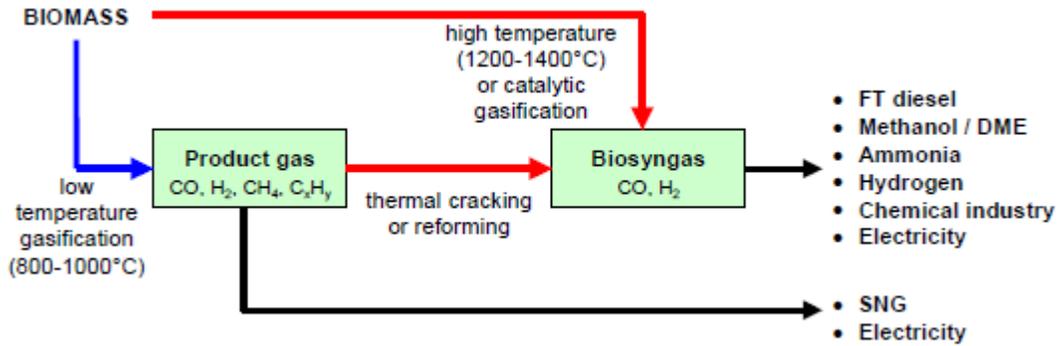


Figure 4. Types of gasification gas[7]

- **Product gas**- produced by low temperature gasification (below 1000°C) and containing CO, H<sub>2</sub>, CH<sub>4</sub>, C<sub>x</sub>H<sub>y</sub> aliphatic hydrocarbons, benzene, toluene, and tars (besides CO<sub>2</sub> and H<sub>2</sub>O). The syngas components H<sub>2</sub> and CO typically contain only ~60% of the energy in the gas, while the remainder is contained in CH<sub>4</sub> and higher (aromatic) hydrocarbons.
- **Bio syngas**- produced by high temperature (above 1200°C) or catalytic gasification. Under these conditions the biomass is completely converted into H<sub>2</sub> and CO (besides CO<sub>2</sub> and H<sub>2</sub>O). Bio syngas is chemically similar to syngas derived from fossil sources and can replace its fossil equivalent in all applications. Bio syngas can also be made from product gas by heating the thermal cracking or catalytic reforming. [5]

This paper mainly focused on petro economical potential investigation of product gas, while both of above types can be generalized and called SYNGAS (synthesis gas).

### 1.1.3.1 Gasification systems [5]

Gasification system can be subdivided into several types according to:

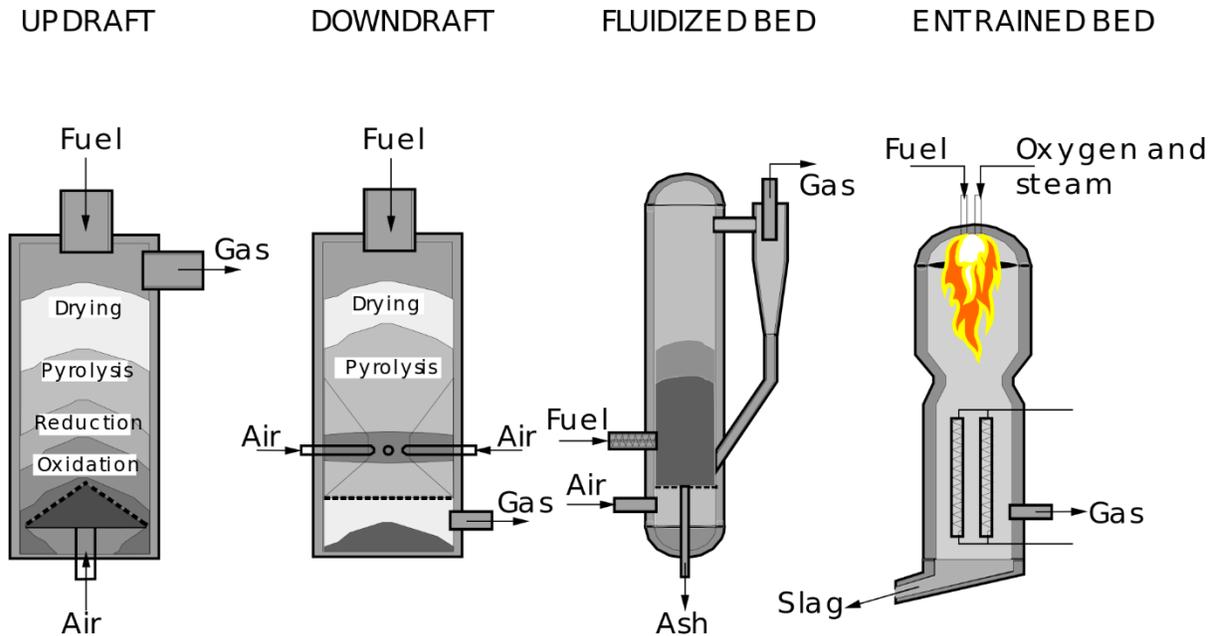
- Source and transport of heat within gasifier reactor : allothermal , autothermal
- Type of reactor used: fixed bed reactor, fluidized bed reactor
- Type of gasification agent used

#### Autothermal – Allothermal

Autothermal gasifiers provide the necessary heat of reaction by means of partial oxidation within the gasification reactor. If air is used as oxidizing agent during the process, the product gas contains a high amount of nitrogen. So for synthesis gas production either pure oxygen (in entrained flow reactors) or mixtures of oxygen and steam (in fluidized bed reactors) are used as gasification agent. The great advantage of the autothermal gasification is the direct heating of the reactants and therefore more efficient energy utilization. The process is simpler as by allothermal gasification and it is easier to operate it under pressurized conditions. Allothermal (or indirect) gasification is characterized by the separation of the processes of heat production and heat consumption. The allothermal gasification facility almost always consists of two reactors, connected by an energy flow. Biomass is gasified in the first reactor and the remaining solid residue (char) or product gas is combusted in the second reactor to produce the heat for the first process. The transport of the heat can be done either by circulating a bed material or by heat exchangers.

#### Types of reactors

According to the design of the fuel bed, the gasifiers can be divided into fixed bed, fluidized bed, and entrained flow. The differences in the design of the gasification reactor are shown in Figure 4.1. The composition of the gas and the level of undesirable components (tars, dust, ash content) produced during biomass gasification process are dependent on many factors such as feedstock composition, reactor type, and operating parameters (temperature, pressure, oxygen fuel ratio).



*Figure 4.1. Types of gasification gasifiers[7]*

The BFB (bubbling fluidized bed reactor) which is a variety of general fluidized bed reactor is chosen for further research. The reason for choosing fluidized bed reactor – it is capable of handling biomass that varies in moisture content, type, the process is easily controlled and suitable for electricity generation or heat generation CHP (combined heat and electricity plant).

### Gasification agents

Types of industrially used gasification agents are mentioned in the fig. 3. Each agent has a certain effect on final gas composition and amount of inert in gas, changing the ultimate application of gas. For fluidized bed reactor, commonly steam and oxygen are used.

### Comparison

The fig 4.2 shows typical composition of syngas at outlet for two basic types of fluidized bed and effect of different gasification agents used.

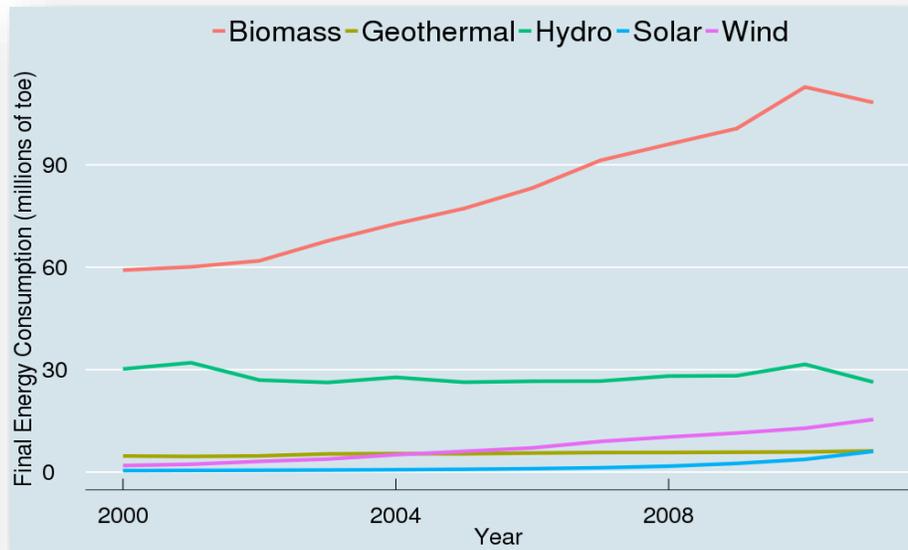
Oxidizing agent	Composition (% vol, dry base)				
	H <sub>2</sub>	CO	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub>
Air (downdraft)	17	21	13	1	48
Air (updraft)	11	24	9	3	53
O <sub>2</sub> (downdraft)	32	48	15	2	3
Air (BFB)	9	14	20	7	50
Air (CFB)	14.1	18.7	14.7	3.5	47.7
Air (BFB)	9.5	18	13.5	4.5	45
Steam (CFB)	34.2	27.2	22.7	11.1	4.8
Steam (BFB)	52	23	18	7	n.d.

*Figure 4.2 . Types of gasification gasifiers[20]*

## 1.2 Global market demand and feedstock availability.

### 1.2.1 Biomass market

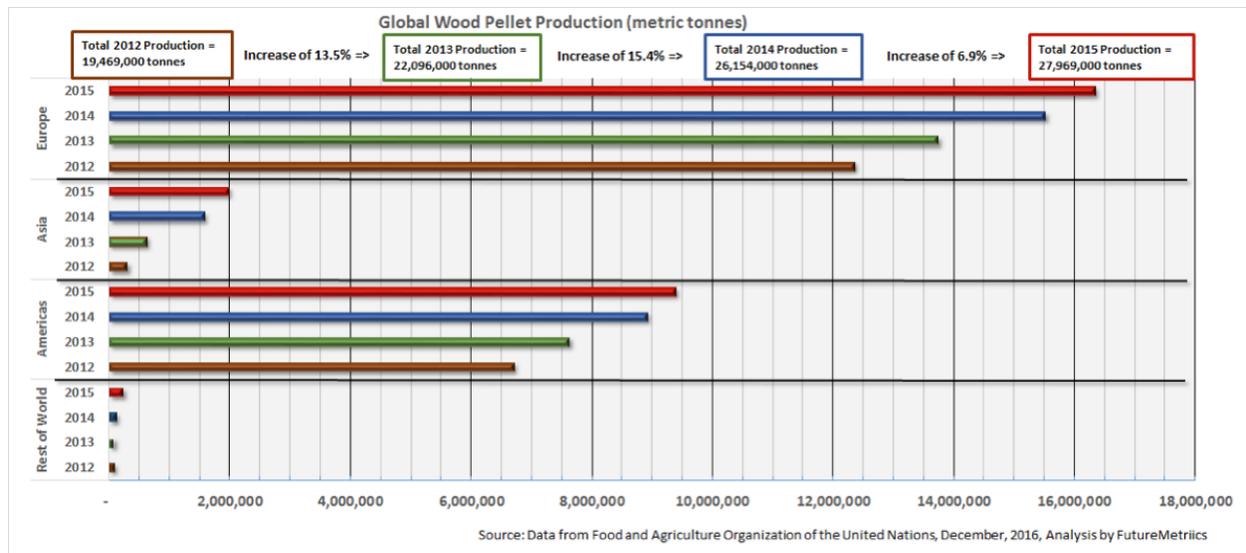
Despite what many perceive, the renewable energy target has, so far lead to a far bigger expansion of bio-energy than wind and solar energy. In 2000 biomass was by a significant margin the biggest source of renewable energy, and made up more than half of final energy consumption in the EU.



*Figure 5. Renewables' share in world energy consumption[7]*

As the demand for biomass usage in terms of energy generation and consumption are relentlessly and rapidly growing, there must be an excess offer of basic feedstock. Future plans of EU is to increase share of energy generation by means of biomass conversion processes up to 20% from overall. Germany is currently leader, having about 11000 bio plants.[7]

Concerning syngas generation where primary and main component are wood waste / wood pellets the chart showing that, production of wood pellets coincides with the rising demand for feedstock. Meanwhile growing demand and growing production consequently leads to cheaper prices i.e. cheap energy, however economical profitability of synthesis gas production is still in doubt and need further investigations and researches for making technology and final product more competitive in terms of price.[7]



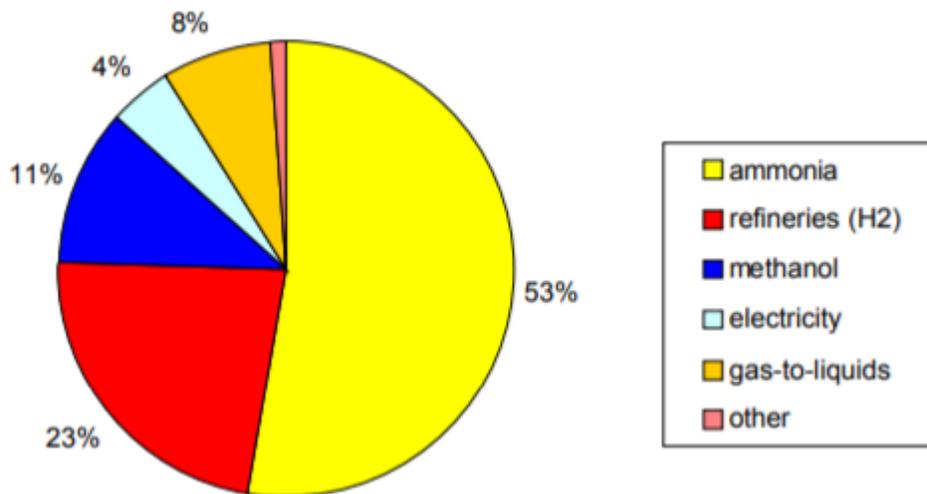
*Figure 6. World wood pellets production chart[19]*



*Figure 7. Example of wood and wood pellets[19]*

### 1.2.2 Syngas Market

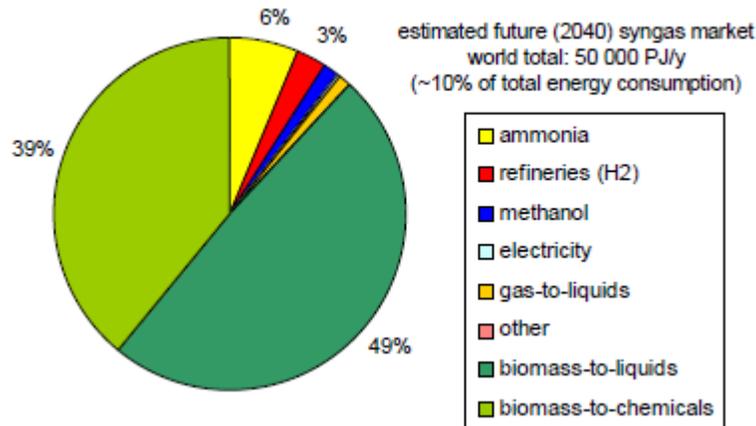
To date, syngas is an important intermediate product in chemical industry. Annually, a total of about 6 EJ of syngas is produced worldwide, corresponding to almost 2% of the present total worldwide primary energy consumption. The world market for syngas (mainly from fossil energy sources like coal, natural gas and oil/residues) is dominated by the ammonia industry. Other main applications are the production of hydrogen for use in refineries, e.g. hydrogenation steps, and for the production of methanol. Figure 8 shows the present syngas market distribution.[8]



*Figure 8. Present syngas market shares[7]*

According to Eurostat, the total transportation sector in the EU25 countries is responsible for 20% of the primary energy consumption. This equals roughly 15 000 litre per second. EU directive 2003/30/EC has set targets of 2% biofuels by the end of 2005 and 5.75% in 2010. For 2020, 8% has been mentioned, but also 15% has been proposed by the EU Alternative Fuels Contact Group. The vision goal of the European Technology Platform Biofuels is 25% biofuels in 2030.[9]

Another huge potential market for syngas is illustrated by the fact that approximately 30% of the world primary energy consumption is for the transportation fuels and chemicals [10]. With biomass being the only sustainable carbon-containing source, it is expected that biosyngas will be the key-intermediate in the future production of renewable fuels and chemicals. When an average of 30% substitution of fossil fuels by biosyngas is assumed, based on extrapolation of current EU Directives, and this is translated to the world energy consumption, the total annual syngas market will be increased to approx. 50,000 PJ in 2040. The world (bio) syngas market will then look as shown in Figure 3 (assuming no changes for the other applications). The major share of the syngas will be used for production of fuels (biomass-to-liquids; BTL) and another major part for the production of renewable chemicals (biomass-to-chemicals) [6].



*Figure 9. Projected future shares of syngas market[7]*

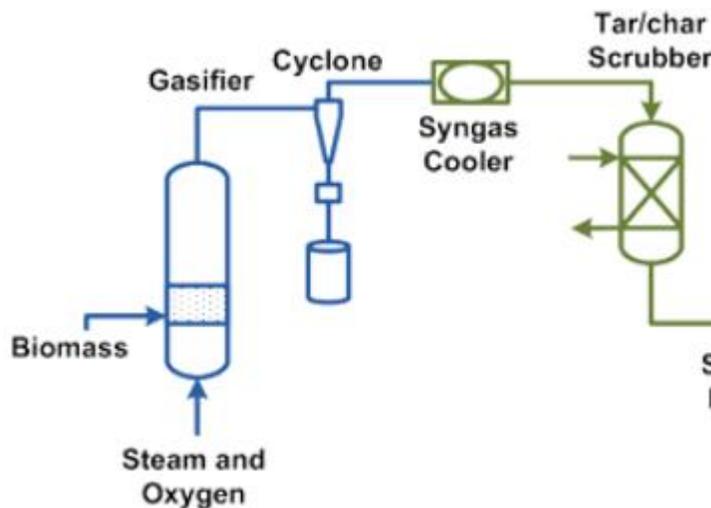
[8]The future bio syngas demand exceeds the present syngas consumption by a factor of eight. Therefore, it is clear that large bio syngas production capacities are needed to meet the European and national renewable energy and CO<sub>2</sub>-emission reduction targets. Not only are large installed capacities necessary, also the individual plants, compared to typical biomass plants, have to be large considering the typical plant scales for the two main applications, i.e.:

- Transportation fuels sector
- Chemical Sector

## 2 Gasification Technology and parameters

### 2.1 Principles of Gasification [8,11,12]

This particular gasification process employs a single, bubbling fluid bed reactor for gasifying biomass with oxygen to produce syngas. A catalyst filled, fixed bed reactor is used for tar reformation. Model includes a biomass handling and feed system, a gasifier, a tar reformer, a bed media handling and feed system, an oxygen handling and injection system, and an ash removal system, syngas cooler and further post treatment equipment. The general technology utilized in the essence is relatively simple and proceeds as follows. Biomass feedstock is conveyed inside gasifier, where under high temperature, pressure and by means of used gasification agents, gasification reactions occur, resulting in escaping of raw syngas, which next passes cyclone treatment in order to get rid of solids, char and ash. Having been cleaned from solids hot syngas is cooled, additional tar reformation might be utilized for purpose of higher H<sub>2</sub> and CO yield. Final stages include filtration, water removal, once done syngas ready to be utilized or converted to another fuels.



*Figure 10. General process flow of biomass to syngas production[21]*

The chemical reactions of gasification can progress to different extents depending on the gasification conditions (like temperature and pressure) and the feedstock used. Combustion reactions take place in a gasification process, but, in comparison with conventional combustion which uses a stoichiometric excess of oxidant, gasification typically uses one-fifth to one-third of the theoretical oxidant. This only partially oxidizes the carbon feedstock. As a "partial oxidation" process, the major combustible products of gasification are carbon monoxide (CO) and hydrogen,

with only a minor portion of the carbon completely oxidized to carbon dioxide (CO<sub>2</sub>). The heat produced by the partial oxidation provides most of the energy required to drive the endothermic gasification reactions.

Within a gasification process, the major chemical reactions are those involving carbon, CO, CO<sub>2</sub>, hydrogen (H<sub>2</sub>), water (steam) and methane (CH<sub>4</sub>), as follows:

The combustion reactions:

1.  $C + \frac{1}{2} O_2 \rightarrow CO$  (-111 MJ/kmol)
2.  $CO + \frac{1}{2} O_2 \rightarrow CO_2$  (-283 MJ/kmol)
3.  $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$  (-242 MJ/kmol)

Other important gasification reactions include:

- |    |                                     |                        |             |           |
|----|-------------------------------------|------------------------|-------------|-----------|
| 4. | $C + H_2O \leftrightarrow CO + H_2$ | "the<br>(+131 MJ/kmol) | Water-Gas   | Reaction" |
| 5. | $C + CO_2 \leftrightarrow 2CO$      | "the<br>(+172 MJ/kmol) | Boudouard   | Reaction" |
| 6. | $C + 2H_2 \leftrightarrow CH_4$     | "the<br>(-75 MJ/kmol)  | Methanation | Reaction" |

With the above, the combustion reactions are essentially carried out to completion under normal gasification operating conditions. And, under the condition of high carbon conversion, the three heterogeneous reactions (reactions 4 to 6) can be reduced to two homogeneous gas phase reactions of water-gas-shift and steam methane-reforming (reactions 7 and 8 below), which collectively play a key role in determining the final equilibrium synthesis gas (syngas) composition.

- |    |  |  |           |
|----|--|--|-----------|
| 7. | $CO + H_2O \leftrightarrow CO_2 + H_2$     | "Water-Gas-Shift<br>(-41 MJ/kmol)          | Reaction" |
| 8. | $CH_4 + H_2O \leftrightarrow CO_2 + 3 H_2$ | "Steam-Methane-Reforming<br>(+206 MJ/kmol) | Reaction" |

In the low-oxygen, reducing environment of the gasifier, most of the feedstock's sulfur converts to hydrogen sulfide (H<sub>2</sub>S), with a small amount forming carbonyl sulfide (COS). Nitrogen chemically bound in the feed generally converts to gaseous nitrogen (N<sub>2</sub>), with some ammonia (NH<sub>3</sub>), and a small amount forming hydrogen cyanide (HCN). Chlorine is primarily converted to

hydrogen chloride (HCl). In general, the quantities of sulfur, nitrogen, and chloride in the fuel are sufficiently small that they have a negligible effect on the main syngas components of H<sub>2</sub> and CO. Trace elements associated with both organic and inorganic components in the feed, such as mercury, arsenic and other heavy metals, appear in the various ash and slag fractions, as well as in gaseous emissions, and need to be removed from the syngas prior to further use.[12]

## 2.2 Feedstock

The feedstock to gasifier is flexible, although has certain requirement on size, density, moisture content and ash content. Wood pellets or briquetted wood is chosen for gasification as feed, which has following properties. Most gasifier technology providers require feedstock with a target range moisture content of 10-20%.[11].

Water in the feedstock is also necessary to drive the water gas shift reaction; however, with a moisture content in the 15-20% range there is substantially more water than is needed for the water gas shift reaction to reach equilibrium.

High moisture content in the feedstock, which translates into high moisture content in the syngas, also puts a condensing load on downstream cooling and filtering equipment.

The impact of feedstock moisture on heat value and energy density is typically only a concern when combusting the syngas in an engine for power production because an oxygen blown system has a higher tolerance, both economically and technically, for moisture in the reactor.

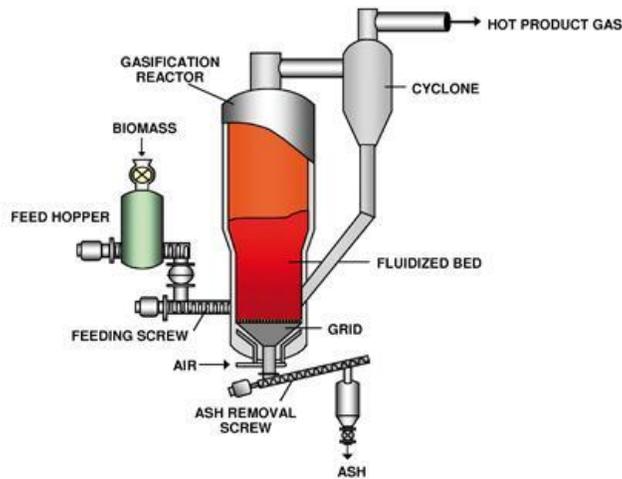
Thus input of biomass has following properties, that are taken into account during further calculations in chapter 3. Input is soft and hard wood, wood, dust, pellets, chips mixture.

<b>Density</b>	<i>600 kg/m<sup>3</sup></i>
<b>Size</b>	<i>20-100 mm</i>
<b>Moisture</b>	<i>10% w.t</i>
<b>Ash content</b>	<i>1% w.t</i>
<b>Sulphur content</b>	<i>0.02</i>

*Table 1.. General wood composition [7]*

## 2.3 Reactor

Fluidized-bed reactors function with a fluidized mix of bed material and biomass. The gasification medium flows in through the nozzle bottom and fluidizes the bed material. This can be inert, as for example quartz sand or also catalytically active with regard to the conversion of organic contaminants in the crude gas through possible after-reactions in the gas phases [3]. For this purpose, substances like dolomite or olivine can be used. The fuel, which is shredded and has a maximal edge length of 50 mm (to 100 mm) is fed into the fluidized or circulating bed. Depending on the degree of fluidization, i.e. inflow speed of the fluidization/gasification medium. The bed material removed from the combustion chamber must be precipitated out of the gas stream by a cyclone and then recirculated into the reaction chamber.



*Figure 11.. General BFB gasifier[8]*

The gasifier system is a direct or autothermal operation, meaning the energy used for heating and maintaining the gasification reaction temperature is supplied by the combustion of a portion of the biomass material processed.

The gasifier is designed to handle a variety of biomass feedstock of varying size and moisture contents. The gasifier feed rate 10 tons/hr of biomass (wood residue composed of wood chips and bark) with a 10% moisture content and a higher heat value (LHV) of approximately 16 MJ/kg

Oxygen is added to the gasifier to gasify the biomass feedstock and form hydrogen and carbon monoxide. Dolomite bed material, medium pressure steam, and recycled syngas are also added with the biomass to form and stabilize the bubbling fluid bed. [11]

<b>Component</b>	<b>Feed kg/h</b>	<b>Temperature °C</b>	<b>Pressure MPa</b>
Biomass (wood)	10000	20	1
Bed (dolomite)	122	20	1
Saturated Steam	1720	200	1.5
Oxygen	3170	200	1.5
Nitrogen	124	20	3.1

*Table 2.. General proportions of components for gasification[11]*

The gasifier is operated at a temperature of approximately 875 °C and a pressure of 3.1 MPa /hr of wet syngas. Note that the syngas production) is actually greater than 10000 kg/hr due to the additional oxygen and steam added .

<b>Reactor type</b>	<i>BFB</i>
<b>Operation mode</b>	<i>Autothermal</i>
<b>Operating temperature</b>	<i>875 °C</i>
<b>Operating pressure</b>	<i>3.1 MPa</i>

*Table 3.. Gasifier parameters[11]*

Feed screw conveyors are used to feed dried biomass and dolomite bed material to the bottom of the gasifier. Since the pressurized in-feed screw conveyors are exposed to hot gases from the gasifier, they are designed with water cooling coils for protection.

Due to the high combustion temperature, the gasifier vessel is constructed with a refractory lining to protect the integrity of the steel shell.

#### 2.4 Ash discharge system

A portion of the dolomite bed material and ash from fuel combustion are periodically removed from the bottom of the gasifier and discharged to an ash removal screw conveyor. The water cooled screw conveyor cools ash/char outflow and then discharge to a conveyor hopper for pneumatic transfer to an ash storage silo where material is accumulated for disposal.

#### 2.5 Dust collection cyclone

Syngas exits the gasifier and is routed through a refractory lined cyclone separator vessel where ash and entrained bed material are removed. The bulk of the entrained particulate is removed from the syngas in the cyclone. The cyclone is efficient enough to keep particulate concentrations below a level acceptable for the tar reformer. The particulate dust is returned through the cyclone

dropleg to the fluidized bed of the gasifier for further carbon conversion. The efficiency of cleaning is 99% of physical matter.

## 2.6 Tar reformer

The tar reformer utilizes a catalyst to decompose tars and heavy hydrocarbons into hydrogen and carbon monoxide. Without this decomposition the tars and heavy hydrocarbons in the syngas will condense as the syngas is cooled in the down-stream process equipment. In addition, the tar reformer increases the hydrogen/carbon monoxide ratio for optimal conversion.

The tar reformer is a refractory lined steel vessel equipped with catalyst blocks. The catalyst is a noble metal or a nickel enhanced material. Syngas is routed to the top of the vessel and flows down through the catalyst blocks. Oxygen and steam are added to the tar reformer at several locations along the flow path to enhance the syngas composition and achieve optimum performance in the reformer.

Medium pressure steam is also piped to nozzles on the tar reformer vessel to provide pulsing steam for removal of ash dust from channels in the catalyst blocks.

Operating temperature is 875 °C ,operating pressure is 1.5 MPa.

<b>Component</b>	<b>Feed kg/h</b>	<b>Temperature °C</b>	<b>Pressure MPa</b>
Saturated steam	552	200	1.5
Oxygen	870	200	1.5

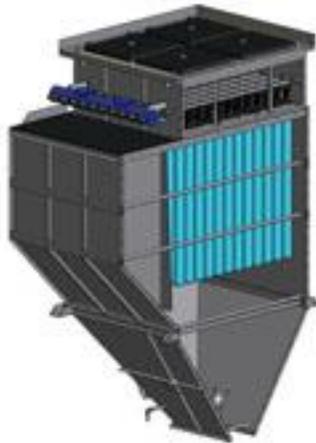
*Table 4.. Feed to Tar reactor[11]*

## 2.7 Syngas cooler

Hot reformed syngas subsequently routed through heat exchanger in order to be cooled from 870 °C , which is tar reformer outlet temperature down to 200 °C, not allowing condensing. Typical condensation temperature is dependent on composition , makes about 140-180 °C. As there is way to much heat dissipated , it would be beneficial to purchase special heat exchanger boiler equipment, which capable of generating huge amount of steam that is vital for maintaining the gasification process.

## 2.8 Filtration

Further treatment of syn gas includes filtration through battery of ceramic filters. Equipment is set in parallel, which ensures uninterrupted work during filter cartridge replacement or cleaning. Working temperature range is very flexible 200-500 °C.

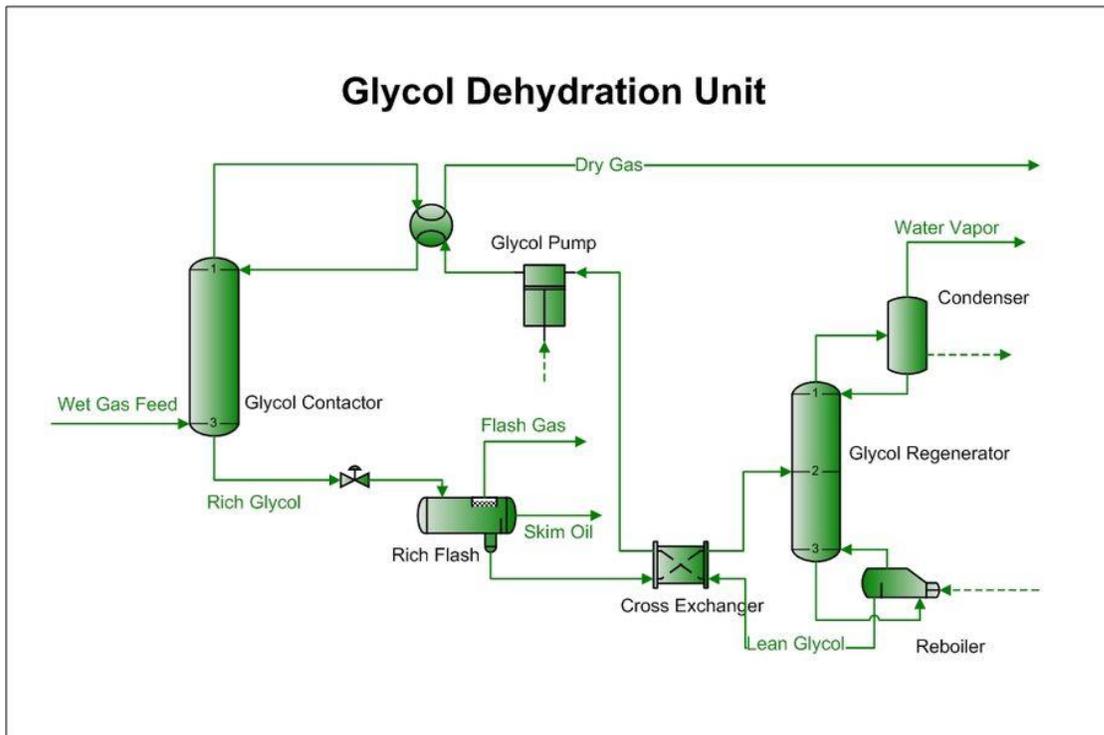


*Figure 12.. General ceramic filtration unit [22]*

## 2.9 Dewatering of gas

After multiples stages of treatment gas may still contain up to 30% moisture, which has jeopardy of condensation , as well as lowering lower heating value of gas . Therefore industrial approach is used by deploying TEG ( tri ethylene glycol) dehydration unit with glycol recovery loop for regeneration of wet glycol. Gas Is passed through gas scrubber tower, filled with packings. TEG comes into contact with syngas , capturing water particles. Dried gas is actually “ready” product and fed to utilization.

Later, wet TEG is regenerated in the sequence described below on picture. Following process is simplified and shown as just one block on process flow.



*Figure 13 TEG gas dehydration loop[23]*

## 2.10 Miscellaneous Systems[11]

### 2.10.1 Gasifier and Tar Reformer Startup Burners

The gasifier is equipped with a light fuel oil (LFO) burner for pre-heating the gasifier pressure vessel's refractory lining and other downstream systems prior to introduction of the biomass. The tar reformer is also equipped with a light fuel oil burner at the top of the vessel for pre-heating purposes as well. Note that natural gas can be substituted for LFO with a modification in burner design. The LFO system also includes a booster pump and piping.

### 2.10.2 Process Air System

The gasification process requires considerable amount of pure oxygen and nitrogen. For this purpose ASU air separation unit with discharge pressure of 0.5 Mpa is installed.

Output :

up to 4000kg/ h 98% purity O<sub>2</sub>



*Figure 14 Air separation unit[24]*

### 2.10.3. Flare Stack

During start-ups, shutdowns and emergency stop events, syngas is routed to an owner-supplied flare stack for incineration and exhaust to the atmosphere.

### 3 OBJECTIVES

#### 3.1 General objective

- Design of syngas production plant– Techno-economical study.

#### 3.2 Specific objectives

- To create based on literature search, a flowsheet of syngas production plant
- To create PFD of the process.
- To perform mass and heat balance of process
- To perform the economical calculations of total investment costs and operating costs.
- To calculate based on economical calculation, the payback period.

## 4 PRACTICAL PART

### 4.1 Process flow diagram.

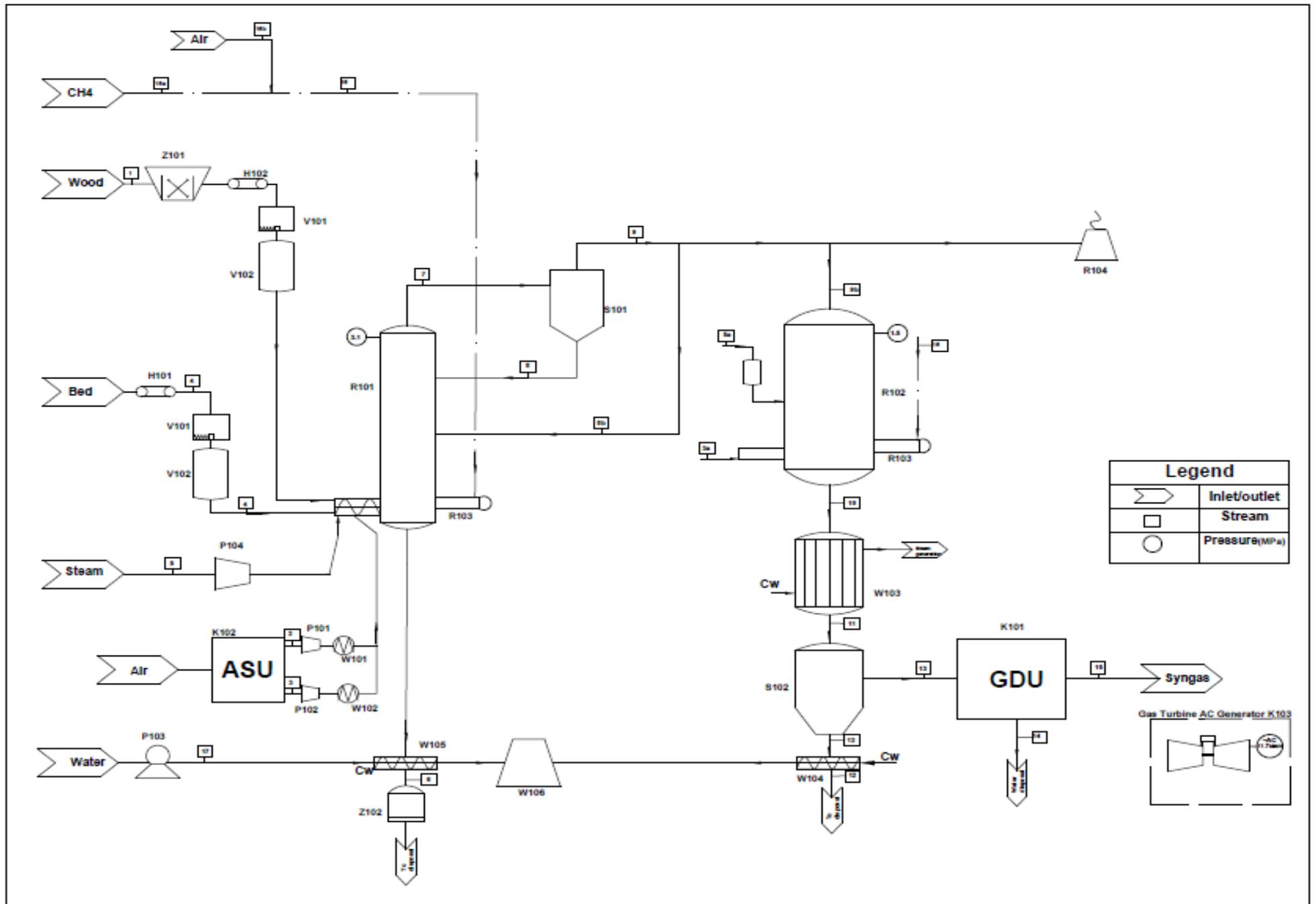
Based on technology described in Chapter 3 of this report, general process flow block diagram is illustrated in figure 15.



*Figure 15 Block diagram of syngas production*

Based on block diagram flow in fig.(15) more detailed PFD drawing is created, where all streams, components and process parameters are shown.

Figure 16 PFD of syngas production plant



## 4.2 Mass balance calculation

Before making mass balance several assumptions and considerations in sight of components' composition must be reviewed.

Input of basic material – wood waste/pellets is set to 10,000 kg/hr.

Based on literature research, the following relation of components vs 1000 kg of biomass gasification is desirably for better yield :

<b>Component</b>	<b>Feed kg/h</b>
Biomass (wood)	1000
Bed (dolomite)	12,2
Steam (100% moist)	172
Oxygen	317
Nitrogen	12,4

*Table 5.. Basic proportion of gasification components [11]*

While for Tar reformer per 1000 kg of biomass input is added:

<b>Component</b>	<b>Feed kg.h</b>
Oxygen	55.2
Steam	87

*Table 6.. Basic proportion of tar reformation components[11]*

Input streams with multi components were set to:

Stream 1 Biomass

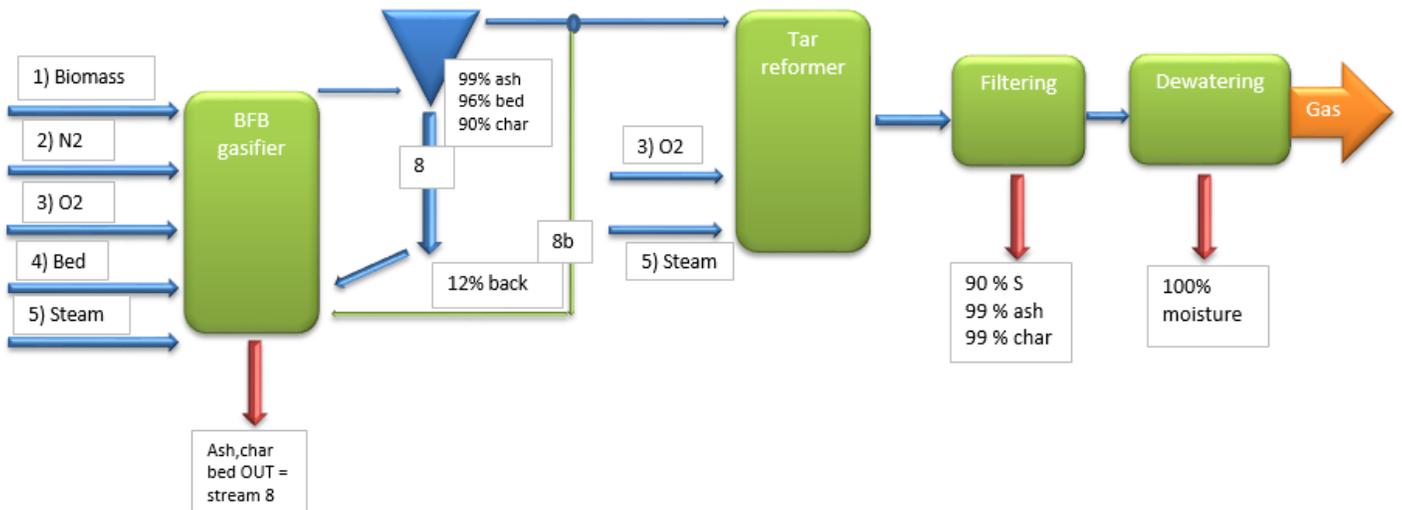
<b>Moisture</b>	10% w.t
<b>Ash content</b>	1% w.t
<b>Sulphur content</b>	0.02 % w.t

*Table 7.. Composition of biomass feed*

Stream 4 Bed dolomite is set to have 1% moisture

Stream 3 Oxygen is assumed to be pure ( 0 % moisture ).

Now let's refer to block diagram below and make assumptions that are crucial for carrying out mass balance.



*Figure 17 Graphical model of process flow for mass balance*

- Streams 1-5 enter gasifier unit
- All gas goes to cyclone where 99% of ash , 96% of bed and 90 % of char components are recirculated back to gasifier stream 8.
- Note that exactly the same amount of solid content (i.e equal do stream 8 )is assumed to be discharged out of gasifier.
- 12% of all gasifier after leaving cyclone filtration it recirculated back to gasifier in order to ensure autothermal regime-stream 8b. ( 12% -value calculate in heat balance section).
- Necessary amount of O2 and Steam is addet to tar reformer , see table XX
- 90% of Sulphur content and 99% of all solids (ash, char) are removed in candle filter
- All remaining moisture content is removed in scrubber unit

All calculation are carried out in excel and included into Appendix A, where element by element mass balance also included. Mass balance is done according to mass conservation principle .On the table below there are results of calculations in terms of total amount in each stream.

(refer to PFD drawing figure 16 or Appendix to see all streams)

<i>List of streams</i>			
<b>Num</b>	<b>Name (component)</b>		<b>Kg/h</b>
<b>1</b>	wood		10000
<b>2</b>	nitrogen		124
<b>3</b>	oxygen		3170
<b>3a</b>	oxygen		870
<b>4</b>	bed		122
<b>5</b>	steam		1720
<b>5a</b>	steam		552
<b>6</b>	solid disposal		520
<b>7</b>	raw syngas		17152
<b>8</b>	solid bed circulation		548
<b>8b</b>	circulated raw syngas		1992
<b>9</b>	raw syngas		16604
<b>9b</b>	raw syngas		14611
<b>10</b>	hot syngas		16033
<b>11</b>	cooled syngas		16033
<b>12</b>	particulate removal		7
<b>13</b>	clean wet syngas		16033
<b>14</b>	water removal		2694
<b>15</b>	final syngas to use		13333
<b>16</b>	CH4+air		6144
<b>16a</b>	Natural gas (CH4)		559
<b>16b</b>	Air for CH4		5586
<b>17</b>	Cooling water		1885

*Table 8.. Table of streams*

The final composition of clean syngas that is ready to be used is[11]:

vol compositon %	
CO <sub>2</sub>	22.1
CO	32.5
H <sub>2</sub>	38.9
N <sub>2</sub>	4.4
CH <sub>4</sub> +C <sub>2</sub> H <sub>4</sub> +C <sub>2</sub> H <sub>6</sub> ...	2.07
C <sub>x</sub> H <sub>y</sub> tars	0.01
sulphur compound	0.01
NHC+HCN	< 0.01
<b>Total</b>	<b>100</b>

*Table 9.. Final Composition of syngas*

### 4.3 Heat Balance calculation

The calculation of energy balance based on: temperatures of outlet and inlet streams, mass flow rates, and properties of the fluid.

Heat balance section includes calculation steps and final results of pieces of equipment that involved heat calculation.

No heat losses assumed in calculations. All units are assumed as perfectly insulated.

#### **R 101 Gasifier reactor**

First of all we need to ensure that temperature within gasifier is 875 °C, and that is done by means of preheaters ,that combust natural gas and air mixture in ratio of 1:15 respectively[6].

Thus :

Amount of natural gas required is calculated as follows:

$$Q = C_{p_{bio}} * m_{bio} * \Delta T = LHV_{gas} * m_{gas} = 5.43 \text{ MW} \quad (\text{Equation 1})$$

$$m_{gas} = 558.57 \text{ kg/h} \quad (851 \text{ m}^3/\text{hr})$$

Where:

*LHV*- lower heating value of CH<sub>4</sub> gas is 35 Mj/kg. [21]

$\Delta T$  – 850 degrees

Natural gas supply is assumed only for 400 hour per year for pre heating purposes only.

The set of reaction that take place and generate heat are not take into account, due to it's complexity. Therefore, in order to maintain desired temperature within gasifier , certain amount of syngas is recirculated back to reactor (stream 8b).

$$Q = C_{p_{bio}} * m_{bio} * \Delta T = LHV_{syngas} * m_{syngas} = 5.43 \text{ MW} \quad (\text{Equation 1a})$$

Where:

**LHV** of syngas is calculated as 10.771 MJ/kg , according to intermediate composition (rawsyngas).

$C_{p_{bio}}$  – specific heat capacity of biomass 2300 J/Kg K

$$m_{syngas} = 1803.954214 \text{ kg/h (stream 8b)}$$

The LHV of recirculated raw and wet syngas can be calculated by equation[18]:

$$LHV = xLHV_{H2} + xLHV_{CO} + xLHV_{CH4} \quad (\text{Equation 2})$$

**X** – fraction of each component

Individual LHV values of each component are below[21]:

<b>Hydrogen</b>	<b>14 MJ/m3</b>
<b>CO</b>	<b>12.7 MJ/m3</b>
<b>CH4</b>	<b>45 MJ/m3</b>

*Table 10.. LHV table of syngas constituents*

Intermediate composition of raw syngas on wet basis is :

vol composition %	
CO2	22.95
CO	20
H2	25.83
N2	3.7
CH4+C2H4+C2H6...	6.41
CxHy tars	0.35
sulphur compound	0.12
NHC+HCN	< 0.14
Moisture	20.5
<b>Total</b>	<b>100</b>

*Table 11.  
Intermediate  
Composition of  
syngas[11]*

Hereby, referring to mass balance values, it is possible to say that exactly 12% of all syngas out of cyclone battery is required to be recirculated to keep autothearmlity.

**W105 Ash cooler**

<b><u>ASH screw cooler W105</u></b>		
<b>Cp ash char</b>	1200	J/kg K
<b>T1</b>	875	C
<b>T2</b>	50	C
<b>flowrate</b>	0.1363726	kg/s
<b>Q</b>	135008.876	W
	135.008876	kW
<b>Cp water</b>	4200	J/kg
<b>cooling water cons.</b>	1780.33682	kg/h
<b>Tw In</b>	20	C
<b>Tw out</b>	85	C
<b>TIn</b>	232.356529	C
<b>U</b>	15	W/m <sup>2</sup> K
<b>A</b>	38.7361256	m <sup>2</sup>

*Table 12.. W105 heat balance table*

Hot ash, char, and other solids are discharged out of gasfier ,to coiled screw coolers.

**Cp** - of discharged mixture is 1,2 Kj/ kg K (reference value [25])

**Cp** – cooling water 4.2 Kj/kg K [25]

Ash,char temperature – 875 °C

Thus,

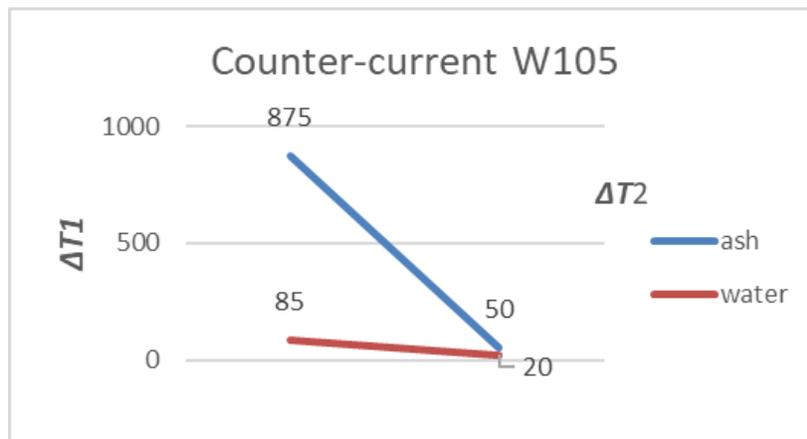
$$Q = C_{p_{ash}} * m_{ash} * \Delta T = C_{p_{h20}} * m_{h20} * \Delta T = 135 \text{ kW (Equation 3)}$$

$$m_{h20} = 1780.33 \text{ kg/h} \quad \text{-Amount of cooling water}$$

Required heat transfer area is calculated using counter current flow principle

$$Q = U * A * \Delta T_{ln} \quad \text{(Equation 4)}$$

Where , **U** – overall heat transfer coefficient is assumed to be **15 W/ m<sup>2</sup> K** (air is circulated thru in order to improve heat transfer, as heat in ash is only due to conduction)

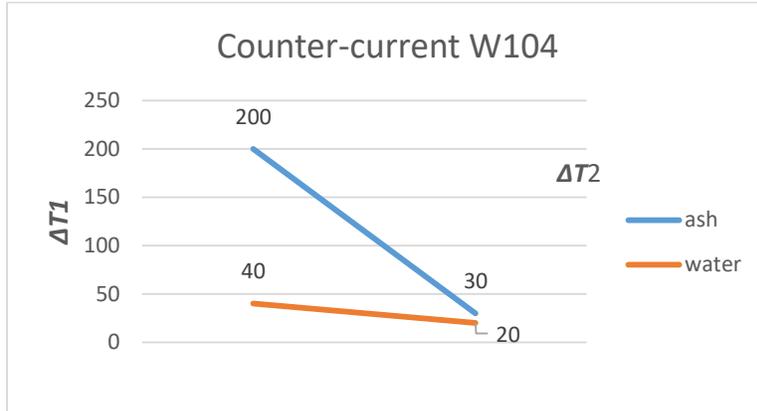


*Figure 18 . W105 LMTD chart*

$$A = 38.73 \text{ m}^2$$

The same steps are applied to W104 unit.

**W104 Ash screw cooler**



*Figure 19. W104 LMTD chart*

<b><u>ASH screw cooler W104</u></b>		
<b>Cp ash char</b>	1200	J/kg K
<b>T1</b>	200	C
<b>T2</b>	30	C
<b>flowrate</b>	0.0018781	kg/s
<b>Q</b>	383.13462	W
	0.3831346	kW
<b>Tw in</b>	20	C
<b>Tw out</b>	40	C
<b>Tlm</b>	156.39326	C
<b>U</b>	15	W/m <sup>2</sup> K
<b>A</b>	0.163321	m <sup>2</sup>
<b>m water</b>	16.420055	kg/h

*Table 13.. W104 heat balance table*

### W106 Water cooling tower

All water from ash , char coolers are fed to cooling tower in order to be cooled. Total heat load:

Water cooling tower (chiller) W106		
Cp water	4200	J/kg K
T1	85	C
T2	20	C
flowrate	0.494538006	kg/s
Q	135008.87574	W
	135.0088757	kW

*Table 14.. W106 heat balance table*

### W 103 Syngas cooler/ steam generator

This unit is very important as necessary amount of steam that is demanded for gasification can be generated by vaporization of water by means of hot syngas , allowing it cool from 875 C to 210 degrees.

**Hvap** = 23 MJ/ kg - enthalpy of vaporization H2O [25]

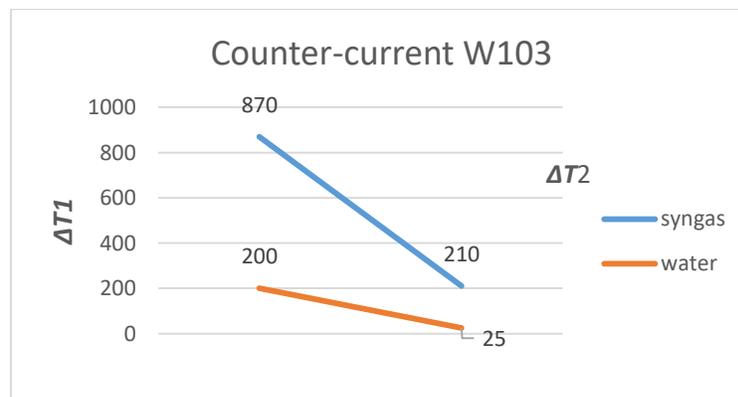
$$Q = C_{pash} * m_{ash} * \Delta T = m_{h20} * H_{vap} \quad (\text{equation 5})$$

Thus,  $m_{h20} = 2522 \text{ kg/h}$  of steam can be generated, while our total demand on steam is 2200 kg/h.

<b>Syngas Coller/steam generator W103</b>		
<b>h vap</b>	23000000	J/kg
<b>Cp syngas</b>	6000	J/kg K
<b>Tin gas</b>	870	C
<b>Tout gas</b>	210	C
<b>m gas</b>	4.069721547	kg/s
<b>Q</b>	16116097.33	W
	16.11609733	MW
<b>steam generated</b>	2522.519582	kg/h

<b>Tw In</b>	25	C
<b>T out</b>	200	C
<b>Tlm</b>	526.2461313	C
<b>U</b>	300	W/m <sup>2</sup> K
<b>A</b>	102.082127	m <sup>2</sup>

*Table 15.. W103 heat balance table*



*Figure 20. W103 LMTD chart*

Units P101 and P102 that transfer and pressurize Oxygen as well as Nitrogen for gasification , may have an impact on final gas temperature. Outlet temperature of gases from compressors is calculated through compressor work approach , assuming 80% efficiency.

**P101 [13]**

$$CW = \frac{Cp * T2}{\mu} * (CPR^{\frac{y-1}{y}} - 1) \quad (\text{Equation 6})$$

Where : **CW**- compressor work/ mass flow

**CPR** – compression ratio i.e P2/P1

**Y** - Cp/Cv

**μ** - efficiency

N2 compression temperature increase		
P1	1000000	Pa
P2	1500000	Pa
T1	300	K
T2	301.58648	K
Eff	0.8	(%*10)
CPR	1.5	
Cp	1040	J /kg K
Cv	685	J /kg K
ratio cp /cv	1.4	
Work/ m	1649.93925	

Table 16.. P101 temperature change

### P102 [13]

Above mentioned steps are also valid for oxygen compressor.

Oxygen compression temperature increase		
P1	1000000	Pa
P2	1500000	Pa
T1	300	K
T2	345.6158303	K
Eff	0.8	(%*10)
CPR	1.5	
Cp	918	J /kg K
Cv	685	J /kg K
ratio cp /cv	1.340145985	
Work/ m	41875.33225	

*Table 16a.. P102 temperature change*

From the results it clear that both streams (nitrogen and oxygen ) needs to be heated.

### W101

Nitrogen heater W101		
Cp	1040	J/kg K
T1	28.58648005	C
T2	200	C
flowrate	0.034444444	kg/s
Q	6140.41320	W
	6.140413204	kW

*Table 16b.. W101 heat balance table*

The heat load is quite small and can be performed by means of electric gas heaters.

## W102

Oxygen heater W102		
Cp oxy	910	J/kg K
T1	72.61583034	C
T2	200	C
flowrate	1.122222222	kg/s
Q	130087.54482	W
	130.0875448	kW

*Table 17.. W102 heat balance table*

## Gas turbine assembly [14]

All gas that has been finally treated is utilized in gas turbine for electricity generation. Amount of electricity generated , can be known by:

$$Q = LHV_{syngas} * m_{syngas} = 41.94 \text{ MW}$$

$$Q_{Electricity} = Q * \mu_{el} = 10.5 \text{ MW/h}$$

Where:

$\mu_{el}$  - efficiency of turbine for electricity generation 25 %

LHV is 12.637 MJ/kg [11] (stream 15)

LHV is calculated using equation 2 for composition.

clean syngas KG	
<b>11950.22857</b>	<b>TOTAL gas</b>
vol compositon %	
C02	22.1
CO	32.5
H2	38.9
N2	4.4
CH4+C2H4+C2H6..	2.07
CxHy tars	0.01
sulphur compound	0.01
NHC+HCN <	0.01
<b>Total</b>	<b>100</b>

*Table 18.. Stream 15 data [11]*

Cold gas efficiency of produced gas is :

$$\mu_{CGE} = LHV_{syngas} / LHV_{fuel (wood)} \quad (Equation 7)$$

$$CGE = 66 \%$$

Where , LHV of wood is 16 MJ/kg [21]

## 5 Economy

Even after understanding whole process, realizing its potential, it is necessary to make economical study, for estimation how much such project need to invest and which payback period it will have.

### 5.1 Capital cost[15]

The capital cost of a plan is calculated according to factorial method, which has an error  $\pm 30\%$ . This method base on purchased equipment cost and that's why require good analyzing for apparatuses cost. In this thesis estimation and calculation of prices was made by some correlations and formula:

$$C_e = a + b \cdot S^n \quad \text{(Equation 8)}$$

Where:

- $C_e$**  – Total cost of equipment in USD
- $a, b$**  – constants from table (book)
- $S$**  – size of equipment
- $n$**  – factorial

One example of calculation is described below for unit W101 :

$$S_{(W101)} = 38.73 \text{ m}^2 \text{ (from table X)}$$

$$a = 11000$$

$$b = 115$$

$$n = 1$$

Thus,

$$C_e = 11000 + 115 + 38.73^1 = 15,454 \text{ USD}$$

There rest of equipment cost calculations are carried out using above technique. All results are presented in pic X. Note, that units which has only price in table are referenced from online sources , such as www.alibaba.com , www.purchasing.com and etc.

N	Name of equipmnet.	Part number	Qty	Unit	S	a	b	n	Cost (USD)
1	<b>Conveyor Belt</b>	H101	2	m	10	21000	340	1	<b>24400</b>
2	<b>Elevator</b>	H102	1	m	5	14000	1450	1	<b>21250</b>
3	<b>Weight bin</b>	V101	2	m3	1				<b>400</b>
4	<b>Lock hopper</b>	V102	2	m3	1				<b>1000</b>
5	<b>Pump (oxygen) parallel</b>	P102	2	l/s	2.777777778	3300	48	1.2	<b>3464</b>
6	<b>Gasifier</b>	R101	1	m3	1	13000	34000	0.5	<b>46409</b>
7	<b>Start up burner</b>	R103	2						<b>5000</b>
8	<b>Cyclone filter(parallel)</b>	S101	2	m3	0.20578304	5700	700	0.7	<b>11863</b>
9	<b>Steam pump</b>	P104	1	liter/s	0.631111111	3300	48	1.2	<b>3328</b>
10	<b>Ash Screw cooler</b>	W105	1	m2	41.00821765	11000	115	1	<b>15716</b>
11	<b>Syngas cooler</b>	W103	1	m2	111.7147272	11000	115	1	<b>23847</b>
12	<b>Tar reactor</b>	R102	1	m3	1	13000	34000	0.5	<b>46409</b>
13	<b>Flue stack</b>	R104	1						<b>10000</b>
14	<b>Gas scrubber unit (glycol)</b>	K101	1	m3/day	up to 100000				<b>125000</b>
15	<b>Gas turbine assembly</b>	K103	1	Mw	up to 100				<b>100000</b>
16	<b>Chopper mill</b>	Z101	1	ton/h	10	400	9900	0.5	<b>31707</b>
17	<b>Nitrogen pump</b>	P101	1	l/s	1	3300	48	1.2	<b>3348</b>
18	<b>ASU</b>	K102	1	m3/hour	up to 3000				<b>1000000</b>
19	<b>Ceramic filter</b>	S102	2						<b>10000</b>
20	<b>Ash screw cooler 2</b>	W104	1	m2	0.163321025	11000	115	1	<b>11019</b>
21	<b>Nitorgen heater</b>	W101	1	kW	7				<b>1000</b>
22	<b>Oxygen heater electric</b>	W102	1	kW	130				<b>10000</b>
23	<b>Water chiller</b>	W106	1	kW	192				<b>45000</b>
24	<b>Ash storage</b>	Z102	1	m3	50				<b>15000</b>
25	<b>H2 Mebarane filter unit</b>		1	m3/h	up to 320,000				<b>780000</b>
	<b>Variant B</b>								

*Table 19.. Cost and size of equipment*

Additional calculation for sizing of basic equipment (reactor, cyclone, scrubber) can be found in appendix D,E,F respectively.

The unit number 25 from table above is referred to Variant B of economical pay back scenario, which is described in the next chapter.

Variant A – assumes final utilization of syngas for combustion in gas turbine generator assembly, to produce and sell eventually electricity in terms of getting profit.

While Variant B is separating Hydrogen from Syngas by means of membrane technology, and selling gaseous or powdered hydrogen.

Thus, CAPEX (capital expenditures) can be known, by summing up all individual cost prices.

<b>Capital cost A</b>	<i>1565159 USD</i>
<b>Capital cost B</b>	<i>2345159 USD</i>

Taking into account additional 40% for construction and extra 30% for project engineering spending, the Grand Total Cost results in :

<b>Grand Total A</b>	<i>2.66 Mln USD</i>
<b>Grand Total B</b>	<i>4.17 Mln USD</i>

### 5.2 Payback period [\[16\]](#)

To estimate the payback time, we should calculate many parameters: direct operating cost (raw material, laboratory etc.), indirect operating cost (insurance, corporate directions), distribution cost (transport), income from sales (see Tab.4.4).

Parameter	Unit	Variant A
<b>(revenues from sales)</b>	<b>USD/year</b>	<b>7,360,065</b>
<b>Operating costs excluding depreciation and interest payments</b>	<i>USD/year</i>	<b>6,131,305</b>
<b>Direct operating costs</b>	<i>USD/year</i>	<b>6,007,358</b>
Raw materials	<i>USD/year</i>	5,402,863
Personal costs of employees of the operation	<i>USD/year</i>	291,600
Supervision	<i>USD/year</i>	23,328
Maintenance costs	<i>USD/year</i>	79,823.110
Consumables	<i>USD/year</i>	26607.70
Laboratory	<i>USD/year</i>	2,916
Reserve	<i>USD/year</i>	180,221
<b>Indirect operating costs</b>	<i>USD/year</i>	<b>23,947</b>
Insurance	<i>USD/year</i>	23,947
Corporate directions	<i>USD/year</i>	0
<b>Distributional costs</b>	<i>USD/year</i>	<b>100,000</b>
Transport	<i>USD/year</i>	100,000
<b>Taxable income</b>	<b>USD</b>	<b>1,228,760</b>

*Table 20. Parameters of scenario A*

The detailed determination of each parameter and all carried out calculations are included into Appendix G.

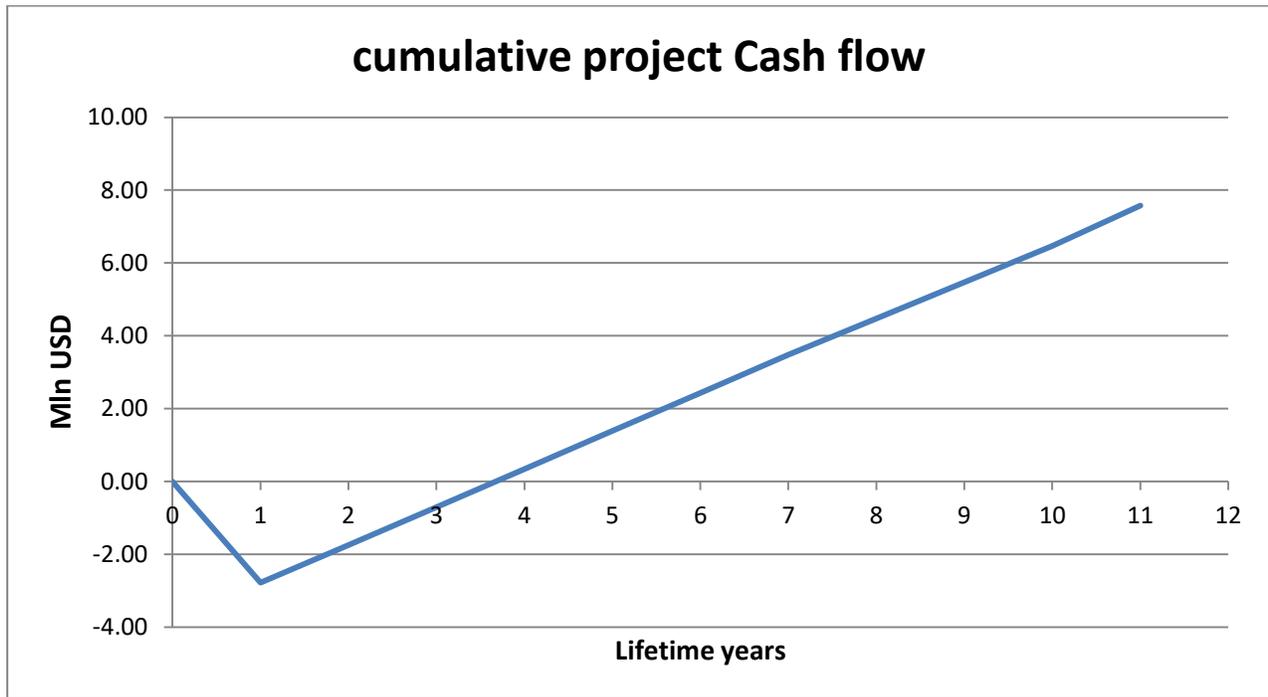
It is seen from table that lion's share of Direct operating cost is raw materials, and in particular that is wood. Thus, it is possible to assume that the economical profitability strongly depends on price of raw material, which is vary depending on place of origin, type of wood, and seller. Consequently, additional sensitivity analysis must be carried out (see next chapter).

Variant A by default is set to have :

Price of raw material wood = 60 USD/ ton

Price of electricity sold = 100 USD/ MWh [28]

The Cumulative project cash flow can be defined and projected using data in table 20



*Figure 21 . Payback time scenario A*

The return of investment time for Variant A is about three and half (3.5) years.

Variant B by default is set to have :

Price of raw material wood = 20 USD/ ton

Price of Hydrogen sold = 1 USD /kg [28]

Parameter	Unit	Variant B
<b>(revenues from sales)</b>	<b>USD/year</b>	<b>4,386,726</b>
<b>Operating costs excluding depreciation and interest payments</b>	<b>USD/year</b>	<b>2,824,948</b>
<b>Direct operating costs</b>	<b>USD/year</b>	<b>2,643,981</b>
Raw materials	USD/year	2,178,783
Personal costs of employees of the operation	USD/year	194,400
Supervision	USD/year	17,496
Maintenance costs	USD/year	137,630.814
Consumables	USD/year	34407.70
Laboratory	USD/year	1,944
Reserve	USD/year	79,319
<b>Indirect operating costs</b>	<b>USD/year</b>	<b>30,967</b>
Insurance	USD/year	30,967
Corporate directions	USD/year	0
<b>Distributional costs</b>	<b>USD/year</b>	<b>150,000</b>
Transport	USD/year	150,000
<b>Taxable income</b>	<b>USD</b>	<b>1,561,778</b>

Table 21.. Parameters of scenario B

The Return of investment time is about 4.5 years

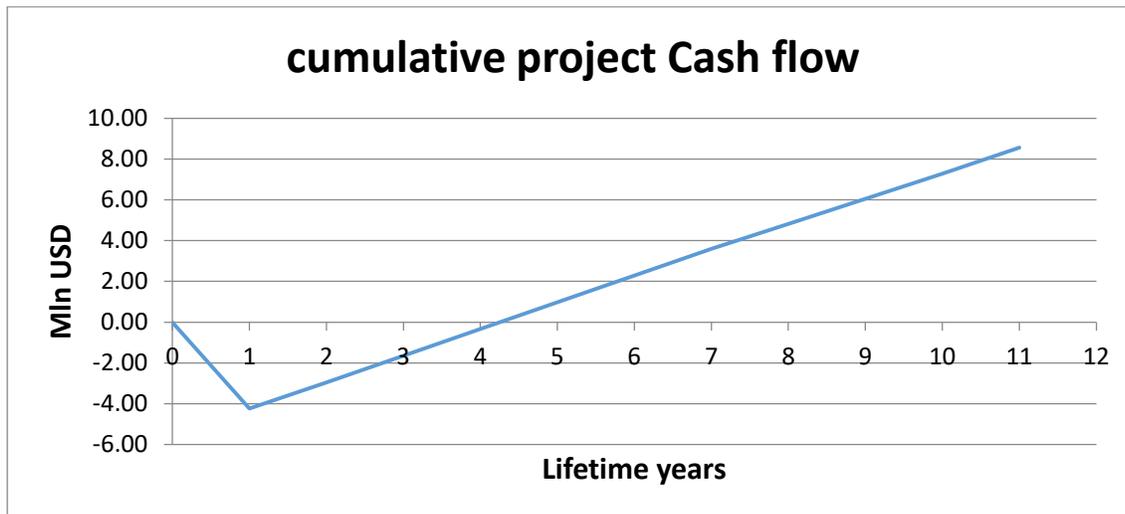
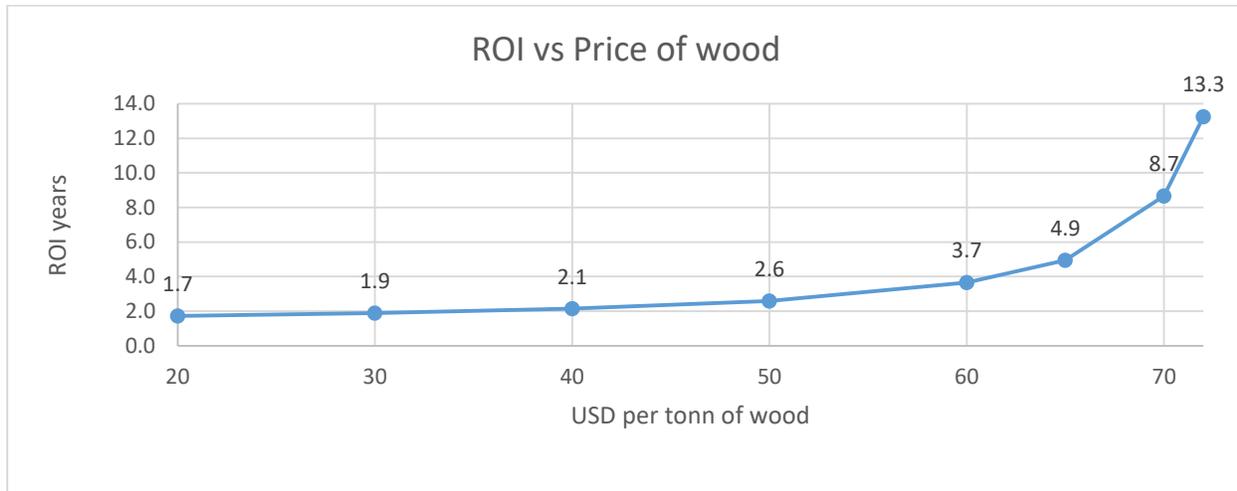


Figure 22 . Payback time scenario B

### 5.3 Sensitivity analysis.

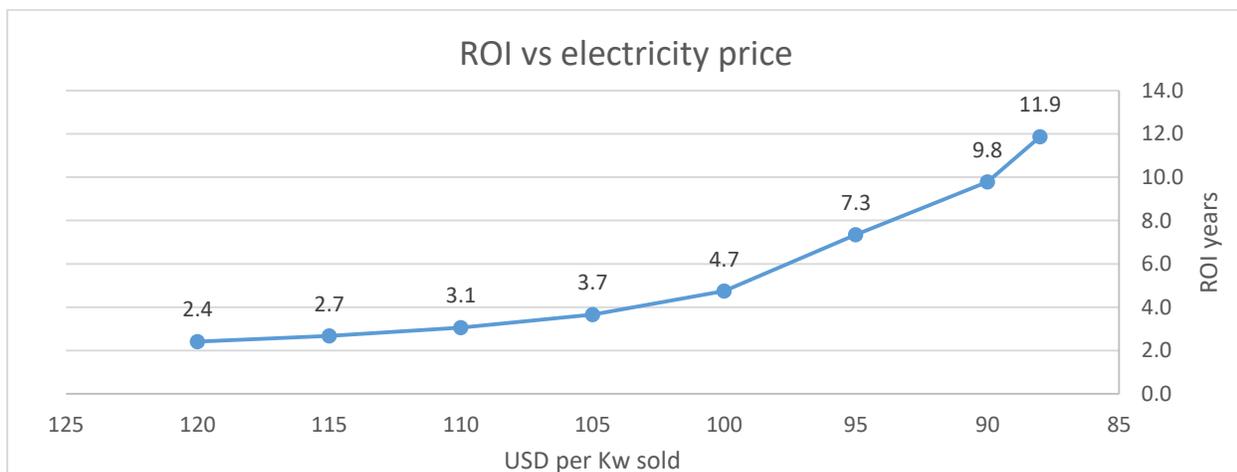
This chapter will show dependence Payback time on various scenarios .

Chart below illustrates ROI time versus price of wood. Price and amount of electricity sold is constant (100 USD MWh ) .It can be noted that, the threshold of economical profitability of this project is at price of wood equals 65-70 USD per ton of wood which ensures payback time of between 4-7 years.



*Figure 23 . Dependence of ROI on wood price*

The Chart below illustrates ROI time versus price of electricity sold. Price wood material is constant (60 USD/ ton) .It can be noted that, the threshold of economical profitability of this project is at price of electricity equals 95-105 USD per ton of MWh sold, which ensures payback time of between 4-7 years.



*Figure 24 . Dependence of ROI on electricity price*

## 6. DISCUSSION

### 6.1 General observations

This section is intended for concluding carried out calculations along with technology used, propose further amendments, discuss what can be improved or eliminated for purpose of better efficiency.

Thus, wrapping up it is possible to claim that, gasification can presumably be one of the best ways to convert waste or specially grown biomass to fuels, in particular as source of relatively cheap and "green" electricity for various usage.

In order to be precise and correctly evaluate potential of gasification several amendments and factors need to be changed/included in further researches.

- Design fully working plant with all PID, safety systems and all auxiliary units included

The real plant requires deployment of more equipment, and more complex technology, which may have direct effect on CAPEX and Payback time eventually.

- Proper and thorough mass and heat calculations must be carried
- Efficiency of plant may be increased by introducing HRSG unit
- Availability of raw materials in vicinity of plant and actual price must be clarified
- Availability of fresh water and WWT facility in the locality of plant

It is important to compare composition of syngas out of gasifier versus composition after tar reformation. Importance of Tar reformer is described in section 2.6

Raw Syngas		Syngas	
vol composition %		vol composition %	
C02	27.9	<b>C02</b>	<b>22.1</b>
CO	25.41	<b>CO</b>	<b>32.5</b>
H2	32.98	<b>H2</b>	<b>38.9</b>
N2	4.6	<b>N2</b>	<b>4.4</b>
CH4+C2H4+C2H6...	8.7	<b>CH4+C2H4+C2H6...</b>	<b>2.07</b>
CxHy tars	0.05	<b>CxHy tars</b>	<b>0.01</b>
sulphur compound	0.02	<b>sulphur compound</b>	<b>0.01</b>
NHC+HCN <	0.34	<b>NHC+HCN &lt;</b>	<b>0.01</b>
Total	100	<b>Total</b>	<b>100</b>

*Table 22 . Syngas tar reformation effect [11]*

Thereby, tar reformation benefits in reduced amount of heavy tars, which can create problems in post processing of syngas and affect H<sub>2</sub>:CO ratio from 1.3:1 to 1.2:1 respectively, which is in fact results in larger amount of H<sub>2</sub> in syngas, making it more calorific ( LHV of Hydrogen is the highest in composition).

Another things, that must be treated with high importance are:

- Effect of changing feedstock on syngas yield

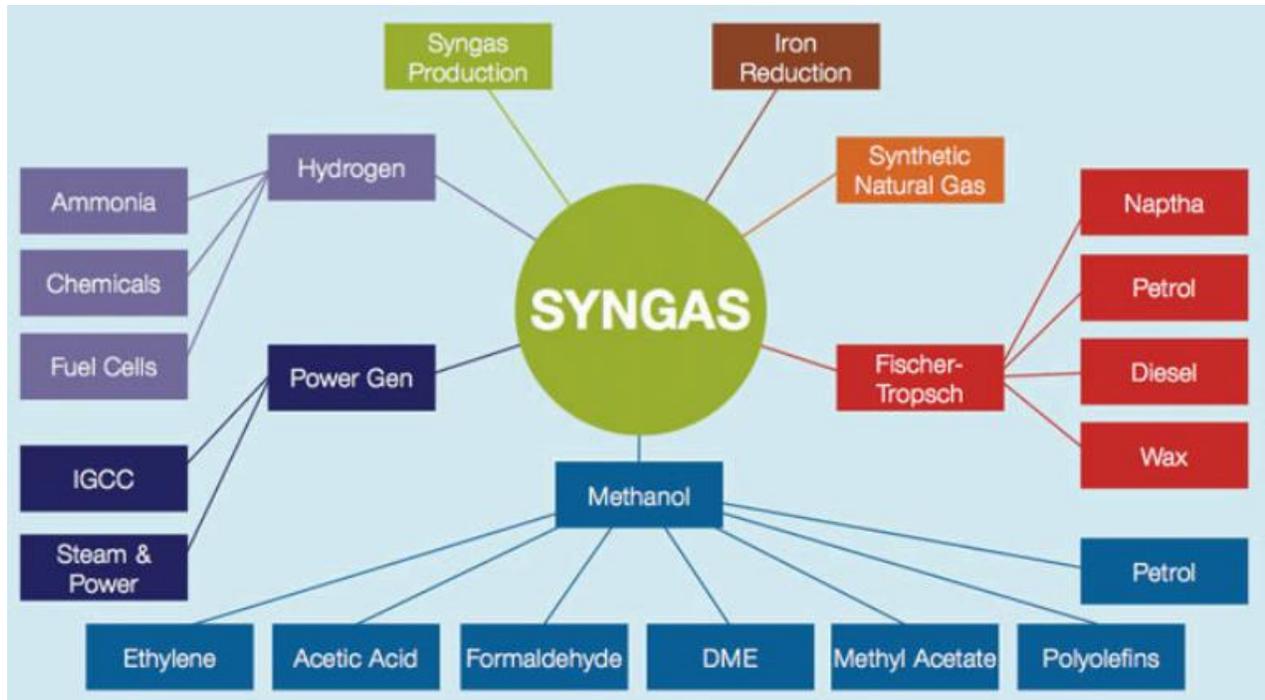
Moisture, ash and Sulphur contents of wood as main raw material is assumed constant, however in reality may vary, changing output gas yield, gas composition and creating possible intermediate process problems.

- Section 6.3 shows that, economical profitability of such project is primarily dependent on raw material price and obviously on final product price (electricity or hydrogen).

Nowadays, there is a tendency of cheaper raw material (wood) ,as it is production is constantly rising. On the reverse, the sources of cheap electricity are in excess, especially from fossil fuels. So, it is possible to presume that, profitability and reasonability of such plant under question in terms of recoument. Making project actual in case of high fossil fuels prices.

## 6.2 Syngas conversion potential

As syngas is extremely versatile in its composition and application, it can be converted through complex technologies to various types of fuels. The potential of syngas conversion is justified owing to high price and value of final (liquid fuel) products and chemicals. All possible routes and product, that can be obtained from syngas are presented below in figure 25.

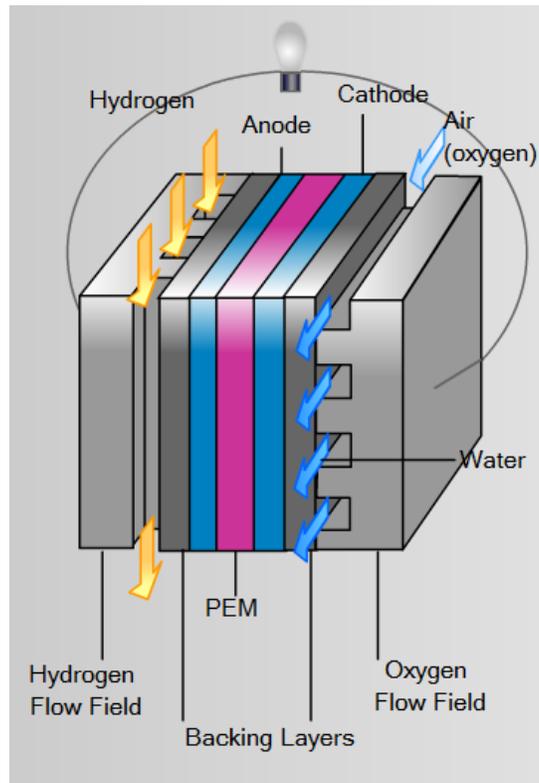


*Figure 25 . Syngas to various fuels conversion routes [25]*

In the previous chapters, the techno-economical potential of syngas to electricity generation was considered. Therefore, using the same process flow, it is possible to upgrade existing technology in terms of separating hydrogen from syngas (membrane technology) and filling (charging) fuel cells.

A fuel cell is a device that converts chemical potential energy (energy stored in molecular bonds) into electrical energy. A PEM (Proton Exchange Membrane) cell uses hydrogen gas ( $H_2$ ) and oxygen gas ( $O_2$ ) as fuel. The products of the reaction in the cell are water, electricity, and heat. This is a big improvement over internal combustion engines, coal burning power plants, and nuclear power plants, all of which produce harmful by-products. The most wide application of fuel cells is powering automobiles, which essentially makes them zero harmful emission “green” and low fuel cost in comparison with others.

Since  $O_2$  is readily available in the atmosphere, we only need to supply the fuel cell with  $H_2$  which can come from an electrolysis process. [26]



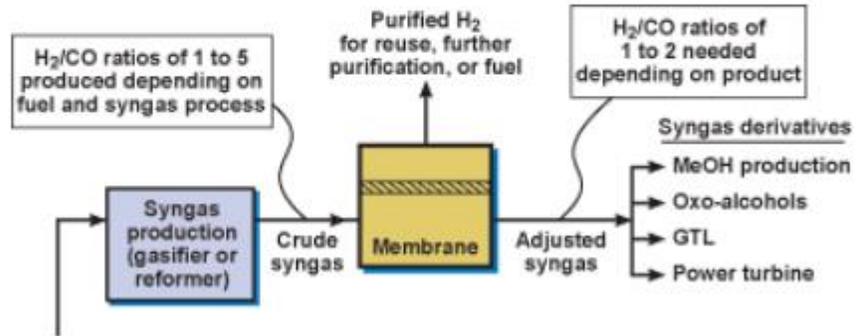
*Figure 26 . General working principle of hydrogen fuel cell [25]*

Hydrogen mainly obtained from natural gas (via steam reforming process) , from coal, or can be separated from syngas.[26]

The membrane separation technology is capable to capture all hydrogen from gas mixture (syngas). There is proprietary technology called “VaporSep- $H_2$ ™ Solution” which suits best for given purpose

VaporSep- $H_2$ ™ offers a simple method for separating  $H_2$  from syngas to adjust the  $H_2:CO$  ratio. In a typical system, the feed gas is first cooled to remove condensable hydrocarbons, and then heated before entering the membrane. Hydrogen preferentially permeates through the membrane, producing a purified hydrogen "permeate" stream and a hydrogen-depleted "ratio-adjusted syngas" stream. This ratio adjustment can even produce high-purity CO for processes requiring it as a feed.[27]

## VaporSep-H<sub>2</sub>™ Solution



*Figure 27 . Process flow of hydrogen separation from syngas [27]*

Mentioned technology costs about 1 mln USD, but deploys quite simple mechanism of separation. Among advantages of this technology are:

- Efficient Hydrogen recovery (up to 95% vol purity)
- Long membrane lifespan
- Simple , reliable and flexible unit
- Easy to install and operate
- Can be integrated to existing line
- Require no chemicals
- Minimal utility usage : low pressure steam, air, Nitrogen, instrument power

### 6.3 Syngas to electricity and syngas to hydrogen results comparison

#### CAPEX

<b>Grand Total A</b>	<i>2.66 Mln USD</i>
<b>Grand Total B</b>	<i>4.17 Mln USD</i>

Where : A – syngas to electricity

B – syngas to hydrogen

According estimates on CAPEX of two different final products from biomass gasification, scenario B (hydrogen generation) is almost twice higher ,due to employment of additional equipment, more complex technology, and disposable replacement parts. The major contribution for the growth of CAPEX is on hydrogen separation unit ( membrane VaporSep-H<sub>2</sub><sup>™</sup>), which costs about 1 Mln USD.

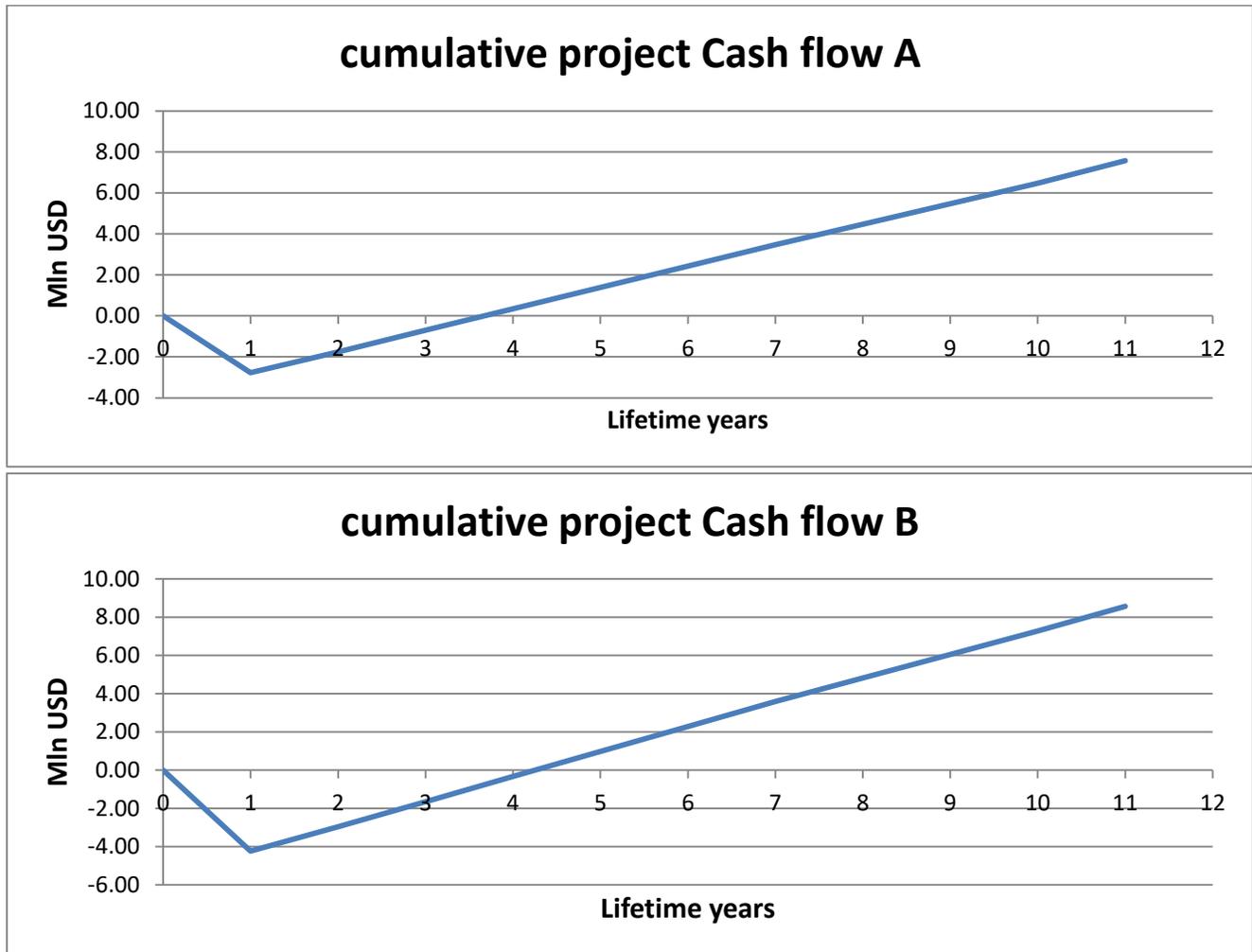
#### OPEX

The operating cost for scenario B , is higher only in small extent, as hydrogen separation does not require any additional raw materials. The most major difference is possibly concealed in transportation cost of final products. Where, for electricity generation (scenario a) , output from generator is connected to a main electricity grid, however hydrogen may create certain difficulties, as it is gas , and takes very huge volumes, thus increasing transportation costs.

For both of scenarios OPEX is mainly comprises and dependent on price of raw materials for gasification.

More detailed and precise research is needed for better comparison of techno economical potential of hydrogen generation.

## ROI



*Table 23. ROI comparison*

The table 23 shows payback time of scenarios A and B respectively. Payback time approximated using on basis of final product price as :

100 USD MWh – for electricity sales [28]

1 USD – for hydrogen sales per kg[28]

In the essence , Hydrogen can be liquefied for easy transportation , but it is very dangerous and expensive process. Therefore, powdered or gaseous hydrogen is assumed to be sold.

From table 23 , it is notable that , profitability of both processes are approximately the same, however more detailed research is needed for accurate results. Moreover , the tendency of cheapening of electricity in contrast with growing demand for hydrogen, will possibly shift the necessity and actuality in favor of hydrogen separation.

## 7. CONCLUSION

The written report covers following section:

- ✓ Comprehensive literature research and carried out calculations show that syngas production might be key conversion technology of biomass to fuels.
- ✓ Further research needed to reveal and increase potential of gasification of biomass.
- ✓ Mass and energy balances were calculated for all streams, suitable machines and apparatuses were chosen for technology. Description of process streams, machines and apparatuses positioning are required part of flowsheet.
- ✓ Detailed flowsheet of a plant was designed. Amount of Electric Power which can be generated was calculated. PFD was prepared using Autocad 2016 software.
- ✓ Based on Economic analysis, were found that ASU is about 30-40% of total cost.
- ✓ Payback period of such plant can be around 3-7 years.
- ✓ Comparison of two possible scenarios from syngas conversion has been made
- ✓ All calculations were programmed and calculated in Microsoft Excel software. Modifying input data, mass, energy and economic balances of new technology are instantly and easily recalculated.

## SYMBOLS

### *Basic quantities*

$a, b, n$	Correlation factors	-
$C_e$	Capital cost	\$
$\dot{m}$	Mass flow rate	$kg \cdot s^{-1}$
$Q$	Power	$kW$
$Q_{el}$	Generated power	$kWh$
$\Delta T$	Temperature difference	$^{\circ}C$
$C_p$	Specific heat capacity	$kJ \cdot (kg K)^{-1}$
$P$	Pressure	Pa
$S$	Heat transfer surface	$m^2$
$V$	Volume	$m^3$
$T$	Temperature	$^{\circ}C$
$\rho$	Density	$kg/m^3$
$\eta$	Efficiency	%
$\eta_e$	Efficiency of electricity production	%
$X$	volume fraction	%

### ***Subscripts***

CAPEX – capital expenditures

HRSR – Heat regeneration steam generation unit

BFB – bubbling fluidized bed

CFB – circulating fluidized bed

ROI – return of investment

PID – piping and instrumentation diagram

WWT – waste water treatment

Eff – efficiency

LHV – lower heating value

HHV – higher heating value

PFD – process flow diagram

ASU – air separation unit

TEG – tri-ethylene glycol

GDU – glycol dehydration unit

EU – Europe union

USD –united states dollar

CGE – cold gas efficiency

CPR – compression pressure ratio

CHP – combined heat and power plant

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